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**MAGYARORSZÁG ENERGETIKAI SÉRÜLÉKENYSÉGÉNEK
FELMÉRÉSE**

ENERGY-RELATED VULNERABILITY ASSESSMENT OF HUNGARY

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1. INTRODUCTION

Climate change has its impacts on our lives, often affecting us even without its presence becoming noticed. In the current era of globalization, pandemics, and international conflicts, the focus on our daily necessities becomes even more pronounced. While it might be evident for many of us living in developed areas, a significant part of the global population is deprived of access to fundamental resources like fresh water, electricity, and food, not to mention their basic physical and mental security. The significance of the Sustainable Development Goals (SDGs) becomes especially apparent under such circumstances and emphasize that the threat to the climate is not solely posed by developing nations.

While at first thought, Hungary may still not be among the most severely impacted regions by climate change, its effects are also visible in the Hungarian citizens' everyday lives. From milder winters without "White Christmas" to immensely hot summers with heatwaves and persistent drought, these changes pose new challenges in many areas, such as agriculture, healthcare, technology and, of course, the energy industry, which is the main topic of the assessment below.

Considering the escalating climate change, the significance of energy and the global initiative of transitioning to sustainable alternatives have never been more pronounced. Energy systems stand as both major contributors to global carbon emissions and central components of strategies for mitigating climate change. The ongoing energy transition, marked by a shift from fossil fuels to renewable sources, underscores a new technological revolution in human history. During this process, the choices we make about energy crucially shape the future of mankind on our planet. This transition is not a uniform process, its impacts vary across regions, as different socio-economic characteristics require different adaptability and mitigation strategies. These diverse conditions and initiatives create distinct vulnerability and resilience patterns. Some areas may thrive in embracing renewables, experiencing an economic boom but a high dependence on weather changes, while others, tied to traditional energy sources, may face increased sensitivity due to public acceptance of fossil fuels. However, the latter can enjoy a temporary but still a relatively lower vulnerability provided by a stable energy supply. Understanding the complex interplay between energy trends, the transition process and regional vulnerability are essential in formulating effective climate policies and fostering sustainable development.

Focusing on the link (or in some cases, the differences) between social characteristics and energy consumption trends, this research aims to determine the degree of vulnerability of

Hungarian counties and explore the spatial patterns. The elaboration of a vulnerability-scoring model, based on an indicator-driven approach, enables a comprehensive comparison of the counties from various perspectives, also allowing a clear interpretation of the obtained data. Such an exploration into Hungary's energy-related climate vulnerability could serve as a valuable resource for stakeholders, ranging from policymakers and researchers to local communities dealing with the impacts of the changing climate. Understanding the specific vulnerability of each county will allow targeted interventions, whether through policy initiatives, target setting or new infrastructural investments.

1. LITERATURE REVIEW

1.1. Climate change

1.1.1. What is climate change?

Climate change is one of the most pressing global challenges of our time. This phenomenon is very often referred to in our daily lives, yet awareness in this topic is still lagging behind expectations. According to the UN (2023), climate change in general refers to long-term and significant changes in temperature and weather. It should be emphasized that climate change is a long-run process: although *weather* can only be referred to as a short-term characteristic, the phenomenon *climate* means the “long-term behavior” of the atmosphere (NASA, 2017).

Changes in weather patterns might not be noticeable for humanity, but after the detailed examination of the long-term effects, several trends might be detected: sea levels are rising, more and more severe weather events are taking place – such as hurricanes, changing precipitation patterns, extreme droughts and heatwaves – not to mention the issues touching biodiversity (European Commission, 2023a). Although these factors may cause serious damages on their own, they are also having their impact on our lives in many other dimensions, such as business, agriculture, industry, politics and even our private habits.

The saddest part of climate change is in its roots, as the process itself is driven mainly by human activities (Trenberth, 2018). The latter include deforestation, burning of fossil fuels, and above all, the releasing of greenhouse gases (GHG) into the atmosphere. The accumulation of greenhouse gases traps the heat in the atmosphere and eventually causes the Earth’s temperature to rise – this process is called global warming. Greenhouse gases include carbon dioxide, methane, nitrous oxide and fluorinated gases, out of which carbon dioxide must be highlighted. CO₂ accounts for three quarters of total emission (figure 1), and is primarily generated by human-induced activities and impacts, such as burning of fossil fuels, industrial processes, forestry and other land use (US EPA, 2023). The biggest emitter sectors throughout the last few decades have been transportation, agriculture, industry and energy systems (Lamb et al, 2021), so either directly or indirectly, we all have taken part at the global warming of the Earth.

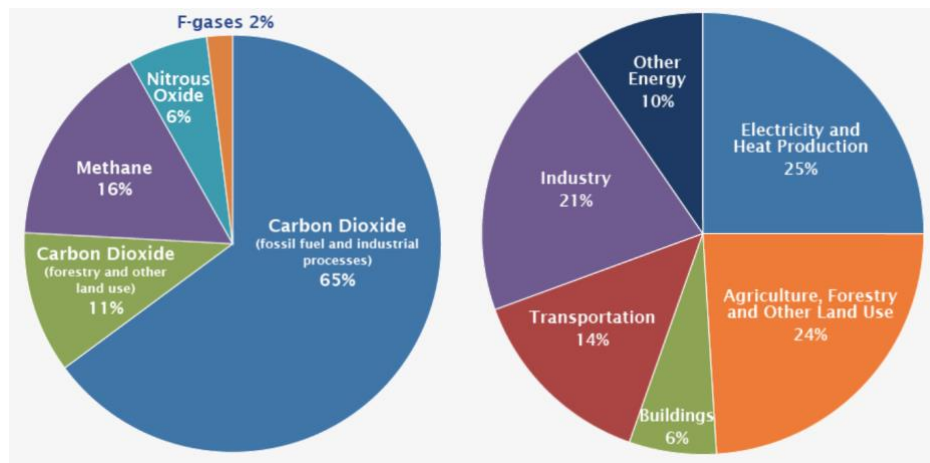


Figure 1: Global greenhouse gas emission breakdown by gases (left) and by economic sector (right)

Source: US EPA, 2023

To emphasize the urge of decreasing greenhouse gas emissions, historical data of global emissions must be analyzed. Figure 2 shows the annual CO₂ emissions from various world regions between 1900 and 2021. As the chart shows, global emissions have seen a general upward tendency in the last decade. At a time when the importance of climate change has already been realized, this is not a feasible way for a sustainable life; on the other hand, emissions must be decreased, and the world should aim for net zero. Unfortunately, contrary to the ambitious global and national decarbonization targets, the world as a whole has not yet reached its peak in GHG emissions (Ritchie et al, 2020).

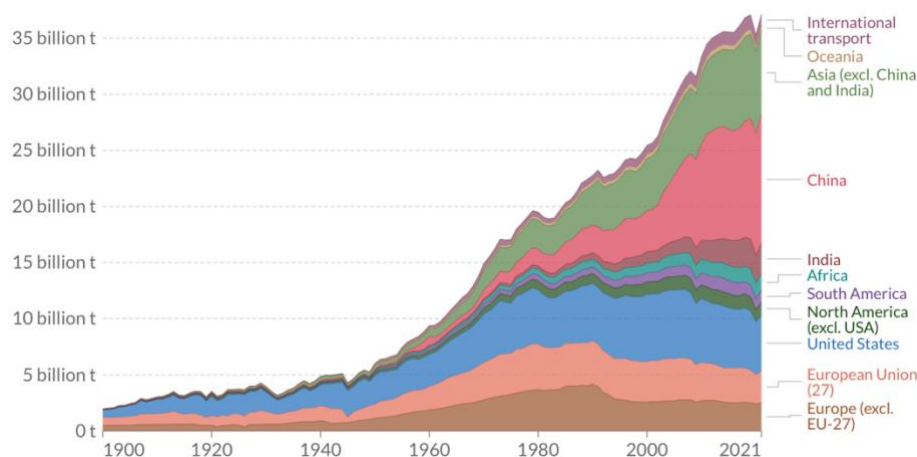


Figure 2: Annual CO₂ emissions by world region

Source: Ritchie et al, 2020

Furthermore, geographical inequalities also must be pointed out. GHG emissions are not distributed equally, different regions have variable amounts of emissions. The biggest emitter is Asia without a doubt, especially China and India, which can be associated with rapid

industrialization and high energy consumption. Europe has already been making its efforts to decrease its emissions. That already had its results, as also seen on the graph. On the other hand, the region must continue its actions to reach the net zero stage in the next few decades. Although Africa emits relatively less GHG, its emissions are expected to grow due to the expected economic development. Another concern for the region is the threat of emission offsets – developed and wealthier countries might consider the opportunity of offsetting their emission-needy activities into continents that have lower emissions and wages (e.g. Africa) thus increasing income and quality-of-life inequalities at the same time (Padilla et al, 2006).

Moreover, inequality between households with different levels of emissions must also be highlighted: IPCC (2023) proved that 10% of households with the highest per capita emissions contribute 34-45% of global household GHG emissions, while the bottom 50% contribute only 13-15%. Based on these data, we may conclude that there is a big gap between different lifestyles and habits of societies and nations in the field of GHG emissions, so regarding inequality patterns, not only environmental, but social and economic impacts must be assessed, as well.

To avoid – or at least, mitigate – the impacts of possible climate-change-caused catastrophic events described by David Wallace-Wells (2019), such as severe biodiversity loss, glaciers melting, water and food shortages in the long run and even unbreathable air quality, urgent and joint action is needed. Global decarbonization targets must be set and humanity needs to be incentivized to take action for a sustainable future.

1.1.2. General impacts of climate change, possibilities for adaptation

Climate change has diverse impacts on both society and economy, to which everyone should adapt in the best possible way so as to avoid negative long-term consequences. Rising temperature, changing precipitation patterns and extreme weather events are direct effects, but they also lead to changes in many aspects of life indirectly. For example, agriculture is one of the most affected sectors by these, as not only productivity is decreasing, but cultivated soil might also be damaged due to extreme conditions. As an adaptation possibility, climate-resilient farming practices, new technologies and digitalization must be utilized to avoid irreversible damages (Howden et al, 2007).

Shifts in climate conditions also impact ecosystems, including changes in distribution of species, loss of biodiversity, and disruption of natural habitats. Nature-conservation measures (such as protected areas) may contribute to adaptation and mitigation as well, but, as Veerkamp

et al (2010) also agreed, more ambitious policy and actions must be taken for a more sustainable future of ecosystems.

The most visible effect of climate change is its impact on human health: many illnesses can be associated with changing climatic factors, while previously existing diseases are also worsened by weather extremes. The best-known climate-related illnesses are vector- and water-borne diseases, while people suffering from cardiovascular diseases or allergies are also more vulnerable to changing weather. Although some symptoms can be relieved to some extent via medicines or vaccines, many other climate-related initiatives are needed as additional parts of adaptation: for example, generating more energy from renewables may improve health conditions and lower human vulnerability by reducing air pollution (Haines et al, 2006).

As climate change is a very complex process, setting up a full list of its impacts would be difficult. However, as a non-exhaustive introduction, agriculture, human health, and biodiversity should be highlighted as being the most vulnerable sectors of human life. Besides those above, local economies, urbanized areas, industry, power markets, and even culture needs to adapt to climate change, as either directly or indirectly, that deeply influences all of our lives.

1.1.3. Climate change vulnerability

As global warming continues to spread all over the planet, its consequences are becoming more and more evident for humanity. Different regions are hit by various climate change issues differently – for example, some regions are experiencing extreme drought, while others face more challenges due to melting of ice caps – yet everyone is affected to some extent. There is no general rule on the spread of such consequences around the Earth. In many cases regions more affected by harmful changes have already been experiencing serious difficulties with issues like poverty or other climatic conditions (Trenberth, 2011). So, climate change may result in “the rich get richer and the poor get poorer”, which is also known as the Matthew effect (Perc, 2014).

To measure susceptibility of regions or societies to harms and damages of climate change, vulnerability is to be assessed. According to IPCC’s Third Assessment Report (2001), “climate change vulnerability” describes the degree to which a system is not able to cope with the effects of changing climatic patterns.

Climate change vulnerability of a system is determined by three factors: exposure, sensitivity and adaptive capacity. To be able to analyze the situation of a certain system correctly, it is important to break down vulnerability into lower-level components. This way, decision-makers

might have the right statistics to build resilience initiatives and targeted interventions on, while potential risks may also be highlighted (Thomas et al, 2019).

Sensitivity refers to the extent a certain system is affected by climate change (IPCC, 2001). For example, mountainous areas and arctic ecosystems are more sensitive to global warming, as they are adapted to cold temperatures, while Mediterranean areas are better accustomed to warmer weather (US EPA, 2019).

Adaptive capacity captures the ability of a system to adjust to the changing climatic conditions. As mentioned before, the Matthew effect occurs in adaptive capacity with a high relevance: for example, countries and societies that have access to better technologies – both know-how and resources – are generally better equipped to cope with changes, thus creating a higher adaptive capacity for wealthier regions (even though this may vary on many factors depending on specific situations) (IPCC, 2014).

Following the IPCC's new approach, we might not highlight exposure as a significant, dedicated part of the vulnerability assessment, but other studies also include that as a key element of the concept (Turner et al, 2003; Fuchs, 2012). Exposure refers to the degree to which a system is exposed to the consequences of climate change (IPCC, 2003). This factor should inevitably be examined for vulnerability, as a certain issue might be less relevant in some regions, thus making the overall vulnerability also lower. For example, sea level rise hardly affects those living on mainland far from water bodies, while coastal areas are much more endangered. Exposure might put additional emphasis on specific characteristics in the general vulnerability (e.g., the above-mentioned sea level rise), so that the measurement should represent a more specific issue-related susceptibility.

To be able to determine and develop efficient adaptation strategies facing changing climatic factors, it is important to get to know the level of vulnerability in different regions. Based on vulnerability measurements, especially supported by the right external socio-economic factors, decision-makers may incentivize activities that could reduce the risk of any potentially harmful event (Füssel et al, 2006).

1.2. Effects of climate change in Hungary

1.2.1. General effects

Temperature rise has diverse effects on our planet, which also concern Hungary to a large extent. As the Earth's climate continues to warm up and human activities causing this process are not dropped or reduced, a wide range of impacts, either directly or indirectly, become more

and more visible for every citizen. Although rising sea level is not exactly the biggest problem of the Hungarian nation, many other effects are seriously present in the region. Understanding and recognizing the urgency of these challenges is inevitable for both mitigation and adaptation. Temperature rise is hard to notice on the short run, especially from day to day, because changing weather is part of human life. Also, there is a high fluctuation in temperature, especially due to seasonal changes, but it is also not unusual to wake up to completely different weather conditions in one morning or the other in the same season, as precipitation, sunshine and wind are all significant parts of the Earth's climate system. Contrary, if we analyze the long-term data about temperature of Hungary, we may notice the increasing tendency as a general principle of the last decade, also seen with a red line on figure 3. This rise is even more problematic in the long run than expected, as the average increase was at least 1.15 °C in Hungary, which is significantly higher than the global estimation of 0.9 °C. Furthermore, summers are even hotter than other seasons, while winters are getting milder – meaning that the number of frosty days (days with minimum temperatures under 0 °C) is decreasing in time (Second National Climate Change Strategy, 2018).

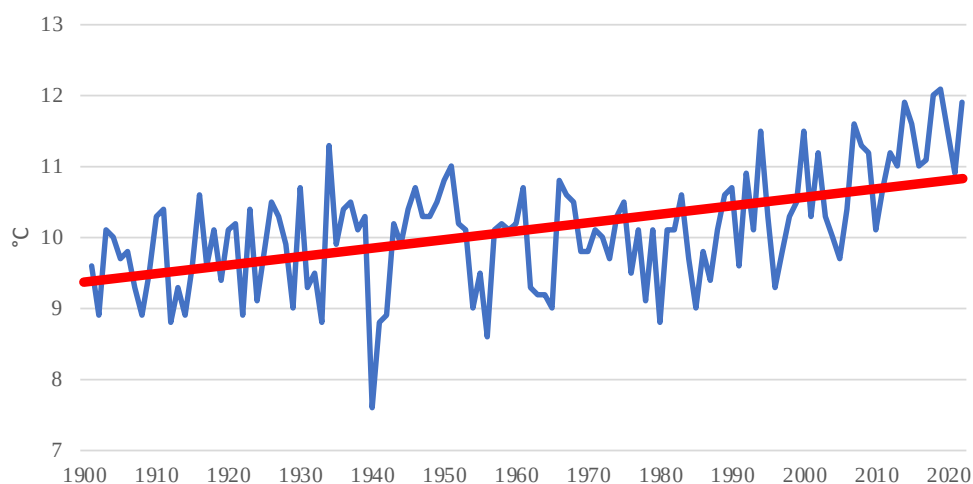


Figure 3: Average temperature in Hungary between 1900 and 2020

Source: KSH, own edit

This trend does not only contain the above mentioned one-degree change, but also the increasing number of heatwaves, the milder winters, and the extreme droughts that the country experienced in recent years.

Furthermore, geographical patterns have also had their role: in general, the southern and the central parts of the country have been affected by the most heatwaves. On the other hand, the

north-eastern corner of Hungary has experienced the most dramatic change of the average temperatures, the increase of which in some cases, was even higher than 1.8 °C per year. The area of the capital city has also seen similar trends in summer (see Figure 4). Unfortunately, higher temperatures, mild winters and heatwaves *ceteris paribus* are expected to stay in the long run in Hungary (Pongrácz et al, 2013).

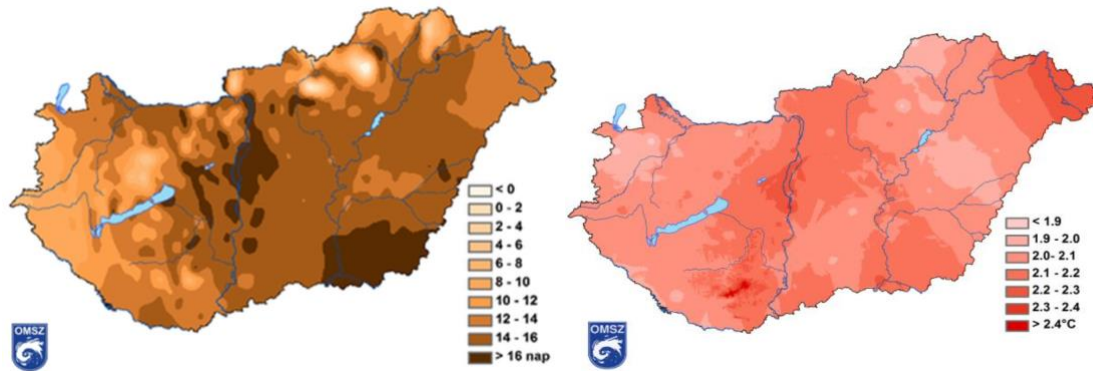


Figure 4: Change of heatwave days between 1981-2015 (left) and average temperature changes in summer between 1981-2017 (right)

Source: OMSZ, NCCS 2

In order to evaluate weather extremes, data from five cities of Hungary were examined in more detail: Budapest, Debrecen, Szeged, Pécs and Szombathely. These settlements are important cities of the country; The National Meteorological Service also shares data of these settlements as benchmarks for the country as a whole. As for weather extremes, the average temperatures above 25 °C, the maximum temperatures above 30 °C and the minimum temperatures under -5 °C were considered to be outliers. Figure 5 shows the number of days per year with extreme temperatures measured in Budapest and Szombathely, those data considered to be two “tails” of the experiment. Generally, it can be observed in both settlements that the number of extremes is increasing, regarding both average and maximum temperatures. Contrary, the number of minimum temperature extremes is decreasing at the same time, also indicating the presence of global warming.

All in all, we can state that the gap between the number of heat and cold extremes is getting wider, which is not a positive trend from the climate’s point of view. One difference between the two cities is the timeframe of these events: while the gap has already been present in Budapest from the 1990s, Szombathely’s data is only following the same pattern delayed in time, and with lower number of cases. As for the other examined cities, their statistics are

between the two above, showing that the more urbanized the area of the settlement and the higher the population, the earlier the gap appears.

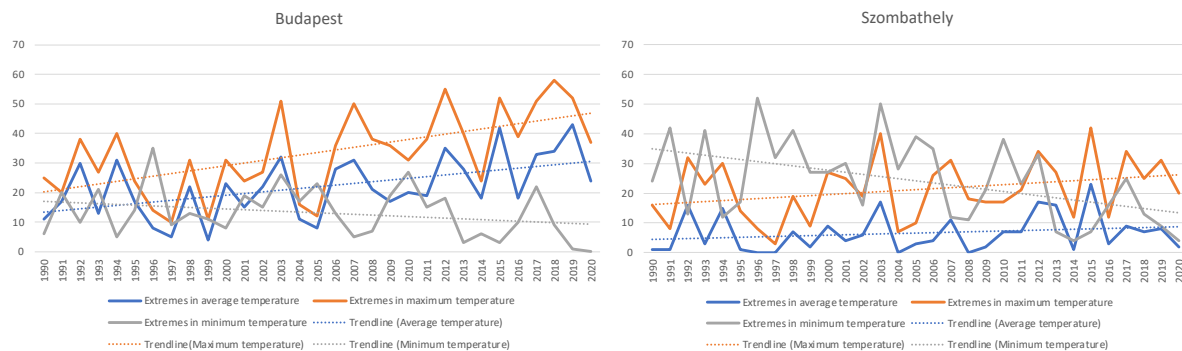


Figure 5: Number of weather extremes per year in Budapest (left) and Szombathely (right) between 1990 and 2020

Source: OMSZ, own edit

Changes in precipitation patterns are less clear than in temperature. There are fewer days with precipitation, with a decrease of 17 days since 1901, and longer dry periods, with an average of 4 days since the beginning of the last century. Between 1961 and 2015, there is a small, non-significant increase in annual average precipitations, with an average of about 4% nationwide, but its distribution varies between both regions and seasons (NCCS 2, 2018). Extended periods of dryness may result in severe challenges for agriculture. Those also badly affect human health via a higher extent of pollutants, leading to different issues, ranging from water-, food-, zoonotic-, and vector-borne diseases to malnutrition (Salvador et al, 2020).

1.2.2. Effects on the energy sector

Like many other countries, Hungary has been experiencing an increase in electricity consumption. The factors causing that are: population growth, economic development and changing technological habits. As, due to electrical devices, technologies and other services, more and more consumers are relying on electricity on a more regular basis, the electricity demand has risen by almost 10 000 GWh as compared to the 1990 level (see figure 6) (KSH, 2023c).

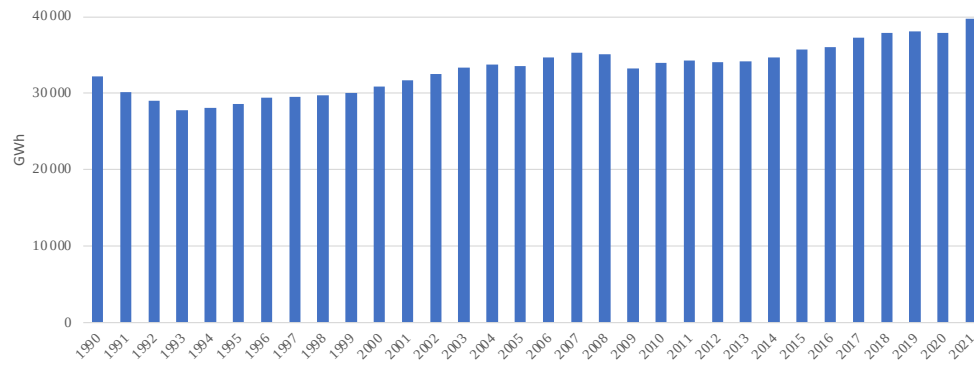


Figure 6: Net electricity consumption of Hungary between 1990 and 2021

Source: KSH, own edit

As for the connection between the increase of temperature and electricity consumption, a very complex relationship may be revealed. Rising temperatures have an unquestionable impact on electricity consumption, causing higher demand for heating and cooling technologies. As for the Hungarian case study, the previously mentioned effect may be observed: there is a strong connection between temperature rise and electricity consumption. As mentioned before, there is a clear difference between the examined cities in terms of temperature (settlements with a larger population are experiencing higher temperatures), but the same pattern is present in each of those. The amount of electricity consumed (at national level) follows the same pattern: the higher the temperature, the higher the demand for electricity in general (also see on figure 7). Of course, there are some outliers (e.g., 2004-2005), which can be explained by the “noise” surrounding these data: although electricity consumption is highly influenced by changing weather conditions, differences in lifestyle and habits, socio-economic background, technologies, market prices and regulations may all have diverse impacts on the quantity of electricity needed.

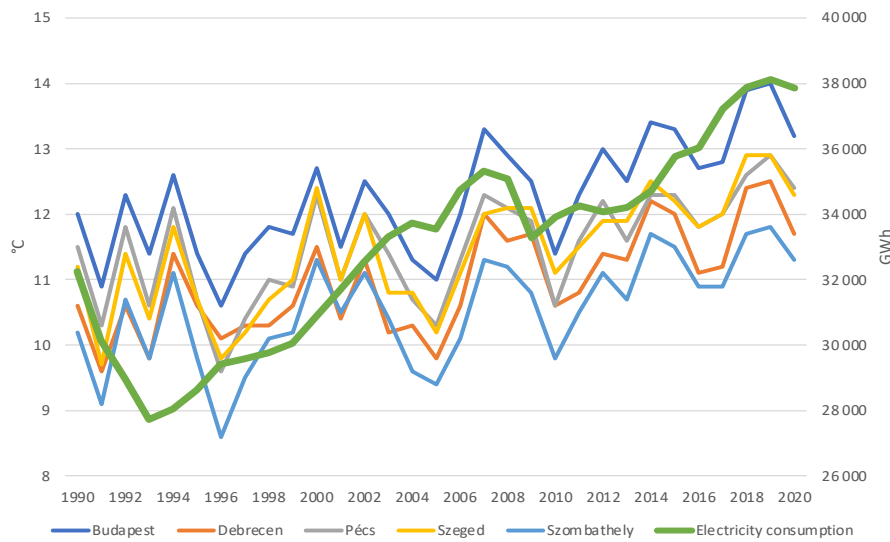


Figure 7: Average temperatures and electricity consumption in the 5 chosen cities between 1990 and 2020

Source: OMSZ, KSH, own edit

Contrary to empirical data, adverse effects have also been observed in different geographical units: as for countries with heating systems highly reliant on natural gas, demand for electricity might decrease on mild winter days, as heating is provided by gas-fired technologies (Blázquez et al, 2013; Kang et al, 2022). Furthermore, under better weather conditions, people are more likely to engage in outdoor activities, resulting in no household consumption. Although Hungary's heating supply also contains a very high amount of natural gas (69% - MEKH, 2022), this situation is expected to change in the near future, due to the dependence on Russia and other initiatives set for decarbonization. Based on the expected transition, including electrification of heating supply, it can be assumed that the electricity consumption in Hungary is going to face an even higher increase in the next few decades.

As for extreme weather events, the increase in the number of those may also influence electricity consumption habits. Based on the data about the number of days with extreme weather events in the examined cities (presented in chapter 2.2.1), it can be proved that there is a linkage between the number of extremes and the electricity consumption. Based on categorization of Guilford (1950), if the value of the correlation coefficient is between 0.4 and 0.7, that represents a medium-strength but significant correlation, which was the case for two of the settlements. On the other hand, Debrecen, Szeged and Szombathely have lower correlation coefficients, meaning that there is a secure, but weak connection between consumption and weather extremes in those cities.

Table 1: Average correlation between electricity consumption and number of weather extremes

Source: own calculation

	Correlation coefficient
Budapest	0,46
Debrecen	0,38
Szeged	0,34
Pécs	0,41
Szombathely	0,29

As a conclusion, it can be stated that the bigger the settlement, the more its consumption is dependent on weather extremes. As for the high correlation in Budapest, two other factors can be highlighted: firstly, as the capital city and the center of the country, Budapest is already more developed than other territories, meaning that it is a location where a higher number of electrified technologies is utilized, and secondly, citizens have a higher urge to stay at home and consume more electricity even under better weather conditions due to the higher number of built-in spaces and the lack of green areas.

In addition to the weather-indicated rise in electricity consumption, there are many other factors that are going to change the demand: from the consumer's point of view, with e-mobility and electrification coming into focus, the number of electric cars is expected to grow rapidly, and the same trend is awaited to happen in the number of public and household electric charging stations. As for the industrial sector, many large investments have already been announced to the public in connection with e-mobility (e.g., manufacturing sites for electric vehicles by BMW and for EV batteries by CATL and Eve Energy in Debrecen), which are also going to result in increased pressure on the electricity grid. Furthermore, another aspect for both small consumers and businesses is the increasing number of (and previously available incentives for) heat pumps and air conditioners, both representing important equipment in the electrification process of the heating sector (MAVIR, 2022).

1.2.3. Decarbonization targets

To efficiently mitigate the effects of climate change, defining clear action plans and goals is necessary. Most directives target greenhouse gas emissions and renewable energy, while energy efficiency and e-mobility incentives are also important steps for achieving sustainability in electricity.

The EU has set short- and long-term goals to transit to a low-carbon economy. The Commission's Proposal (adopted in 2020) and Green Deal summarize its targets, while REPower EU added new initiatives to be able to cope with the energy crisis on a sustainable

way (European Commission 2023c, 2023d). Hungary must also set its own targets making them conforming to the EU's requirements. Most of the final goals are included in the Climate Law, besides the supporting strategies. The latter contain relevant information on the actual stat and the detailed explanation of the initiatives to be developed and carried out (National Energy Strategy, Second National Climate Change Strategy, National Energy- and Climate Plan).

The most important group of targets contains decarbonization-related goals. The EU is committed to reducing its greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. EU aims to achieve climate neutrality by 2050, meaning that the EU's total greenhouse gas emissions will be balanced by carbon removals or offsets. Hungary has the same target for 2050, but for 2030, the country has defined a less ambitious target, with a GHG decrease of 40%. Two important conclusions can be made with reference to these targets: firstly, Hungary has less strict regulation in the short run, but in the long run, it has to decrease its emissions much more quickly; secondly, neither EU nor Hungary aims to be completely zero-emitters, as carbon offsetting is still going to be an opportunity for remaining emissions, even if only to a small extent.

As for renewable sources, EU has decided to increase its outdated target of 30% electricity generated from renewables to 42.5% by 2030. Hungary, again, is less ambitious, as based on the latest government documents, only 21% renewable share is targeted by 2030, even though it is expected to reach 30% in most sectors. Mobility should be highlighted in this part, as only 14% renewable share is earmarked in this sector, due to low availability of biofuels and the high need (and costs) of electrification in public transport.

An EU-level mechanism – that also affects Hungarian businesses –, EU ETS (Emission Trading System) must be highlighted. EU ETS is a market-based mechanism that sets a cap on greenhouse gas emissions. Companies can trade allowances, encouraging them to reduce emissions and invest in cleaner technologies (European Commission, 2023b).

All in all, it can be concluded that Hungary's target setting is a bit delayed compared to the ambitiousness of European goals. On the other hand, examining thoroughly EU's strategies, there is a high probability of even EU-level targets not being ambitious enough to be in line with the Paris Agreement's objectives. To hold the Earth's global warming under 1.5 °C, net zero emissions should be achieved by 2040 the latest (Greenpeace, 2018), which is one decade earlier compared to both the EU's and Hungary's targets of achieving carbon neutrality (not even net zero).

Furthermore, to be able to achieve the targets already set, a high number of initiatives and sub-targets are needed, regarding both national and global level. For example, EU or state-funding should be made available to promote renewables to households and businesses, also incentivizing connected technologies and equipment, such as installing heat pumps or household storage (batteries) for photovoltaics. Moreover, with the advance of technology, more and more smart solutions have become available for the public, such as smart meters, which may decrease the pressure on the electricity grid, thus resulting in higher capacity for intermittent sources. Although these devices do not substitute physical grid extension and upgrade, they may provide advantages for both grid operators and consumers.

1.3. Electricity market in Hungary

1.3.1. Market actors

The electricity sector plays a crucial role in the country's economy, as it provides energy to households and businesses. Electricity is an essential utility, especially due to electrification- and climate change-related increasing energy needs.

To be able to cover the growing demand and to provide stable supply to consumers, the market must be operated through a combination of regulated activities and market-based mechanisms. In Hungary, Hungarian Energy and Public Utility Regulatory Authority is the regulatory body for the energy and utility sectors, regarding electricity, natural gas, water supply, district heating and waste management. Its responsibilities include market monitoring and related tariff regulations, licensing market participants, consumer protection, statistical reporting, promotion and incentivization of renewables and other environment-friendly developments (MEKH, 2021).

As for energy trading, transmission and distribution of electric power are two differentiated components of the supply chain. Transmission is mostly focused on long-distance transportation and "movement" of electricity, at higher voltage. However, distribution is also inevitable, as its role is to deliver electricity from the transmission system to end-users (for example, households). The structure of market actors responsible for transmission and distribution varies in each region, but generally, network operators have their own operating territory, where they are in a monopoly position regarding the infrastructure used (Országgyűlés Hivatala, 2022).

In Hungary, only one TSO (Transmission System Operator), MAVIR Hungarian Independent Transmission Operator Company Ltd. is present. The company is responsible for the operation,

maintenance, and development of the high-voltage transmission system, while also ensuring the reliable and secure transmission of electricity across the country and maintaining grid stability (MAVIR, 2023).

However, distribution infrastructure is more complex: the country is divided into 6 subregions, where 3 firms operate 6 subsidiaries. The regions have been created on a geographical basis, where each company is responsible for operating, maintaining, and managing their own distribution system. Figure 8 shows these territories and the operating DSOs (Distribution System Operators).

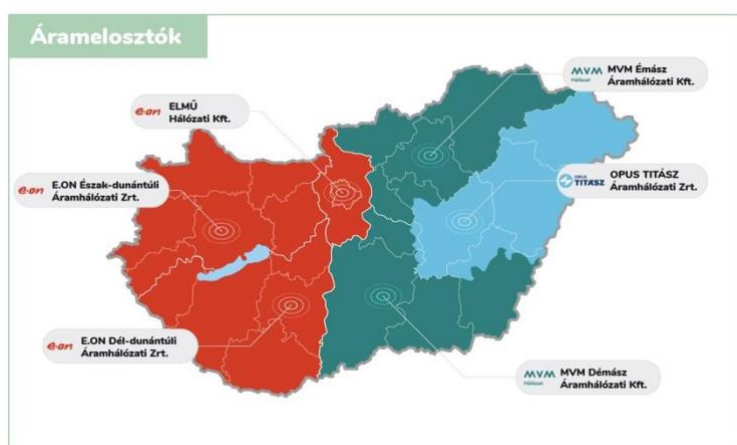


Figure 8: Electricity DSOs in Hungary

Source: MVM Next

As for wholesale and retail, no governmental tariff regulations exist, these markets must be operated on a competitive way via market-based mechanisms. Fees are based on negotiations between suppliers and customers, while each consumer is entitled to choose their supplier based on their preferences and proposals (Országgyűlés Hivatala, 2022). At present, 186 companies have electricity trading licenses in Hungary (MEKH, 2023), which makes the market diverse and suitable for consumers with small and larger electricity demands, as well. On the other hand, some governmental regulations help support households and SMEs, so that they can be less vulnerable to price volatility (Magyarország Kormánya, 2022).

HUPX (Hungarian Power Exchange) is another important player on the Hungarian electricity market. HUPX is the central platform for electricity trading, which is responsible for operating spot, forward and balancing markets, while ensuring the right reference prices (HUPX, 2023). It also serves as a platform for selling and buying Guarantees of Origin (GOs), which are major instruments for greening the electricity supply of companies.

1.3.2. Statistic overview of electricity consumption and production

Figure 9 shows the composition of the electricity consumption of Hungary between 2002 and 2021. In the last 20 years, there has been a general upward trend in electricity demand, driven by many changing factors, such as economic growth, electrification and a growing number of innovative digitalization technologies in both households and businesses. Also, even urbanization processes incentivize higher energy consumption (Durkó et al, 2016). Furthermore, Sugár (2011) approves that both electricity and natural gas demands are influenced by temperature changes as increasing temperature is one of the factors that might have resulted in higher consumption.

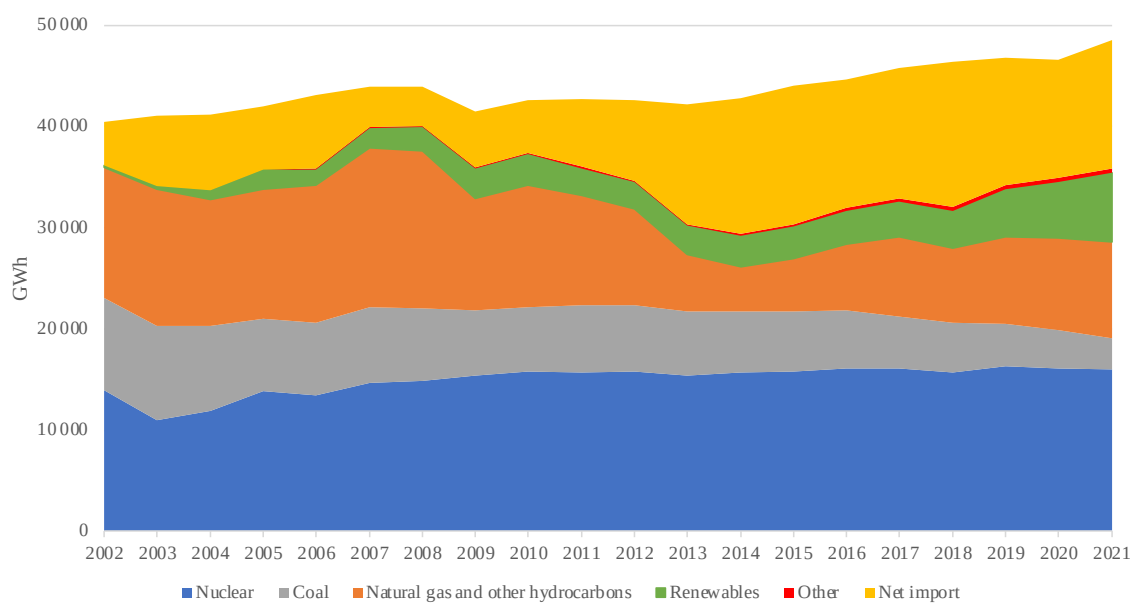


Figure 9: Gross electricity consumption of Hungary between 2002 and 2021 (GWh)

Source: KSH, own edit

Hungary's electricity mix is highly reliant on nuclear power, one third of the electricity demand is generated via nuclear power, which is expected to stay so in the next decade, as the Hungarian nuclear power plant in Paks is planned to be expanded with a new bloc in the next few years (Paks 2, 2023). The first plant has been a significant generation facility of the country since the 1980s. The possibility of a new bloc would make the electricity supply more stable and less dependent on imports, but the Russian technology utilized at the plant is surrounded by safety and even stability debates all over the country. However, although many safety questions arise whenever nuclear power is mentioned, its importance in generating environmentally friendly electricity is clear: nuclear power plants operate with a low level of carbon emissions, especially compared to traditional natural gas or coal-based technologies (note that it is not completely

emission-free, especially from a life-cycle point of view, so renewables are still the best available opportunity) (Sovacool, 2008).

As for climate-friendly electricity generation, two significant processes need to be mentioned: firstly, lowering coal and natural gas-based technologies, secondly, switching to emission-free (or low emission) generating methods. In Hungary, coal is almost completely eliminated from the electricity mix, but the country is still highly reliant on natural gas. On the other hand, the share of renewables has doubled in the last decade, which is inevitable for a climate-friendly electricity supply (Figure 9). The main renewable energy source is solar power, which is getting more widespread across the country. In addition to industrial size photovoltaics, household-size solar PVs are also becoming more and more popular: by 2032, 2400 to 3100 MW (depending on the dynamics of the market) of electricity may be generated from household-size small power plants, which is a high increase from the recent capacity of 722 MW in 2021 (MAVIR, 2022). Moreover, the country has unexploited capacities in wind power, but in the last years, unsuccessful political decisions, long permitting procedures and only little attention to the renewable transition made it hard (and not feasible) for market players to establish wind farms (Antal, 2019).

1.3.3. Future challenges of electricity grid

The recent trends in the electricity market have led to new, previously unseen challenges for market operators. Not only is the grid infrastructure, but the whole power system influenced by the transition. The most important challenges are summarized in this chapter.

Hungary's electricity consumption is highly reliant on import (see Figure 9). As the demand for electricity constantly grows, the domestic generating might not be able to cope with the speed of the increase, thus creating an even higher need for import. Another factor that might result in higher import rates is the spread of renewables: due to their intermittent characteristics, they cannot provide stable supply because of the weather conditions. Importing more electricity makes a country and its consumers vulnerable in terms of energy security and price volatility, while also resulting in more electricity loss during transmission and distribution (Hadmérnök, 2009). Although import dependence might be less risky due to the diversification of connections and EU-level regulations, Hungary still aims to get closer to self-sustainability.

The more renewable sources are utilized, the more decentralized the market becomes, thus putting higher pressure on the electricity grid. Grid renewal and expansion are inevitable. Unfortunately, the Hungarian grid's development cannot keep pace with the increasing needs.

As a result of grid congestion, since November 2022, new solar PV owners cannot feed back their excess electricity to the grid due to the higher quantities of loads (note that the ban is only temporary until further notice of the grid expansion, but there is no news about the situation changing soon) (Magyar Közlöny, 2022). This change has slowed down the return of solar panels, so consumers are less motivated to transit to renewables at households. This incident shows that there is a clear need for grid expansion and renewal of the old wires, but this activity could cost up to 425 billion euros on EU level (Eurelectric, 2021).

Another method to take off some burdens from the electricity grid is to invest in smart solutions. Digitalization is already in progress: e-mobility, heat pumps and solar panels all utilize smart technologies that are able to collect data for remote and smart control. Moreover, artificial intelligence and Internet of Things provide several innovative opportunities for monitoring and optimizing energy usage: smart meters and smart grids may make the grid less congested, while also making the presence of demand-side management and virtual power plant agreements possible. In Hungary, mostly smart meters have started to appear on the market representing this change, but generally, only those consumers have them in their households who also have their own electric car chargers or solar panels. Although there is no information available about the number of smart meters in the country, it might be assumed that Hungary is still behind the EU average as there is no obligation or incentive on installing smart meters for households, except for household-size small power plants (MVM, 2023).

Hungary, as member of the EU, needs to participate at implementing EU targets regarding market modernization and decarbonization. Hungary is obliged to: strive for declining emissions in the energy sector, apply more smart devices and take the necessary regulatory actions for promoting transformation. Moreover, the regulatory background needs to adapt to new concepts and notions, such as new market players (e.g., prosumers and energy communities) or smart devices. Meeting the EU's expectations is an essential step for Hungary to be able to cope with the international standards and to aim for a climate-friendly future.

2. MATERIALS AND METHODOLOGY

2.1. Methodology selection

As the aim of this research is to analyze the impact of climate change on the energy sector in different regions of Hungary, a vulnerability assessment was performed. Vulnerability is important to be examined for both decision-makers and citizens, independently from each other, as adaptation to the changing climate is clearly necessary for both sides, and that can only be achieved by joint efforts and cooperation.

Although, due to its subjective content and static understanding (Ford, 2018), we should treat vulnerability scores with criticism, it is indisputable that there is an increasing need for such measurements in order to analyze the overall effects of climate change (Wamsler et al, 2013). With new and innovative thinking and methodology used in vulnerability assessments, more accurate details can be discovered, which may lead to more efficient strategy-making in obtaining climate awareness and protection.

As for methodologies used in vulnerability assessments in literature, designing vulnerability scoping diagrams (VSD) has been the most widespread practice in research work. The methodology is based on the dimensions of vulnerability, defining representative components for each dimension and converting them into real-life data and indicators, depending on the availability of data and according to a review of literature (Polsky et al, 2007).

Although there are many other ways to describe vulnerability of the specific territories, such as grey relational analysis (GRA) as a statistical tool (Lin, 2007), or the development of a composite index (Gatto et al, 2020), an indicator-based model development at the basis of vulnerability scoping diagrams was selected in this assessment. After careful consideration of various methodologies, this calculation approach was chosen because it best reflects a number of perspectives in the most effective manner, even on county-level. As data were available for many indicators in each county, with the help of this methodology, it was possible to approach vulnerability from a separate social and a standalone energy-related perspective. Also, these approaches could have been included into an overall vulnerability score.

Additionally, the extensive use of vulnerability scoping diagrams in similar literature provided numerous exemplary articles and methodologies, serving as a foundation for developing the model. As for the most influential ones, a few articles must be highlighted: in an energy-related research, Wang et al (2014) developed the vulnerability scoping diagram of renewable energy. All dimensions were defined by 6-10 indicators related to the renewable energy situation in

China. For example, the dimension for exposure contained information on the share of renewable energy, population density and weather characteristics. Sensitivity indicators included wind speed, sunlight, humidity, and temperature changes. Adaptive capacity was defined by indicators like per capita GDP, literacy rate, reserves of other energy and government effectiveness index. The indicators chosen in this assessment served as the basis of the longlist of the indicators used in this research. In this study, however, the list had to be slightly adjusted to account for variations in the topic, its perspective, regional specificities, and data availability.

Secondly, as for the detailed steps of the model development, the calculations of Buzási were mostly considered as an example (Buzási, 2022; Buzási et al, 2021). Even though the topics investigated in the referenced studies (such as vulnerability analyses centered on heatwaves and agricultural drought) may not align perfectly with the focus of this research, the methodologies and computational approaches applied could be used in a similar way for the energy-related vulnerability assessment. The Hungarian context of the studies mentioned, provide further convenience in adopting the methodology, given the similarity in the availability of the indicators utilized across these studies.

Despite limitations and criticism against vulnerability assessments, those are valuable tools in for supporting the process of climate change adaptation and fostering science-based decision-making processes. With the help of methodologies presented and their further development, addressing of climate change and adaptation strategies may become much more efficient in the long run. Furthermore, defining vulnerable areas may also help raising awareness in regions that need more attention for preserving the climate.

2.2. Methodology and chosen indicators

In the context of enhancing adaptability to climate change and extreme weather events, comprehending spatial patterns plays a crucial role in decision-making. While individuals may not be directly engaged in the strategic aspects of the adaptation process, gaining insight into the vulnerability of our localities and surroundings relative to other regions ensures that informed decisions are made. These choices not only lead to the reduction of our individual carbon footprint but also contribute to attaining broader decarbonization and further mitigation targets and fostering the development of a more resilient region.

To comprehend the vulnerability of Hungarian counties, an indicator-based method is employed, utilizing widely available socio-economic and energy consumption-related

statistical indicators. The analysis is conducted across two primary domains: sensitivity and adaptive capacity, aligning with the IPCC's recommended approach. Although IPCC's earlier documents also analyzed exposure as a third dimension, in this study it was not taken into consideration as a separate perspective. This is primarily due to the minimal territorial climate-related differences in Hungary (and even across Europe). If these insignificant differences were also taken into account – for example, as a weighting factor –, it would have resulted in over-amplifying the gaps between the vulnerability scores of each region.

It must be emphasized that the two highlighted dimensions are further analyzed in separate sections, delving into a social- and an energy-specific part of sensitivity and adaptive capacity. While the results from these sections will be averaged in the overall vulnerability analysis, the initial separation enhances the depth of the examination and provides a detailed explanation for each observed pattern.

In selecting indicators, the main aim was to choose data that was up to date for the entire country, and also available on the county level. At the same time, special focus was put on ensuring the ability to analyze energy-related vulnerability comprehensively, while being able to pay attention to local specificities as well.

During the calculation phase, a linear transformation had to be performed to guarantee comparability among indicators measured in distinct units. Whether the indicators fell under the sensitivity or the adaptive capacity category, normalization was executed uniformly using two distinct equations. For indicators where a higher value corresponds to lower vulnerability (such as average net monthly income, GDP per capita, number of doctors, installed capacity of household-sized small PVs and natural gas-fired power plants, and investment in energy infrastructure), the following equation was applied:

$$\text{Normalized value} = \frac{\text{Original value} - \text{Minimum value of the indicator}}{\text{Maximum value of the indicator} - \text{Minimum value of the indicator}}$$

Conversely, when a higher value causes higher vulnerability (registered job seekers, installed solar capacity, ratio of old (65+) and young (0-3) people, aging index, number of people died in cardiovascular diseases, number of people receiving domestic care, average monthly electricity and natural gas consumption per household, average electricity consumption generated by renewables per household), the equation is modified as follows:

$$\text{Normalized value} = 1 - \frac{\text{Original value} - \text{Minimum value of the indicator}}{\text{Maximum value of the indicator} - \text{Minimum value of the indicator}}$$

The average sensitivity and the adaptive capacity were calculated as means derived from the resulting values. Vulnerability represents the average of these two factors and is portrayed as a

social, an energy-related and an overall vulnerability indicator, consistent with the previous categorization. Evaluating the obtained averages, the closer a county's indicator is to 0, the higher its vulnerability in the aspect under consideration, while values nearing 1 indicate lower vulnerability.

The QGIS software was employed to map the calculated values across all dimensions. Data visualization played a crucial role in the analysis, facilitating the identification and transparency of spatial patterns. In the visual representation, vulnerability values were not displayed in uniform intervals. Instead, natural breaks, corresponding to the smallest and the largest values of the resulting values, delineated the boundaries of vulnerability categories. This approach was essential in the analysis, as it aimed to compare the real conditions of the counties with each other rather than determining the degree of vulnerability in relation to an unrealistic maximum/optimal value for each county.

Given the emphasis on energy, it must be highlighted that this analysis does not focus on the sustainability of energy consumption but rather on individuals' and thus, regions' vulnerability to energy consumption. This distinction is significant for the study because the assessment of certain indicators may vary across different approaches to the topic. For instance, an analysis prioritizing sustainability might view the high use of intermittent renewable resources positively, whereas an analysis focusing on vulnerability might perceive the same factor as negative due to heightened exposure to weather conditions.

In the research, indicators were chosen in the categories of sensitivity and adaptive capacity. For the final model, the most recent data available in Hungarian databases were employed, with their key characteristics summarized in Table 2.

Table 2: Selected indicators

Source: own edit

No.	Indicator	Unit of measure	Source	Year	Category	Sector
1	Ratio of old (65+) and young (0-3) people	%	Hungarian Central Statistical Office, own calculation	2022	Sensitivity	Social
2	Aging index	%	Hungarian Central Statistical Office, own calculation	2022	Sensitivity	Social
3	Number of people died in cardiovascular diseases	people / 1000 people	Hungarian Central Statistical Office, own calculation	2022	Sensitivity	Social
4	Number of people receiving domestic care	people / 1000 people	Hungarian Central Statistical Office, own calculation	2022	Sensitivity	Social
5	Average monthly electricity consumption	kWh / household	Hungarian Central Statistical Office	2022	Sensitivity	Energy
6	Average monthly natural gas consumption	kWh / household	Hungarian Central Statistical Office	2022	Sensitivity	Energy
7	Share of energy produced from renewable energy sources in gross final energy consumption	%	TeIR	2021	Sensitivity	Energy
8	Average net monthly income	HUF / person	Hungarian Central Statistical Office	2022	Adaptive capacity	Social
9	Registered job seekers	people / 1000 people	Hungarian Central Statistical Office, own calculation	2023	Adaptive capacity	Social
10	GDP per capita	HUF	TeIR	2020	Adaptive capacity	Social
11	Number of doctors	people / 1000 people	TeIR, own calculation	2020	Adaptive capacity	Social
12	Installed capacity of household-sized small PVs	kW	TeIR	2021	Adaptive capacity	Energy
13	Installed solar capacity	MW	TeIR	2021	Adaptive capacity	Energy
14	Installed capacity of natural gas-fired power plants	MW	TeIR	2021	Adaptive capacity	Energy
15	Investment in energy infrastructure	HUF / 1000 people	TeIR, own calculation	2021	Adaptive capacity	Energy

2.3. Sensitivity

Seven indicators were chosen for the sensitivity analysis, with four reflecting this characteristic from a social perspective and three from an energetic standpoint.

The first indicator focuses on social groups most likely to be vulnerable to climate change. It is important to emphasize the sensitivity of the elderly who are inherently more sensitive from a health point of view to weather changes and extreme heatwaves. Additionally, those people are more exposed to rapid climatic changes due to their lower income (Marvuglia et al, 2020; Calvo et al, 2021). Alongside the exposure of older generations, the vulnerability of young children must also be noted, as extreme weather conditions may affect their immune system as well and increase the risk of potential illnesses for them (Buzási, 2022; Gouveia et al, 2019; Smith, 2019). The indicator depicting the ratio of the elderly (65+) and young (0-3) was selected to incorporate these demographic characteristics into the model, illustrating the spatial distribution of age-sensitive groups.

The aging index, while conveying a similar concept, also holds significance from other points of view (Buzási-Jäger, 2020). Unlike indicators comparing the proportion of older and younger individuals in the total population, the aging index assesses the two generations in relation to each other. This indicator differs from the previous one in its forward-looking nature, as it reflects not only the current but also the oncoming demographic dynamics. The age structure of regions plays a pivotal role in determining resource allocations, including budgets, across various sectors and services (Park et al, 2020). For instance, aging regions may require more emphasis on social support or health enhancements rather than direct adaptability measures (such as developing locally based power plants).

Another crucial factor in pinpointing vulnerable groups is health status. Social groups with poorer health or limited access to quality care are more sensitive to the impacts of climate change, particularly as more frequent and severe weather extremes can disproportionately affect their well-being. For instance, individuals receiving domestic care, due to heightened exposure, are likely to possess limited resources for adaptation and may have less motivation to engage in such activities.

In healthcare terms, cardiovascular patients stand out as the illness group most closely linked to climate change. This association arises not only from the heightened vulnerability to weather changes of the individuals with these diseases, but also because extreme weather events escalate the risk of developing similar health conditions (Kollanus et al, 2021). While current statistics on the prevalence of cardiovascular diseases by the counties are unavailable, a parallel can be

drawn with the mortality rates associated with these diseases. The higher number of people died of cardiovascular diseases in a certain region suggests a greater sensitivity of the society and the health system to the impacts of climate change, on the emergence of such diseases.

Referring to sensitivity, the indicators employed in the energy analysis are more straightforward compared to the social dimension. The average monthly electricity and natural gas consumption reveal the amount of energy utilized per household, and those are important to measure in the energy-related assessment (Wang et al, 2014). A higher monthly consumption signifies a greater reliance on energy for various aspects of daily life (such as operating electric vehicles or running smart household systems), especially compared to “traditional” households. A risk factor associated with natural gas use, import dependency, is a concern that has gained heightened attention globally, especially since the commencement of the Russian-Ukrainian conflict. Exposure to import dependency makes natural gas users more sensitive.

While a higher average quantity of energy produced and consumed from renewable sources is favorable to sustainability, the reliance on weather introduces heightened sensitivity in this analysis, so the indicator showing the share of energy produced from renewable energy sources in gross final energy consumption was also included into the analysis. Another argument proving the negative effect of weather-dependent technologies from a vulnerability standpoint is the limited prevalence (and high cost, resulting in low willingness to invest) of energy storage technologies for surplus energy generated but not consumed. Consequently, household producers (“prosumers”) find themselves even more exposed to weather variations, while the current situation is even worsened by the ongoing ban on grid feedback (see Chapter 2.3.3 for additional details).

2.4. Adaptive capacity

The indicators on adaptive capacity reveal how well the studied regions can cope with and adapt to the consequences of climate change, considering factors such as socio-economic background, energy-related preparedness, and the willingness of the citizens for participating at adaptability initiatives.

In this study, social adaptive capacity is characterized by economic performance in various aspects. On one hand, the average net monthly income of individuals determines the extent to which people can financially invest into addressing environmental impacts. Similarly, residents in regions with higher GDP per capita may have better access to resources, technology, and infrastructure, which allows them more effective adaptation measures to mitigate negative

consequences of climate change. Additionally, an economy with higher GDP per capita is considered to be more robust, so it may facilitate more investments in research and development, which also contributes to increased adaptive capacity (Formetta, 2019; Wang et al, 2014).

Conversely, the number of registered jobseekers negatively affects adaptive capacity. In regions with higher unemployment rates, decision-makers allocate more resources to assisting individuals in their job search, diverting attention and financial resources away from adaptation efforts. The instability in the income of jobseekers, while being reliant on public subsidies, further undermines adaptive capacity, also impacting the first two indicators presented above. Given that health status is also reflected in sensitivity indicators, it should also be considered as part of adaptive capacity. A higher quality of health services can significantly enhance adaptive capacity, and the number of doctors per 1,000 people can serve as an approximate measure of this quality. In this scenario, the assumption is that a higher number of doctors per capita corresponds to a better quality of health care services. While this may not be universally true, shorter waiting times and prompt care can be essential in extreme situations, such as extreme weather and health conditions like intense heatwaves or epidemics.

Considering the energy-related assessment, the first indicator in the model was the installed capacity of household-sized small PVs. In Hungary, the successful integration of renewables into households has been facilitated by the widespread distribution of these small-scale plants across the country, also incentivized by a favorable accounting regime. This contributes positively to the adaptive capacity, as decentralizing power generation reduces dependence on large generating units. Consequently, not only does this enhance stability of household self-supply, but it also reduces dependence on the national grid.

While the spread of small PVs enhances adaptive capacity, their weather-dependent characteristics can pose a threat to system stability. To address the fluctuation associated with small PVs, it is important to evaluate the installed solar capacity in the country, but with an acknowledgment also considering it as a negative factor. As emphasized earlier, this analysis centers on vulnerability rather than on sustainability. Consequently, it can be stated that a significant reliance on weather-dependent energy sources might diminish resilience owing to heightened exposure to weather-related variables. For similar reasons, the inclusion of the installed capacity of natural gas-fired power plants in the model has required positioning the sustainability aspect of natural gas-based power generation in the background. Despite ongoing debates on import dependence on Russia, natural gas-based power generation stands out as one

of the currently most stable methods when compared to weather-dependent power generation. It must be noted that while nuclear power is also significant in Hungary, it cannot be included into this analysis due to the territorial centralization of such generation in Paks (Tolna county). Beyond technological considerations, the behavior of individuals is also an important factor in adaptive capacity, necessitating additional focus on the willingness to invest. The annual investment in energy infrastructure per 1000 inhabitants serves as an indicator for measuring this aspect. This indicator is significant to be included in the model, as a higher investment value predicts a greater willingness to invest, which suggests that more advanced and innovative technologies can be spread within the region.

3. RESULTS

The research employed an indicator-based approach, with indicators outlined in detail above in Table 2. These indicators underwent a normalization process, the resulting values of which are presented in Table 3 and Table 4. Visualization of the values was carried out using the QGIS software, and the spatial patterns and outcomes are expounded in this chapter.

Table 3: Normalized values of selected sensitivity indicators

Source: own results

County	Social				Energy		
	1	2	3	4	5	6	7
Bács-Kiskun	0,40	0,55	0,58	0,87	0,46	0,70	0,49
Baranya	0,29	0,31	0,72	0,77	0,74	0,81	0,80
Békés	0,04	0,19	0	0	0,61	0,63	0,71
Borsod-Abaúj-Zemplén	0,65	0,85	0,50	0,72	0,69	0,76	0,09
Budapest	0,58	0,31	0,80	0,98	0,58	0,98	0,71
Csongrád-Csanád	0,37	0,36	0,60	0,94	0,61	0,99	0,60
Fejér	0,64	0,67	0,79	0,97	0,48	0,68	0,40
Győr-Moson-Sopron	0,79	0,73	0,85	0,97	0,53	0,86	0,46
Hajdú-Bihar	0,75	0,77	0,81	0,63	0,48	0,61	0,09
Heves	0,33	0,52	0,54	0,85	0,43	0,52	0,51
Jász-Nagykun-Szolnok	0,38	0,58	0,34	0,83	0,48	0,56	0,54
Komárom-Esztergom	0,71	0,66	0,58	0,95	0,39	0	0,57
Nógrád	0,29	0,48	0,12	0,82	0,36	0,40	0,46
Pest	1	1	1	1	0	0,06	0,37
Somogy	0,06	0,24	0,46	0,82	0,81	0,93	0,77
Szabolcs-Szatmár-Bereg	0,96	0,97	0,79	0,24	0,35	0,54	0
Tolna	0,16	0,37	0,44	0,87	0,36	0,38	0,60
Vas	0,45	0,39	0,78	0,90	0,62	0,88	0,83
Veszprém	0,34	0,40	0,57	0,76	0,75	0,74	0,46
Zala	0	0	0,49	0,85	1	1	1

Table 4: Normalized values of selected adaptive capacity indicators

Source: own results

County	Social				Energy			
	1	2	3	4	5	6	7	8
Bács-Kiskun	0,28	0,69	0,22	0,22	0,39	0,44	0,01	0,23
Baranya	0,25	0,50	0,13	0,83	0,31	0,49	0,01	0,28
Békés	0,08	0,43	0,09	0,22	0,19	0,79	0	0,24
Borsod-Abaúj-Zemplén	0,16	0	0,16	0,18	0,33	0	1	0,49
Budapest	1	0,90	1	1	0,45	1	0,85	0,37
Csongrád-Csanád	0,29	0,86	0,19	0,86	0,37	0,79	0,02	0,39
Fejér	0,51	0,78	0,33	0,19	0,31	0,80	0,09	0,09
Győr-Moson-Sopron	0,64	1	0,42	0,34	0,28	0,79	0,44	0,44
Hajdú-Bihar	0,25	0,40	0,17	0,83	0,42	0,72	0,11	0,62
Heves	0,40	0,39	0,18	0,20	0,07	0,81	0,01	0,13
Jász-Nagykun-Szolnok	0,20	0,42	0,14	0,06	0,12	0,19	0,01	0,03
Komárom-Esztergom	0,53	0,84	0,31	0,13	0,10	0,88	0,06	0,14
Nógrád	0,13	0,06	0	0	0	0,76	0,02	0
Pest	0,38	0,84	0,21	0,21	1	0,42	0,72	0,03
Somogy	0,19	0,40	0,12	0,19	0,19	0,44	0,00	0,73
Szabolcs-Szatmár-Bereg	0	0,18	0,08	0,18	0,36	0,47	0,07	0,15
Tolna	0,42	0,58	0,19	0,14	0,10	0,83	0,00	1
Vas	0,40	0,84	0,24	0,34	0,12	0,68	0,01	0,12
Veszprém	0,36	0,77	0,19	0,20	0,23	0,76	0,11	0,22
Zala	0,20	0,66	0,16	0,33	0,13	0,72	0,00	0,17

3.1. Sensitivity

Sensitivity introduces factors that make a population sensitive to climate change. Social characteristics, such as age and state of health play a significant role in this analysis. Additionally, the study, given its energy-centric focus, equally focuses on analyzing energy consumption patterns. The outcomes of these aspects are illustrated in Figure 10.

The social sensitivity analysis resulted in previously unexpected findings: beyond Pest county, the least sensitive regions were in the North-Eastern and the North-Western parts of the country, whereas the South experienced a moderate-to-high level of sensitivity.

The North-Western counties and the region of the capital city show a low level of social sensitivity. These areas feature the country's highest living standards, including favorable economic conditions (such as appealing job opportunities) and higher quality healthcare services. The region's attractiveness to young employees results in a concentrated younger population. Given that diseases and the need for domestic care predominantly affect older generations, as indicated by the examined indices, this accounts for why the counties above are the least socially sensitive regions.

Contrarily, low sensitivity is less obvious in the case of the North-Eastern counties, as those regions are generally deemed to lag behind in the economic development of Hungary (except for Hajdú-Bihar county, which has attracted several foreign direct investments in recent years). Even though Szabolcs-Szatmár-Bereg county has the highest number of people receiving domestic care, for instance, this area is less affected than those in the South, owing to a younger population and a lower incidence of cardiovascular diseases.

Although there is only a minimal difference between the number of temperature extremes and the average temperature in different parts of the country, this small difference may still explain the "average" or higher sensitivity of Southern regions to some extent. As demonstrated earlier, heatwaves may contribute to the development of cardiovascular diseases or worsen condition of those with a history of the disease. Consequently, populations in the Southern region experiencing somewhat more weather extremes have developed a higher sensitivity to those. Békés county scored the lowest in this aspect of the study. This can be attributed to the county's rapidly aging population and the discouraging state of health situation, leading to underperformance in all the examined indicators.

On the other hand, when analyzing trends in energy consumption, county-specific sensitivity varies significantly. The most affected social group is the population of Pest County (excluding the capital), being the largest electricity consumer in the country. While the technology used in

the region is progressing favorably from a sustainability perspective with a substantial share of renewable energy in final energy consumption, from a vulnerability standpoint, this represents a significant sensitivity factor for the inhabitants due to weather dependency.

Zala county is almost completely in contrast with this, as, in terms of energy sensitivity, it has scored an exceptionally great result. The county has the lowest electricity and natural gas consumption per household in the country and, although not optimal in terms of sustainability, it is also the least prevalent in the use of intermittent generators. However, these data alone are misleading since, although there is a significant difference in energy consumption between the lowest and highest values, there are not any relevant differences for the country as a whole.

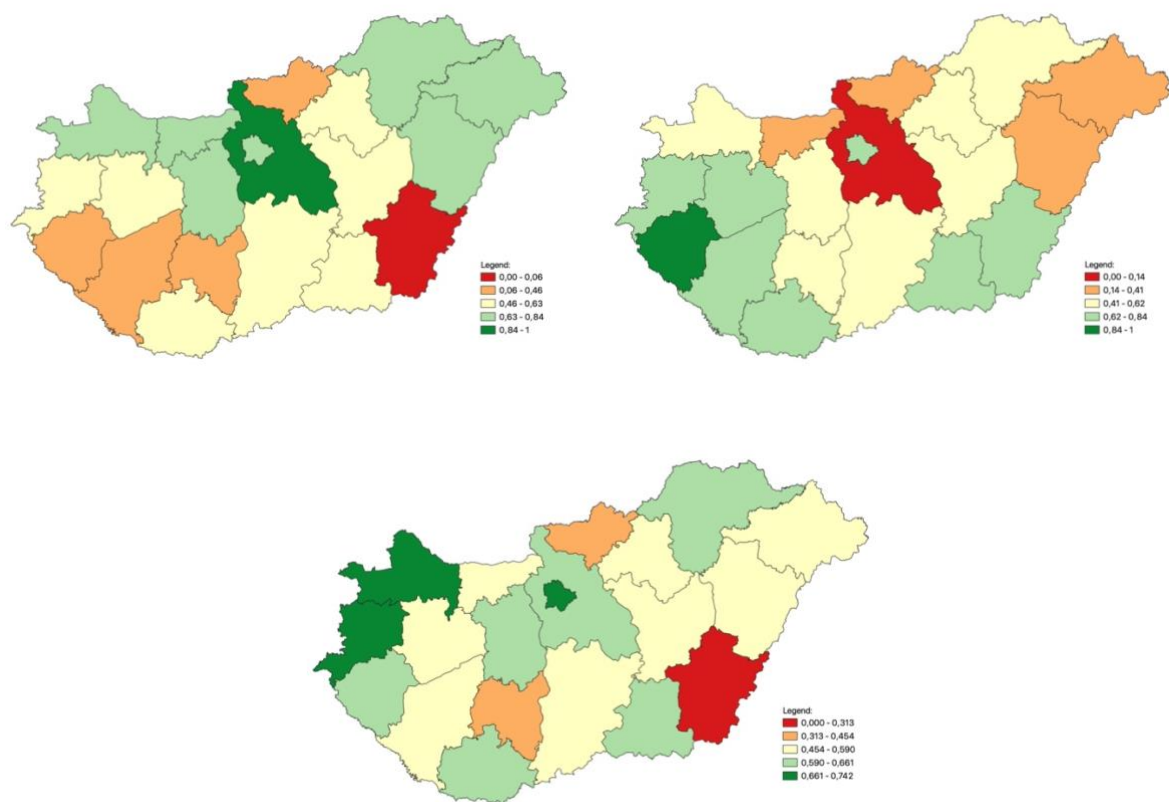


Figure 10: Mapped social (top left), energy-related (top right) and overall (down) sensitivity scores

Source: own calculations and edit

To gain a sufficiently comprehensive understanding of sensitivity, both presented aspects must be given equal consideration in the analysis. In this regard, the most intriguing aspect is perhaps the contrast inside the Pest region, described as the least sensitive in the first aspect but the most affected region in the second. This observation highlights the complexity of the energy sector: while a younger society may positively influence the energy network in terms of innovation

and willingness to invest, the younger generation also has a higher energy demand, potentially pushing the population of regions towards greater vulnerability. Furthermore, utilizing innovative energy generation technologies might be helpful for grid operators, and also, in terms of reaching decarbonization targets. On the other hand, the transition to renewables without a simultaneous spread of smart solutions (such as smart meters or demand-side response) might end up in increased energy-related sensitivity.

Hence, when considering overall sensitivity, individuals residing in Budapest, Győr-Moson-Sopron, and Vas counties appear to be the least affected by climate change sensitivity. On the other hand, the pursuit of energy efficiency is not negligible in these areas either. In the summary figure, only Békés county is marked in red, where the predominant causes of high sensitivity are the mentioned social characteristics of aging and of poorer health conditions.

Concerning the overall sensitivity of the country, it can be generally observed that most regions fall within a robust middle range between counties, showing a tendency from medium to lower sensitivity, with only a few exceptions.

3.2. Adaptive capacity

Given that adaptive capacity closely mirrors the population's ability to respond to changing climatic conditions, analyzing both social well-being and energy consumption habits is essential for making a comprehensive assessment of overall energy-related adaptive capacity.

The results of the adaptive capacity assessment in all three fields can be seen in Figure 11.

Social background serves not only as an indicator of citizens' opportunities to engage in activities enhancing adaptive capacity concerning their income but also as a reflection of how their health and living conditions enable such pursuits. From a social point of view, the stereotype of the country's development is evident: the Western part of the country and the capital region exhibit higher adaptive capacity, whereas the developing Eastern counties significantly lag behind in this dimension. As expected, Szabolcs-Szatmár-Bereg, Borsod-Abaúj Zemplén, and Nógrád counties scored notably low in this aspect. The map's depiction of unfavorable conditions, reflected in red, can be attributed to factors such as high unemployment in Borsod-Abaúj-Zemplén, low incomes and economic performance in Szabolcs-Szatmár-Bereg, and a parallel lack of health support (as indicated by a low number of doctors per 1000 inhabitants) in Nógrád.

The outlook is much more optimistic in the North-Western part of the country. In contrast to the previously highlighted regions, there is a noticeable income disparity, with the Western

counties also boasting significantly higher economic performance. In evaluating Győr-Moson-Sopron, Vas, and Komárom-Esztergom counties, the proximity to the Austrian and Slovakian borders emerges as a significant factor, as many citizens commute through these counties daily for work and leisure activities. While this contributes to the low unemployment rate, the presence of crucial manufacturing sites, particularly in the automotive industry, further explains the economic stability in this region. Hajdú-Bihar county, in the Eastern part of the country stands out as the sole green-shaded county for similar reasons, having been a favoured destination for foreign direct investment in recent years. Moreover, job stability not only ensures higher long-term earning potential, but also results in an enhanced health coverage, at least in terms of a higher number of doctors per 1,000 inhabitants in more developed areas.

In contrast, the energy-related adaptive capacity exhibits significant differences. Notably, Jász-Nagykun-Szolnok county stands out as the most distinct one, scoring the lowest among all counties and even lower than in the social dimension. The explanation is straightforward: the county lacks significant power plant capacity, and despite this, there were no substantial energy investments made during the reviewed year. Consumer attitudes are also relatively unfavourable and reflected in one of the lowest levels of small power plant capacity in the country. Considering these factors, it can be inferred that neither consumers nor the energy sector prioritizes adaptation or energy self-sufficiency in this region. Consequently, without specific public intervention or education, this region ranks and remains among the most endangered counties.

While Szabolcs-Szatmár-Bereg county lags behind in the Eastern region, Borsod-Abaúj-Zemplén county notably boosts its score, primarily due to having one of the highest installed capacities of natural gas-based power plants in the country. The region has also demonstrated a significant inclination for investment (based on the 2020 data used), most likely influenced by the urgent need for infrastructure renewal in one of the most outdated county infrastructures in the country. This surge in investment indicates a substantial increase in the county's adaptive capacity in recent years. In the future, this positive trend is expected to further escalate with the construction of a newly announced natural gas-fired power plant in Tiszaújváros.

A similar scenario unfolds in the case of Heves county, marked by a low adaptive capacity generated by its outdated energy technology infrastructure. While the calculations predominantly focused on solar energy and natural gas usage, their exceptionally low values in this case necessitated a qualitative exploration of additional factors. The pivotal energy production unit in Heves county is the Mátra Power Plant, predominantly utilizing coal firing.

Given Hungary's commitment to phasing out coal-based power generation in alignment with EU decarbonization mandates, the operational lifespan of this power plant is expected to be limited. Consequently, the infrastructure of Heves county not only exhibits outdated features but also registers an overall low adaptive capacity across the selected indicators. The closure of the Mátra Power Plant may widen this gap, although the establishment of a new natural gas-fired power plant is poised to maintain the county in its current position (Forbes, 2023).

However, this does not mean that the Eastern region is not at the forefront of renewable energy, as it has the highest installed solar capacity in the country. Although this is a very good value from a sustainability point of view, when looking at vulnerability, it should be considered as a negative factor due to the weather-dependent nature of solar photovoltaics.

Another significant factor in the utilization of solar energy is the prevalence of household-sized small power plants at the household level. While the capital does not stand out concerning the number and installed capacity of small plants, the surrounding region does. This can be attributed to the high proportion of residential buildings in the capital, limiting room and the opportunity for households to install solar panels on their homes. Conversely, in surrounding municipalities where individuals reside in detached houses, there is a greater willingness and motivation to invest in solar panels which is also favorized by higher incomes. However, the situation is less advantageous in the South-Western part of the country, where the penetration of small-scale installations, although not particularly low, remains average. This could be explained by both a similarly close-to-average income situation and the mobility of citizens. A significant number of younger individuals and of those relocating for job opportunities are likely to live in rented properties, typically in blocks of flats where they lack the motivation to invest, as they do not own the property that would benefit from a small power plant.

It is also notable that in the South-Western counties, mentioned above and with a low adaptive capacity, the number of energy-related investments was quite limited, and were coupled with a lower preference for small power plants. This trend resulted in the absence of major gas-fired power plants in that area. A crucial factor underscoring this and also being worth highlighting, might be the fact that Tolna county, the sole county in the region marked in green, houses the country's only nuclear power plant (the Paks Nuclear Power Plant), contributing to almost half of the country's electricity generation. Although installed nuclear capacity is not factored into the model due to its concentration in one county, it could be observed that Tolna county still ranks among the counties with the highest adaptive capacity. Given the major role of the Paks

Nuclear Power Plant not only in the region, but also in the country, the energy-related development of the surrounding counties may be of lesser significance for this reason.

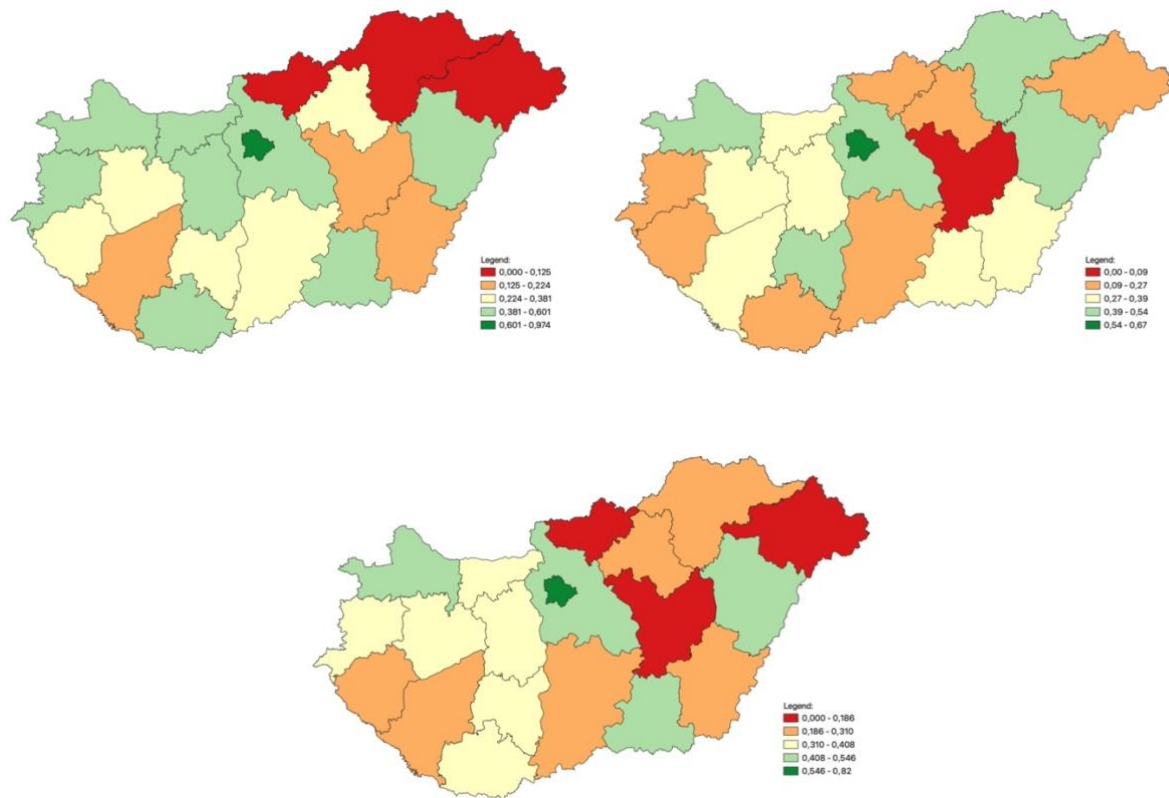


Figure 11: Mapped social (top left), energy-related (top right) and overall (down) adaptive capacity scores

Source: own calculations and edit

In summarizing the research from both social and energy perspectives, a more profound interpretation could be carried out to the calculated adaptive capacity in this context. Consequently, regions with the lowest adaptive capacity are in Szabolcs-Szatmár-Bereg, Nógrád, and Jász-Nagykun-Szolnok counties. Their low values are attributed to a negative socio-economic environment on one hand and to a low willingness to develop the energy infrastructure on the other.

As anticipated, Budapest has emerged with the highest overall adaptive capacity. Similarly, the neighboring regions (further parts of Pest county), Győr-Moson-Sopron, Hajdú-Bihar, and Csongrád-Csanád counties also performed similarly well. These highlighted areas underscore that increased financial capacity and well-being often result in a greater willingness to invest, thereby fostering better technological supply.

3.3. Vulnerability

The sensitivity and adaptive capacity indicators discussed in the previous chapters provide an overview of the vulnerability of Hungary's counties. An average value calculated from those indicators shows higher vulnerability when closer to 0, while a value nearing 1 signifies lower vulnerability in each region. The results of the calculations are presented in Figure 12.

The results of the social and energy-focused calculations reveal significant differences. The social picture is generally more positive, while the energy-related indicators depict a more vulnerable Hungary. The only consistent and almost self-evident commonality in the two analyses is the situation of Budapest, which scored the highest data in both aspects, earning the title of the least vulnerable region of the country. This underscores Hungary's centralization, as Budapest not only serves as the administrative and economic hub for citizens but also stands out as a hotspot for the adaptation process. The development and progress in Budapest has set a model for the entire country, and although citizens in other regions may not directly be able to influence many indicators, collective efforts toward energy efficiency and healthy lifestyles can contribute to reducing the vulnerability of at least our own neighborhoods.

Social vulnerability presents a much more different picture than anticipated at the beginning of the research. My initial hypothesis suggested a substantial negative impact on social vulnerability in the relatively unfavorable socio-economic state of the East, a region slightly lagging behind in economic development. However, the study has incorporated indicators focusing on well-being, on financial situation, as well as on factors unrelated to income level status (such as age and health trends), significantly enhancing the region's assessment. Nonetheless, the North-Western region has aligned with the expectation of a lower social vulnerability. This outcome is attributed, in part, to local economic development as well as the proximity of the Austrian border, contributing to various improvements and positive changes that elevate well-being and, consequently, resilience in this region.

In the coming years, in addressing energy vulnerability, strategic decision-making and active consumer participation will be inevitable. The central region of the country is predominantly energy vulnerable, and improvement in this regard is improbable without proactive measures or other incentives. Conversely, the Western region's high willingness to invest and to consume energy more efficiently has positioned it among the less impacted areas. However, it is crucial to emphasize that the current state is insufficient to sustain resilience in a stable manner. Ongoing monitoring and maintenance of the implemented measures will be essential for these counties, as well.

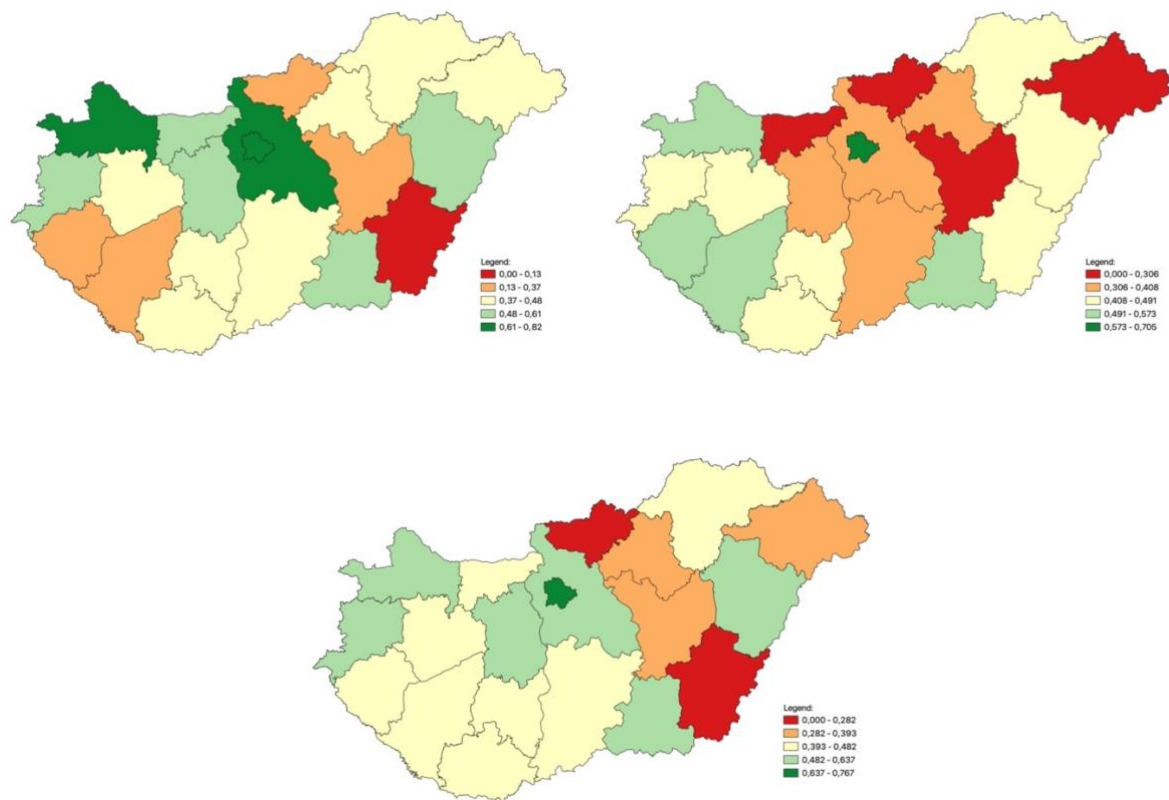


Figure 12: Mapped social (top left), energy-related (top right) and overall (down) vulnerability scores

Source: own calculations and edit

Yet, when summarizing the overall energy vulnerability with both a social and energy focus, a spatial pattern emerges that aligns with the hypotheses formulated at the beginning of the research. From an energy perspective, the country's centralization near Budapest, the flourishing Western region, and the lagging Eastern counties exhibit various levels of vulnerability to climate change. Factors such as higher incomes, increased living standards, energy-efficient consumption, and stable energy supply collectively contribute to lower vulnerability. However, these factors alone cannot optimize a region's resilience, as the severity of climate change impacts is also influenced by demographic factors like age and state of health. Conversely, as observed in the East, even with a society possessing a favorable age or state of health, it may be accompanied by a low willingness to invest or an unfavourable energy mix. Therefore, in an energy-specific vulnerability analysis, a comprehensive understanding emerges only when considering all social and energy-related issues and indicators together.

3.4. Discussion

The calculations outlined in the preceding sections highlight the importance of separately examining social and energy-focused indicators in the context of this vulnerability analysis. Although it was expected that the vulnerability landscape varies when considering different perspectives, surprisingly, it has been revealed that Hungarian counties exhibit lower vulnerability concerning social factors, whereas much more regions can be categorized as vulnerable when focusing on energy consumption trends. While citizens may have limited direct influence on many of the examined indicators, collective efforts towards more conscious planning, target setting, and investment can locally mitigate vulnerability. Studies like this one performed may contribute to this achievement.

Nevertheless, a certain criticism is crucial when dealing with the results. While it has been aimed to incorporate indicators that consider the most possible aspects in developing the model, the availability of data had a significant influence on the final outcome. Further refinement of the calculation results can be achieved by integrating additional indicators; however, such a correction may necessitate primary data collection or collaboration with statistical offices to enhance the comprehensiveness and accuracy of the assessment.

On the other hand, it is important to note that, despite utilizing the most recent available data for all indicators, they may not precisely mirror the current scenario. The varying years of origin for different indicators introduce a degree of distortion to the results. Moreover, obtaining up-to-date, nationwide data for the current month or quarter in all the examined aspects is practically unfeasible without collaboration with the relevant authorities.

Considering these limitations and risks, this study can provide a solid foundation for individual, regional, or national climate-related planning and decision-making. While developing strategies at the national level may demand a more thorough clarification, the methodology employed can be readily enhanced through collaboration with public stakeholders.

Beyond enhancement possibilities made in data collection, the timeliness and significance of the topic suggest several areas for additional research. For instance, exploring the current energy and climate strategies of the counties in relation to how they address the identified vulnerabilities – be it through mitigation or adaptation measures – could provide valuable insights. Furthermore, delving into international best practices might offer actionable strategies that could be adopted by the country and its counties to complement or further develop their existing approaches.

While the study emphasized vulnerability resulting from energy consumption rather than sustainability, another future research topic could be how vulnerability indicators might shift if sustainability became the central focus of calculations. Given the global significance of sustainability and decarbonization as urgent challenges, such an exploration could prove especially valuable for supranational organizations. Examining the sustainability dimension would offer insights into the impacts of ongoing developments and the status of current decarbonization targets, enabling the comparison of a future state with the current situation. This comparative analysis could provide decision-makers with valuable overview of the effectiveness and impact of their initiatives and strategies.

4. SUMMARY

This study aimed to evaluate the energy vulnerability of Hungarian counties by examining their sensitivity and adaptive capacity through statistical indicators. The data used were categorized into social and energy-related perspectives, resulting in separate vulnerability scores for each category and an overall combined vulnerability score. The research underscored the significance of this sectoral separation, as the multidimensional analysis brought attention to spatial variations that might have gone unnoticed in a different approach.

Most of the preliminary hypotheses, particularly those regarding Budapest, have been largely confirmed. The centralization of society, economy, and consequently, low vulnerability around the capital aligns with these expectations. However, this picture is nuanced by the observation that Pest county (except for Budapest) exhibits higher vulnerability in terms of energy consumption, (despite having highly positive social characteristics in this region).

Higher vulnerability, conversely, was predominantly identified in the Eastern half of the country, particularly when assessing energy-related and overall vulnerability. While this observation is the result of various factors, it is fundamentally reasonable to argue that economic underdevelopment significantly contributes to the vulnerability of this region. However, nuances in the picture emerge as non-financial economic indicators, such as age or the state of public health, significantly contribute to determining a lower sensitivity of the region than expected.

Of course, the research does not present a flawless picture, as the indicators used may not always accurately depict the current situation, despite efforts to incorporate the most recent data available. Nonetheless, the analysis reveals fundamental spatial patterns between counties and underscores regions that are particularly vulnerable. With some updates or additional data supplementation, this study could serve as a valuable starting point for designing county- or national-level strategies, enhancing their effectiveness with tailor-made initiatives for mitigation or adaptation.

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