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Analysis of Potential Energy Transition Schemes in Hungary: from Natural Gas to Electricity

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Hungary, as a landlocked nation with limited raw material resources, faces significant challenges in ensuring a stable energy supply, necessitating extensive interconnectors with neighbouring countries for gas, oil, and electricity. While progress has been made, especially in electricity interconnections, the Russian-Ukrainian conflict and the EU's decarbonisation goals for 2050 introduce new pressures on energy security. Hungary's energy trilemma—balancing access and affordability, environmental targets, and security—guides its strategy as it seeks an optimal energy mix. By 2050, energy demand is projected to hold steady at 210 TWh, though the current 65 % fossil fuel share, largely imported, highlights Hungary's vulnerabilities (exposure to risks and insecurities in its energy supply). Goals include net-zero emissions, reduced foreign dependency, and manageable energy costs, with targets to reduce gas consumption to 4×10^9 m^3 (1.5×10^9 m^3) and ensure over 50 % of the energy mix is carbon-neutral electricity. The paper examines three key actions based on statistical data to achieve these targets: (a) reducing natural gas dependency, (b) boosting domestic alternative sources like local gas production and green solutions, and (c) enhancing energy system flexibility through regulation, storage, and generation. These strategies are assessed for their potential to satisfy the trilemma's demands and provide a resilient path forward amidst evolving challenges.

1. Introduction

The energy trilemma—balancing energy security, equity, and sustainability—has become central in sustainable development and energy transition literature. Fu et al. (2021) analysed the relationship between energy security, equity, and sustainability in the context of economic growth and CO_2 emissions, using the Energy Trilemma Index (ETI) to assess the energy efficiency of leading nations, demonstrating how energy policies can stimulate economic growth. Similarly, Khan et al. (2021) examined how the energy trilemma drives economic performance over time. The World Energy Council's "World Energy Trilemma Index 2022" emphasised that balancing energy security, accessibility, and sustainability is essential for a just energy transition. Shirazi et al. (2023) explored the interconnections between the trilemma and sustainable development, underlining how different policies yield varied impacts. However, studies specific to countries like Hungary, which are dependent on high energy imports, remain scarce. This study seeks to fill that gap by analysing Hungary's potential energy transition pathways, focusing on practical measures to achieve energy security, emissions reductions, and sustainability. It considers Hungary's unique challenges, such as its external energy reliance and recent geopolitical pressures, providing actionable insights aligned with national and EU targets.

2. Energy Supply and Interconnection Infrastructure of Hungary

Hungary's total final energy consumption was 773 PJ in 2023. Direct gas consumption accounted for 28 % of total energy use, petroleum products for a further 33 %, electricity for 21 %, and renewables for 11 %, based on statistical estimates using the Hungarian Energy and Public Utilities Regulatory Office (HEPURO, 2024) and Hungarian Central Statistical Office (HCSO) data sources (Figure 1). Hungary's energy supply continues to be

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characterised by high import dependence, with 75 % of the primary energy supply in 2023 coming from external sources (including nuclear fuel). Although the share of net electricity imports in total consumption (excluding self-consumption by power plants and grid losses) decreased from 36 % in 2014 to 30 % in 2023, this share remains high, especially given that seasonal electricity storage is still unresolved. Dependence on foreign markets is most pronounced in the purchase of hydrocarbons, with import dependence reaching 85 %. Within this, dependence on Russian imports is particularly high, with 65 % of oil imports and 70 % of natural gas imports coming from Russia before the energy crisis.

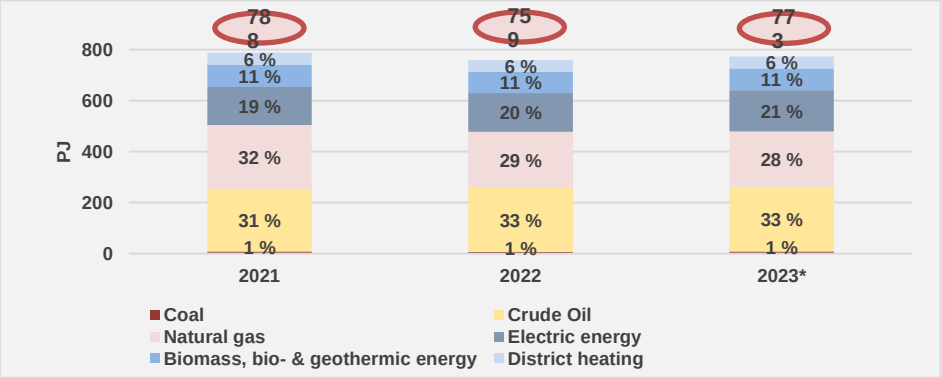

*Figure 1: Final primer energy consumption in Hungary, 2021-2023 (HEPURO, 2024) * 2023 estimation*

Over-dependence on Russian imports became evident during the 2009 gas supply crisis. Drawing on the lessons from this crisis, Hungary has prioritised diversifying its gas sources by both building physical infrastructure and fostering a competitive wholesale market (Horváth, 2022). In the past decade, progress has been made in enhancing gas supply security, with bi-directional interconnectors established in all neighbouring countries except Slovenia. The global LNG markets are now accessible through the Krk LNG terminal, and there are ongoing efforts to connect to northern terminals in Poland as well. These developments enable Hungary to access new potential sources of supply. The Hungarian electricity system is now directly interconnected with all neighbouring countries, with Slovenia, which joined in 2023, being the last. The transmission capacity of the cross-border high-voltage lines will reach approximately 50 % of Hungary's gross installed capacity, significantly exceeding the 15 % target set by the European Union. The current transmission capacities allow Hungary to flexibly diversify its trade (NECP, 2023).

2.1 The Impact of the Russian-Ukrainian War on the Energy Supply of Europe and Hungary

The rise in energy prices that began in 2021, following the economic recovery after the COVID-19 crisis, continued into 2022 and was further exacerbated by the Russian-Ukrainian war. Prior to the Russian invasion of Ukraine, Russia was Europe's leading supplier of primary energy. In 2022, Russia suspended gas supplies to several EU countries, making supplies even more uncertain and pushing gas prices to record highs (Gros 2022). Amid the energy crisis, EU gas consumption fell by 55×10^9 m^3/y in 2022, a decrease of about 13 %. While some factors behind this decline are cyclical or temporary, such as record-high energy prices, EU policy-driven changes (e.g., REPowerEU) involving increased renewable capacity and energy efficiency are laying the groundwork for a permanent reduction in gas demand in the long term. Additionally, the structure of the EU energy market has led to a surge in electricity prices due to soaring gas prices, resulting in a 3 % decline in EU electricity demand from 2022 to 2023, while global demand grew by 2 % (IEA, 2024). By 2024, as natural gas prices stabilise, the EU's gas supply portfolio has been radically transformed. By 2023, the share of Russian gas (pipeline and LNG) in imports had dropped to 15 %. Norway (pipeline) and the United States (LNG) have become the EU's largest gas suppliers, providing about half of the total gas demand (Figure 2). Other major suppliers include North African countries, the UK, and Qatar. A similar trend has been observed in Russian oil imports. EU sanctions—specifically, the ban on imports of Russian crude oil by sea and the embargo on refined oil products—have reduced the share of Russian oil in imports to a minimal 3.5 %. The drastic reduction in Russian energy imports has resulted in only a minimal decrease in the volume of imported oil and a 10 % decrease in natural gas imports in 2023 compared to 2022. This reduction aligns with the EU's reduction plan, where Member States committed to cutting their gas consumption by at least 15 % compared to the average gas consumption over the previous 5 y.

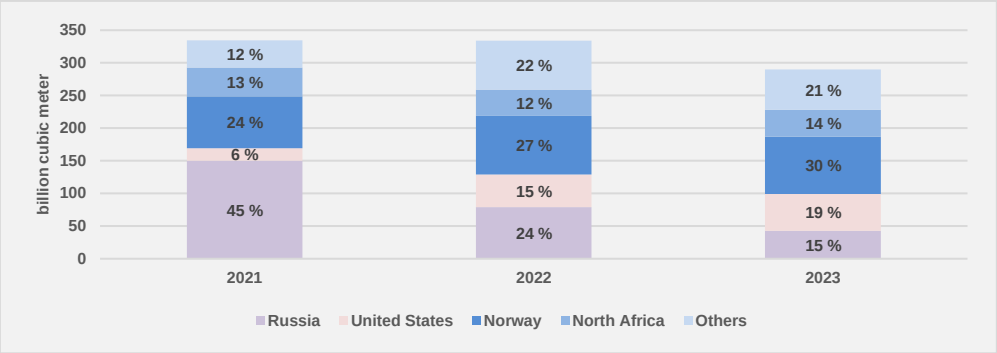

Figure 2: Main partners of the EU in gas supply between 2021 and 2023 (Source: European Council)

As a result of the energy crisis, Hungary's total energy consumption has decreased compared to 2021, mirroring the EU trends. Among the major energy carriers, natural gas saw the most significant decrease at 14.9 %, exceeding the EU average, based on data from the Hungarian Central Statistical Office. Alongside milder weather, the reduction in total energy consumption was driven by changes in regulatory price controls for natural gas and electricity, which also encouraged households to conserve energy (Tóth et al., 2023). The share of Russian gas imports to Hungary has slightly decreased: while between January and September 2021, Russian imports exceeded 70 %, following the Russian invasion of Ukraine, these imports dropped to 55-60 % of the average monthly gas demand. The difference of about 10-15 % points between the two values was already replaced by non-Russian sources in 2022. Thanks to interconnectors built in recent years, gas can also be imported from Romania, Croatia, Slovakia, and Austria. While it is not possible to determine the exact proportion of Romanian and Austrian supplies containing Russian gas, it is evident from flow directions that in 2022, more gas came from outside Russia than in previous years (NECP, 2023). This has initiated a diversification of gas sources, but Hungary's dependence on Russian gas remains significantly higher than the EU average. Although efforts have been made to establish import routes for gas from Qatar, Azerbaijan, and, more recently, Turkey, the short- and medium-term substitution of large quantities of Russian gas does not seem feasible for Hungary or for other landlocked Central and Eastern European countries in similar situations (Horváth, 2022).
Oil supplies from Russia via pipeline (through Ukraine) to Hungary are currently unaffected by the war, though risks remain. The exposure to oil supply is mitigated by the fact that oil and petroleum products can be transported by rail, tanker, and barge, and alternative pipeline options (the Friendship and Adriatic pipelines) are available in addition to the Russian pipeline (CPOH, 2023). In the short term, the bottleneck to substituting Russian oil is refinery technology, but by the end of 2025, refinery and infrastructure improvements will enable Hungarian refineries to process various types of oil from sources other than Russia.

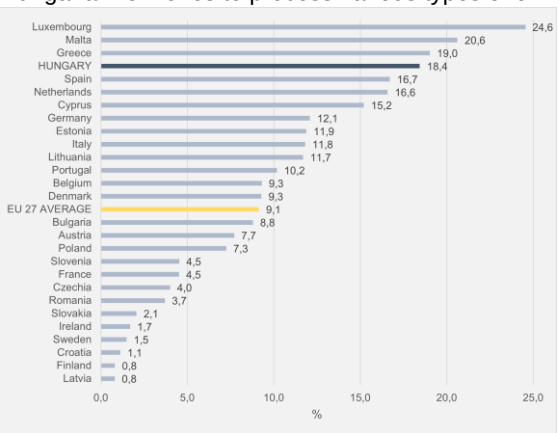

Figure 3. Share of solar power in domestic electricity generation in EU members, 2023 (Source: Ember)

The energy crisis and concerns about energy sovereignty have also spurred an increase in domestically produced renewable electricity generation. Solar power capacity increased by approximately 2,600 MW in 2022 and 2023, now accounting for 18 % of electricity generation, the fourth-highest share in the European Union (Figure 3). Additionally, plans target 12,000 MW of capacity by 2030, compared to the current 6,000 MW.

However, it is important to note that weather-dependent renewable sources require a certain environment: accurate weather predictions and appropriate storage solutions, which will be discussed further in this paper.

3. Energy Trilemma

In today's era of energy transition amid global crises, the energy trilemma—balancing energy security, affordability, and sustainability—has gained prominence. Sustainability mainly refers to decarbonisation, energy security ensures steady supply, and affordability focuses on accessible pricing. Navigating this trilemma is challenging, as exemplified by the Russian-Ukrainian war, which underscored energy security's priority at the potential cost of affordability and sustainability.

The World Energy Trilemma Index (WETI), published by the World Energy Council in 2010, remains the primary measure of trilemma performance, ranking 133 countries with 32 indicators across the three pillars, each weighted at 30 %, with additional country-specific indicators accounting for 10 % (Šprajc et al., 2019; Sobik, 2023). While some critics argue that WETI overemphasises standardisation, its comprehensiveness makes it valuable, particularly for assessing Europe and Hungary's trilemma positioning. The top-ranking countries are largely European, with Denmark, Sweden, and Finland leading, indicating that high-income economies often excel across the trilemma (Marti-Puertas, 2022).

The Russian invasion has impacted Europe's energy security, with rising energy prices affecting equity and a renewed reliance on traditional energy sources impacting sustainability. In WETI's 2023 ranking, Hungary ranks 15th, up from 20th, with energy security as its weakest area due to reliance on Russian imports. Hungary's strengths lie in energy equity, scoring over 90 points due to affordable prices, and moderate strength in sustainability. Despite a solid starting position, Hungary faces challenges, including a high fossil fuel dependency—over 65 % of its 2022 energy mix—90 % of which is imported, and a transport sector dominated by fossil fuels. Hungary's goals include achieving net-zero emissions, reducing foreign energy reliance, and controlling costs, which the following sections will explore in depth.

3.1 Reduction of Natural Gas in the Energy Mix

According to preliminary data from the Hungarian Energy and Public Utilities Regulatory Office, natural gas accounted for 20.5 % of Hungary's gross electricity production in 2023, representing a decrease of more than 4 percentage points compared to the previous year (Figure 4). The 7,170 GWh produced by gas power plants is 19 % lower than the previous year's value. Whether we consider the gigawatt-hours produced or the proportion within the mix, we have not observed such low figures since 2016. After nuclear energy, natural gas remains in second place in the energy mix; however, the gap between natural gas and solar energy is rapidly closing. Solar power has increased from 7 % of electricity generation in 2020 to nearly 19 % now, approaching the share of natural gas (HEPURO, 2024)

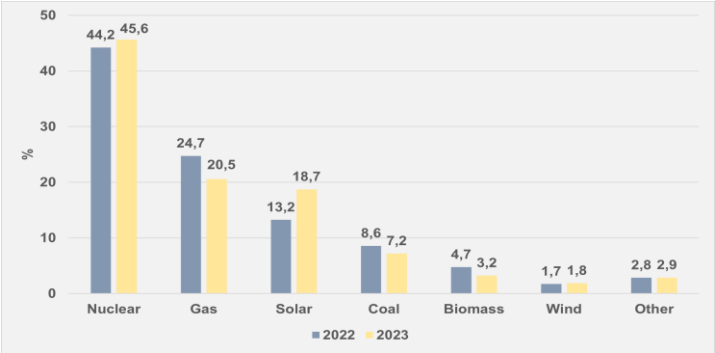

Figure 4: Gross electricity generation by energy source, 2022-23 (HEPURO, 2024)

These developments are promising, but a significant challenge remains: 84 % of natural gas is imported, posing a notable energy security risk. Reducing the demand for natural gas would significantly enhance Hungary's energy security. This requires implementing measures to reduce demand, improve energy efficiency, and promote electrification (NECP, 2023).

As mentioned, demand is steadily decreasing, largely due to more conscious energy consumption. This trend should be further encouraged through increased awareness campaigns and the promotion of alternative energy sources. The greatest savings in natural gas can be achieved through measures to improve energy efficiency, which will be a primary focus in the coming years. In 2023 Hungary's final energy consumption was 773 PJ, with residential consumption accounting for one-third of this total (HCSO, 2024). Of the energy used in residential

settings, three-quarters is for heating and cooling, and nearly half of this is natural gas (HEPURO, 2024). Consequently, future measures will concentrate on the approximately 2.6 million residential properties that require some level of energy modernisation. The strategic target is to achieve a 20 % reduction in energy use across the domestic housing stock by 2030 and to reach a 90 % share of near-zero energy buildings by 2050. To meet these targets, Hungary will continue to launch residential home renovation tenders that include non-refundable grants and subsidised interest loans. Additionally, Hungary will support the reduction of residential natural gas consumption through the electrification of heating systems and will prioritise renewable heating solutions where feasible (NECP, 2023).

3.2 Increase of the alternative sources

To enhance energy sovereignty, it is crucial to reduce reliance on natural gas and the proportion of imported gas. Additionally, Hungary should diversify its import sources to improve security. The goal is to decrease the proportion of imported natural gas to 80 % by 2030. Currently, Hungary receives significant physical gas supplies from six neighbouring countries, totalling more than 144 Mm^3/d (HEPURO 2024). Previously, the main entry routes were from Ukraine and Austria. However, since October 2021, the new bi-directional pipeline from Serbia has assumed this role. Since the onset of the Russian-Ukrainian war, this has been the only pipeline continuously delivering Russian supplies. A key objective is the further expansion of cross-border capacities, including the construction of the Hungarian-Slovenian bi-directional gas pipeline and the expansion of the Romanian-Hungarian cross-border capacity. Additionally, plans are in place to secure further LNG resources from Croatian, Greek, and Polish LNG terminals (NECP 2023).

Expanding domestic natural gas production is also a priority. Over the next decade, Hungary plans to build new highly efficient (low CO_2 intensity) and flexible gas power plants with a total capacity of 1,500 MW. Besides increasing domestic gas production and diversifying imports, Hungary aims to promote green solutions such as biogas, biomass, and green hydrogen. Biogas plants can meet local heat demand, and the purified biomethane can be injected into the natural gas network, potentially replacing imported natural gas. The goal is to gradually increase biogas production from the current 100 Mm^3/y to 1 Gm^3/y, with intermediate targets of 300 Mm^3 by 2027 and 1 Gm^3 by 2030 (NECP, 2023).

To advance green hydrogen production, the National Energy and Climate Plan envisions installing at least 240 MW of electrolysis capacity by 2030. However, the value lies not just in producing green hydrogen but in its cost-effective use. Hydrogen will be utilised in industries that are challenging to electrify and are typically energy-intensive, including the chemical, steel, cement, glass, and ceramic industries (NECP, 2023).

It is important to note that while the recent focus has shifted to energy sovereignty and affordability, Hungary remains committed to its climate policy commitments. Thus, the measures outlined above are designed to align with these existing commitments.

3.3 System Flexibility Development

A critical issue for renewable energy production, particularly weather-dependent sources like solar, is surplus energy storage. Current energy storage technologies fall into four categories: mechanical, electrical, thermal, and chemical, with most capacities in the range of a few hundred megawatts or less than 100 MW. In contrast, pumped hydro storage, which utilises mechanical energy, dominates with about 90 % of the total global storage capacity, reaching nearly 160,000 MW by 2021 (IEA. 2024).

Hungary’s energy strategy includes a substantial expansion of solar photovoltaic (PV) capacity. However, rapid solar growth in Europe has led to instances of unsold electricity during peak production. Solar PV technology's intermittency requires complementary non-weather-dependent power sources; hence, Hungary plans to install 1,500 MW of gas-fired power plants to enhance grid flexibility and ensure stable supply, given their rapid response to demand fluctuations. Energy storage systems can further support or even partially replace, these gas plants. Both pumped storage and nuclear thermal storage are seen as viable solutions for Hungary (Németh, 2022), with plans to build 1 GW of energy storage facilities by 2030, a sharp increase from the current 20 MW (NECP, 2023). Of these, a 20 MW battery storage unit is under construction, and plans are underway for 500-600 MW in pumped storage. Pumped storage’s efficiency is optimal at large scales but does not resolve sub-grid issues like overloading and reverse flows. The distribution network’s development lags behind the growth of renewables, necessitating significant investment. Rising residential renewable installations and electric vehicle numbers pose challenges for Hungary’s grid, making substantial grid expansion essential. Regulatory improvements, such as innovative market management practices and targeted heat storage promotion for balancing, could further aid in network modernisation (NECP, 2023).

4. Conclusion

Hungary, like many nations, faces the energy trilemma—balancing energy security, affordability, and sustainability—made increasingly complex by geopolitical instability and evolving energy markets. As highlighted by the World Energy Trilemma Index (WETI), achieving equilibrium among these pillars requires challenging trade-offs. Hungary performs well in energy equity, with relatively affordable energy prices, but its heavy dependence on imported fossil fuels underscores its vulnerability in energy security. The authors suggest Hungary should prioritise three actions to address the trilemma effectively. First, reducing reliance on natural gas in the energy mix is crucial, particularly through energy efficiency upgrades targeting around 2.6 million homes in need of modernisation. Second, increasing domestic alternative energy production is essential for energy sovereignty, such as scaling biogas production from 100 Mm^3 to 1 Gm^3 annually and developing 240 MW of electrolysis capacity for green hydrogen by 2030. Third, advancing energy system sustainability and security requires significant investments in energy storage and grid flexibility. Plans include building new gas power plants with a combined 1,500 MW capacity and adding 1 GW in energy storage by 2030 to support the growing solar infrastructure. By pursuing these actions alongside its climate commitments, Hungary can navigate the energy trilemma's challenges, enhancing resilience and advancing toward a sustainable energy future.

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