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# In Search of Energy Security: Nuclear Energy Development in the Visegrad Group Countries

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**Abstract:** The Visegrad Group, comprising Czechia, Hungary, Poland, and Slovakia, has several common features, including their geographical proximity, membership in the EU and NATO, and similar levels of economic development. However, they also have significant differences. The Russian invasion of Ukraine has exposed new disagreements among them, particularly regarding how to ensure energy security amid a changing geopolitical landscape and the issue of sanctions on Russian energy supplies. Despite these differences, the Visegrad Group countries have shown unity in their approach to nuclear power. Although their use of nuclear technology varies, they have recently aligned their nuclear energy policies. Czechia and Slovakia have a long history with nuclear technology, dating back to the 1970s, while Hungary began its nuclear program in the 1980s. Poland, which had paused its nuclear program after the Chernobyl disaster, has recently resumed its nuclear energy efforts. All four countries aim to expand their nuclear energy capacity to either maintain or increase its share in their electricity mix. This paper provides a comparative analysis of their nuclear energy policies, focusing on the political initiatives driving advancements in this field. It argues that these nations see nuclear energy as crucial for creating a resilient, crisis-resistant, and secure energy sector.

**Keywords:** crisis; energy policy; energy security; nuclear; Visegrad group

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## 1. Introduction

The Visegrad Group (V4), consisting of Czechia, Hungary, Poland, and Slovakia, was once a relatively visible regional grouping within the European Union (EU). The main goal immediately after its establishment in the early 1990s was to serve as a platform supporting its countries on their path to EU membership. After all four countries became part of the EU in 2004, the group seemed to lose its purpose. Eventually, however, they learned that the Group could be used to improve their negotiation position within the EU [1] and therefore began to support the Visegrad Group—especially members who wanted to use it to pursue their own preferences within the EU. This led to internal disagreements, as other members viewed these efforts as a misuse of the Group. These developments resulted in the suspension of the Group's activities, which is evident today.

However, there are still some areas where V4 members can find common ground. For example, energy policy is one sector where V4 countries can collaborate and support shared positions. However, this is not case in all areas; for instance, there is significant disagreement regarding the (energy) sanctions against Russia that were adopted at the EU level following the Russian invasion of Ukraine [2]. While Czechia and Poland support all sanctions, including those in the energy sector, Hungary has challenged these from the very start [3], and Slovakia has become much more critical since the formation of a new government led by Robert Fico in autumn 2023.

One of the very few areas in which V4 countries speak in unison is their support for nuclear energy. Czechia and Slovakia had been developing this technology within their

common state of Czechoslovakia since the 1970s and Hungary joined these efforts in the 1980s. Although Poland does not have commercial reactors, it is very supportive of the technology and plans to establish its own fleet by the mid-2030s. The rest of the Group is either currently building new reactors (Hungary), is in the preparatory phase of building new ones (Czechia), or engaged in both activities (Slovakia). This makes the Group a unique region from a global perspective. There are much larger countries developing much bigger nuclear fleets (especially China, but also India), but there is no other group of neighboring countries that shares such a positive attitude towards nuclear energy, especially in the period following the Fukushima nuclear disaster [4]. Although the attitude of many countries towards nuclear energy has changed since the Russian invasion of Ukraine, and there have been calls to increase its capacity (including a declaration at COP 28), these have not yet materialized in any significant way [5].

This paper explores developments within the Visegrad Group and examines why nuclear technology is so strongly supported in this group, while the rest of the world (especially the West) has been rather lukewarm towards nuclear for more than a decade. Although this sentiment has not significantly changed after the Russian invasion of Ukraine, that event has influenced the position of Visegrad Group member countries, leading to even greater support for nuclear energy. This paper claims that nuclear energy is viewed through the prism of energy security in the Visegrad Group and, therefore, these countries—lacking domestic energy sources—support this technology. Nuclear is considered a domestic energy source by these countries, even though they have to import both technology and fuel.

This paper is structured as follows. In the Section 2, we present an overview of the development of nuclear energy worldwide. The Section 3 discusses the Visegrad Group and its members' positions on nuclear energy since they began to utilize this energy source in the middle of the 20th century. The Section 4 examines the place of nuclear energy in the energy mix of these countries. The Section 5, divided into four sub-sections, explores plans for the further development of the nuclear industry in the four countries of the Visegrad Group. The Section 6 summarizes our findings.

## 2. Nuclear Power Around the World

Recent years have seen variable developments in energy policy regarding nuclear energy. On one hand, some countries have abandoned this source or phased it out, such as Germany, Japan, and Lithuania. On the other hand, there are countries that view nuclear energy favorably, such as France, the USA, or South Korea. Germany's phase-out of nuclear power, finalized in April 2023, is crucial for the future of nuclear energy within the EU. The decision was underpinned by strong social and political anti-nuclear sentiments [6], which were reinforced after the Fukushima disaster [7]. However, the Chernobyl disaster is considered a critical juncture in the German opposition to nuclear energy [8]. The phase-out of nuclear energy has become a key component of the *Energiewende* policy, which focuses on the decarbonisation of the German economy [9,10] and aims to achieve climate neutrality [11].

The Fukushima disaster led to a similar policy shift for Japan [12]. Following this event, the country temporarily shut down all its nuclear reactors. The energy source, which supplied approximately 31% of electricity in 2011, was thus completely excluded from Japan's energy mix [13]. However, Japan's energy strategy of 2014 already emphasized the need to bring its reactors back online [14]. Unlike Germany, no decision was made to abandon nuclear power, which is expected to account for 20–22% of Japan's electricity generation mix by 2030. Moreover, the construction of new nuclear power plants (NPPs) to replace decommissioned ones is under consideration [15]. While the pro-nuclear camp in Japan argues that nuclear energy is necessary for the stability of the power system, Knuepfer et al. [16] argue that this can be achieved by increasing capacity in renewable energy sources (RESs).

Lithuania phased out nuclear power for different reasons. One of the conditions for Lithuania's accession to the EU was the shutdown of the Ignalina NPP in 2009. This decision

arose from the safety risks posed by outdated technology, even though improvements in safety systems enabled its operation until 2025 [17]. As a result, Lithuania went from being an electricity-exporting country to an importer, which led to the emergence in 2012 of the idea of returning to nuclear energy [18]. Indeed, one of the reasons for the development of nuclear power is the country's dependence on energy imports [19].

The USA, France, South Korea, Russia, and China are countries that have been using nuclear energy for decades and are global leaders in the field. NPPs are an indispensable component for the US energy system, and the country therefore pays considerable attention to the development of nuclear technology, with particular emphasis on small modular reactors (SMRs) [20,21], fluoride salt-cooled high temperature reactors (FHRs), and molten chloride fast reactors (MCFRs) [22]. The USA is also focused on the challenges and opportunities arising from decommissioning and rebuilding NPPs, as well as nuclear waste management [23–25]. France has the largest share of nuclear power in its electricity mix worldwide. However, the fleet of French NPPs is ageing, raising questions about the feasibility of maintaining this share in the future [26]. This concern also impacts France's ability to achieving carbon neutrality by 2050 [27,28]. Investment in new nuclear units is crucial for achieving this goal [29,30], especially as the downtime rate of existing power plants increases [31]. Another important challenge for France, given its need to import nuclear fuel, is recycling of spent nuclear fuel [32]. The case of nuclear power development in South Korea is particularly interesting, as this sector is vulnerable due to the country's geopolitical location, making nuclear safety of utmost importance [33–35]. The Korean energy sector is heavily dependent on fossil fuels, which makes the development of nuclear and renewable energy essential [36–38]. The need to establish domestic decommissioning capabilities arises from the fact that more than ten units will have been shut down by 2030 [39,40].

Russia is steadily advancing its plans for an expanded role of nuclear energy, including development of new reactor technology. A significant challenge is the gradual phasing out of old reactors while simultaneously connecting new units to the electricity grid. Russia is a world leader in fast neutron reactor technology and is consolidating this position through its Proryv ('Breakthrough') project [41,42]. Moreover, exports of nuclear goods and services represent a major Russian policy and economic objective [43]. Over 20 nuclear power reactors have been confirmed or planned for export construction. However, in the aftermath of the war in Ukraine, many of Rosatom's projects were suspended or canceled [44]. China is the global leader in the development of nuclear energy, largely due to air pollution from coal-fired plants [45,46]. The notable feature is that China has become largely self-sufficient in reactor design and construction while making extensive use of Western technology and adapting it. As a result, nuclear technology is currently being intensively developed, enabling China to become a significant supplier of affordable nuclear reactors [47].

The number of countries without nuclear power that are planning to introduce it is increasing. According to the World Nuclear Association, there are about 30 such countries, several of which have already begun building NPPs. For example, Turkey is constructing two units, Mersin/Akkuyu and Sinop [48] to decrease its energy import dependence, increase energy diversification, and minimize the environmental impact of electricity generation [49]. Over the last decade, Turkey's energy needs have rapidly grown, leading to increased imports of fossil fuels, especially from Russia [50]. New NPPs together with renewables are expected to ensure the sustainability of the country's electricity grid and lower electricity costs [51]. A similar rationale has been put forward in the case of Egypt, were Comsan [52] claims that to ensure sustainable development, nuclear power should reach 13% of installed capacity by 2052. However, Hickey [53] argues that nuclear technology creates technical and financial dependencies on countries supplying it.

Countries developing nuclear power programs from scratch include Saudi Arabia, which is trying to decrease its dependence on fossil fuels in its electricity sector [54]. The nuclear program is one of the priorities of the Vision 2030 project, intended to modernize

the power industry [55] and ensure its long-term stability [56]. The low-emission nature of nuclear energy is also an important factor in achieving carbon neutrality [57,58] for many countries, including Indonesia [59] and Kazakhstan [60]. In Indonesia, there is growing political and social awareness of the need for long-term nuclear deployment [61], while Kazakhstan has identified nuclear power as an alternative to hydro and solar energy [62].

The literature on the nuclear sector of the Visegrad Group countries focuses on individual countries or at the EU level. Despite being a non-nuclear state, interest in the Polish nuclear sector is relatively high, usually linked to its connection to decarbonization [63–67]. A lot of attention has been given to Poland's current over-reliance on carbon-intensive fossil fuels, which could be mitigated by the commissioning of NPPs [68], as well as development of environmentally friendly energy projects [69]. The other V4 countries have several decades of experience in the nuclear sector, and the impact on their energy transition is somewhat more limited as they are primarily building new installations to replace aging ones (though there is ongoing discussion about the prolongation of the lifespan of existing NPPs). A major challenge remains to justify the operation of nuclear facilities in the future [70,71], with an emphasis on the need for technological change, the expansion of existing installed capacity [72–74], and the role of nuclear power in achieving climate neutrality [75].

## 3. The Development of Nuclear Energy in the Visegrad Group Countries in a Nutshell

The development of nuclear power in the individual countries of the Visegrad Group countries was generally similar, with origins dating back to the Communist period. Nuclear programs were implemented in all these countries between 1960s and 1980s, leading to the construction of NPPs equipped with Soviet technology in Czechia, Hungary, and Slovakia (see Table 1). In Poland, the construction of a NPP started but was never finalized. Following the Russian invasion of Ukraine, the V4 countries are facing serious threats to their energy security, stemming not only from disrupted supply chains of Russian energy sources but also from the transformation process of the energy sector [76,77]. Despite significant differences in the energy policies of these countries, a common factor can be identified in the development of nuclear energy, which is expected to provide a foundation for a secure and stable energy source in the coming decades.

The Slovak nuclear power development program was initiated as early as 1956, when the design of the very first Czechoslovak NPP in Jaslovské Bohunice (referred to as A1) was presented. Construction was completed in 1972, and the reactor was shut down after two major accidents in 1976 and 1977. These failures had little impact on the further development of the Slovak nuclear sector, as work continued on four other reactors during the same period (2xVVER 440/V−230 and 2xVVER 440/V−213). All the reactors were connected to the electricity grid between 1978 and 1985. The two oldest units (referred to as Jaslovské Bohunice V1) were shut down in 2006 and 2008, respectively, which was one of the conditions for Slovakia's accession to the EU [70]. The remaining two reactors, with a total capacity of 1010 MW (Jaslovské Bohunice V2), were originally scheduled to operate until 2015, but their lifespan was extended through upgrades to (so far) 60 years. This NPP is, however, not the only nuclear project implemented in Slovakia.

In the early 1980s, the construction of a NPP in Mochovce was commenced, with the plant originally intended to consist of four reactors (VVER 440/V−213). However, due to a lack of funding and regional political and economic changes (connected to the fall of Communism and the transition to a market economy), construction was halted in 1991. It was resumed four years later, and two reactors were completed in 1998 and 2000, respectively [73]. Work on the other two reactors had been repeatedly postponed, and it was not until the end of 2023 that the Mochovce 3 was commissioned [78]. The fourth reactor is still under construction.

Similarly, the Czechs have been expanding their nuclear sector for decades. Construction of the first Dukovany NPP began in 1974, and four reactors (VVER 440/V−213) were commissioned between 1985 and 1987 [79]. Over the past two decades, the Dukovany

NPP has undergone modernization, increasing the capacity of each reactor from 440 to 510 MW. In 2019, the Czech government gave preliminary approval for at least one new unit (to be built by 2035), intended to replace the four units currently in use (scheduled for phase-out between 2035 and 2037). The second Czech NPP, Temelin, began construction in 1987 and was also planned to consist of four reactors. Following the political and economic transition, work was delayed until the beginning of the 21st century, and two reactors (VVER 1000/V−320) were finally commissioned in 2002 and 2003, respectively, with a total capacity of 2180 MW [80]. Over the next several years, attempts were made to resume work on the two remaining reactors, but all efforts in that direction proved futile.

The development of the nuclear sector in Hungary has not differed significantly from the previous two cases. The decision to build the Paks NPP was made as early as 1966, and construction began in the mid-1970s. Development was completed between 1982 and 1987, resulting in the commissioning of four reactors (VVER 440/V−213) [81]. Thanks to upgrades carried out in the 2000s, the total capacity is now 2000 MW, and the reactors are expected to remain in operation until the period between 2032 and 2037. In 2009, the Hungarian Parliament approved the preparatory work for new nuclear power units [82]. According to an agreement with Rosatom signed by the Hungarian government in January 2014, the Paks NPP will be expanded by two reactors (VVER 1200) to be installed by the Russian state-owned company [83]. Work on this project is still ongoing.

Poland's experience with nuclear power dates back to the 1950s when the Nuclear Research Institute was established and the experimental EWA (Eksperymentalny Wodny Atomowy, Experimental Water Atomic) nuclear reactor was commissioned. In the 1970s, the authorities decided to build a NPP in Żarnowiec and established cooperation with the USSR in this context. Work commenced in 1982, but due to the Chernobyl disaster and the subsequent collapse of the Communist regime, it was discontinued [65]. The concept of a Polish NPP was revived in 2005, as it was included in the Energy Policy of Poland until 2025 [84]. Nevertheless, no progress was made in the following several years. Only in recent years have decisions been made to build the first NPP in Poland, which is to be constructed by 2033.

**Table 1.** Reactors operating in the V4 countries.

| Country | Reactor Name | Type | Capacity (MW) | First Grid Connection |
|---|---|---|---|---|
| Slovakia | Jaslovské Bohunice 3 | VVER V-213 | 466 | 1984 |
| | Jaslovské Bohunice 4 | VVER V-213 | 466 | 1985 |
| | Mochovce 1 | VVER V-213 | 408 | 1998 |
| | Mochovce 2 | VVER V-213 | 408 | 1999 |
| | Mochovce 3 | VVER V-213 | 440 | 2023 |
| Czechia | Dukovany 1 | VVER V-213 | 510 | 1985 |
| | Dukovany 2 | VVER V-213 | 510 | 1986 |
| | Dukovany 3 | VVER V-213 | 510 | 1986 |
| | Dukovany 4 | VVER V-213 | 510 | 1987 |
| | Temelin 1 | VVER V-320 | 1086 | 2000 |
| | Temelin 2 | VVER V-320 | 1086 | 2002 |

**Table 1.** *Cont.*

| Country | Reactor Name | Type | Capacity (MW) | First Grid Connection |
|---|---|---|---|---|
| Hungary | Paks 1 | VVER V-213 | 479 | 1982 |
| | Paks 2 | VVER V-213 | 479 | 1984 |
| | Paks 3 | VVER V-213 | 479 | 1986 |
| | Paks 4 | VVER V-213 | 479 | 1987 |

Sources: Authors, based on [85].

## 4. The Energy Sector in the Visegrad Countries with Focus on Nuclear Energy

The V4 countries, despite being neighbors and having similar political and economic backgrounds (experience with the Communist regime, democratization, membership of the EU, NATO, etc.), are characterized by different energy sectors. A good example is electricity. In 2022, the main source of electricity for Poland and Czechia was coal (both hard and lignite), accounting for approximately 72% and 44%, respectively. In Slovakia and Hungary, the main electricity sources are nuclear (60% and 44%, respectively). In general, apart from Poland, nuclear power is a key energy sector for the V4 countries. Conversely, a notable trend in natural gas usage is primarily observed in Hungary (25%), while in the other countries its share does not exceed 8%. Another characteristic feature of the V4 electricity generation structure is the low utilization of renewable energy sources [86]. In Poland, Slovakia, and Hungary, this source is responsible for approximately 21–22% of generation, while this figure is only 14% in Czechia (see Table 2).

**Table 2.** Structure of electricity generation in 2022 by energy sources in Visegrad countries.

| | Poland | Slovakia | Czechia | Hungary |
|---|---|---|---|---|
| Coal and other fossil | 71.8 | 9.7 | 44.1 | 8.7 |
| Natural gas | 6.6 | 7.9 | 5.1 | 24.8 |
| Nuclear | 0 | 59.7 | 36.6 | 44.3 |
| Renewables | 21.1 | 21.9 | 13.7 | 20.9 |

Source: Authors, based on [87].

The V4 countries are characterized by a high share of carbon-intensive fossil fuels in electricity generation, especially Poland (almost 80%) and Czechia (approx. 50%), for which coal remains the main source. Hungary (approximately 33%) performs better in this comparison, although natural gas plays an important role here, as it does in Slovakia (below 8%). The V4 countries were dependent on Russian hydrocarbons for decades [88]. Until the Russian invasion of Ukraine in February 2022, Russia had been the most important energy partner for most of the Central European countries with regards to natural gas or oil imports, particularly for Slovakia and Hungary [83,89]. One of the most important challenges for the V4 countries, and in a broader context for the EU, is the diversification of sources of strategic energy supplies [2,90]. The EU's sanctions against Russia have revealed the weaknesses of the energy policies of these countries pursued in recent years. The V4 countries either failed to secure alternative transmission infrastructure (Hungary, Slovakia, and Czechia) or investments were delayed (Poland). Consequently, these countries now find themselves in the unfavorable position of having to reduce or fully exclude fossil fuel supplies from Russia from their energy mix in a very short time (with the exemption of natural gas that has not yet been sanctioned).

The difficult geopolitical situation in Central and Eastern Europe (CEE) has repercussions for the decarbonization of the energy sector in the V4 countries. This issue is also related to the dynamically changing stance on renewable energy sources. After joining the EU, CEE countries initially supported the EU's renewables targets due to post-accession

compliance; however, once this accession legacy faded away, they began to pursue their preferences more assertively, resulting in differing strategies [1]. In Poland, the process of moving away from fossil fuels, especially coal, presents a major challenge for ensuring energy security. This fuel has been fundamental to electricity generation for many decades, and its role remains crucial despite investments in other energy sources. Coal was expected to be offset by natural gas [91]; however, due to the Russian invasion of Ukraine, the role of natural gas has become unclear not only in Poland but also across the entire EU.

RESs have developed unevenly within the V4 countries. On one hand, there has been noticeable growth in solar power generation in Poland [92]; on the other hand, wind power generation has stagnated for several years [93]. The Czech energy sector is still characterized by high carbon, with plans to achieve decarbonization at least partly through nuclear power [94] resulting in a low share of renewables [95]. The Czech natural gas sector is affected by major changes in European markets and therefore requires increased investment, especially concerning supply [96]. In Slovakia, the decarbonization of the energy sector does not involve deep changes in the structure of electricity generation, as nuclear fuel remains the dominant source. Nevertheless, fossil fuels, particularly coal, are still important energy resources [97]. In recent years, there has been an increasing emphasis on the development of RESs in Slovakia, with significant opportunities for energy transition seen in this respect [75]. In Hungary, major decarbonization opportunities arise from nuclear power; however, the strategic importance of natural gas as a transition fuel is underlined [98]. Similarly to Poland, the largest development among RESs has occurred in the photovoltaic sector [99].

Similarly to decarbonization, the individual V4 countries are pursuing different, even opposing, preferences in response to the energy crisis connected to the Russian invasion of Ukraine. Their policies towards Russian fossil fuels are clearly divergent. Poland has diversified its sources of fossil fuel supplies through dynamic investments in energy infrastructure, achieving complete independence from Russian energy sources since May 2023. This country has been and remains one of the biggest proponents of increasing pressure and sanctions against Russia [100]. It advocates for regional energy integration, particularly in developing alternative natural gas transmission infrastructure [101]. Hungary, in contrast, has a completely different vision and remains heavily dependent on Russian energy resources. The country's stance towards sanctions imposed on Russia is characterized by pragmatism, manifested in the preservation of the status quo regarding the distribution of Russian fossil fuels [102]. Notably, Polish and Hungarian policies towards Russia align with the prevailing public sentiments in these countries [103].

An intermediate position, although closer to Poland with regard to the need to counteract the energy crisis caused by the war in Ukraine, is represented by Czechia and Slovakia. The former seeks to reduce the share of Russian energy sources in its energy mix as much as possible and generally advocates for maintaining existing sanctions while marginalizing Russian influence in Central and Eastern Europe [104]. Slovakia, on the other hand, is characterized by pronounced political polarization towards Russia; consequently, relations with this country depend significantly on which political forces are in government at any given moment [105]. There is also a noticeable dependence on Russian energy resources and limited access to alternative energy sources [106]. Thus, over time, Slovakia may be moving closer to Hungary's position on sanctions. Recent political changes (the return of the pro-Russian Fico government after the 2023 elections) support this notion. Russia has built its influence in the V4 countries through state-owned companies, such as Gazprom and Rosneft, which have established themselves as key—and sometimes sole—suppliers of hydrocarbons over the decades. A similar situation exists in the nuclear sector, where the supply of technology and nuclear fuel has been dominated by Rosatom [107].

Despite the differences outlined above (such as the structure of electricity generation, energy policy, the role of Russian energy resources, etc.), it is possible to identify a common feature across the Visegrad Group: the effort to achieve an efficient and resilient energy sector, and in the longer term, the pursuit of energy stability. A key means to achieve this

is through the use of nuclear energy. While Poland has not yet utilized nuclear energy, Czechia, Slovakia, and Hungary have extensive experience with the technology [108].

Nuclear energy is viewed not only as a clean energy source but also as a stable and reliable one. Unlike RESs, it is not intermittent and is independent of weather conditions [109,110]. Compared with fossil fuel power plants, nuclear facilities require less frequent refueling (typically every 18–24 months) and maintenance. Another advantage is the specific characteristics of nuclear fuel, which allow the production of a significant amount of energy from a small amount of material. For instance, the energy generated from 1 ton of uranium is comparable to that produced from 3 to 4 million tons of fossil fuel. Burning 1 kg of firewood generates 1 kWh of electricity; 1 kg of coal produces 3 kWh; and 1 kg of oil yields 4 kWh. In contrast, 1 kg of nuclear fuel in a modern light-water reactor generates 400 MWh of electricity.

From fossil fuel plants, even those equipped with pollution-control systems, thousands of tons of greenhouse gases, particulate matters, and heavy metals (including radioactive ash) are released, along with solid hazardous waste. In contrast, a 1000-MWe nuclear plant emits no noxious gases or other pollutants directly, and it produces much less radioactivity per capita than is encountered from activities like airline travel, operating a home smoke detector, or watching a television set [111]. It is worth mentioning that NPPs produce significantly less waste compared with fossil fuel power plants. According to Cohen [112], the annual waste produced by a large NPP is 2 million times smaller by weight and a billion times smaller by volume than the waste generated by a coal-fired power plant. This issue is particularly pertinent for 'coal countries', i.e., Poland or Czechia. For example, mining waste dumps in Poland cover an area of 11,000 hectares, with the majority located in the highly urbanized region of Upper Silesia [113].

It is also important to address the issue of nuclear waste management. Radioactive waste is generated at all stages of the nuclear fuel cycle—the process of producing electricity from nuclear materials. This fuel cycle includes several phases: mining and milling of uranium ore, processing and fabrication into nuclear fuel, usage in the reactor, potential reprocessing, treatment of the used fuel taken from the reactor, and finally, disposal of the waste. While waste is produced during mining, milling, and fuel fabrication, the majority (in terms of radioactivity) originates from the actual 'burning' of uranium to produce electricity. When spent fuel is reprocessed, the volume of waste is significantly reduced. Spent nuclear fuel can be regarded as a resource or simply as waste. Notably, nuclear waste is neither particularly hazardous nor difficult to manage compared with other types of toxic industrial waste. Storage involves keeping the waste in a manner that allows retrieval whilst ensuring isolation from the external environment. Nuclear waste may be stored temporarily to facilitate the next stage of management (for example, allowing its natural radioactivity to decay). Storage facilities are commonly located onsite at the NPP but can also be situated separately from the facility where the waste was produced [114,115]. Research indicates that nuclear waste can be effectively stored in geological repositories, which could allow future reuse [116].

Furthermore, accessing uranium and its distribution does not present the same challenges as those associated with natural gas or oil. However, there are other complexities related to the fuel cycle. Uranium, the raw material for nuclear fuel, can be sourced from various countries around the world, including Kazakhstan, Canada, Australia, and Namibia [117]. Its distribution does not require capital-intensive investments in transmission infrastructure, such as pipelines. Instead, a complex infrastructure is necessary to convert uranium ore into nuclear fuel. This includes processes like conversion, enrichment, and manufacturing of fuel assemblies, which pose significant challenges for CEE [118]. Most enrichment capacity is concentrated in Russia, making it a key player in the nuclear industry. Consequently, countries of CEE, including those in the Visegrad Group, remain dependent on Russian nuclear fuel [119].

There are only very limited uranium deposits in the V4 countries. The estimated reserves in Poland are about 100,000 tons, with identified reserves at only 7000 tons. This

discrepancy arises from the lack of comprehensive studies, as uranium ore was mined only between 1947 and 1967 [120]. Czech experience with uranium mining is far richer and covers the years 1947–2017, during which approximately 110,000 tons were extracted, with a large portion sent to the USSR and later to Russia. Mining at Rožná, the last operational deposit in CEE, ceased in April 2017 [121]. A technical and economic assessment in 2013 estimated that Czechia had just over 119,000 tons of uranium resources. However, these resources are located within groundwater source protection zones, making their exploitation unlikely [122]. In Slovakia, uranium ore mining occurred from 1954 to 1990, primarily as a by-product of copper mining. Geological surveys conducted between 2011 and 2014 indicated that Slovak uranium reserves totaled just over 19,000 tons. During this period, plans were made to develop deposits near Košice, but these were withdrawn following protests. Hungary's uranium mining history spans from 1956 to 1997. The potential resumption of mining at the Mecsek deposit, which has reserves of nearly 17,000 tons, was revisited in 2007, but little progress has been made since then [117].

Another advantage of nuclear technology is the small physical footprint of NPPs. In comparison, a solar or wind power plant with an output capacity of 1 GW requires an area 75 or 360 times larger, respectively. According to the U.S. Energy Information Administration, NPPs are nearly twice as efficient as coal-fired plants, operating at maximum output for approximately 93% of the time [123]. By comparison, the capacity factor for natural gas power plants is approximately 62%, while hydroelectric or wind power plants have capacity factors of about 36% and solar power generation only around 25% [124].

When considering energy security, the ability to store an energy source is also significant. Nuclear fuel stocks can be stored for many years without deterioration, which reduces the risk of supply disruption or price volatility—challenges we have recently witnessed, particularly regarding natural gas supplies from Russia. The impetus for further development of nuclear energy mainly stems from climate change, which encourages national governments to opt for stable and environmentally benign technologies [125]. Indeed, scenarios involving nuclear power predict the lowest $CO_2$ emissions for EU member states. It has been argued that shutting down NPPs despite increased solar and wind capacity can lead to higher $CO_2$ emissions, reduced supply, and greater demand for energy storage [126].

## 5. Plans for the Development of Nuclear Energy in the V4 Countries

### *5.1. Poland*

The Polish experience with development of nuclear power has been marked by failures, significantly influenced by the Chernobyl disaster. However, the crucial factors have been political decisions, which have largely been unfavorable to the nuclear sector over past decades. Nevertheless, attitudes towards nuclear energy have been shifting in recent years, with an increasing acknowledgement of the need for an NPP in Poland [66]. Nuclear power is extensively covered in the current Polish Energy Policy until 2040 (PEP 2040). This document identifies the development of nuclear energy as the second pillar of Polish energy transition, aiming to achieve a net-zero emissions energy system by 2040 [127]. Poland finds itself in a challenging position, as its energy sector remains largely dependent on coal. The goal of net-zero emissions, as well as low emissions in the short term, is expected to be achieved through a significant increase in RESs. However, even with intensive investment in RESs over the coming decade, it is unlikely that coal-fired power generation can be fully replaced. PEP 2040 argues that a new NPP is essential to address this challenge.

The first NPP, with a capacity of 1–1.6 GW, is expected to commence operation in 2033. Subsequent nuclear reactors are planned to be completed every 2–3 years, with the entire nuclear program aiming to construct six similar units by 2043 [128]. It is expected that up to 70% of the construction for these units will be carried out by Polish enterprises in cooperation with domestic scientific and research centers. Over 60 Polish companies have already gained experience in the nuclear sector abroad. It is estimated that the launch of this new energy sector will generate approximately 25,000–38,000 jobs. However, the successful implementation of the nuclear program requires the development of brand-

new infrastructure: legal, organisational, institutional, scientific, and research facilities, as well as staff training systems and cybersecurity measures [127]. In addition, selecting the technology and the general contractor for the project, along with determining the investment location, are essential steps. It should be emphasized that the Polish energy policy also envisions the use of small modular reactors (SMRs) for district heating and industrial applications [129].

The need for a more dynamic energy transition, exacerbated by the war in Ukraine, has intensified Poland's efforts to implement the plans outlined in the PEP 2040 regarding nuclear power generation [130]. A milestone in this process was the signing in October 2020 of a cooperation agreement between Poland and the USA on civil nuclear energy [131]. The concept for the first NPP in Poland is being developed by Westinghouse Electric Company, an American enterprise specializing in nuclear equipment production. Furthermore, negotiations have been conducted with the French EDF and South Korea's KHNP [132]. In September 2022, the President of Westinghouse visited Poland and, together with the US ambassador to Poland, presented a concept and implementation report on cooperation in the field of civil nuclear power. This report provided a roadmap for the development of the nuclear sector in Poland.

Finally, in late 2022, the Morawiecki government decided to adopt nuclear technology from the USA (AP 1000) and South Korea (APR 1400). The Westinghouse project plans for the commissioning of the first nuclear unit in 2033, with development set to take place in Lubiatowo-Kopalino. KHNP, on the other hand, intends to finalize the design for a second NPP located in Pątnów [133]. With the selection of the general contractor, technology, and development location now concluded, the state-owned company Polskie Elektrownie Jądrowe signed a contract with Westinghouse in February 2023 for pre-design work on the NPP in Lubiatowo-Kopalino [134]. The next steps will involve obtaining environmental approvals, a construction permit, and a permit required under the Water Law Act. Construction of the first NPP is scheduled to begin in 2026. In mid-2023, Orlen Synthos Green Energy identified several potential sites for the construction of SMRs (BWRX-300), which are expected to be operational in the 2030s (see Table 3).

**Table 3.** Reactors planned and proposed in Poland.

| Location | Type | Capacity (MW) | Construction Start |
|---|---|---|---|
| Lubiatowo-Kopalino | AP 1000 | 3 × 1250 | 2026 |
| Pątnów | APR 1400 | 2 × 1400 | before 2030 |
| Dąbrowa Górnicza | BWRX-300 | 4 × 300 | after 2030 |
| Nowa Huta | BWRX-300 | 4 × 300 | after 2030 |
| Ostrołęka | BWRX-300 | 4 × 300 | after 2030 |
| Stawy Manowskie | BWRX-300 | 4 × 300 | after 2030 |
| Tarnobrzeg | BWRX-300 | 4 × 300 | after 2030 |
| Włocławek | BWRX-300 | 4 × 300 | after 2030 |

Sources: Authors based on [85].

Poland's experience with nuclear power thus far warrants a cautious assessment of the prospects for implementation within the next decade. However, it is important to highlight that this is the first time in history that the Polish authorities have undertaken a genuine initiative in this direction. It is highly probable that the Polish energy sector will be powered by NPPs in the 2030s. Nonetheless, for this to happen, the unwavering cooperation of all stakeholders involved in the development of Poland's nuclear power sector will be essential.

### *5.2. Czechia*

Czechia is also facing the challenge of decarbonizing its electricity sector, with the development of its nuclear program being particularly important in this process [135]. However, the past two decades have been characterized by stagnation in this regard. Following the Russian invasion of Ukraine, the country boosted its efforts to build new reactors. The Czech energy policy of 2014 already envisioned a 50% share of nuclear energy in the energy mix by 2040, a target to be achieved by commissioning two new units at Temelin and one at Dukovany [136]. At the same time, the lifespan of the four Soviet reactors at Dukovany was to be extended by at least 20 years, to 2045–47. These measures aimed to reduce coal consumption to one-third of 2012 levels. The 2015 National Action Plan for the Development of the Nuclear Energy Sector in Czechia projected an increase in nuclear generating capacity by 2500 MWe over 20 years [137]. In 2016, a commission chaired by the Prime Minister was set up to coordinate the development of the nuclear sector. However, in December 2019, the Czech Prime Minister announced that the expected date for the Dukovany 5 Unit had been postponed to 2029, with expected commencement expected no earlier than 2036 (see Table 4) [138].

**Table 4.** Reactors planned and proposed in Czechia.

| Reactor | Type | Capacity (MW) | Construction Start |
|---|---|---|---|
| Dukovany 5 and 6 | EPR 1200, AP 1000, APR 1400 | 2 × 1000–1400 | 2029 |
| Temelin 3 and 4 | EPR 1200, AP 1000 or AP5 1400 | 2 × 1000–1400 | after 2030 |

Sources: Authors, based on [85].

The tender procedure for the construction of two units at Temelin NPP dates back to 2009, when negotiations were initiated with three bidders: Westinghouse, Škoda JS/Atomstroyexport/OKB Gidropress, and Areva [79]. Three years later, all three companies/consortiums submitted formal bids, but the tender was ultimately cancelled. One of the reasons for this was a dispute between the operator of Telemín NPP (ČEZ) and Bohuslav Sobotka's government over the system of guaranteed power purchase price. Additionally, the cancellation was indirectly influenced by the earlier sudden collapse of the center-right cabinet led by Petr Nečas, who had been more supportive of nuclear expansion [138]. The National Action Plan for the Development of the Nuclear Energy Sector in Czechia, adopted in June 2015, prioritized Dukovany unit 5 over Temelin due to the need to maintain electricity production at Dukovany after phasing out the existing units around 2047 [137]. Interest in building new units was expressed by Westinghouse, EDF/Areva, Rosatom, Atmea, KHNP, and China General Nuclear Power Corp. In March 2021, the Czech government selected Westinghouse, Rosatom, EDF, and KHNP to participate in the pre-qualification round for the tender for Dukovany unit 5 [139]. However, Rosatom was later eliminated after investigation linked Russia to the 2014 explosion at an ammunition depot in Moravia [140].

A year later, Elektrárna Dukovany II, a subsidiary of ČEZ, announced a tender for the construction of a new NPP in Dukovany. In November 2023, the Czech government received final bids for the planned investment from Westinghouse (AP 1000), EDF (EPR 1200), and KHNP (APR 1400) [141]. It is anticipated that the contract will be signed at the end of 2024. Additionally, ČEZ received non-binding bids from three consortiums for the construction of another reactor at Dukovany and two more at Temelin. Similarly to Poland, there is significant interest in SMRs. ČEZ plans to select a supplier for the first modular reactor, to be installed at the Temelin NPP and connected to the grid between 2032 and 2035 [142].

Finalization of the Czech investment in the development of nuclear power is bolstered by strong political and public support, alongside the urgency created by the impeding

shutdown of older nuclear units and coal-fired power plants [143]. Notably, 72% of Czech citizens favor expansion of nuclear power capacity [144].

### *5.3. Hungary*

Hungary has revisited its nuclear power development strategy in the early 21st century, recognizing the need to commission new reactors within the coming decades. Hungary's energy strategy, published in 2012 amidst a general unfavorable climate for nuclear energy following the Fukushima disaster, still incorporated nuclear power in all scenarios for expanding electricity generation capacity. These scenarios included extending the lifespan of the existing NPP (Paks) beyond 2032–2037—potentially up to 70 years—or replacing the old reactors with new ones. Given that the current Paks reactors have a lifespan of 50 years, the phasing out of these units is anticipated to occur during the 2032–2037 period. Consequently, plans are in place to construct the Paks 5 unit in the latter half of the 2020s and Paks 6 unit by the end of 2030 [145].

In 2012, the state-owned MVM Paks Nuclear Power Plant Ltd (MVM Paks II) was established with the task to implement the nuclear power development program in Hungary. Although a nuclear cooperation agreement had been signed with South Korea, the Hungarian government decided in January 2014 that two new reactors with a total capacity of 2400 MW would be built by Rosatom [146]. It was originally envisaged that these units (Paks 5 and Paks 6) would be connected to the electricity grid by the late 2025 or early 2026. In December 2014, MVM Paks II signed three implementation agreements with the Russian company NIAEP-ASE, which included the parameters for the design, purchase, and construction of the new units, the conditions related to their operation and maintenance, as well as the details concerning fuel supplies.

The Hungarian–Russian agreement stipulated that Rosatom was to be the sole supplier of nuclear fuel for 20 years after the commissioning of the new reactors. In 2015, this provision was challenged by the Euratom Supply Agency and the European Commission. Following the objections raised, this period was reduced to 10 years [147]. Other doubts raised by the European Commission concerning, e.g., the compliance of the contract with Rosatom with EU procurement rules were also clarified. Another obstacle to the development of Hungarian nuclear power was the Austrian lawsuit against the European Commission in February 2018 relating to the approval of Hungarian state aid for the expansion of the Paks NPP. The case was dismissed by the General Court of the European Union in November 2022 [148]. Undoubtedly, these political disputes delayed the expansion of the Paks NPP, thus making impossible the capacity increase announced for the mid-2020s. Only in August 2022 did Rosatom obtain permission to build two nuclear reactors (VVER−1200/V−527) [149]. Thus, work is due to start in 2025 and completion is planned for 2032. Ultimately, Paks II is intended to replace the existing four reactors that are currently scheduled to be shut down by the end of 2037 (see Table 5).

**Table 5.** Reactors planned and proposed in Hungary.

| Reactor | Type | Capacity (MW) | Construction Start |
|---|---|---|---|
| Paks 5 and 6 | AES-2006E: VVER-1200/V-527 | 2 × 1200 | 2025 |

Sources: Authors, based on [85].

Nuclear power supplies about a half of the electricity consumed in Hungary, which makes nuclear power the key element of Hungarian electricity generation. The currently operating reactors will be shut down in just over ten years, and it is therefore necessary to couple the phasing out of the old reactors with the integration of the new units into the electricity grid. However, the contract with Rosatom turned out to be problematic and raises questions in the context of EU sanctions against Russia [76,150]. Hungary's push to execute the contract reflects its commitment to achieving electricity self-reliance in the coming years. Given the country's energy needs and reliance on external sources,

expanding its nuclear capacity is seen as a crucial step to ensure a stable and independent energy supply.

### *5.4. Slovakia*

Slovakia's nuclear sector stands out among the V4 countries due to its significant reliance on nuclear energy. The share of nuclear in its energy mix had been much higher than in the other V4 countries (see Table 2), even before the commencement of the third unit at the Mochovce NPP in autumn 2023. This development further increased the share of nuclear in the electricity mix, although we do not know the exact figures, as 2024 will be the first full year of operation for this unit. The reactor (together with the Mochovce 4 unit) began construction in the 1980s, and both reactors were mothballed in the early 1990s due to economic reasons connected to the post-Communist transition to a market economy and democratic political regime [73]. The Mochovce 3 and 4 project was restarted in the late 2000s, with 2012 and 2013 initially set as the completion dates for both reactors. However, due to economic issues and other factors, such as the 2008 economic crisis and the 2011 Fukushima nuclear disaster, the construction faced repeated delays, budget expansions, and pushed completion dates [151]. As of October 2024, the fourth reactor is still not complete despite ongoing construction.

However, once the fourth unit in Mochovce is finalized in a couple of years, Slovakia is likely to become one of the countries with the highest share of nuclear energy, not only in the EU but also worldwide (each of these units represents approximately 12% of the electricity consumption in the country—see Table 2). This will place Slovakia in a unique position where a vast majority of electricity will be produced in NPPs, with the reminder (less than 20%) coming from other sources, especially renewables. Although Slovak governments have not been very supportive of renewables since the late 2000s, this has led to challenges connected to their rapid development [1]. This existing situation has already created pressure on the Slovak electricity grid, which requires significant capacity from other sources able to provide secondary and tertiary regulation of the electricity grid and thus guarantee its stability. Nuclear sources in Slovakia are not used for regulation purposes and are considered exclusively as base load sources of electricity. The high share of rigid nuclear power, combined with intermittent renewables, creates a situation with substantial regulation needs, which are often blamed on renewables by the grid operator or the government.

Some of these regulatory needs used to be fulfilled by two coal-fired power plants located in eastern and central Slovakia, respectively. However, these are no longer connected to the grid. Slovakia stopped supporting electricity generation from domestic coal in the coal-fired thermal power plant in central Slovakia (Elektráreň Nováky) in 2023, which also meant the closure of the last coal mine in Slovakia, whose production was almost complete utilized for electricity generation [152]. The other coal-fired power plant in eastern Slovakia (Elektráreň Vojany) was shut down due to its economic unfeasibility after years of being used exclusively for regulation purposes, despite its size. Thus, one of the main challenges for Slovakia in connection with the further development of nuclear energy is guaranteeing grid stability in a situation with a very high share of nuclear energy and a rather limited availability of regulation capacity.

However, the share of nuclear in the Slovak energy mix in the future depends not only on the completion of the Mochovce 4 unit but also on the materialization of the newly proposed project at Jaslovské Bohunice (unit 5) and—of course—the lifespan of the existing units (see Table 6). Jaslovské Bohunice units 3 and 4 are expected to be shut down in the mid-2040s, if a 60-year lifespan is assumed. However, similar to discussion in other European countries, there is talk of extending the lifespan of these two reactors to 80 years. This extension would bring not only advantages but also several challenges connected to nuclear fuel. Currently, the reactors at Jaslovské Bohunice units 3 and 4 and Mochovce 1–3 (and also 4), belong among a very small group of European reactors using Russian fuel of a special design that does not yet have an alternative supplier [119]. Alternative

suppliers are working on developing suitable fuel for this type of reactor (for example, the APIS project), to replace Rosatom as the current sole fuel supplier. However, the question remains whether these alternative suppliers will be willing to produce a low number of fuel assemblies for a very limited number of reactors, mostly located in the V4 countries (except for Poland), in the long-term, such as after 2040s.

**Table 6.** Reactors planned and proposed in Slovakia.

| Reactor | Type | Capacity (MW) | Construction Start |
|---|---|---|---|
| Mochovce 4 | VVER V-213 | 471 | 1987 |
| Jaslovské Bohunice 5 | EPR 1200, APR 1400, AP 1000 | 1000–1200 | N/A |

Sources: Authors, based on [85].

Indeed, Slovakia imported five shipments of nuclear fuel from Russia during 2022, even after sanctions were adopted. Although these sanctions did not directly target the nuclear sector, the Slovak government had to invoke an exception from sanctions on the aviation sector in order to fly in fresh nuclear fuel from Rosatom [153]. While the operator of Slovak NPPs and several nuclear authorities are members of a consortium that is developing new nuclear fuel for Russian-type reactors used in Slovakia, the Slovak government is not critical of Russia and is not in a hurry to replace the current fuel supplier. On the contrary, Prime Minister Robert Fico has repeatedly criticized EU sanctions against Russia and has sided with Hungarian Prime Minister Viktor Orbán on this matter.

## 6. Conclusions

This paper has examined the development of the nuclear sector in the Visegrad Group countries. Its main argument revolves around the rather interesting situation in which the nuclear policies of these countries converge, despite the growing divergence of the group as a whole. Indeed, support for nuclear energy is one of the very few topics on which the countries of the Visegrad Group can still find a common voice. They consider this energy source crucial for safeguarding their energy security, especially following the 2022 Russian invasion of Ukraine, which resulted in a significant shift in the EU's position on its main energy supplier [154]. However, the Visegrad countries diverge on many issues, including their geopolitical stance (Hungary has been relatively supportive of Russia, as has Slovakia since autumn 2023), which has a direct impact on their nuclear sectors, traditionally dominated by the Soviet and then Russian technology and fuel. While Czechia excluded Russian nuclear companies from entering its nuclear sector after the invasion, Poland had been very sceptical of this nuclear technology supplier even before 2022. In contrast, Hungary has been cooperating with Russian nuclear companies on a new NPP since 2014, while Slovakia has remained neutral regarding the source of technology for its planned new NPP, although it is currently finalizing one reactor based on Russian technology.

Given that all four countries are currently preparing or building (or both, in Slovakia's case) new NPPs, this energy source is expected to be present in the group at least into the early 2100s, due to the expected 80-year lifespan of the new NPPs. This development, along with the increased share of renewables in the electricity mix and the phase-out of fossil fuels even in the most carbon-intensive countries (Czechia and Poland), will create a new situation in the electricity sector of these countries. Grid operators, consumers, and decision makers will need to adapt to this change by finding ways to manage very different energy sources in a manner that supports safe, secure, and stable electricity generation and distribution to end consumers.

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