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Decarbonization challenges and opportunities in the Central European energy sector: Implications for management

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ABSTRACT

While decarbonization and hydrogen energy are at the top of European policymakers' agenda, research and innovation (R&I) management of energy companies must focus on clean technologies (cleantech) which could decrease greenhouse gas (GHG) emissions in the sector. The Central European energy sector, however, might face a decarbonization challenge because of the specific geopolitical situation, so aligning R&I directions with regional policy and conditions seem to be crucial to accelerate sectoral and corporate adaptation. This study focuses on the decarbonization progress and strategies of the Visegrád 4 (V4) countries, concerning some of the most promising hydrogen-driven cleantech R&I directions which might induce strategic changes in Central European energy companies. Besides promoting renewable energy sources, results show that V4 strategies usually include the development of nuclear energy capacities to reduce GHG emissions and using the extended natural gas infrastructure for renewable energy storage. The analysed cleantech innovations are included but usually not central in these strategies. Strategic changes in energy companies, however, could be driven by these promising R&I directions, e.g., the hydrogen economy development by power-to-X (P2X) technologies, industrial decarbonization by carbon capture, utilization or storage (CCUS) technologies in the mid-term, and cross-sectoral integration and optimization by smart energy system (SES) development in the long-term.

KEYWORDS

decarbonization, hydrogen economy, energy sector, research and innovation

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M10, O13, O32, O38

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1. INTRODUCTION

Renewable electricity and green hydrogen production are key to decarbonizing the energy sector, and this opportunity has already led to new energy strategies in the European Union (Falcone et al. 2021). To foster decarbonization, the EU Climate Target Plan 2030 (EC 2021) and the European Green Deal (EC 2019) emphasized the need for a sustainable, resilient, and green economy in which growth and resource use could be decoupled, moreover, new sustainable technologies and disruptive innovations drive a resource-efficient and competitive economy. To cut GHG emissions by at least 55% by 2030, the Fit for 55 package (European Commission 2021) outlines key energy-related areas for development, such as the EU emissions trading system (EU ETS), alternative fuels infrastructure, energy taxation, renewable energy, and energy efficiency. Most recently, the REPowerEU Plan (EC 2022a) promotes diversification, saving energy and the production of clean energy. Compared to the Fit for 55 package, REPowerEU aims to reach 1236 GW instead of 1067 GW in total renewable energy generation capacities, with 600 GW solar energy capacities. Moreover, the goal is to produce 10 million tonnes of green hydrogen and 35 bcm of biomethane in 2030, to substitute fossil fuel imports as much as possible, and accelerate industrial decarbonization through projects with a €3 billion budget (EC 2022a). The Central European energy sector, and especially the Visegrád 4 (V4) countries (the Czech Republic, Hungary, Poland and Slovakia), however, could have distinct characteristics from the aspect of these goals. For example, the high volume of fossil fuel imports in the energy mix or the geographical barriers to sourcing coastal liquid natural gas (LNG), could create a situation in which energy security and rapid decarbonization might challenge each other. Nevertheless, in the long term, the hydrogen economy comes with the promise of not only environmental (e.g., reducing greenhouse gas emissions, reducing air pollution) and economic benefits (e.g., resource abundance and prevalence, rural manufacturing jobs, investments in plants and equipment), but improved energy security due to the domestic production and distribution of the energy and reducing the dependency on import (Demirbas 2017).

In line with the EU-level policies and hydrogen-based opportunities (Csedő et al. 2021), Poland, the Czech Republic, and Slovakia have started to work on national hydrogen strategies, and Hungary has already published the strategy (World Energy Council 2021). National climate and energy strategies have been also published recently to meet the Paris Agreement's goals (EC 2022b). Despite the significance and specificities of decarbonization and hydrogen-driven cleantech in this region, however, only a few studies focus on the V4 countries from this perspective (Pintér 2020; Zsiborács et al. 2023). Indeed, the strategic alignment of national strategies and promising cleantech research and innovation (R&I) management of energy companies seem to be overlooked in the literature, even though the exploration of new technologies is key in driving the green transition (Magyari et al. 2022), while organizational changes based on new technologies and/or sustainability-aimed innovation projects could contribute to corporate adaptation (Csedő – Zavarkó 2019) and competitiveness (Stocker – Várkonyi 2022), CSR performance (Danaf – Berke 2021) and regional development (Szabó 2016), as well. This study aims to analyse the current status of decarbonization and national climate strategies of the V4 countries concerning the key EU plans and some of the innovative cleantech concepts, which were repeatedly considered critical for decarbonization by the international literature: hydrogen-driven power-to-X (P2X) (Incer-Valverde et al. 2022), carbon capture, utilization or storage (CCUS) (Quarton – Samsatli 2020), and smart energy systems (SES) (Lund et al. 2022). The research question is the following: *How could these cleantech R&I directions be aligned with the decarbonization situation and strategies of the V4 countries?* From a theoretical perspective, the main contribution of this study is the combination of technical, management, and policy aspects in hydrogen economy research. From a practical perspective, this study highlights the differences and similarities of the V4 countries regarding climate and energy strategies and provides guidance for decision-makers of Central European energy companies for choosing R&D directions.

The rest of the study is structured as follows. In Section 2, the role of the focal technologies and systems are introduced and justified, moreover, data collection and analysis are described. After that, the results of V4 data analysis are presented, which are discussed later from the perspective of further cleantech literature. Finally, conclusions, limitations and future research directions are outlined.

2. MATERIALS AND METHODS

2.1. Theoretical opportunities for technological and system R&I

Hydrogen economy development and industrial decarbonization require innovative technologies and system concepts. Regarding technological opportunities, the power-to-X (P2X) pathways are considered promising tools for the future energy sector (Palys – Daoutidis 2022). One of these approaches emphasizes that a flexible and sustainable energy system could be built on the utilization of excess renewable electricity with power-to-hydrogen (P2H) and the hydrogen-to-X (H2X) processes, producing, e.g., methane, liquid fuels, methanol, syngas, or (again) electricity from hydrogen (Chehade et al. 2019). Table 1 presents the processes of this hydrogen-driven P2X approach.

P2X could be also interpreted from the aspect of different sectors. For example, the power industry, transportation, chemical industry, or residential heating could be relevant for power-to-gas (P2G), power-to-liquid (P2L), power-to-chemicals (P2Ch), and power-to-heat (P2Heat) processes which could provide the above-mentioned low-carbon energy carriers (Koj et al. 2019). From the P2X processes, P2G technologies for renewable hydrogen and methane (or synthetic natural gas) production are crucial due to their ability to be used in multiple sectors (Zavarkó et al. 2021; Csedő – Zavarkó 2020), and additional flexibility for the energy system with sector coupling and seasonal energy storage (Csedő et al. 2020; Kummer – Imre 2021). In addition, P2L technologies could be beneficial for low-carbon mobility (Varone – Ferrari 2015). Figure 1 shows that these energy conversion processes could even be interconnected, i.e., end-products could be inputs for other conversion processes and/or end-products in multiple sectors. Moreover, given the goal of industrial decarbonization and the need for carbon dioxide input for many P2X processes, carbon capture, utilization or storage (CCUS) technologies seem to be important in the future energy sector as well (Pörzse et al. 2021).

In case of these P2X pathways, research and innovation projects have been launched in Europe. For example, a commercial P2H plant was implemented during the HyBalance project in Denmark (Airliquid 2018), and several pilot, semi-industrial, and industrial P2M plants have been developed in Germany (Ghaib – Ben-Fares 2018; Zavarkó et al. 2021). Moreover, P2L technologies are developed by Sunfire in Germany and by Haldor Topsøe in Denmark (Choe et al. 2022), focusing on renewable syngas and fuels, and a P2Ch process is in the scope of the Carbon2Chem project, to use surplus renewable energy and carbon emissions as raw materials for chemicals (Thyssenkrupp 2023).

Table 1. Options of the hydrogen-driven P2X approach

	Category	Acronym	Description
Step 1	Power-to-Hydrogen	P2H	Hydrogen production from low-carbon electricity from the grid or off-grid
Options for Step 2	Hydrogen-to-Power	H2P	Supply of electricity to the grid from hydrogen with a fuel cell or a gas turbine
	Hydrogen-to-Gas	H2G-H_2	Hydrogen injection in the natural gas grid
		H2G-CH_4	Methanation process, and synthetic methane injection in the natural gas grid
	Hydrogen-to-Fuel	H2G-H_2	Hydrogen injection in the natural gas grid
		H2G-CH_4	Methanation process, and synthetic methane injection in the natural gas grid
	Hydrogen-to-Industry	H2I	Hydrogen for industrial applications (e.g., refinery)
	Hydrogen-to-Heat	H2Q	Heating via H_2-fired boilers, or producing heat and power (e.g., fuel cells, turbines)
	Hydrogen-to-Chemicals	H2Ch	H_2 to methanol/syngas to C2, C3 olefins
			Methanol/syngas to hydrocarbons and alcohols
			H_2 to ammonia and formic acid

Source: Chehade et al.(2019).

Besides these hydrogen-driven technological opportunities, however, new system concepts have also been developed for the energy sector. Following Smart Grids (SG), which were first introduced to make power grids more secure, flexible, economical, and suitable for green power services, the Energy Internet (EI) was conceptualized which could integrate power grids, heat networks, fuel networks, and transportation networks in a secure, flexible, economical, and sustainable way (Zhao et al. 2021). When all energy-related sectors are interconnected with synergistic energy services, one could talk about Smart Energy Systems (SES), as Lund et al. (2017) suggest a shift away from single-sector thinking into cross-sectoral optimization. New technologies and infrastructures are needed to develop SESs, “which create new forms of flexibility, primarily in the ‘conversion’ stage of the energy system” (2017: 560). This conversion stage makes the P2X technologies highly important, as different energy conversion processes could support the development of the SES sub-systems. Table 2 shows how certain P2X pathways could appear in different categorizations of SES sub-systems.

Other energy system concepts in the literature also reinforce the role of P2X technologies in future energy systems. For example, P2X seem to be a transformative technology to enable hybrid energy systems (HES) (Ramsebner et al. 2021). In multi-sectoral energy systems (MSES), P2G would be important to enhance the flexibility of the network (Cruz et al. 2018), while in a smart multicarrier energy hub (SMEH), P2G would be integrated for hydrogen production and

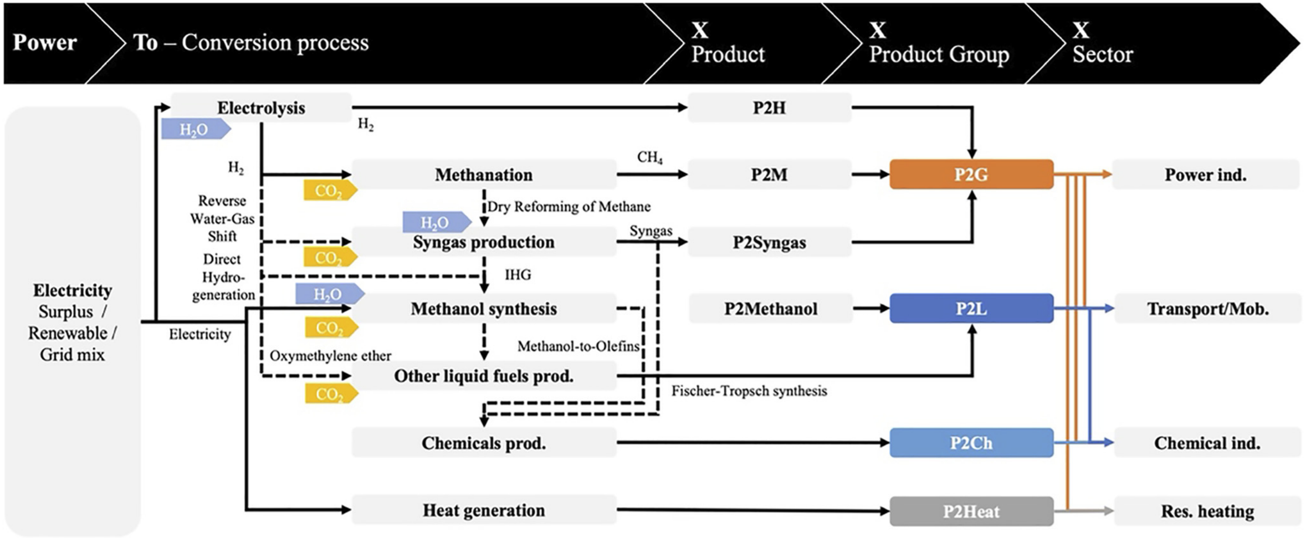

Fig. 1. Processes, products, product groups and sectors of power-to-X (*Source:* Koj et al. (2019))

Table 2. Connections of SES sub-systems and P2X pathways

SES sub-system categorizations		**P2X Examples**
Lund et al. (2017)	**Zhao et al. (2021)**	
Smart Electricity Grids	Smart Grids	P2G: Using hydrogen in fuel cells; Burning biomethane in Combined Heat and Power Units
Smart Thermal Grids	Smart Heat Networks	P2G/P2Heat: Using hydrogen and/or biomethane/synthetic natural gas in boilers
Smart Gas Grids		P2G: Sector coupling by biomethane production
–	Smart Fuel Networks	P2G2L: Compressing or liquifying biomethane/ synthetic natural gas (CNG/LNG)
		P2L: Producing diesel, and kerosine from hydrogen and carbon dioxide

Source: author.

storage (Agabalaye-Rahvar et al. 2021). Furthermore, it could increase the resilience of the power system in a regionally integrated energy system (RIES) (Wang et al. 2021), coupling power and gas grids in the EI concept (Wu et al. 2021). In a broader view, P2G and P2X could accelerate climate action response and extend chains towards different industries (e.g., the chemical industry) (Elavarasan et al. 2022).

In line with these cleantech concepts for hydrogen economy development and decarbonization, a presumption for the empirical research could be that P2X, CCUS, and SES development might appear in the (long-term) national climate and energy strategies of the V4 countries.

2.2. Data collection and analysis

The empirical data collection and analysis were focused on the status and goals of the V4 countries' decarbonization strategies, and the appearance of the above-mentioned innovative and transformational technologies and system concepts in the strategies. To ensure the balance between coherent data and specific information about the V4 countries, on the one hand, quantitative data from Eurostat and the European Parliamentary Research Service (EPRS) was used, while on the other hand, texts of national strategies were also qualitatively analysed. The main criteria for sampling the national strategies were the long-term horizon of the document (e.g., until 2040 or 2050) and the direct connection to low-carbon or climate-neutral development. Table 3 presents the details of the data analysis.

3. RESULTS

3.1. Overview of decarbonization status, progress, and plans

First, decarbonization could be directly linked to GHG emissions and carbon intensity, which is "defined as carbon emissions per unit of GDP, an important metric for measuring energy and

Table 3. Details of data sources and data analysis

Type of data source	Focus points	Title	Source
Uniform	- GHG emissions - Carbon intensity - Reductions - Renewable energy capacities - Emissions of the energy sector	Climate action in Czechia	EPRS (2021a)
		Climate action in Hungary	(2021b)
		Climate action in Poland	(2021c)
		Climate action in Slovakia	(2021d)
		Renewable energy statistics	Eurostat (2022)
Country-specific	- Long-term energy goals and decarbonization plans - Examples of recent plans - P2X, SES and CCUS	National Energy and Climate Plan of the Czech Republic	Ministry of the Environment of the Czech Republic (2019)
		National Clean Development Strategy 2020–2050	Ministry for Innovation and Technology of Hungary (2021)
		Energy Policy of Poland Until 2040	Ministry of Climate and Environment of Poland (2021)
		Low-Carbon Development Strategy of the Slovak Republic until 2030 with a View to 2050	Ministry of Environment of the Slovak Republic (2020)

Source: author.

environmental performance” (Wang et al. 2018: 12). Figure 2 shows that the V4 countries together represent about 17% of total EU GHG emissions. While Poland is dominant in total GHG emissions and carbon intensity, the emissions per capita are also relatively high in the Czech Republic. Emissions per capita in Hungary are the lowest in the V4 countries.

This is in line with the dominant role of the energy sector in GHG emissions in these countries. Figure 3 shows that the energy sector is the leading emitter in the Czech Republic and Poland, while in Hungary and Slovakia, energy industries represent a smaller share compared to other industrial processes.

Regarding the progress in decarbonization so far, shown in Fig. 4, the Czech Republic and Slovakia are above the EU average in the reduction of carbon intensity since 2005. Poland reduced its carbon intensity in the past decades; however, it does not appear in the reduction of the total GHG emissions. Hungarian data are close to the EU average in both dimensions. The figure also presents that V4 countries together are over the EU average in reducing carbon intensity, while below the average in reducing total emissions. This is similar to the case of the share of renewables in the energy mix, which would contribute to reducing the volume of total GHG emissions.

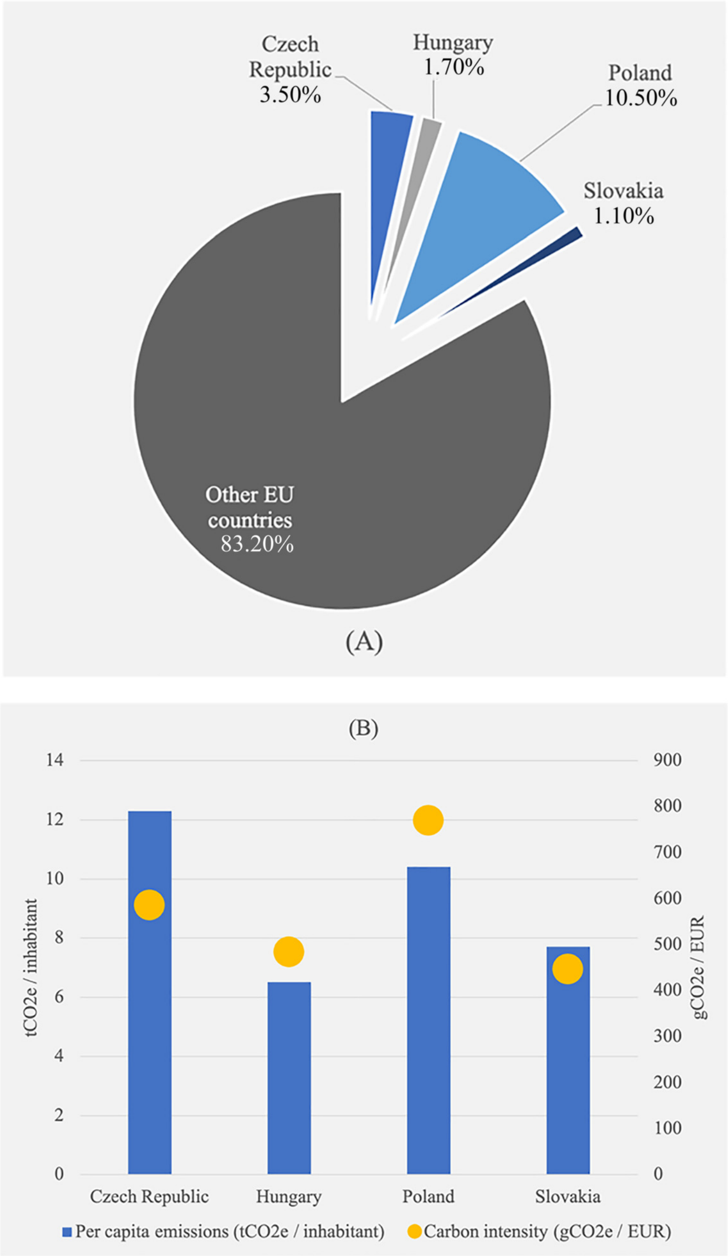

Fig. 2. Decarbonization status in the V4 countries (A) Total share of GHG emissions in the EU (2019) (B) Relative carbon emissions (2019). *Source:* author, based on EPRS (2021)

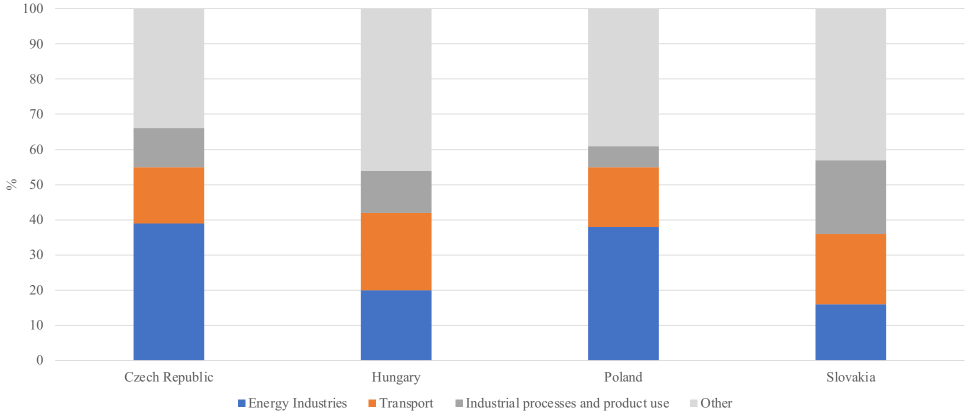

Fig. 3. GHG emissions by sector in the V4 countries (2019). *Source:* author, based on EPRS (2021)

To accelerate decarbonization, the V4 countries have included similar elements in their long-term strategies. For example, solar, wind, and nuclear energy are often emphasized as key factors of decarbonization, but biomass is also mentioned multiple times. Nevertheless, in line with the differences in carbon intensity and total GHG emissions, Hungary and Slovakia seem to be explicit about aiming for climate neutrality by 2050 (Ministry of Environment of the Slovak Republic 2020: 6; Ministry for Innovation and Technology of Hungary 2021: 8). The Czech Republic determines an indicative target by 2050 “corresponding to a reduction of 80% compared to 1990” (Ministry of the Environment of the Czech Republic 2019: 17) and Poland emphasizes the development of a “low-emissions energy system” (Ministry of Climate and Environment of Poland 2021: 5). Table 4 shows examples of long-term energy goals and recent plans.

3.2. The role of P2X, CCUS, and SES in V4 strategies

P2X and CCUS appear multiple times in the V4 strategies but in slightly different contexts. The Czech policy document states that “hydrogen produced from natural gas by pyrolysis or steam reformation in combination with carbon capture technologies is considered decarbonised gas and can also contribute to the Czech Republic’s climate and energy goals” (Ministry of the Environment of the Czech Republic 2019: 213), and P2G is mentioned in case of the gas sector, where hydrogen by electrolysis and synthetic methane by methanation could be produced to decarbonize the sector. In the Hungarian strategy, CCUS is mentioned to produce blue hydrogen. The document also writes about preferring CCS or CCU: in Hungary, there are “limited capacities to store carbon, the utilization of captured CO_2 should be primarily in focus” (Ministry for Innovation and Technology of Hungary 2021: 108). ‘P2G’ is considered an energy storage solution in Hungary, but the production of ‘carbon-free materials’ would be also important, for example, hydrogen, synthetic methane, synthetic ammonia, and biomass-based fuels (Ministry for Innovation and Technology of Hungary 2021). The Polish document writes about CCUS in the case of researching and implementing clean coal technologies and highlights that large-scale

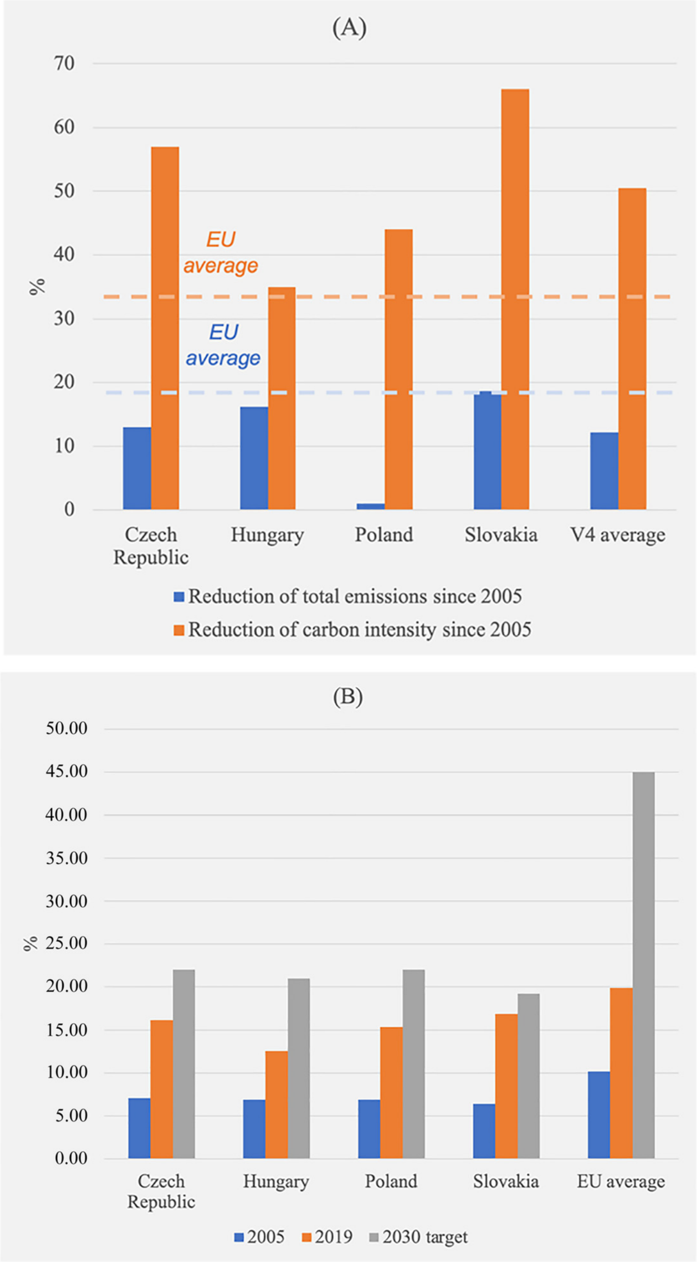

Fig. 4. Decarbonization progress in the V4 countries. (A) Reduction of carbon emissions and intensity. (B) Rollout of renewables. *Source:* author, based on EPRS (2021) and Eurostat (2022)

Table 4. Analysis of decarbonization strategies of V4 countries

	Czech Republic	Hungary	Poland	Slovakia
Examples of long-term energy goals	- Solar and wind as the main components in the renewable energy mix, but also promote biomass - Energy system modernization, energy efficiency - Increasing nuclear energy in electricity generation	- Decarbonized, clean, smart, and affordable - Decentralized, efficient, secure, interconnected, sovereign, and building upon renewable and nuclear energy	- The transition of coal regions, smart grids, diversification of supply and development of network infrastructure - Implementation of nuclear power and RES, development of district heating and cogeneration	- Increasing the share of nuclear energy in the energy mix - Using existing gas infrastructure for renewables - Biomass with the largest potential among renewable sources
Examples of recent plans	- Updating Clean Mobility Action Plan from 2015 - Revision of the renewable energy law of the Czech Republic is underway - National Action Plan for Smart Grids (2019)	- 200 MW solar farm - Geothermal heating - Nuclear power - Green bus program	- Planning six nuclear plants, the first will start operating in 2033 (1–1.6 GW)	- Decarbonization of the US Steel Košice steel plant
Source	Climate Protection Policy of the Czech Republic; EPRS	National Clean Development Strategy 2020–2050; EPRS	Energy Policy of Poland Until 2040; EPRS	Low-Carbon Development Strategy of the Slovak Republic until 2030 with a View to 2050; EPRS

Source: author.

implementation of CCUS could be important for climate neutrality. Furthermore, it writes that developing energy storage solutions is desirable with ‘P2H/P2G/P2L/P2A/P2X’ systems (Ministry of Climate and Environment of Poland 2021: 31). Their other goal is to increase the domestic production potential of biogas, biomethane, syngas, synthetic gas or hydrogen to cover partially the demand for gaseous fuels (Ministry of Climate and Environment of Poland 2021) According to the Slovak strategy, ‘P2X’ is as a long-term opportunity, that is why promoting research and innovation for CCUS and synthetic fuels and setting up long-term support for ‘decarbonized gases’ (biogas, biomethane, hydrogen, synthetic methane) is necessary (Ministry of Environment of the Slovak Republic 2020: 39).

In case of being ‘smart’, the cross-sectoral integration and the ideas of SES also appear in the national strategies, but with less emphasis. The national plan of the Czech Republic discusses SGs in electricity infrastructure development (Ministry of the Environment of the Czech Republic 2019), regarding which the national action plan concerns the “account distribution and production capability and cybersecurity” as well (EPRS 2021a: 6). Nevertheless, SES development is mentioned once as a part of a specific objective of an operational programme. In the Hungarian strategy, a ‘smart ecological system’ appears in case of waste management (allowing the harmonization of material and energy flows, inputs and outputs). Moreover, SGs in case of the electricity sector, and smart water supply systems in water management are mentioned besides individual smart solutions (e.g., smart charging, smart measuring) (Ministry for Innovation and Technology of Hungary 2021). Besides writing about the role of SGs in the electricity sector multiple times, the Polish strategy mentions ‘smart energy management systems’ which would replace the one-way passive grid to balance renewable energy sources (RES) and to support the thermal modernization of buildings (Ministry of Climate and Environment of Poland 2021). Similarly, the strategy of Slovakia plans to focus on SES and energy storage together with developing efficient district heating systems and promoting RES (Ministry of Environment of the Slovak Republic 2020).

In sum, the focal technologies and system concepts are incorporated into the V4 climate and energy strategies. Technologies for P2X and CCUS, however, get more attention compared to the cross-sectoral SES concept, the implementation of which would require more mature technologies first (including P2X and CCUS).

4. DISCUSSION

In the following, the results are discussed from the focal technological and system perspectives based on recent literature, indicating R&I management and strategic change directions for the Central European energy companies.

4.1. Hydrogen economy development by green, blue, and pink hydrogen

As the results highlighted, increasing renewable electricity and energy storage plays a key role in V4 strategies, for which, hydrogen production via water electrolysis could be a useful tool in longer time horizons (e.g., weeks) (Sterner – Specht 2021). According to Sadik-Zada (2021), there are a few characteristics which could help the development of the hydrogen economy and decarbonization. First, the high share of RES in the energy mix must be analysed as it is necessary to increase the production of green hydrogen (produced by electrolysis using electricity generated from RES). In this dimension, the V4 countries are below the EU average, as shown previously, but promoting RES is an unquestionable element of V4 strategies. Nevertheless, not only green hydrogen could be useful. CCUS could enable the production of low-carbon blue hydrogen, which is mentioned, for example, in Hungary’s plan. Blue hydrogen might be an important tool during the green transition, and it could supplement green hydrogen in the (hydrogen) energy mix. Renewable green and low-carbon blue hydrogen production are both promising to increase decentralized energy production and reduce the market risks of energy sourcing in case of energy companies.

Second, pink hydrogen, which is produced by electrolysis using electricity from nuclear power plants (Ajanovic et al. 2022) could also replace fossil fuels. Increasing nuclear energy capacities is also a clear goal in the V4 countries, which is a beneficial characteristic for hydrogen economy development (Sadik-Zada 2021). Third, the extended natural gas infrastructure could be useful for seasonal energy storage and hydrogen distribution (e.g., through hydrogen blending; Sadik-Zada 2021), which is in line with the conditions in the V4 countries. For example, Hungary has a 6,330,000,000 m^3 storage capacity (Ministry for Innovation and Technology of Hungary 2020). As nuclear energy-related projects usually belong to state-owned initiatives, R&I directions of private energy companies might be focused on the second stage of the hydrogen value chain, such as developing different water electrolysis technologies to produce pink hydrogen or integrating decentralized renewable electricity and green hydrogen production. Currently, four different methods for electrolysis are used and/or studied: (1) alkaline-based (AEL), which is the most mature technology; (2) proton exchange membrane (PEMEL), which is also mature and more flexible technology; (3) solid oxide electrolysers (SOEL), which is highly efficient but not mature; and (4) anion exchange membrane (AEM), which combines the advantages of AEL and PEMEL and small-scale units are commercially available (Hu et al. 2020; Fasihi et al. 2016). Regarding the technology readiness levels (TRL), AEL and PEMEL with TRL8-9 are close to widespread application in a commercial scale, while SOEL and AEM with TRL5-6 need further research and validation in an industrial environment (Varela et al. 2021; Ferreira et al. 2023).

Nevertheless, hydrogen production is possible by other technologies which could use solar energy which would mostly need, however, a lot of research before reaching an actual innovation phase. First, photocatalytic water splitting is the most promising form of solar fuel-related hydrogen production technologies as it ensures reasonable efficiency, low cost, product (hydrogen and oxygen) separation during the reaction, and scalability suitable for household applications (Nguyen – Wu 2018). Second, thermochemical water splitting entails the collection and use of solar energy for heat to thermochemically split water into hydrogen and oxygen. Third, photobiological water splitting is also possible by different types of microorganisms (e.g., algae). Until now, photocatalytic water splitting and biophotolysis methods have only been developed at a lab scale or only a small-scale in a relevant environment, which indicates only a TRL4-5 (Frowijn – van Sark 2021).

4.2. Industrial decarbonization by CCUS

As the empirical results reinforced the presumption about the potential role of CCUS in the V4 strategies, industrial decarbonization could also represent a key direction of cleantech R&I. One of the key policy drivers for industrial decarbonization is the EU Emissions Trading System (EU ETS), in which the cap for free allowances is decreasing, creating an economic challenge for companies with large-scale GHG emissions (Teixidó et al. 2019). According to the data of the European Environmental Agency (EEA 2023) and the EU Transaction Log (EC 2023), there are around 1,000 facilities which belong to the EU-ETS in the V4 countries, and facilities in the V4 countries emitted 263.483.012 tCO_2 -eq in 2020, from which only 83.559.055 tCO_2 was part of the free EUA allocation (EEA 2023). For these facilities, these emissions represent a growing financial challenge as market prices of CO_2 emissions grow.

To decrease these emissions, with the costs of carbon emissions over the allowances, fossil-fuel plants can be equipped with various carbon capture technologies for which three strategies are available currently based on when CO_2 is separated. In case of pre-combustion CC, the fuel is pre-treated before being fired and CO_2 is captured by techniques before combustion takes place. Oxyfuel combustion CC means that combustion is performed with pure oxygen instead of air, resulting in a flue gas with a high CO_2 concentration. Post-combustion solutions are the most mature and the most suitable for already existing plants, as these technologies enable to separate the CO_2 from the flue gas of the combustion (He et al. 2018; Mazza et al. 2018). Additionally, Direct Air Capture (DAC), a relatively new technology in the early commercial stages provides an option for capturing CO_2 directly from the atmosphere (or diluted gases and distributed sources of carbon) (Fasihi et al. 2019).

V4 strategies include research and development support for CCUS, which would be important also because of the lack of such initiatives in this region. According to the data of the International Association of Oil & Gas Producers (IOGP), there are only two projects in the V4 countries: one in the Czech Republic, focusing on onshore storage of captured emissions in cement plants, with a planned start date in 2024/2025; and one in Poland, focusing on the carbon dioxide transport and storage value chain with 2.7 Mtpa CO_2/year (IOGP 2022). These two projects are very few compared to 65 total projects in Europe (i.e., 3% of the projects are in the V4 countries, while they generate around 17% of the total GHG emissions in the EU), thus energy companies could step ahead by initiating new projects, to explore new CCUS technologies or exploit more mature ones. While there are more than 15 different CC methods between TRL1 and TRL7, the most advanced technologies include, for example, traditional amine solvents or physical solvents, pressure swing adsorption or gas separation membranes (TRL9; Chen et al. 2022).

4.3. P2X technologies for SES development

According to the V4 strategies, P2X – beyond P2H – has appeared as a long-term opportunity, for energy storage and synthetic methane and ammonia production. Since the power-to-methane (P2M) process is built on the P2H process, the first part of the chain is also water electrolysis which converts electrical into chemical energy in the form of hydrogen. In the second conversion step of the process chain, methane is formed by the reaction of hydrogen with carbon dioxide. The required carbon dioxide can be obtained from several different sources such as biomass plants, power plants, industrial processes, or even ambient air (Ghaib – Ben-Fares 2018). One of the P2M technologies is thermochemical catalytic methanation which is based on the Sabatier reaction and entails the conversion of H_2 and CO_2 at a high temperature (about 150–500 °C) and a pressure range from atmospheric pressure to 100 bar usually with metal-based catalysts (Younas et al. 2016). In contrast, in case of biological methanation, the reaction is catalyzed by one or multiple strains of microorganisms that must be provided with lower temperature and pressure conditions and suitable nutrients (as a solution to the reactor) to foster their growth (Gantenbein et al. 2022; Zavarkó et al. 2021). These microorganisms could be a very diverse archaeal group of methanogens characterized by their ability of methane production (the archaea use CO_2 and H_2 and/or small organic molecules, such as acetate, formate, and methylamine and convert it to methane; Enzmann et al. 2018). Based on TRLs, catalytic methanation is at TRL7-9, while biomethanation at TRL7 (De Roeck et al. 2022).

To produce synthetic ammonia, a power-to-ammonia (P2A) process could be developed, as hydrogen can be converted to a nitrogen-based fuel. Ammonia (NH_3) is a commonly produced industrial chemical, and it has several uses, for example as fuel for different types of engines (Cheema – Krewer 2018). In addition, it is important to mention that (based on experience to date within the fertilizer industry) ammonia is safe to use and has a well-established transport network (Cheema – Krewer 2018; Ikäheimo et al. 2018). The high- and medium-pressure Haber-Bosch process for ammonia synthesis has already been applied industrially (TRL9), while the absorbent-enhanced Haber-Bosch process needs further research (TRL4-5; Rouwenhorst et al. 2019).

Beyond interconnecting the electricity and gas networks (and the chemical industry) by P2G, the SES concept would integrate the heating and fuel networks as well, in line with brief considerations in the V4 strategies. For the heating sector, another P2X pathway, P2Heat solutions could be considered, which involve the conversion of electricity into thermal energy, e.g., in a centralized way by district heating or in a decentralized way by thermal energy storage (TES)-coupled heating (Bloess et al. 2018). Low-temperature solutions below 90 °C are at TRL9, and as the output temperature increases up to 160 °C, the TRL of the methods decrease until TRL3 (Maruf et al. 2022).

To create a connection between (smart) electricity and (smart) fuel networks, power-to-liquid (P2L) technologies must be developed. The Fischer-Tropsch P2L (FT-P2L) is a synthesis process in which carbon monoxide is a mandatory element. While other synthesis processes (e.g., Biomass-to-Liquid) introduce carbon monoxide into the system during gasification, the Fischer-Tropsch P2L process allows carbon monoxide to be recovered from a concentrated source or air. The conversion of carbon dioxide to carbon monoxide is carried out by a so-called reverse water gas shift (RWGS; Fasihi et al. 2016), but the TRL of the RWGS reactor is only TRL6 while the FT reactor is at TRL9 (Markowitsch et al. 2023). The reverse reaction step is not required if solid oxide electrolysers (SOEL) are also part of the system. The result of the FT-P2L is raw fuel, which is further developed into a special fuel in the refining and upgrading process (Schmidt – Weindorf 2016). Another technology for the P2L process could be based on the use of methanol, and the methanol synthesis via direct CO_2 hydrogenation is reported to be at TRL8 (Wassermann et al. 2020). In this process of producing liquid hydrocarbons, methanol is added to the hydrogen formed after electrolysis as an intermediate step (Schmidt – Weindorf 2016). The process results in the same end product as the Fischer-Tropsch method.

5. CONCLUSIONS

The goal of this study was to explore how certain cleantech R&I management directions (which were highly recognized in the international literature), i.e., P2X, CCUS, and SES development could be aligned to the decarbonization situation and climate strategies in Central Europe. Historical and recent data showed that V4 countries must further decrease their total GHG emissions, even though their carbon intensity was reduced in the past decades. V4 strategies include very similar elements to accelerate decarbonization, for example, promoting RES and biomass, using the remarkable capacities of the natural gas grid for energy storage, building smarter and more flexible power systems, and increasing the nuclear energy capacities. While green hydrogen from renewable electricity will be important, pink hydrogen (from the electricity produced by nuclear power plants) could also be beneficial to develop the hydrogen economy. Furthermore, CCUS technologies could enable the production of blue hydrogen which could have a contributing role during the energy transition. Green, blue, or pink hydrogen could be utilized by other P2X technologies to provide additional flexibility to the energy system and produce other gases (e.g., methane, ammonia) or liquid fuels for mobility. Based on these individual technology developments, cross-sectoral integration and optimization within an overarching SES might be only feasible in the long run, however, SGs and smart devices are implementable earlier.

The explored sectoral integration opportunities might induce changes not only in the technological or system operations but also in the strategies of energy companies. For example, P2X technologies will allow the generation of new end-products for electricity producers which affect their business models, including their customer segments and distribution channels. Business model changes with new customers, however, will impact the dynamics of industry competition, generating further strategic changes in other companies in the sector. Also, optimizing cross-sectoral integration in a SES will require new capabilities which must be sourced from external actors or developed by internal learning processes, while it will also require new structures and coordination mechanisms among experts of previously separated and different fields (e.g., electricity, gas, fuel technologies, distributions, and markets), and smart devices which support real-time decision making. Nevertheless, these long-term strategic and organizational changes will be relevant after engaging in the proper R&I management directions and the strategic management of the technological and innovation portfolio, in line with existing and upcoming regional and national policies.

The limitations of this research are mainly based on the selection of promising cleantech directions, which was primarily hydrogen focused (in line with the hydrogen economy development initiatives). Nevertheless, other technologies and systems, for example, battery energy storage systems, algae-based biofuels or electric vehicles could be the subject of further V4 research.

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