

The Economic Viability of Carbon-Dioxide Capture and Storage in Hungary
A Szén-Dioxid-Leválasztás és -Tárolás Gazdasági Lehetőségei Magyarországon

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Abstract

This paper attempts to determine whether carbon dioxide capture and storage is economically viable in Hungary. To achieve this, costs for each part of the carbon capture and storage (CCS) value chain must be estimated. The paper uses mixed-method research: a combination of a literature review, interviews with relevant experts, and cost analysis to determine the price of CO₂ captured for various industrial and energy generation processes. In the cost analysis an optimistic, a pessimistic, and an average scenario was calculated for each part of the carbon capture and storage process. From the expert interviews, it was determined that CO₂ storage is indeed technically feasible in Hungary, and associated risks can be handled. The results from the cost analysis are on the other hand much more bleak for the technology. Under the 2023 average carbon price, few industries could utilize CCS. There will probably be more possibilities by 2030, but even then, roll-out will be hampered by the associated financial risk. As a result, the technology will probably only be used in hard-to-decarbonize but essential sectors such as cement manufacturing.

Contents

I.	Introduction.....	1
I.	Methodology.....	2
II.	Introduction of CCS technologies.....	2
III.1.	What is Carbon Capture and Storage (CCS)?.....	2
III.2.	Where could CCS be used?	3
III.3.	Carbon dioxide capture.....	3
III.4.	Cost of carbon dioxide capture	4
III.5.	Carbon dioxide transport	6
III.6.	Cost of carbon dioxide transport	7
III.7.	Carbon dioxide storage	9
III.8.	Cost of carbon dioxide storage	11
IV.	Economic viability of CCS.....	12
IV.1.	Pitfalls of CCS cost estimates	12
IV.2.	Incentive policies	13
IV.3.	European Carbon Price Forecasts	14
V.	Background of CCS in Hungary	15
V.1	Role of CCS in Hungarian climate strategy	15
V.2.	Legal background.....	17
VI.	Interviews	17
VI.1	György Falus	18
VI.2.	Csaba Gál	19
VI.3.	Eszter Sendula	20
VI.4.	Csilla Király	20
VII.	The economics of the Hungarian CCS sector	21
VII.1.	CCS capture sources in Hungary	21
VII.2.1.	CCS Use in Industry	22
VII.2.2.	CCS in the energy sector	25
VII.3.	CCS storage sites in Hungary	27
VII.4.	CO ₂ transport in Hungary.....	29
VII.5.	Identifying CCS clusters in Hungary	29
VII.5.1.	The Dunaújváros Cluster.....	29
VII.5.2.	Baranya cement Cluster.....	31

VII.5.3. Clusters in the Duna-Tisza-köze region	32
VII.5.4. Budapest-Vác Cluster.....	32
VII.5.5. Visonta Power Plant	33
VII.5.6. Borsod Cluster	33
VII.6. CCS Cost Analysis	34
VIII. Discussion	39
VIII.1. Risks of CO ₂ storage in Hungary	39
VIII.2. Public perception	40
VIII.3. Limitations of the Research	41
IX. Conclusions	42
X. Citations:	43
XI. Appendix	50
I. Interview questions	50

Table of Tables

Table 1 Cost of CO ₂ capture, by cost category, excluding the cost of compression. Source: Own calculations based on Kearns, Liu, and Consoli, 2021, pg. 29; Farkas Csamangó et al., 2023, pg. 158.....	5
Table 2, Cost of CO ₂ transport, source: Own calculation, based on: Zero Emissions Platform, 2011, pg 52-53.....	8
Table 3, Advantages and disadvantages of geological formation for CO ₂ storage, Source: Own-making, based on: Hartai, 2014 and Tomić et al., 2018.....	10
Table 4, Cost of CO ₂ storage, based on: Zero Emissions Platform, 2019, pg. 25.....	11
Table 5, Interviews, Source: Own-editing.....	18
Table 6, Cement factories and their emissions in Hungary:, Soure. Own-making, based on: European Commission, 2024	23
Table 7, Bioethanol factories and their emissions in Hungary, Soure. Own-making, based on: European Commission, 2024	23
Table 8, Steel and iron factories and their emissions in Hungary, Soure. Own-making, based on: European Commission, 2024	24
Table 9, Refineries and Petrochemical factories and their emissions in Hungary: Soure. Own-making, based on: European Commission, 2024	24
Table 10, Steel and iron factories and their emissions in Hungary, Soure. Own-making, based on: European Commission, 2024	25
Table 11, Energy-sector emitters in Hungary, Soure. Own-making, based on: European Commission, 2024.....	26
Table 12, The Dunaújváros Cluster, Soure. Own-making, based on: European Commission, 2024.....	30
Table 13, The Dunaújváros Cluster, potential storage locations, Soure. Own-making, based on: European Commission, 2024	31
Table 14, The Baranya Cement Cluster, Soure. Own-making, based on: European Commission, 2024.....	31
Table 15,, The Baranya Cement Cluster, potential storage locations, Soure. Own-making, based on: European Commission, 2024	31
Table 16, The Budapest-Vác Cluster, Soure. Own-making, based on: European Commission, 2024.....	32
Table 17, The Budapest-Vác Cluster, potential storage locations, Soure. Own-making, based on: European Commission, 2024	33
Table 18, The Visonta Power Plant, Soure. Own-making, based on: European Commission, 2024.....	33
Table 19, The Visonta Power Plant, potential storage locations, Soure. Own-making, based on: European Commission, 2024	33
Table 20, The Borsod Cluster, Soure. Own-making, based on: European Commission, 2024...	34
Table 21, The Borsod Cluster, Soure. Own-making, based on: European Commission, 2024...	34
Table 22, Table 23, Per tonne of CO ₂ cost calculations for different Hungarian installations, Source:.. Own-making, based on: European Commission, 2024; Kearns, Liu, and	

Consoli, 2021, pg. 29; Farkas Csamangó et al., 2023, pg.158; Zero Emissions Platform, 2011, pg 52-53; Zero Emissions Platform, 2019, pg. 25 38

Table of Figures

Figure 1, Price evolution of EU ETS carbon price, between 2021 and 2024, Source, Own-making, based on: Bloomberg, EU ETS Last Price	15
Figure 2, Expected CO2 emissions under Early-Action (EA) scenaria, Source: Own-making,based on: Innovációs és Technológiai Minisztérium, 2021, pg. 42.....	16
Figure 3, Total CO2 Emissions in Hungary by Sector (Thousand Tons, Source: Own-making, based on: KSH, 2024a).....	21
Figure 4, Electricity Production in Hungary, Source: Own-making, based on KSH, 2024b ...	22
Figure 5, Top Industrial Emitter in Hungary, Soure. Own-making, based on: European Comission, 2024.....	22
Figure 6, Top Energy-sector emitters, in Hungary, 2022 CO2 emissions, Soure. Own-making, based on: European Comission, 2024	25
Figure 7, Depleted oil and gas fields potentially suitable for CO2 storage in Hungary, soruce: Kubus (2010).....	27
Figure 8, Deep saline aquifers potentially suitable for CO2 storage in Hungary, soruce: Szamosfalvy, 2013 as cited by Toldi, Jenei, and Jenei (2018)	28

I. Introduction

With climate change becoming an increasingly urgent issue, there is a consensus among the scientific community that it is human-made, and we must make every effort to reduce greenhouse gas (GHG) emissions. In accordance, the Paris Agreement signed in 2015, which sets the goal of limiting global temperature increases (United Nations, 2015). However, the subsequently submitted Intended Nationally Determined Contributions (INDCs) are not projected to keep warming below 2°C compared to pre-industrial levels, as would be required, and not even close to the 1.5°C target as would be preferred under the treaty (Rogelj et al., 2016). Also, according to a recent study, the world may have already surpassed 1.5°C warming and is on track to reach 2°C warming compared to pre-industrial levels by the late 2020s (McCulloch et al., 2024). It is clear, that more action is needed to avoid the disastrous effects of climate change. This is why many experts argue that a portfolio approach is necessary to reduce GHG emissions, including not only avoiding but removing CO₂ from the atmosphere, and directly from emission sources (Kearns, Liu, and Consoli, 2021). In addition, in strategic but hard-to-abate sectors like the cement industry, iron, steel, and chemicals manufacturing, carbon capture could be the only method to reduce carbon emissions and make the sectors compatible with a low-carbon future (Paltsev et al., 2021). As a result, for a future with net negative carbon emissions, CCS may not be an option but rather a necessity.

The goal of this paper is to assess the economic viability of carbon dioxide capture and storage in Hungary. I first survey the relevant global literature and then turn my attention to Hungary-specific elements. The goal is to gain an understanding about global advancements in carbon dioxide capture (CCS), and then see how this can be applied to emissions in Hungary. I aim to gain both a qualitative and a quantitative answer to whether the technology is viable in Hungary. The qualitative one will be done through a series of interviews and a careful review of the literature. During the quantitative research I will calculate per tonne prices of CO₂ captured for CCS used in various industrial processes, and compare them to the current and potential future European carbon price, to determine whether firms will use this technology. Whether carbon capture and storage is economically viable in the country can mean a lot for both market participants in industrial and the energy sector, but also to the entire national climate strategy. As a result, papers such as mine are absolutely vital in assessing the potential future path the nations green infrastructure could take.

I. Methodology

The paper will use mixed-method research to assess the economic viability of carbon capture and storage in Hungary. First, a detailed literature review will be used to understand carbon capture and storage technologies and understand the elements of the process in addition to the associated costs. Second, a series of expert interviews will be conducted with those understanding the possibilities of carbon dioxide capture and storage in Hungary. Finally, based on the results of the literature review and the interviews, I construct a model to estimate the price of CCS per tonne of CO₂ captured, in 2023 EUR. I will use these to determine whether large-scale carbon dioxide capture and storage is economically viable in Hungary by 2030.

II. Introduction of CCS technologies

III.1. What is Carbon Capture and Storage (CCS)?

Carbon Capture and Storage is a technology where the release of CO₂ into the atmosphere is prevented by capturing it at the source of emissions (usually industrial sites, power plants, or factories) (Kearns, Liu and Consoli, 2021). The captured CO₂ is then transported to storage sites usually via pipelines (but options for ship or truck-based transport are also in development) and is injected into geological formations such as depleted oil- or gas fields, deep saline aquifers, or unmineable coal seams (Kearns, Liu and Consoli, 2021). The traditional method, where the sequestration of CO₂ from exhaust gases happens at the source of emissions is called point-source capture (Kearns, Liu and Consoli, 2021). Alternatively, CO₂ could be directly removed from the air via direct air capture (DAC), which not only leads to the prevention of emissions, but also the net removal of CO₂ from the atmosphere (Custelcean, 2022). Carbon capture and storage (CCS) is different from carbon capture and utilization (CCU) in that the latter aims to use the captured CO₂ in various products or processes (Al-Mamoori et al., 2017). The main use of captured CO₂ is enhanced oil recovery (EOR, where the oil flow from the well is improved by injecting CO₂), but other uses exist such as the use of CO₂ either as a solvent or in chemicals production, and potentially utilizing it to create fuels (Baena-Moreno et al., 2019). Due to the high cost of DAC or the unclear environmental consequences of CCU, my research will be restricted to CCS technologies.

III.2. Where could CCS be used?

Carbon Capture and Storage can primarily be applied to reduce emissions in power generation or the industrial sector (Budinis et al., 2018). In energy production, it can be used both in coal, gas, or oil powered plants (Rashid, Benhelal and Rafiq, 2020). In addition, Bioenergy with Carbon Capture and Storage (BECCS) can capture the carbon previously contained in trees and plants, leading to net negative carbon emissions overall (Gough and Upham, 2011).

In 2022, the industrial sector was directly responsible for around 9.0 Gt of CO₂ emissions (25% of all energy-systems emissions) (International Energy Agency, 2023). 29% of this was the result of the iron and steel sector, 27% was in cement manufacturing, 15% in the chemical and petrochemical industry, 2% in pulp and paper, while other industrial processes emitted 24% (International Energy Agency, 2023). Carbon capture and storage could be even more important here than in energy generation, as industrial processes produce higher-purity CO₂ streams and thus have lower capture cost, and in many cases, there are no alternatives for decarbonization as opposed to renewables and nuclear energy in the other sector (Kearns, Liu and Consoli, 2021). It can be used in a wide range of manufacturing processes, including steel and iron making, lime manufacturing, fertilizer and ammonia related processes, and the cement industry (Kearns, Liu and Consoli, 2021). It can additionally be utilized in natural gas processing, in bioethanol production, or in refineries (Kearns, Liu and Consoli, 2021). It could also be potentially utilized in the pulp and paper industry, large part of emissions of which are from biogenic sources, such as waste or biomass combustion (Sagues et al., 2020).

III.3. Carbon dioxide capture

The first part of the CCS process is the capture of carbon at the source of emissions. The two main sectors where CCS could be utilized are industrial processes and power generation. According to Mikunda et al. (2014), carbon capture could primarily be utilized in steel and cement production, and the synthetic fuel and refining industries. Additionally, according to the Center for Climate and Energy Solutions (2024), the technology could further be used in ethanol and fertiliser production and coal gasification (Center for Climate and Energy Solutions, 2024). In energy generation, CCS could be utilized at coal-fired, gas-fired, oil-fired, and combined cycle gas turbines (CCGT) power plants (Madejski et al., 2022). Mikunda et al. (2014) argued that early deployment of CCS technologies may be more available in industrial processes, since here there are more cases of high-purity CO₂ streams with high partial-pressure, which will be shown to decrease the costs of carbon sequestration. Also, CCS in this sector does not face

competition from renewable energy or nuclear power, and in many cases few alternatives exist to decarbonize certain processes (Mikunda et al., 2014). In my paper, I am going to discuss both uses of carbon capture and evaluate their affordability separately.

Three main methods exist for carbon capture: pre-combustion capture, post-combustion capture and oxy-combustion capture (Madejski et al., 2022). In pre-combustion capture, sequestration happens before the combustion process, in post-combustion capture after the combustion process, and in oxy-combustion capture after the combustion process in an oxygen atmosphere (Madejski et al., 2022). The post-combustion capture process has the highest state of technological readiness, with the technology already reaching commercial phase of development (Bui et al., 2018). The actual sequestration of CO₂ from gas fumes can be done in several ways: absorption, the cryogenic method, adsorption, or membrane separation (Madejski et al., 2022). Chemical absorption is the most popular method of carbon capture, and it has been used in post-combustion coal power plants such as the Boundary Dam power station in Canada or the Petra Nova project in Texas (Bui et al., 2018).

III.4. Cost of carbon dioxide capture

According to Kearns, Liu and Consoli, (2021), carbon capture is the most expensive part of the CCS process, and its cost depends on several parameters. The partial pressure of CO₂ in the gas stream and economies of scale are the two most important determinants of separation costs. Gas with higher partial pressure will reduce capture costs, since it reduces the amount of energy needed for the process. It also allows for physical, rather than chemical-based solvents to be used, which reduces costs even further. Economies of scale is also an important phenomenon, with capital costs non-linearly decreasing with the amount of CO₂ captured. According to modelling results, the cost saving from economies of scale is generally lower given high partial pressure, so expensive processes where partial pressure is low may be made economically viable given high quantities.

Since I am going to construct the supply curve for CCS technologies based on the price of CO₂ captured, I am going to use estimates by Kearns, Liu and, Consoli (2021) for per tonne of CO₂ captured costs in different industrial processes. I converted all non-euro estimates to euro based on the average exchange rate in the study year, and used the European producer prices in industry index to account for changes in the price level since the estimates were calculated (Eurostat, 2024).

Type	Activity	Lower bound	Average Estimate	Upper bound
Power Generation	NGCC	82	112	141
	SCPC	62	73	83
	Waste/Biomass Fired Power	72	85	99
Industry	Natural Gas processing	0	6	13
	Fertiliser	0	6	12
	Bioethanol	0	6	12
	Refinery and Petrochemicals	47	65	82
	Cement	55	66	77
	Lime	63	77	90
	Pulp and Paper	58	59	60
	Iron and Steel Average	66	82	97
	Corex Plant	52	58	65
	Blast Furnace	55	62	69
	Lime Calcining	71	89	106
	Sinter Plant	87	118	149
	Aluminim Smelter	223	292	362

Table 1 Cost of CO2 capture, by cost category, exluding the cost of compression. Source: Own calculations based on Kearns, Liu, and Consoli, 2021, pg. 29; Farkas Csamangó et al., 2023, pg.158

Please note that although the Kearns, Liu, and Consoli (2021) paper only calculated costs for Natural Gas Combined Cycle (NGGC) plants, I am going to use these estimates for all kinds of natural gas power infrastructure. Although this may seem like an oversimplification, it is a reasonable assumption given the fact that most gas-fired power plants examined were NGCC plants. Similarly, I use the same gas category for the only mixed-fuel power plant, the ISD Power Plant in Dunaújváros, as it uses natural gas among many exhaust gasses to generate power (isdpower.hu, 2024). I am also going to use estimates for a supercritical pulverized coal

plant (SCPC) for all types of coal plants, which may be a less reasonable assumption. These cost categories will be referred to as either “energy: gas”, or “energy: coal” categories. I am also going to compute the average cost of different types of, and processes used in refining: FCC, Process Heater, Ethylene steam cracking, and Ethylene oxide production, and use this as the combined category of “refinery and petrochemicals”. In the analysis, I am going to treat refineries and petrochemical manufacturing facilities as the same cost category, since the two processes share similar characteristics (da Silva, 2023). In fact, petrochemical feedstocks are suggested as possible ways the industry can cope with the expected decline in demand for gasoline (Fitzgibbon et al., 2022). I am also going to combine the steel and iron manufacturing categories, to form one joint (average) cost class. I acted similarly in the case of cement manufacturing.

As we can see in (Table 1), carbon capture is the cheapest in natural gas processing, fertilizer manufacturing, and bioethanol production, so in these industries is large-scale roll-out first expected. Due to the extremely high costs, no or only limited application is expected of CCS in aluminium smelter (Table 1).

Besides the costs, the rate at which CO₂ emissions of a plant can be captured also matters. For both industrial, and power sector emissions, I am going to use the baseline estimate capture rate of 90% (Brandl et al., 2021, pg. 1). This corresponds to the assumptions used in cost calculations by Kearns, Liu, and Consoli (2021).

These calculations did not include the cost of CO₂ compression (Kearns, Liu, and Consoli, 2021).

III.5. Carbon dioxide transport

Since industrial facilities and power plants where the CO₂ is captured are usually not located at sites where the material can be stored (such as in the case of Hungary), the CO₂ may have to be transported over several hundred kilometres before it is injected into geological formations (Kearns, Liu, and Consoli, 2021). As a result, it is essential to properly examine transportation methods and incorporate it into our analysis (Kearns, Liu, and Consoli, 2021).

Generally, most CO₂ is transported over pipelines, with countries like the United States operating several thousand kilometres long networks, but alternative transport methods also exist, such as truck, rail, or ship based transport (Kearns, Liu and Consoli, 2021). The technology for these is well understood, but most large-scale transport happens via pipelines,

and there are no significant quantities transported using any of the latter three methods (Kearns, Liu and, Consoli, 2021).

Truck-based transport suffers from high transportation costs, and CO₂ emissions and storage locations may not be close to major railway lines (Lu et al., 2020). Ship based transport may be competitive when transporting medium quantities over large distances, but there are technical challenges regarding temperature and pressure control during shipping, and such is hardly an option for a landlocked country like Hungary (Kearns, Liu and, Consoli, 2021; Lu et al., 2020). Although pipelines face large one-time investment costs and may require higher quantities of CO₂ to be economically viable, they are still expected to be the primary mode of CO₂ transport in the upcoming decades (Lu et al., 2020). Furthermore, the technology is already in the commercial phase of development, with the United States already hosting more than 8000 kilometres of CO₂ transporting pipelines (Kearns, Liu and, Consoli, 2021, pg. 20).

When captured, CO₂ contains water, so it must be dehydrated to stop the erosion of pipelines (Kearns, Liu and Consoli, 2021). Also, CO₂ may be either compressed to a pressure more than 74 bars to be transported via pipelines, or refrigerated to a liquid phase to support ship, rail, or other vehicle transport. (Kearns, Liu and, Consoli, 2021, pg. 22)

III.6. Cost of carbon dioxide transport

The cost of pipeline transport is primarily driven by the length and diameter of the pipeline (Zero Emissions Platform, 2011). As expected, longer distances incur higher transport costs, while the diameter carries economies of scale, where wider pipelines lead to lower relative costs (Zero Emissions Platform, 2011).

Generally, CO₂ pipeline transport benefits from economies of scale, with a larger million tons per annum (MTPA) capacity being associated with a lower cost per tonne per kilometre (Zero Emissions Platform, 2011). As such, it is essential that the pipeline is designed for maximum potential capacity, as it is much cheaper to have one large pipeline than having to build two smaller ones (Zero Emissions Platform, 2011). This may however lead to infrastructure operating below capacity and the lack of scalability increases the risk associated with the investment (Zero Emissions Platform, 2011).

There are options for point-to-point transport, where the material is shipped directly from the capture site to the reservoir, but for cost-saving and risk-reducing purposes, a network model would be preferred (Zero Emissions Platform, 2011). Here, CO₂ could be transported via short

“feeders” from the facilities to a main trunk line, which will carry it across tens or hundreds of kilometres (Zero Emissions Platform, 2011). From then, distribution pipelines will carry the CO₂ to multiple storage sites (Zero Emissions Platform, 2011). This allows smaller emitters to enjoy the benefits of economies of scale and reduce the need for extra land because of multiple pipelines (Zero Emissions Platform, 2011). This also may allow industry to flourish in CCS clusters, where CO₂ permit costs could be lower due to cheap abatement using carbon capture (Zero Emissions Platform, 2011).

I am going to use the Zero Emissions Platform estimates to assess the expenses of pipeline transport, which modelled three capacities, and five potential pipeline distances (with the 10 km one being reserved for feeders and distributors) (Zero Emissions Platform, 2011, 7). Again, prices were converted to 2023 euros based on the European producer prices in industry index.

Price of CO₂ Transport Modules, EUR per tonne of CO₂ transported, 2023 EUR, Adjusted by producer prices in industry					
Distance (KM)	10	180	500	750	1500
2.5 MTPA¹ CO₂	0,6	8,1	NA	NA	NA
10 MTPA CO₂	0,2	3,0	8,0	11,9	23,7
20 MTPA CO₂	0,1	1,9	5,1	7,6	15,0

Table 2, Cost of CO₂ transport, source: Own calculation, based on: Zero Emissions Platform, 2011, pg 52-53

As we can see, there is a clear cost reduction from economies of scale, while expenses are largely proportional to associated transport distances.

There are many factors on the other hand which increase the price or risk of CO₂ transport: river or lake crossings present technical challenges, elevation in the terrain increases costs, fault lines and past seismic activity make construction riskier, and it is best to avoid protected natural areas and major population centres (Balaji and Rabiei, 2021).

As these calculations assumed a flat terrain, no right-of-the-way issues, and simple soil conditions, actual cost may increase when these features added (Zero Emissions Platform,

¹ MTPA: million tonns per annum

2011). The compression of CO₂ is not included in the calculations (Zero Emissions Platform, 2011).

The cost of CO₂ compression and dehydration increases expenses further by between 15 and 28 *EUR*₂₀₂₃, with an average number of 21 *EUR*₂₀₂₃ (Kearns, Liu and Consoli, 2021, pg 38). These were also corrected by the mid-year exchange rate ²and the European producer prices in industry index.

III.7. Carbon dioxide storage

The final phase of the process is injecting CO₂ into geological formations, where it can be stored for long periods (Hartai, 2014). The main storage sites are either onshore or offshore deep saline aquifers, depleted hydrocarbon fields (with the option of enhanced oil recovery, EOR), or unmineable coal seams (with the option of enhanced coalbed methane recovery) (Hartai, 2014).

When selecting the CO₂ storage site, careful consideration should be given to whether the formation has enough capacity, is injectable, and whether the necessary cap rocks or sealing faults are present to avoid CO₂ escaping and entering groundwater (Ajayi, Gomes and Bera, 2019). Depleted oil and gas reservoirs can be the most suitable location, since here the presence of oil or natural gas means that the formation is suitable for geological storage (Tomić et al., 2018). Also, after years of hydrocarbon production, there is a significant amount of data available about the site, in addition to wells and already-built surface equipment (Tomić et al., 2018). On the other hand, existing wells (which may be abandoned and not even known) may present leakage risks (Tomić et al., 2018). Saline aquifers provide much larger storage capacity, but the lack of existing infrastructure or explorations means higher investment costs (Tomić et al., 2018). They may still be a better option, as deep saline aquifers tend to be distributed along wider areas, reducing the distance between capture and storage locations (Cao et al., 2020). Large-scale application of CCS could begin with depleted oil and gas fields, with storage in deep saline aquifers being added once the capacity of the former is running out, and carbon prices allow greater investments (Cao et al., 2020). Storing CO₂ in unmineable coal seams has two main advantages: coal-fired plants (a significant source of emissions where the technology could be utilized) tend to be near coal deposits, reducing transport costs, and it also enhances coal bed methane recovery (White et al., 2005). Storage through enhanced oil recovery has

² from <https://www.exchangerates.org.uk/>

increased commercial viability through oil production, but some of the CO₂ captured is extracted with the oil, so it must be reinjected through a closed-loop system (McGlade, 2019). This is probably the cheapest form of carbon storage, with the US producing large amounts of oil utilizing EOR (McGlade, 2019). The majority of this CO₂ on the other hand is from natural sources (e.g. CO₂ appearing in geological formations), which adds no positive value to environmental sustainability. To make sure the process is less polluting than regular oil production, the CO₂ must come from sources that otherwise would have been emitted into the Earth's atmosphere (McGlade, 2019). Storage costs increase with reservoir depth, so no storage is expected beyond a depth of 3500 meters, but the formation must be situated below 800 meters for CO₂ to reach the supercritical phase (due to the increased pressure and temperature) for safe storage (Uliasz-Misiak, Lewandowska-Śmierzchalska and Matuła, 2021).

Storage Type	Advantages	Disadvantages
Depleted oil and gas fields	Data availability Proven sealing capability Existing infrastructure	Abandoned wells pose leakage risks Limited capacity Uneven spatial distribution
Deep saline aquifers	Large capacity Diverse spatial distribution	No infrastructure or data available
Unmineable coal seams	Enhanced coalbed methane recovery (ECMR) May be located close to coal power plants	Not available in Hungary
Enhanced oil recovery (EOR)	Increased commercial viability	Oil production is heavily polluting Abandoned wells pose leakage risks Not covered under EU-ETS

Table 3, Advantages and disadvantages of geological formation for CO₂ storage, Source: Own-making, based on: Hartai, 2014 and Tomić et al., 2018

III.8. Cost of carbon dioxide storage

The cost of carbon dioxide storage depends on many factors. Offshore storage for example is much more expensive, than onshore storage (Zero Emissions Platform, 2011). Data about the potential reservoir will reduce cost of proving that the formation has sufficient storing capability (Zero Emissions Platform, 2011). Existing infrastructure such as surface facilities or wells may impact them differently: Existing surface infrastructure such as surface pipes, and electricity access will reduce them, and converting to injection from extraction costs third as much as drilling a completely new well, (Gál, 2024). On the other hand, if many existing wells are present, such as in the case of an exhausted oil and gas field, plugging unused ones may significantly increase expenses (Falus, 2024).

To assess the costs of CO₂ storage, I used estimates from the Zero Emissions Platform (2019). They modelled both offshore and onshore storage in deep saline aquifers and depleted oil and gas fields, either with or without the reuse of legacy wells. They assumed a project lifetime of 40 years, and they assumed a 200 Mt capacity in low-cost scenario and 66 Mt in the medium one, while in the case of the high-cost scenario assumed 200 Mt stored (Zero Emissions Platform, 2019, pg. 25).

Cost of Storage per Tonne of CO₂ Stored (EUR)	Deep Saline Aquifers		Depleted Oil and Gas Fields		Depleted Oil and Gas Fields with Legacy Wells Used	
	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
Low (200 Mt)	3.0	8.9	1.5	4.5	1.5	3.0
Medium (66 Mt)	7.4	20.8	6.0	14.9	4.5	8.9
High (40Mt)	17.9	29.8	14.9	20.8	10.4	13.4

Table 4, Cost of CO₂ storage, based on: Zero Emissions Platform, 2019, pg. 25

They assumed workover on a well costs 60% as much as drilling a new one, while sites, where many wells must be abandoned, were not considered for CO₂ injection. Although according to these calculations, storage in depleted oil and gas reservoirs is cheaper, especially with the reuse of legacy wells, we must keep in mind that generally aquifers have a much larger capacity, and in a process that highly benefits from economies of scale, this might tilt numbers towards storage in aquifers. In Hungary, depleted hydrocarbon reservoirs can store between 3 to 20 Mt of CO₂, while in the case of aquifers, just the Szolnok formation may have over 1000 Mt of

capacity (Falus and Szamosfalvi, 2016, pg. 166). This means that even the high-cost scenario contains much higher amount of CO₂, so estimates will probably have to be adjusted upwards. Falus (2024) provided a detailed breakdown of a per unit cost estimate for an unnamed Hungarian aquifer storage project. According to him, research and exploration costs (including planning and boring a well) amounted to 1 euro per tonne of CO₂ stored, while each additional well costs slightly less than 1 euro. Operating expenses amount to a further 1 euro per tonne. In total, including performing a seismic test in fixed time intervals, costs amount to a maximum of 5-6 EUR per tonne over the entire project lifetime. In normal circumstances, storage costs must remain below 10 EUR per tonne, maximum.

IV. Economic viability of CCS

IV.1. Pitfalls of CCS cost estimates

Merrow, Philips, and Myers (1981) pointed out that most cost estimates of new and innovative energy process plants and chemical facilities don't make an accurate assessment of the actual expenses. Factors responsible for this are the complexity of the plant and the degree to which the applied technology departs from the previously used. Being a new technology, that is not currently applied on a large scale, this likely will not be different in the case of carbon capture and storage. This is why it is essential to understand what previous estimates used in the paper get wrong, since a systematic over- or underestimation of true costs involved may lead us to a vastly different conclusion of the commercial viability of carbon dioxide storage.

Rubin (2012) seeks to understand the ways various studies differ in their methodology, and what assumptions or parameters lead to different or even wrong conclusions. The most important is the actual measure used for cost. The relevant literature generally identifies three, which may have entirely different meanings: Cost of CO₂ capture, cost of CO₂ avoided, and cost of CO₂ abated. All three are usually reported in currency/ton of CO₂, but the meaning is not similar, which may lead to confusion. CO₂ captured is the price of the process per total CO₂ captured. It can be used to compare the project against the cost of CO₂ as an industrial commodity, for use in industries like the beverage or the petroleum sector (for enhanced oil recovery). This measure on the other hand does not consider the potential CO₂ emissions through the energy that is needed through the process. This is why cost of CO₂ avoided is a better measure, which compares extra costs and reduced emissions compared to a reference plant without CCS. It will always be higher than the cost of CO₂ captured since the captured

amount will always be lower than the amount avoided, given the extra energy requirement. It can be used to assess the viability of the project compared to a government-set limit on emissions, such as a carbon tax or the price of a tradable quota. Here, the total cost should be included, but some studies omit transport or storage costs. The Cost of CO₂ abated is not used for a single project, but generally for energy-economic models where we want to analyze the cost of moving from the current situation to a low-carbon one, with many alternatives used for abatement, ranging from renewables to CCS. Additionally, in the case of power generation, the increased cost of electricity can be used in comparison to a similar plant without CCS. Also, during the review one can use different methods, ranging from commissioning detailed engineering studies to deriving new results from a model, modifying published values, using published values without modification, or simply asking experts. It also matters whether current or constant prices are used. Using the two will produce the same rankings between options, but using current dollars will yield higher absolute results. It is also important to account for uncertainty, drawing possible values from a distribution rather than deterministic values, with confidence intervals being wider in the case of new, not commercially used technologies.

Given the complexity of calculating cost per CO₂ avoided, but we have to keep in mind that this leads to an underestimation of expenses.

IV.2. Incentive policies

Since CCS projects generally suffer from high costs and risks, in addition to low expected returns, it is essential to have appropriate economic incentives for a large-scale roll-out of the technology (Cabrera et al., 2022).

According to Akihiro et al., (2019) economic policies to incentivize CCS roll-out can be divided into three groups: regulatory instruments, economic instruments for investment support, and finally market-based instruments. Regulatory instruments are where the government sets a limit on emissions. It includes policies such as the emissions performance standard, which limits companies to a pre-determined amount of emission per level of output, or portfolio energy standards, which could require energy operators to utilize CCS during energy generation. Market-based mechanisms include the use of a carbon tax, which will incentivize stakeholders to use CCS to reduce tax expenditures. An emissions trading scheme sets the maximum amount of emissions and allows companies to buy or trade quotas if they wish to emit more. Instruments for investment support include government subsidies, and guaranteed loans which the

government uses to reduce the amount and risks associated with the CAPEX required to undertake such projects.

One of the most famous such systems is the European Union Emissions Trading System (EU ETS). This follows the cap-and-trade model, where the European authorities fix the total amount of emissions with allowances, which firms either receive for free, buy on auctions, or trade with each other (European Commission, 2015). This system is particularly useful for us since its market-based mechanism allows us to compare paying for “carbon emissions” or avoiding them in total. Of course, companies will not pay more for CCS per tonne of CO₂ avoided than the price they could pay for permits (Akihiro et al., 2019). The price of the permits on the other hand will reflect the stringency of the regulations and the efficiency of substitute technologies. If other abatement measures, such as renewables or avoiding emissions in the first place are cheaper, carbon prices will be lower, and no company will pay for expensive CCS. As a result, forecasting the European carbon price will be essential for the future economic viability of carbon capture.

In the contrary, the US Inflation Reduction Act sets a tax credit per tonne of CO₂ captured and stored. For CO₂ captured at power or industrial facilities and stored in geological formations, an \$85/ton tax credit is offered (Steinber et al., 2023, pg. 5). For carbon removed via direct air capture, the tax credit is \$180/ton (Larsen et al., 2022, pg. 7).

IV.3. European Carbon Price Forecasts

In 2023, the average EU ETS price was 86.17 per tonne of carbon dioxide, which has risen sharply since the Covid-19 pandemic (Statista, 2024). In my analysis, I intend to compare the cost curve to the European carbon price, since this relation will determine whether companies will invest in the technology. Thus, it is essential to know not only current allowance prices but also where they are going to evolve by 2030.

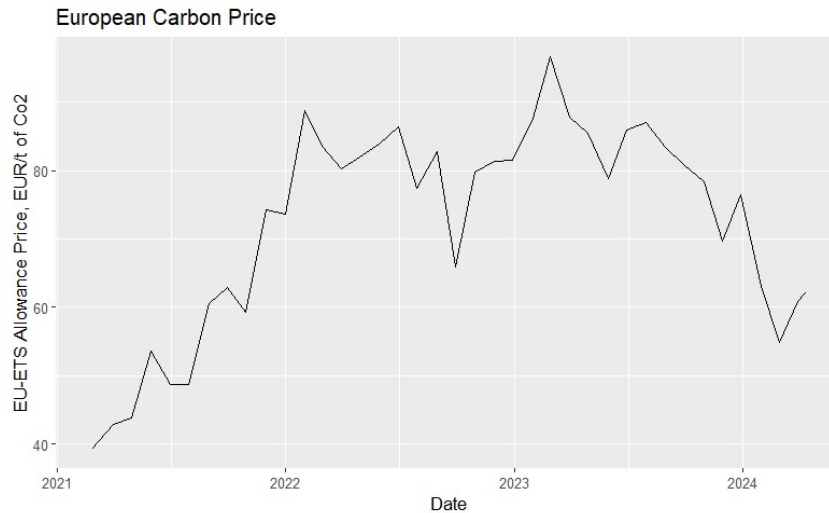


Figure 1, Price evolution of EU ETS carbon price, between 2021 and 2024, Source, Own-making, based on: Bloomberg, EU ETS Last Price

Pahle et al. (2022) examined different models forecast regarding the future of the European carbon price. They found that although the models generally differed in their predictions for the mid-2020s (between 56 and 111 EUR per tonne), these findings converged by 2030. Here, out of six surveyed, five showed results between 130 and 160 EUR per tonne (Pahle et al., 2022, pg. 2). This sounds surprising since normally we would expect lower variance in short-term predictions than long-term ones. But this can clearly be explained by two effects. First, the shrinking of the total EU emissions cap will tighten the market, causing higher and more predictable prices. Second, there is more consensus on the implementation of renewables and negative-emissions technologies by the late 2020s, which will have the opposite effect and drive prices downwards. Since the forces that drive the price can be predicted with greater accuracy, more confidence can be found in the prediction.

V. Background of CCS in Hungary

V.1 Role of CCS in Hungarian climate strategy

In 2021, the Hungarian Ministry of Innovation and Technology devised the National Clean Development Strategy 2020-2050 with the aim of reaching carbon neutrality by 2050. The strategy modelled three scenarios: A business-as-usual (BAU) scenario with no action and only current policy in place, a late-action (LA), where the green transition is slow until 2045, and an early-action (EA) scenario where emissions between 2030 and 2050 follow a linear trajectory

to reach net zero. In both LA and EA scenarios, Hungary achieves climate neutrality by 2050, but the early-action (EA) scenario was deemed economically more appealing due to the business opportunities offered by the green transition. The plan only expects CCS to become economically viable after 2030, but expects widespread application in the energy sector and in industrial processes following the 2030s. Large-scale use of Bioenergy with Carbon Capture and Storage (BECCS) is also expected, which leads to net negative emissions. (Innovációs és Technológiai Minisztérium, 2021)

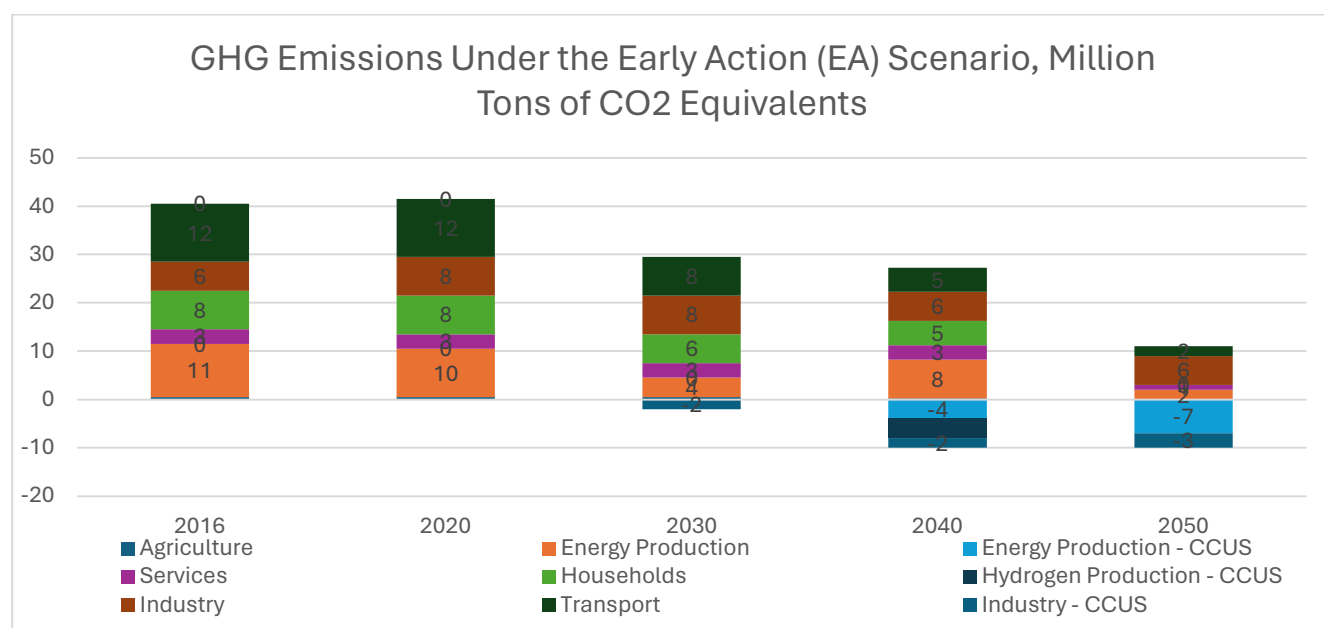


Figure 2, Expected CO2 emissions under Early-Action (EA) scenario, Source: Own-making, based on: Innovációs és Technológiai Minisztérium, 2021, pg. 42

As we can see, by 2030, only two million tons of CO2 will be removed according to the scenario in industrial processes (Innovációs és Technológiai Minisztérium, 2021, pg 42). This will grow to four in energy production and 2 in hydrogen production and industry respectively by 2040 (Innovációs és Technológiai Minisztérium, 2021, pg 42). By 2050, the seven million tons removed in energy and three in industry will compensate for all emissions, leading to a carbon-neutral Hungary (Innovációs és Technológiai Minisztérium, 2021, pg 42). The plan stresses that further research is needed in the field for use of CCUS technologies on this scale (Innovációs és Technológiai Minisztérium, 2021, pg 42).

The plan was even criticized by the National Society of Conservationists – Friends of the Earth Hungary for relying too much on CCS technologies towards 2050, whose actual viability is uncertain (Magyar Természetvédők Szövetsége, 2021)

V.2. Legal background

The geological storage in Hungary is regulated by the Supervisory Authority for Regulated Activities decree 29/2022 (I.31.). Accordingly, the Supervisory Authority must survey the potential CO₂ storage sites in Hungary and must publish them on its website. If an actor wants to store CO₂ in Hungary, he/she must make an application for a permit that will allow them to conduct research in the area. This must include the plan, budget, and location of the research, and potential dangers that may be encountered. If the permit is granted and the exploration is carried out, risks of leakage or other harm potentially arising from CO₂ storage in the formation must be assessed in a report. Only after the submission of this report can the actor apply for a permit to store CO₂ at the respective site. In this application, the amount of stored CO₂ and its sources must be included, in addition to modelling results about storage in the formation. The operator is responsible for monitoring the site for leakage.

VI. Interviews

To assess the costs and obtain a qualitative assessment of the risks and potentials of CO₂ storage in Hungary. The names, positions, and institutions of the experts can be seen in (Table 5). There are clear limitations to using expert interviews for the study, as thus it is only meant to be supplementary to the modelling of expenses and literature review, and to gain a better understanding of the topic. The first such drawback is the relatively small number of expert interviews, partly due to the small number in the field and due to non-responses. Secondly, the economic potentials of CO₂ storage in Hungary are not that well understood, and as such, most of the information recovered was qualitative in nature and concerned the geological characteristics of the reservoirs. Thus, limited amount of information could be recovered about actual cost calculations, but they were still important for assessment of the risks and expert opinions of carbon capture and storage in Hungary. The interviews were conducted in a semi-structured way, based on a set of questions from which there was deviation across the sessions. Please note that not all interviewees could answer each question, so I highlighted only relevant information in the analysis.

Interviewee	Organization	Position	Interview Date
György Falus	Supervisory Authority for Regulated Activities	Head of the Department of Geology	19th, March
Csaba Gál	MOL Group	CCS Senior Expert	21st, March
Eszter Sendula	Arctic University of Norway	Postdoctoral Research Fellow	25th, March
Csilla Király	Geographical Institute Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences.	Research Fellow	8th, April

Table 5, Interviews, Source: Own-editing

All interviews were conducted online, between the 19th of March and 8th of April, 2024.

VI.1 György Falus

Falus (2024) stressed that only deep saline aquifers and depleted oil and gas fields are suitable for carbon dioxide storage in Hungary. Unmineable coal seams lacked permeability, and injection would only be possible through fracking, which would harm reservoir integrity. He highlighted, that although depleted gas fields are better known, abandoned wells pose the biggest risk of leakage (which all need to be plugged), and thus storage in aquifers may come with lower expenses. He stressed, that in a study conducted with a Hungarian oil company ten years ago, aquifers were found to be the preferable storage location, as in that case only the sealing capability needs to be proven, and legacy wells need not be dealt with. In addition, Hungarian depleted oil and gas fields are in poor condition as in the past focus was on increased oil recovery through the highest number of wells possible, neglecting reservoir integrity. He also brought exact estimates about an unnamed CO₂ storage project in a Hungarian deep saline aquifer: research and exploration costs (including planning and boring a research well) amounted to 1 euro per tonne of CO₂ stored, while each additional well costs slightly less than 1 euro. Operating expenses amount to a further 1 euro per tonne. In total, including performing a seismic test in fixed time intervals, costs amount to a maximum of 5-6 EUR per tonne over the entire project lifetime. In normal circumstances, storage costs must remain below 10 EUR per tonne, maximum. About risks, he mentioned a case where a village had to be evacuated over CO₂ leakage related to oil production enhanced by CO₂-injection, but the issue could be

resolved within a matter of days without the loss of human life, demonstrating that such a situation can be handled. He also mentioned that these incidents are most likely to occur at the beginning of the project's lifetime and are unlikely to cause issues decades after. Regarding the potential scale of storage in Hungary, the expert estimated that no storage will occur beyond a few million tonnes of CO₂ per year. It is most likely that CCS will roll-out in a limited scale in hard-to-decarbonize but easy-to-capture industries such as bioethanol and cement manufacturing, with other industries following if it is successful. Although the current carbon price (60-80 EUR) will probably be enough for long-term economic viability, grants and support for the first projects will be necessary. The expert thinks that the Újfalu formation is suitable as well for storage but is explored less frequently since it is extensively for geothermal purposes. There are also possible hydrocarbon sites in the Transdanubia region that potentially could serve as a CO₂ reservoir. Transport across the Danube is possible but may not be economically desirable.

VI.2. Csaba Gál

According to Gál (2024), it is important to distinguish between surface infrastructure and assets used during oil and gas production. The former includes surface pipelines, injection technologies, and electricity access and will decrease expenses (in CO₂ transport) by about 5-10 EUR per tonne of CO₂. Assets such as legacy wells will have to be converted from extraction to injection but retraining one such well costs generally third as much as drilling a completely new one. The biggest risk to human life in the process occurs during transport, and extra care (monitoring and frequent sealing valves) will have to be taken near populated areas. Leakage during storage could endanger groundwater bodies. Regarding the social acceptance of CCS, the expert stressed the importance of including GHG reduction, control, and environmental protection in school curriculum. If the technology is mentioned in a positive manner, information will spread among children and to their parents, improving public perception of the issue. According to Gál, the biggest reservoir identified in Hungary had a net capacity of 9 Mt (which is low compared to offshore sites such as the Neptune project). As a result, when asked the question whether large-scale storage in Hungary will be possible, he stressed that instead, the focus should be on whether safe storage is possible, to which the answer is clearly yes. Storage in gas reservoirs is generally preferred over oil reservoirs, as though both share the same safety features, in the former 80-90% of gas is extracted leaving much space for CO₂ in the reservoir. On the other hand, oil exploration leaves 70% in the formation, limiting space

available for storage. When asked about the feasibility of pipeline transport across the Danube, the expert noted that it is technically possible, but will increase expenses. According to Gál (2024), there are no identified depleted hydrocarbon fields in the Transdanubia region suitable for carbon storage, but the Újfalu formation could be used for such purposes.

VI.3. Eszter Sendula

Sendula (2024) thinks that storage will likely start first in depleted hydrocarbon fields due to infrastructure availability, but aquifers are safer and provide much greater capacity, encompassing almost the entirety of the great Hungarian plain. In both aquifers and depleted hydrocarbon fields, it also matters how the injected CO₂ reacts with nearby rock formations and pore fluids. It can dissolve certain minerals or the geochemical reaction could precipitate and store CO₂ in minerals as a solid phase. The former has a negative, while the latter has a positive impact on permanent storage. Hungarian aquifers have the potential to store only a minor amount of injected CO₂ in minerals, meaning that physical storage (including CO₂ dissolved in formation water) will be of major importance. This will bring the need for rigorous assessment of storage sites before CO₂ injection and long-term monitoring of the subsurface movement of CO₂ in liquid or supercritical phase. This may limit drilling in the area in some respects for centuries to come.

VI.4. Csilla Király

Király (2024) stressed that out of the two deep saline aquifers, the Újfalu formation might not be suitable for CO₂ storage, due to being situated not deep enough and close to underground freshwater bodies, in addition to less-than-perfect caprock. She also highlighted that environmental protection authorities will probably not allow pipeline transport across the Danube. This severely limits CCS in Hungary, as most suitable industrial sites are in the Transdanubia region, while storage formations (Szolnok aquifer, and depleted hydrocarbon fields) are situated on the other side of the Danube, which will limit CCS roll-out. As a result, emitters in the western region will need to find formations to store CO₂ closer to them. Like Falus (2024), she also expects the technology to be used first in the bioethanol and cement industry. In the Transdanubia region, further research will need to be carried out, particularly about the plausibility of CO₂ storage in Miocene rocks. It would also be important to have details about monitoring set out in legislation: what parameter needs to be monitored, where, and at what frequency.

VII. The economics of the Hungarian CCS sector

VII.1. CCS capture sources in Hungary

In 2021, Hungary emitted 63.8 million tons of CO₂ into the atmosphere, with the processing industry and energy generation being responsible for 12.6 Mt each (KSH, 2024a).

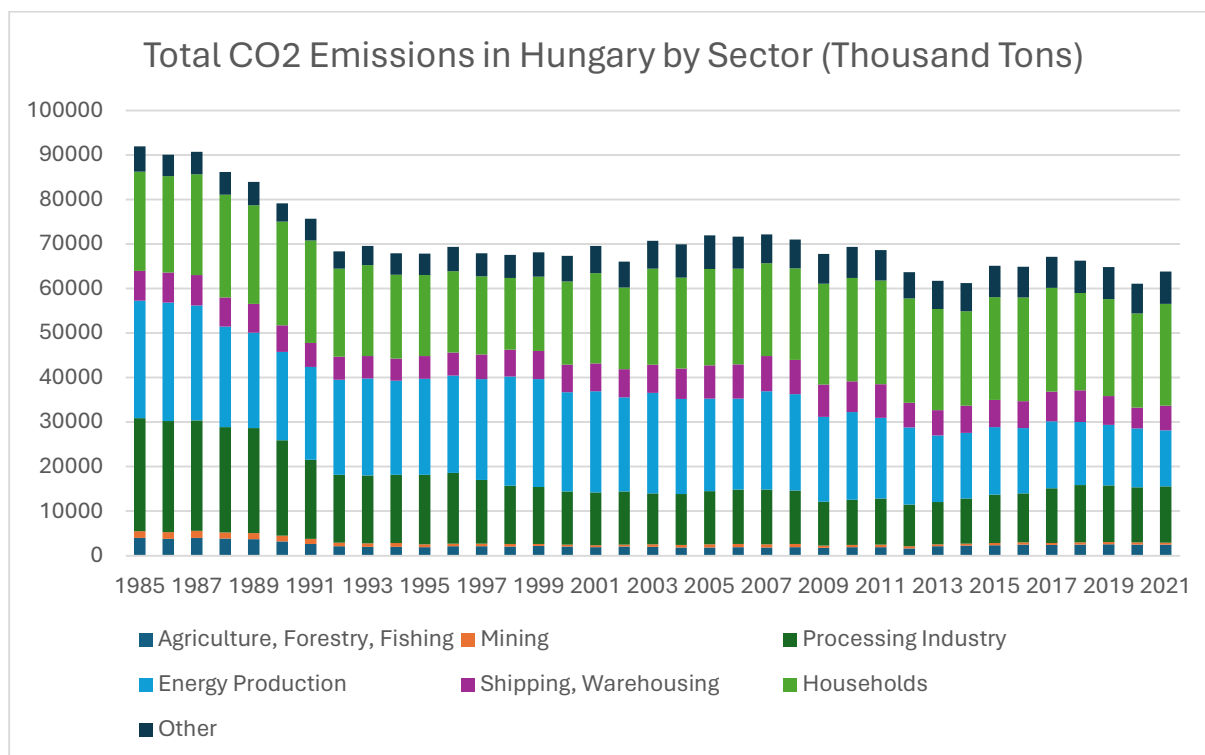


Figure 3, Total CO₂ Emissions in Hungary by Sector (Thousand Tons, Source: Own-making, based on: KSH, 2024a)

In the country, CO₂ emissions fell considerably between 1985 and 2021, much of it being attributed to the economic crisis and loss of industry following the transition to market economy around 1990 (Farkas Csamangó et al., 2023). Emissions have remained almost constant since then.

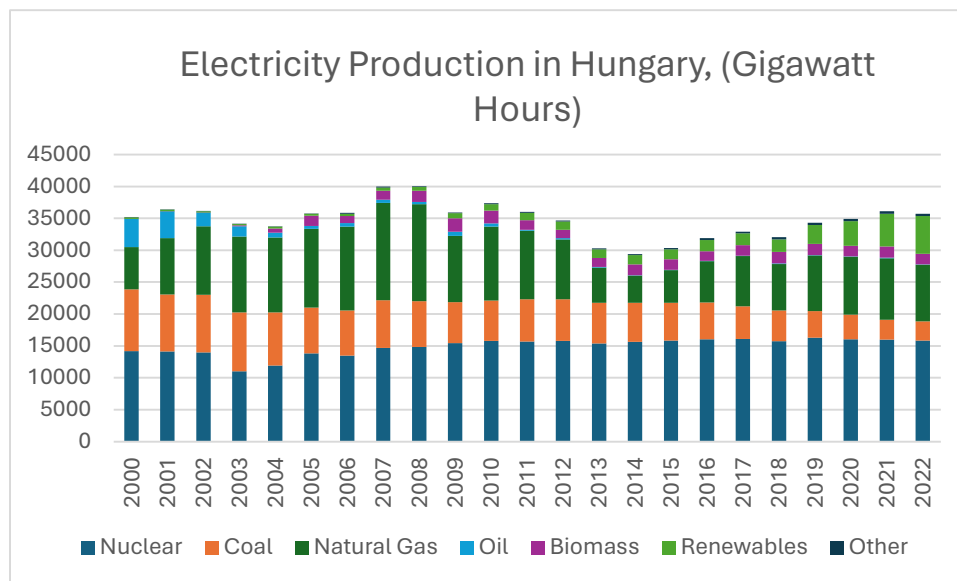


Figure 4, Electricity Production in Hungary, Source: Own-making, based on KSH, 2024b

The two biggest sources of electricity production in Hungary are nuclear and natural gas, with coal making up an increasingly smaller part of the energy mix.

VII.2.1. CCS Use in Industry

I identified the biggest industrial CO₂ emitters in Hungary, where CCS could be used to reduce emissions based on the EU ETS database (European Commission, 2024).

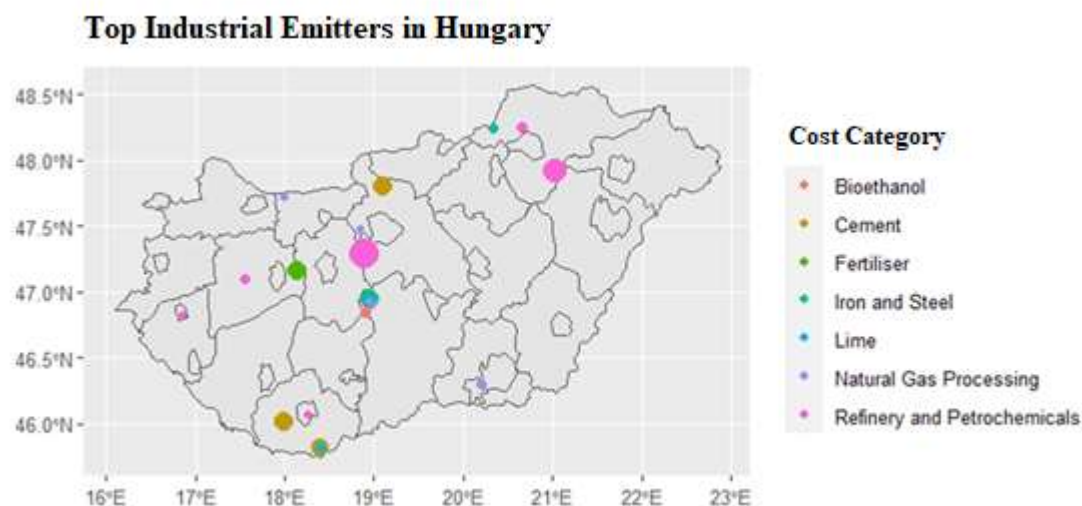


Figure 5, Top Industrial Emitter in Hungary, Source: Own-making, based on: European Commission, 2024

CCS could best be in industries hard-to-decarbonize industries, or in industries where CO₂ could be captured at a low cost, such as bioethanol and cement manufacturing (Kearns, Liu, and Consoli, 2021). Among the top emitters covered by EU ETS, there are three cement factories in Hungary.

Company	Location	Emissions (kt CO ₂)		
		2021	2022	2023
Holcim	Királyegyház Cement Factory	539	448	249
Duna-Dráva Cement	Vác Cement Factory	514	397	342
Duna-Dráva Cement	Beremend Cement Factory	459	378	223

Table 6, Cement factories and their emissions in Hungary; Soure. Own-making, based on: European Comission, 2024

As we can see, although the cement industry is a significant source of carbon emissions in Hungary, these declined significantly in the period from 2021 to 2023. This may be due to a reduction in production because of the price cap on cement and extra taxes issued in 2022 (Portfolio, 2022).

In bioethanol manufacturing, key player Pannonia Bio ltd. has already signalled the intent to use the technology in the reduction of emissions (Hódos, 2023).

Company	Location	Emission (kt of CO ₂)		
		2021	2022	2023
Pannonia Bio	Dunaföldvár	121	86	122

Table 7, Bioethanol factories and their emissions in Hungary, Soure. Own-making, based on: European Comission, 2024

The iron and steel sector is also a very important source of CO₂ emissions in Hungary.

Industrial Complex	Process	Emission (kt of CO ₂)		
		2021	2022	2023
Dunaújvárosi Vasmű	Blast Furnace	523	416	195

Dunaújvárosi Vasmű	Sinter Plant	191	165	74
Dunaújvárosi Vasmű	Coking plant	142	66	82
Dunaújvárosi Vasmű	Hot Rolling Mill	88	64	26
Ózdi Acélművek	Steel Manufacturing	44	34	31

Table 8, Steel and iron factories and their emissions in Hungary, Soure. Own-making, based on: European Comission, 2024

As we can see, the Dunaújváros Vasmű is by far the biggest source of CO₂ in the sector. The four iron- and steel-making facilities it contains emitted 0.71 Mt of CO₂ alone in 2023 (Table 8). If we also include the ISD Power facility, which generates energy from the waste gasses of the facility, this is increased by 0.86 Mt to 1.57 Mt of carbon dioxide (Table 8). This amounts to 8.8% of Hungarian carbon emissions covered under the ETS in 2022 (European Commission, 2024).

Significant amounts of carbon emissions could be also captured from refineries and petrochemical facilities. In the analysis, I am going to use refineries and petrochemicals as a common category, for reasons discussed previously (Fitzgibbon et al., 2022; da Silva, 2023).

FitProcess	Emission (kt of CO ₂)		
	2021	2022	2023
MOL Danube Refinery	1509	1493	1569
MOL Tisza Chemical Works	1069	835	880
BorsodChem Chemical Works	123	92	No Data
MOL Zala Refinery	22	20	21

Table 9, Refineries and Petrochemical factories and their emissions in Hungary: Soure. Own-making, based on: European Comission, 2024

The MOL Danube Refinery is by far the biggest emitter, with the MOL Tisza Chemical Works coming in second place. Together, these two facilities emitted 2.3 Mt of CO₂ in 2022, which amounted to 13% of emissions under ETS (European Commission, 2024).

One of the cheapest sources of capture is fertilizer production, where CO₂ can be separated at an average cost of 6 EUR/t (Kearns, Liu, and Consoli, 2021, pg. 29). Located in Pétfürdő, Nitrogénművek ltd. is the only producer of ammonia and fertilizer products in Hungary (Nitrogen.hu, 2024).

Company	Location	Emission (kt of CO ₂)		
		2021	2022	2023
Nitrogénművek Zrt.	Pétfürdő	903	463	713

Table 10, Steel and iron factories and their emissions in Hungary, Source. Own-making, based on: European Commission, 2024

VII.2.2. CCS in the energy sector

In the following section, I analysed energy sector CO₂ emission sources based on the EU ETS database (European Commission, 2024).

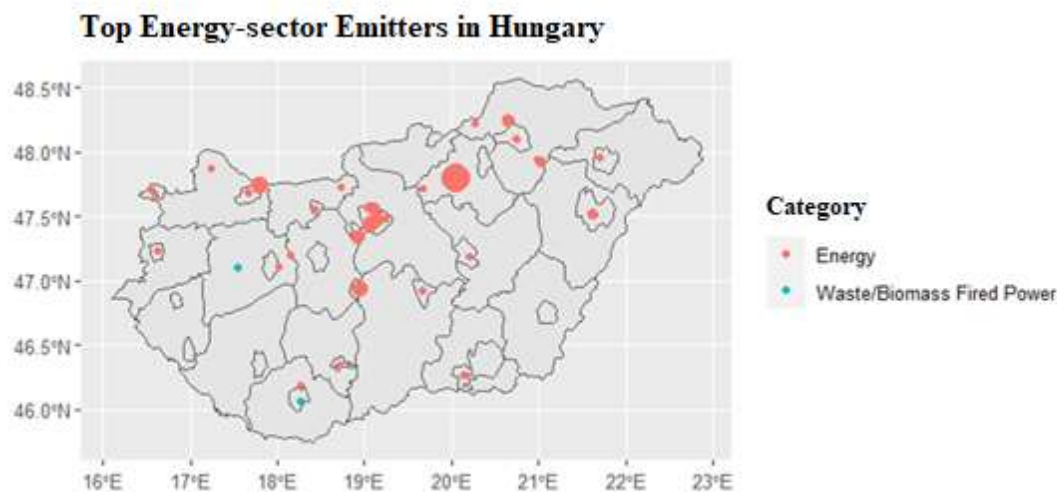


Figure 6, Top Energy-sector emitters, in Hungary, 2022 CO₂ emissions, Source. Own-making, based on: European Commission, 2024

Although carbon dioxide capture in the energy sector suffers some drawbacks compared to that in the industrial sector: it must compete with renewables, and flue gases have lower partial pressure of CO₂ there leading to somewhat higher capture cost (Mikunda et al., 2014). Nevertheless, I thought it interesting to include energy production in the supply curve. In the data, I could identify 54 power plants of different sizes and technologies, which emitted 8.34 Mt of CO₂ in 2022 alone (European Commission, 2024).

Since many of these sites are small, and the energy sector is not the primary focus in my research, I restricted the analysis to the top 15 facilities, as measured by 2022 emissions.

Power Plant	Emissions (kt of CO ₂)			Fuel Used	Technology
	2021	2022	2023		
MVM Mátra Energia ZRt. Visontai Erőmű	3472	3460	2965	Coal	
Gönyői Kombinált Ciklusú Erőmű	831	897	836	Gas	NGCC
ISD POWER Kft. Erőmű	866	688	356	Mixed	
Alpiq Csepel II. Erőmű	513	586	252	Gas	NGCC
Dunamenti Erőmű Zrt.	645	457	394	Gas	NGCC
BC-Erőmű Kft.	313	294	255	Gas	NGCC
BERT Rt. Kelenföldi Komb.Cikl. Gázt.Hoszolg. Eromu	276	255	213	Gas	NGCC
BERT Rt. Újpesti Komb. Cikl. Gázt. Hoszolg. Eromu	288	247	208	Gas	NGCC
TVK-Erőmű Kft.	225	240	216	Gas	NGCC
BERT Rt. Kispesti Komb. Cikl. Gázt. Hoszolg. Eromu	246	212	194	Gas	NGCC
Debreceni Kombinált Ciklusú Erőmű	216	193	182	Gas	NGCC
Észak-Budai Fűtőerőmű	138	109	90	Gas	
BC kazántelep	100	96	67	Gas	Boiler Plant
Nyíregyházi Kombinált Ciklusú Erőmű	71	58	43	Gas	NGCC
Bakonyi Gázturbinás Erőmű	48	43	5	Gas	OCGT

Table 11, Energy-sector emitters in Hungary, Soure. Own-making, based on: European Comission, 2024

In total, these emitted 7.83 Mt, or 94% of all identified power-plant emissions, justifying the restriction of the data (European Commission, 2024). As we can see, the rankings are consistent over the years, except for the drastic reduction of emissions in the ISD POWER plant. The largest emitter in energy generation is by far the MVM Visontai Erőmű. As Hungary's only coal-fired power plant, it generates energy from the burning of lignite (MWM., n.d.). According to the company website, it is scheduled to undergo investment aimed at aligning the power plant more with the sustainability requirements of the 21st century (MWM., n.d.). A Natural Gas Combined Cycle (NGCC) is scheduled to be built, along with the expansion of biomass burning (MWM., n.d.). Although the lignite-fired blocks are scheduled to be closed by 2025, the Hungarian government is reviewing plans to extend their lifetimes until 2029, for reasons of

energy security in view of the war in Ukraine (MWM., n.d.). The company is also planning on using CCS as a pilot project in NGCC turbines (MWM., n.d.).

VII.3. CCS storage sites in Hungary

In Hungary, possible options for carbon capture and storage are deep saline aquifers and depleted oil and gas fields. In order for a formation to become an appropriate storage site, several requirements will have to be met: 1, large vertical and horizontal extent for sufficient storage capacity, 2, high porosity and permeability to allow for CO₂ to move around in the reservoir, 3, an impermeable layer above the formation to prevent leakage, 4, it must be tectonically stable, 5 and it must be isolated from freshwater to prevent contamination (Hartai, 2014). According to Kubus (2010), depleted oil and gas reservoirs have a theoretical capacity of 430 million tonnes of CO₂, but only 171 Mt could be exploited until 2035 (Kubus, 2010, pg. 2.). Different estimates find the effective storage capacity in such reservoirs to be around 100 Mt of CO₂ (Falus and Szamosfalvi, 2016, pg. 166). Before injection, careful analysis and modeling should take place, including checking for abandoned wells, to reduce the chance of leakage from such reservoirs. Kubus (2010) split up the potential storage sites into 3 three blocks, with the Transdanubian depleted oil and gas fields being excluded due to transmission difficulties.

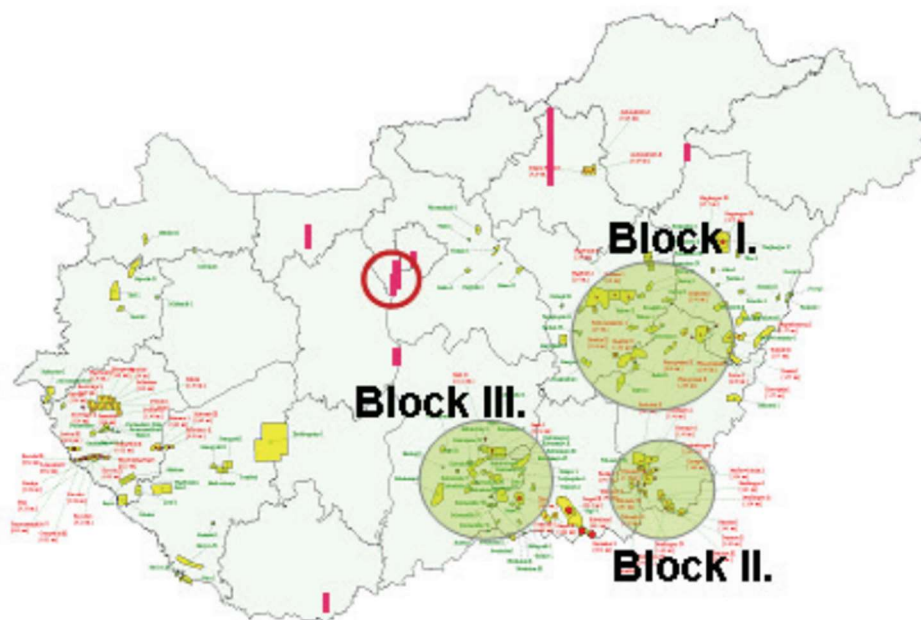


Figure 7, Depleted oil and gas fields potentially suitable for CO₂ storage in Hungary, source: Kubus (2010)

Deep saline aquifers provide larger, but less explored reservoirs for CO₂ storage (Kubus, 2010). In Hungary, the Szolnok and Újfalú formations could be used for such purposes, with a total theoretical capacity of 2510 Mt of CO₂, with 2090 Mt in the former and 424 Mt in the latter (Kubus, 2010, pg 4.). According to other estimates, such reservoirs contain about 750 Mt of potential storage capacity (Toldi, Jenei and, Jenei, 2018, pg. 12).

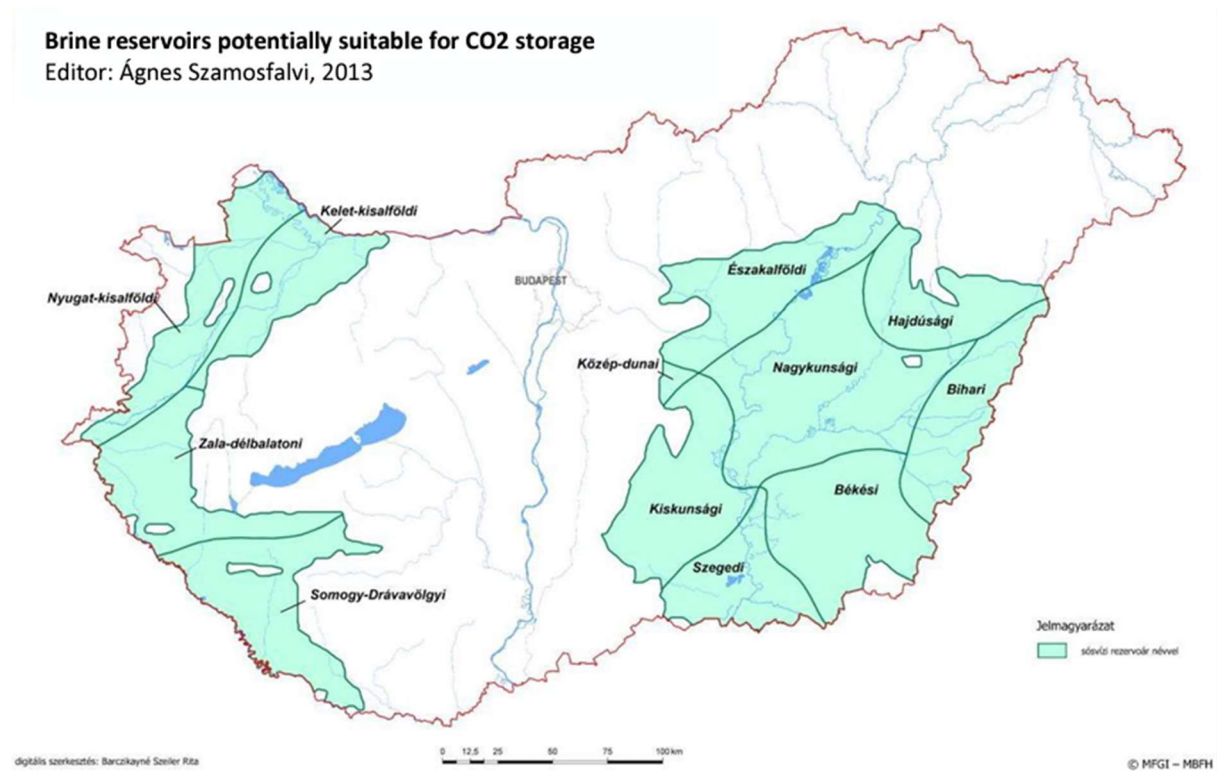


Figure 8, Deep saline aquifers potentially suitable for CO₂ storage in Hungary, source: Szamosfalvi, 2013 as cited by Toldi, Jenei, and Jenei (2018)

Unmineable coal seams were deemed not suitable as a storage site because of low absorption quality, so they will not be part of my analysis (Kubus, 2010).

Deep saline aquifers could be a good opportunity for storage at a later date, but currently, storage in depleted hydrocarbon fields is considered less risky due to proven capacity to store oil and gas over an extended period (Kubus, 2010). According to Falus (2024) however, deep saline aquifers have considerable advantages in terms of greater storage potential and no leakage risk due to abandoned wells and infrastructure. In a study conducted with an unnamed Hungarian oil company, deep saline aquifers were considered better targets for permanent storage (Falus, 2024).

VII.4. CO2 transport in Hungary

Although facing high one-time investment costs, pipelines will be the primary mode of CO2 transport (Lu et al., 2020). Rivers, lakes, population centres, past seismic activity, and protected natural areas all present challenges for shipping via this method, so these all need to be carefully evaluated when examining the issue in Hungary. The most prominent obstacle is the Danube River, which according to Király (2024) even prevents pipeline transport from the Transdanubia to the Tiszántúl and Duna-Tisza köze region. Unfortunately, almost all industrial and the majority of energy sector emitters are located West of the Danube.

River crossing present a significant obstacle to carbon dioxide pipelines and its environmental safety is up for constant debate. River crossings also present challenges to natural gas pipelines, but the issue can be handled via multiple construction techniques (Folga, 2007). Even the vast network envisioned to be needed in Europe by 2050 requires some pipelines to cross major rivers (Zero Emissions Platform, 2013). As a result, I am going to assume that it is indeed possible to cross the Danube River, but it increases costs of transport.

VII.5. Identifying CCS clusters in Hungary

According to findings by Zero Emissions Platform (2011), due to the large one-time investment cost and overwhelming economies of scale characterizing pipeline transport, a feeder-trunk-line-distributor network is considered the most viable. As a result, I identify CCS clusters where multiple emitters are in close proximity. I also identify possible geological formations where carbon can be transported from these clusters.

VII.5.1. The Dunaújváros Cluster

One of the most apparent such location is the area near Dunaújváros, where many industrial sites and several energy facilities exist. Apart from the city's facilities, the Százhalombatta refinery, and the Pannonia Bio bioethanol factory are also in proximity.

Facility	2022 Emission (Mt of CO2)	Capturable Emissions (Mt of CO2)	Distance from Center (km)	Relevant Cost Category
Dunai Vasmű Nagyolvasztómű és Konverteres Acélmű	0.42	0.37	0	Iron and Steel
Dunai Vasmű Zsugorítómű	0.17	0.15	0	Iron and Steel
Dunai Vasmű Kokszoló	0.07	0.06	0	Iron and Steel
Dunai Vasmű Meleghengermű	0.06	0.06	0	Iron and Steel
ISD POWER Erőmű	0.69	0.62	0	Energy: Gas
Hamburger Hungária Kft. vegyes tüzelésű erőmű	0.27	0.24	0	Energy: Gas
Dunacell Dunaújvárosi Cellulózgyár Kft.	0.01	0.01	0	Pulp and Paper Industry
DUNAFIN Papírgyár	0.01	0.00	0	Pulp and Paper Industry
MOL Dunai Finomító	1.51	1.36	40	Refinery and Petrochemical s
Dunamenti Erőmű	0.46	0.41	40	Energy: Gas
Pannonia Bio	0.09	0.08	14	Bioethanol
Nitrogénművek	0.46	0.42	65	Fertilizer
Total	4.19	3.77	-	-

Table 12, The Dunaújváros Cluster, Source. Own-making, based on: European Commission, 2024

There are several areas where CO2 can be transported from the cluster, both to the west and to the east of the Danube.

Possible Storage Locations	Approximate Distance (km)	Major River Crossing
Szolnok Formation	120 km	Duna/(Tisza)
Újfalu Formation	160 km	No
Block III. Oil and Gas Fields	100 km	Duna

Table 13, The Dunaiútváros Cluster, potential storage locations, Soure. Own-making, based on: European Commission, 2024

VII.5.2. Baranya cement Cluster

Another potential source of large-scale carbon emissions is the Királyegyháza and Beremend cement factories. To these, the lime factory in Beremend could possibly be added.

Facility	2022 Emission (Mt of CO ₂)	Capturable Emissions	Distance from Center (km)	Relevant Cost Category
Királyegyházi Cementgyár	0.45	0.40	0	Cement
Duna-Dráva Cement Kft. Beremendi Cementgyár	0.38	0.34	40	Cement
Carmeuse Hungária Kft. Beremendi Mészüzem	0.06	0.05	40	Lime
Total	0.89	0.80	-	-

Table 14, The Baranya Cement Cluster, Soure. Own-making, based on: European Commission, 2024

Here, there are also many possibilities for CO₂ storage, with the Újfalu formation being the closest and potentially the cheapest option.

Potential Storage Locations	Distance	Major River
Újfalu Formation	70 km	No
Szolnok Formation	160 km	Danube/(Tisza)
Block III. Oil and Gas Fields	130 km	Danube

Table 15., The Baranya Cement Cluster, potential storage locations, Soure. Own-making, based on: European Commission, 2024

VII.5.3. Clusters in the Duna-Tisza-köze region

Although most Hungary's potential CO₂ storage areas are in the southeast of the country, the majority of possible capture sites are located either in the Transdanubia region or in the Northern region of the country. Nevertheless, there are several CCS clusters that I could establish in the eastern regions as well.

VII.5.4. Budapest-Vác Cluster

One of the most obvious such locations is near the capital, Budapest. There are several large power plants there (mostly natural gas combined cycle, NGCC), but the Vác Cement Factory (Váci Cementgyár) could be connected as well.

Facility	Emission 2022 (Mt of CO ₂)	Capturable	Distance from Center (km)	Relevant Cost Category
Alpiq Csepel II. Erőmű	0.59	0.53	0	Power: Gas
BERT Rt. Kelenföldi Komb.Cikl. Gázt.Hoszolg. Eromu	0.26	0.23	0	Power: Gas
BERT Rt. Újpesti Komb. Cikl. Gázt. Hoszolg. Eromu	0.25	0.22	0	Power: Gas
BERT Rt. Kispesti Komb. Cikl. Gázt. Hoszolg. Eromu	0.21	0.19	0	Power: Gas
Észak-Budai Fűtőerőmű	0.11	0.10	0	Power: Gas
Duna-Dráva Cement Váci Cementgyár	0.40	0.36	35	Cement
Total	1.80	1.62	-	-

Table 16, The Budapest-Vác Cluster, Soure. Own-making, based on: European Comission, 2024

Transport of carbon dioxide from these pipelines could present some challenges, as the power plants are located close in highly populated areas, which requires valves to be built in the pipeline at closer intervals (Gál, 2024).

Potential Storage Locations	Distance	Major River
Szolnok Formation	80 km	No
Block I. Gas Fields	120 km	(Tisza)
Block III. Gas Fields	110 km	Tisza

Table 17, The Budapest-Vác Cluster, potential storage locations, Soure. Own-making, based on: European Comission, 2024

VII.5.5. Visonta Power Plant

The Visonta Coal-Fired Power Plant also presents an opportunity for CCS as it is responsible for so high carbon emissions that it does not require its own cluster but could easily support pipeline capacity on its own.

Facility	2022 Emission (Mt of CO2)	Capturable Emissions	Relevant Cost Category
MVM Visontai Erőmű	3.46	3.11	Energy: Coal

Table 18, The Visonta Power Plant, Soure. Own-making, based on: European Comission, 2024

Although the Coal-fired plant was supposed to shut down by 2025, the government is reviewing plans to extend its lifetime by 2029, prompting me to include it in the analysis (MWM., n.d.).

Potential Storage Locations	Distance	Major River
Szolnok Formation	60 km	No
Block I. Gas Fields	100 km	Tisza
Block III. Gas Fields	150 km	(Tisza)

Table 19, The Visonta Power Plant, potential storage locations, Soure. Own-making, based on: European Comission, 2024

VII.5.6. Borsod Cluster

The final CCS cluster identified is the cluster located in Borsod county, in the Northeast of the country.

Facility	Emissions 2022 (Mt of CO ₂)	Capture ble	Distance from Center (km)	
TVK	0.84	0.75	0	Refinery and Petrochemicals
BorsodChem Zrt.	0.09	0.08	50	Refinery and Petrochemicals
ÓAM Ózdi Acélművek Kft.	0.03	0.03	65	Iron and Steel
BC-Erőmű Kft.	0.29	0.26	50	Energy: Gas
TVK-Erőmű Kft.	0.24	0.22	0	Energy: Gas
BC kazántelep	0.10	0.09	50	Energy: Gas
Total	1.59	1.43	-	-

Table 20, The Borsod Cluster, Soure. Own-making, based on: European Comission, 2024

Potential Storage Locations	Distance	Major River
Szolnok Formation	100 km	(Tisza)
Block I. Gas Fields	70 km	Tisza
Block II. Gas Fields	160 km	(Tisza)

Table 21, The Borsod Cluster, Soure. Own-making, based on: European Comission, 2024

VII.6. CCS Cost Analysis

Initially, I wanted to construct a marginal cost curve for carbon dioxide technologies in Hungary by summing up all the potential storage capacity in Hungary (including capture and transport costs), and add them up from cheapest to most expensive. The theory was that since companies with the ability to capture carbon dioxide at a low cost would embrace it first. Similarly, in the case of reservoirs, cheap storage sites would be reserved first, followed by more expensive ones later. But carbon dioxide transport and storage benefits immensely from economies of scale. Also, the technology is surrounded by large uncertainty, which makes constructing a full cost curve almost an impossibility. Instead, I summed up possible costs from potential storage capture sites based on the relevant cost category. I did this for each carbon cluster and then presented the results in (Table 22).

For each location in each cluster, I am going to devise an optimistic, an average and a pessimistic scenario. For each scenario, I will take the respective (optimistic, average, pessimistic) estimate, symbolizing the “minimum”, “mean”, and “maximum” of the distribution.

When it comes to the price of carbon capture, I will simply use the lower bound, average estimate, and upper bound from (Table 1). For carbon dioxide storage, I devised three prospective scenarios. In the optimistic scenario, I am going to use estimates for storage a high-capacity onshore deep saline aquifer as reported in (Table 3), which is 3 EUR/t of carbon-dioxide (Zero Emissions Platform, 2019, pg. 25). This is a reasonable assumption, given that just the Szolnok formation has a potential capacity of 1000 Mt (Falus and Szamosfalvi, 2016, pg. 166). For the average scenario, I am going to use the number reported by Falus (2024) for a Hungarian storage project in a deep saline aquifer. For the high-cost scenario, I am going to use estimates for a low-capacity depleted oil and gas field, but I am going to allow for the use of legacy wells. The per tonne cost of this is 10.4 EUR per tonne of CO₂, as reported by (Table 3). It is also reasonable to penalize depleted hydrocarbon fields and use estimates for a low-capacity reservoir, as in Hungary the size of these reservoirs is between 3 and 20 Mt of CO₂ (Falus and Szamosfalvi, 2016, pg. 166). This is considerably lower than the 40 Mt estimate used for low-capacity formations in the ZEP study, which may mean that we are already overestimating size-related cost reductions (Zero Emissions Platform, 2019, pg. 25). Although I discussed calculations related to CO₂ capture and storage, for this process to happen, CO₂ must be compressed and transported between these locations. For transport, I used the lower bound, average, and upper bound values of 15, 21, and 28 Euros respectively (Kearns, Liu, and Consoli, 2021, pg. 38). The transport of CO₂ is a bit more complicated, as it varies according to pipeline length and experiences a phenomenon of economies of scale. According to the White Book on CCUS in Hungary, the scenario envisioning 2.5 MTPA capacity, with a length of 180 km best represents Hungarian conditions (Farkas Csamangó et al., 2023, pg. 145). I am going to treat the capacity as constant and then adjust costs based on length linearly. I am going to use the estimates reported (and then modified by the author) by Zero Emissions Platform (2011) as the average scenario estimate. The study uses a confidence interval of $\pm 30\%$, so I am going to multiply optimistic scenario transport estimates by 0.7 and pessimistic scenario estimates by 1.3 (Zero Emissions Platform, 2011, pg. 6). As the estimates assumed no river crossings, flat topography and unobstructed right of way, there must be some effort made to address less than ideal conditions. The extra costs from crossing the Danube must also be accounted for. As a

result, I multiplied transportation expenses by 1.25 if no crossing of the Danube had to be made, while in case there was, the multiplying factor was 1.5. Although these do not reflect actual economic estimations, they are nevertheless a reasonable try to account for the cost differences caused by such obstacles. Besides that, since transportation makes up only a small part of total costs, this should not cause huge issues in the calculations.

I also must find a way to account for the cost of feeder pipelines. Although these are generally shorter but also transport much lower volumes, which in the case of a technology benefiting immensely from economies of scale, could increase expenses significantly (Zero Emissions Platform, 2011). We learned from (Table 2) that a 4-fold decrease in capacity multiplies per MTPA costs by 2.7. Also, a 2-fold- decrease in capacity from 10 Mt per annum increases costs by a factor of 1.6. As a result, I will use the following strategy: if the amount of CO₂ transported through a feeder or trunkline is at least 50% less than 2.5 MPTA, I will multiply transportation expenses for said section of the pipeline by 1.6. If the amount transported is at least 75% less, I will multiply expenses by a factor of 2.7. This underestimates expenses and may not be reliable given that 90% of expenses in case of a pipeline are CAPEX (Zero Emissions Platform, 2011, pg, 7). Also, this does not factor in the price of potentially not having the entire capacity of the pipeline used. Nevertheless, since feeder pipelines constitute only a small part of the entire cost, this will be sufficient to provide answers about the viability of CCS projects on a macro scale.

The possibility of enhanced oil recovery will not be modelled, as under European regulation, no carbon credits are awarded for the activity (Falus, 2024).

Dunaújváros Cluster					
Facility	Capturable Emissions (Mt of CO2)	Relevant Cost Category	Optimistic	Average	Pessimistic
Dunai Vasmű Nagyolvasztómű és Konverteres Acélmű	0.37	Iron and Steel	90	117	145
Dunai Vasmű Zsugorítómű	0.15	Iron and Steel	90	117	145
Dunai Vasmű Kokszoló	0.06	Iron and Steel	90	117	145
Dunai Vasmű Meleghengermű	0.06	Iron and Steel	90	117	145
ISD POWER Erőmű	0.62	Energy: Gas	106	147	189
Hamburger Hungária Kft. vegyes tüzelésű erőmű	0.24	Energy: Gas	106	147	189
Dunacell Dunaújvárosi Cellulózgyár Kft.	0.01	Pulp and Paper Industry	82	94	108
DUNAFIN Papírgyár	0.00	Pulp and Paper Industry	82	94	108
MOL Dunai Finomító	1.36	Refinery and Petrochemicals	72	102	133
Dunamenti Erőmű	0.41	Energy: Gas	110	153	197
Pannonia Bio	0.08	Bioethanol	25	43	63
Nitrogénművek	0.42	Fertilizer	31	50	73
Baranya Cement Cluster					
Facility	Capturable Emissions (Mt of CO2)	Relevant Cost Category	Optimistic	Average	Pessimistic
Királyegyházi Cementgyár	0.40	Cement	77	99	131
Duna-Dráva Cement Kft. Beremendi Cementgyár	0.34	Cement	81	104	137
Carmeuse Hungária Kft. Beremendi Mészüzem	0.05	Lime	89	115	150
MVM Visonta Power Plant					

Facility	Capturable Emissions (Mt of CO2)	Relevant Cost Category	Optimistic	Average	Pessimistic
MVM Visontai Erőmű	3.11	Energy: Coal	82	103	129
Budapest-Vác Cluster					
Facility	Capturable Emissions (Mt of CO2)	Relevant Cost Category	Optimistic	Average	Pessimistic
Alpiq Csepel II. Erőmű	0.53	Power: Gas	103	143	187
BERT Rt. Kelenföldi Komb.Cikl. Gázt.Hoszolg. Eromu	0.23	Power: Gas	103	143	187
BERT Rt. Újpesti Komb. Cikl. Gázt. Hoszolg. Eromu	0.22	Power: Gas	103	143	187
BERT Rt. Kispesti Komb. Cikl. Gázt. Hoszolg. Eromu	0.19	Power: Gas	103	143	187
Észak-Budai Fűtőerőmű	0.10	Power: Gas	103	143	187
Váci Cementgyár	0.36	Cement	79	101	129
Borsod Cluster					
Facility	Capturable Emissions (Mt of CO2)	Relevant Cost Category	Optimistic	Average	Pessimistic
TVK	0.00	Refinery and Petrochemicals	69	97	126
BorsodChem Zrt.	0.00	Refinery and Petrochemicals	73	103	133
ÓAM Ózdi Acélművek Kft.	3.11	Iron and Steel	93	122	151
BC-Erőmű Kft.	0.0000005	Energy: Gas	108	150	192
TVK-Erőmű Kft.	0.0000002	Energy: Gas	104	144	185
BC kazántelep	0.0000002	Energy: Gas	108	150	192

Table 22, Table 23, Per tonne of CO2 cost calculations for different Hungarian installations, Source: Own-making, based on: European Commission, 2024; Kearns, Liu, and Consoli, 2021, pg. 29; Farkas

As we can see, virtually no industrial or energy generation process could use CCS under the average 2023 EU ETS price of 86.17 EUR if looking at the average cost scenario (Statista, 2024). When taking into account calculations for the optimistic scenario, refinery and petrochemicals, pulp and paper, cement manufacturing, and even CCS in the Visonta coal power plant becomes viable. We can also see that carbon capture in gas-fired power plants is so expensive that it is unlikely to be utilized, even by 2030. When looking at the whole picture, we see that CCS on a large scale could only become a reality by or after 2030 when carbon prices could reach between 130 and 160 EUR (Pahle et al., 2022, pg. 2). This corresponds to the expectations of the National Clean Development Strategy (Innovációs és Technológiai Minisztérium, 2021). It also echoes the comments made by Falus (2024), that carbon dioxide capture and storage in Hungary will be on a limited scale, and government support will be essential given the risks and costs of CCS projects. We have to take into account the high confidence intervals of our estimates: firms will not just jump at the opportunity if the EU ETS price reaches the necessary threshold, but instead wait until the technology is proven and estimates can be relied upon. We also have to keep in mind that these are just prices per tonne of CO₂ captured, and per tonne of CO₂ avoided costs can be as much as 37% higher (Rubin, Davison and Herzog, 2015, pg. 382). Firms will have to use the price per tonne of CO₂ avoided, as avoided CO₂ emissions will be the one based on which they could save on having to purchase expensive carbon credits.

VIII. Discussion

VIII.1. Risks of CO₂ storage in Hungary

The biggest risk present in geological storage is CO₂ leakage, which can migrate back to the surface via wells, the caprock, or through geological faults or fractures (Li and Liu, 2016). Generally, it is expected that the greatest chance of leakage presents during injection, and after it stops, risks are significantly reduced, though do not reach zero (Li and Liu, 2016). It can pose serious dangers and pollute underground freshwater bodies (Little and Jackson, 2010). In

addition, the injection of CO₂ into rock formation may possibly cause earthquakes (White and Foxal, 2016).

Deep saline aquifers have much better safety profiles, as here only sealing capacity needs to be proven, while in the case of depleted oil and gas fields, we have to worry about CO₂ leakage through legacy wells (Falus, 2024).

In Hungary, the Szolnok formation provides the safest opportunity for CO₂ storage. The Újfalú formation is not situated deep enough and is situated close to underground freshwater bodies (Király, 2024). Depleted oil and gas reservoirs are in poor condition in Hungary, as in the past focus was on oil production through drilling as many extraction wells as possible, not respecting reservoir integrity (Falus, 2024). One issue with aquifers is that they can store only limited amounts of CO₂ in mineral form following a chemical reaction, meaning that the majority will be stored in a physical form, limiting drilling in the region for centuries (Sendula, 2024).

VIII.2. Public perception

As for any large-scale project which requires government support, public perception will be crucial for large scale adoption of CCS technologies (Selma et al., 2014). It is also very hard to measure current public perception about CCS technologies, as the technology is not known or adopted on a wide scale, so responses depend highly on how information is presented to respondents (Selma et al., 2014). A series of other factors can also affect public perception of CCS as reported by Braun (2017). He found that in Germany areas with coal mining report lower acceptance of CCS technologies, and so do areas with potential CCS sites (Braun, 2017). What is also interesting, is that increased knowledge of the technology decreases rather than increases public perception of it (Braun, 2017). As carbon capture and storage has mainly global benefits (in the form of reduced carbon in the atmosphere) and local risks (carbon leakage), such projects may face strong local opposition, as residents value safety in their areas more than their contribution to fighting global carbon emissions (Braun, 2017). In 2023, Navigator, a company that planned on building 1300 miles of pipelines connecting corn ethanol producers was forced to scrap the project over opposition from local property owners and environmentalists, highlighting the need for improved perception for implementation (Smyth, 2023). Upham and Roberts (2013) show across pan-European focus groups, that negative perceptions about the technology can arise from an intent of environmental protection: people view CCS as a means of fossil fuel preservation. As we can see, if we want CCS to play a strong part in Hungary's climate strategy, we must find a way to convince the public that the

technology benefits outweigh its risks. One would say that the public will accept the technology once it learns about it, but such thinking is contradicted by Braun's (2017) findings. On the other hand, Wallquist et al. (2011) conclude that it is true only for a certain type of information: if respondents were given information about the role of reservoir pressure, perceived benefits of the technology decreased while perceived risks increased. For all other type of information, such as the liquid state of CO₂ in the reservoir or CCS as a technology in a broader portfolio of measures taken to combat climate change (such as being used in combination with renewables), the examined effect was exactly the opposite. Whitmarsh, Xenias, and Jones (2019) conclude that since it is a new technology, framing will be key in influencing public opinion. Communication about CCS must be tailored to audience values, and highlighting the connection between CCS and CCU improves perceptions. Costs are one of the biggest obstacles facing public acceptance, so appropriate communication about them is essential. The researchers conclude that communicating these costs as low will potentially backfire, and instead they should be in the context of the complete energy system transformation or should even be compared to the cost of not mitigating climate change.

VIII.3. Limitations of the Research

It is not hard to see that the methods used have several limitations. First such limitation is the use of aggregation of steel and iron manufacturing, refinery and petrochemicals, and cement categories. Similarly, the assumption to use natural gas combined cycle (NGCC) plants for all gas and mixed power plants and to use critical pulverized coal plants (SCPC) for all coal power-plants can also be brought into question. My choice to use a 90% capture rate can also be brought into question, as another Hungarian study only uses an 85% capture rate for energy generation in gas power plants, heat generation, and ammonia generation, and only a 50% capture rate for other processes (Farkas Csamangó et al., 2023, pg. 122). It is also not perfect to use 2022 emissions as the baseline for my calculations, as several facilities experienced emission reductions by 2023. Nevertheless, it was the last year for which data was available for most facilities, and it seemed like a reasonable assumption to use. Also, in my calculations I used the price of CO₂ captured as opposed to the price of CO₂ avoided. This could be considered as underestimating costs, as capture costs will always be lower than avoidance costs, due to the emissions caused by the energy required to operate carbon sequestration equipment (Rubin, 2012). According to some estimates, using price per CO₂ avoided instead of per CO₂ could mean an increase of per tonne of CO₂ costs from 46 to 63 USD, or a 37% increase in SCPC plants (Rubin, Davison and Herzog, 2015, pg. 382). On the other hand, economies of

scale resulting from higher amount of captured emissions at a specific source were not modelled, which might take real prices to the opposite direction (Kearns, Liu, and Consoli, 2021). Although the limitations of the research are clear, its mission is not to provide the exact answer, but rather to use a range of methods (literature review, expert interviews, cost analysis) to gain an understanding about the potential of carbon capture and storage in Hungary.

IX. Conclusions

As confirmed by the relevant experts, carbon dioxide capture and storage in Hungary is technically feasible, and associated risks can be handled. On the other hand, based on the cost estimations performed in (Table 22), most industries cannot use CCS profitably under the current EU ETS price (Statista, 2024). The technology is only expected to become economically viable by or after 2030, primarily driven by a better understanding of associated financial risks and the increase in the price of carbon permits (Pahle et al., 2022). Regarding CO₂ storage, deep saline aquifers were determined as the cheaper and safer option. Nevertheless, it may also be possible that carbon storage will first start in depleted oil and gas fields, due to the advantage in the amount of data available, and since the cost benefits of aquifers only materialize at high quantities of stored CO₂. I also concluded that the roll-out of the technology is further hampered by the large confidence intervals surrounding CO₂ calculations, making manufacturers think twice about investing in CCS infrastructure. As mentioned by Falus (2024), government support will be necessary, and high carbon prices alone will not be enough for the first firms to embrace this possibility. Public acceptance will be vital, as the lack of it can easily derail similar projects (Selma et al., 2014). We will have to devise plans about how to implement information and communications campaigns about the technology, even possibly including the technology in school curriculum (Gál, 2024). We also have to think about what we communicate about carbon storage, as feeding the wrong type of information can cause respondents to be less accepting (Wallquist et al. 2011). Creating CCS clusters will be a high priority, since carbon dioxide transport benefits immensely from the economies of scale phenomenon (Zero Emissions Platform, 2011). I devised a model of CCS clusters in Hungary, where the technology could be best used economically, with many large emitters located in close proximity. Out of these, the Dunaújváros cluster seemed the most promising, due to the large amount of emissions and the presence of industrial processes that could be decarbonized at a low cost (fertilizers and bioethanol). Research will also have to be carried out in Hungary, primarily targeted at understanding CO₂ storage in the Transdanubia region, and also regarding pipeline transport

across the Danube (Király, 2024). Nevertheless, according to my assessment the future is bleak for CCS technologies, as the already high prices only reflect CO₂ captured as opposed to CO₂ avoided, with the latter being always higher (Rubin, 2012). Also, CO₂ avoided is the measure that can better be compared to the EU ETS price (Rubin, 2012). Probably the process will be used exclusively in hard-to-decarbonize sectors if we want to reach net carbon neutrality by 2050, as stated under the National Clean Development Strategy (Innovációs és Technológiai Minisztérium, 2021). Probably, it will still only happen if there is no other possibility to decarbonize a given sector, and its products are necessary to maintain the quality of life desired by the population.

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XI. Appendix

I. Interview questions

1. What are the main formations where CO₂ storage can happen in Hungary?
 - a. Which are located in the Transdanubia region?
2. How are the costs of storage in different formations related to each other?
3. What are the main risks of CO₂ storage in Hungary?
4. Is large-scale CO₂ storage in Hungary realistic in the near-to-mid future?
5. Could you name any cost per tonne based estimates for CO₂ storage in Hungary?
6. Will storage on a large scale take place In Hungary?
7. Is the market-based carbon price enough, or will government support be necessary?
8. Is transport across a large river like the Danube feasible?