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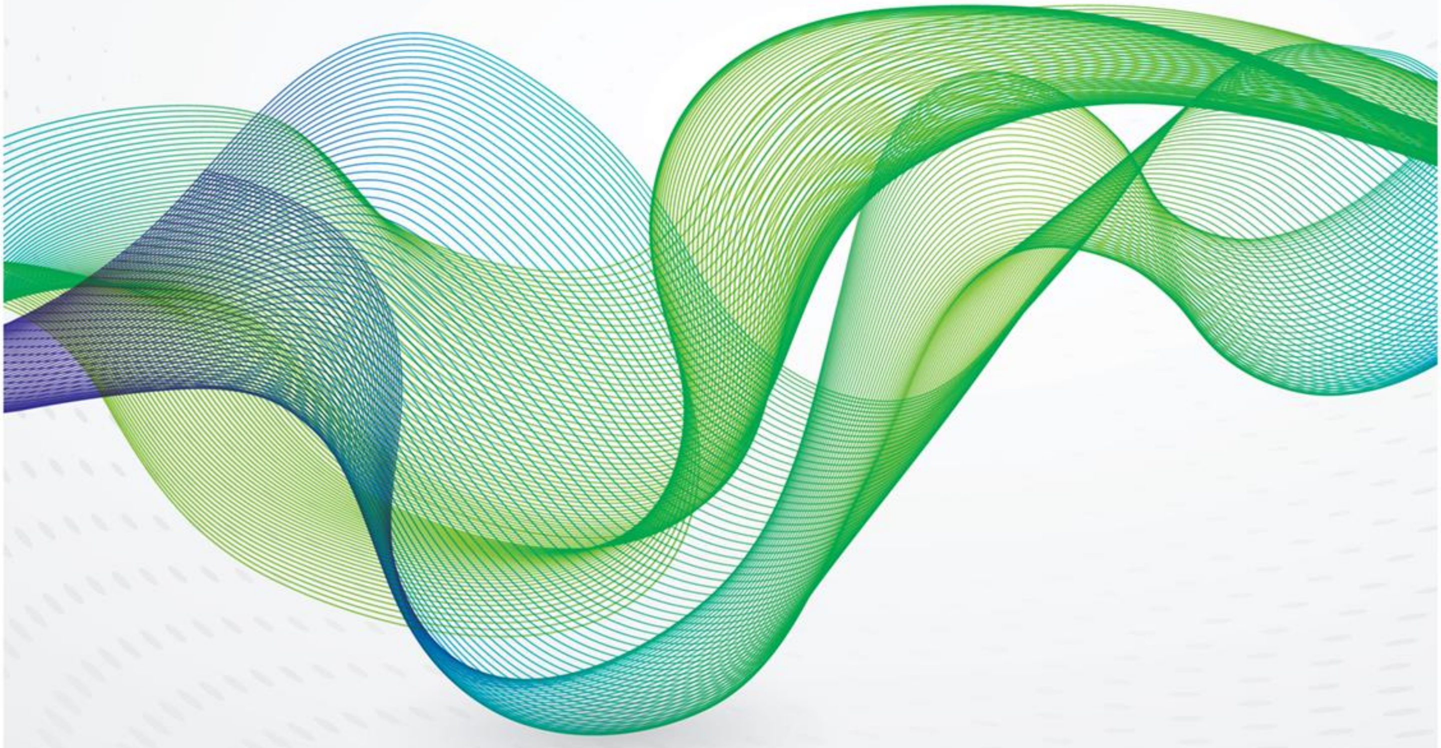
Hydrogen pipelines vs. HVDC lines: Should we transfer green molecules or electrons?



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Abstract

As the world races to decarbonize its energy systems, the choice between transmitting green energy as electrons through high-voltage direct current (HVDC) lines or as molecules via hydrogen pipelines emerges as a critical decision. This paper considers this pivotal choice and compares the techno-economic characteristics of these two transmission technologies.

Hydrogen pipelines offer the advantage of transporting larger energy volumes, but existing projects are dwarfed by the vast networks of HVDC transmission lines. Advocates for hydrogen pipelines see potential in expanding these networks, capitalizing on hydrogen's physical similarities to natural gas and the potential for cost savings. However, hydrogen's unique characteristics, such as its small molecular size and compression requirements, present construction challenges. On the other hand, HVDC lines, while less voluminous, excel in efficiently transmitting green electrons over long distances. They already form an extensive global network, and their efficiency makes them suitable for various applications. Yet, intermittent renewable energy sources pose challenges for both hydrogen and electricity systems, necessitating solutions like storage and blending.

Considering these technologies as standalone competitors belies their complementary nature. In the emerging energy landscape, they will be integral components of a complex system. Decisions on which technology to prioritize depend on factors such as existing infrastructure, adaptability, risk assessment, and social acceptance. Furthermore, while both HVDC lines and hydrogen pipelines are expected to proliferate, other factors such as market maturity of the relevant energy vector, government policies, and regulatory frameworks around grid development and utilization are also expected to play a crucial role. Energy transition is a multifaceted challenge, and accommodating both green molecules and electrons in our energy infrastructure may be the key to a sustainable future. This paper's insights underline the importance of adopting a holistic perspective and recognising the unique strengths of each technology in shaping a resilient and sustainable energy ecosystem.

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Introduction

The energy sector is presently undergoing a transition from traditional fossil fuels towards more sustainable sources, with the goal of achieving ultimate decarbonization. While renewable electricity has long been considered a key component of a net-zero carbon future (National Grid ESO, 2022), it is unlikely to serve as the exclusive solution for powering our economies in the coming decades (Schellenberger, 2022). Despite its evident advantages in producing power without carbon emissions, popular forms of renewable energy generation, such as solar and wind farms, exhibit significant limitations. Notably, they are subject to geographical constraints and spatial challenges, restricting their universal applicability, and they do not consistently generate stable energy output (Patonia and Poudineh, 2020). Consequently, the future energy system, where renewable energy sources are envisioned to dominate, will require a complementary mix of energy sources to address intermittency issues.

Presently, during periods when weather conditions are unfavourable for adequate renewable energy generation to meet demand, renewables are frequently supplemented by fossil fuels, such as natural gas and coal. Paradoxically, this occurs even as we strive for a net-zero carbon paradigm (Bloomberg, 2022). Conversely, when renewable energy sources produce surplus power that cannot be stored or utilized, they are often curtailed, leading to the wasteful dissipation of energy (McDermott, 2023). In light of these challenges, the concept of converting renewable power into carbon-neutral hydrogen (H_2) through power-to-X processes has gained substantial traction. 'Green' hydrogen,[1] in principle, offers the potential not only to integrate renewable energy sources and balance the grid but also to serve as a versatile product and feedstock for decarbonizing hard-to-abate sectors that are unlikely to transition fully to electrification, such as the chemical or steel industries (Yang et al., 2022).

The growing awareness of environmental degradation and climate change has led to a concurrent expansion of green hydrogen and renewable energy generation initiatives across the globe (Globe Newswire, 2023). However, a common challenge emerges: many renewable generation facilities, capable of producing both green electrons and molecules, are located far from the points where zero-carbon energy is ultimately consumed. Consequently, the efficient delivery of both green electrons and molecules to their intended consumers is pivotal in advancing our transition towards a net-zero carbon future.

While green electrons can technically be transferred directly to users via transmission lines, delivering electricity over long distances, such as interstates or oceans, typically results in significant energy losses and reduced efficiency, resulting in higher costs (Pillay, Kabeya, and Davidson, 2020). To mitigate power loss during electricity transmission, transmission voltages are often increased, reducing line currents (ibid). High-voltage alternating current (HVAC) transmission systems, which span approximately 4.7 million kilometres (km) worldwide, are the prevalent method for long-distance electricity transmission (Kalt, Thunshirn, and Haberi, 2021). However, HVAC lines have inherent drawbacks that hinder their efficiency in transporting green electrons over extended distances. This is where high-voltage direct current (HVDC) transmission lines can play a transformative role.

In general, HVDC lines are expected to be more efficient in transmitting electricity over longer distances compared to HVAC lines (Reed et al., 2019). This advantage stems from the lower capacitive losses associated with direct current power compared to alternating current power, particularly when conductors are in close proximity to the ground (Cence Power, 2022a). As a result, HVDC lines have gained prominence as the preferred transmission technology for long-distance bulk power supply, both in Europe and worldwide (Power Technology, 2020). Although the combined length of HVDC lines globally remains shorter than that of HVAC alternatives, at slightly over 100,000 km, their number is steadily increasing, with a cumulative capacity exceeding 30 GW (*Figure 1*).

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[1] Green hydrogen could be generally defined as that produced via the electrolysis of water that is powered by renewable electricity generation equipment (European Commission, 2023).

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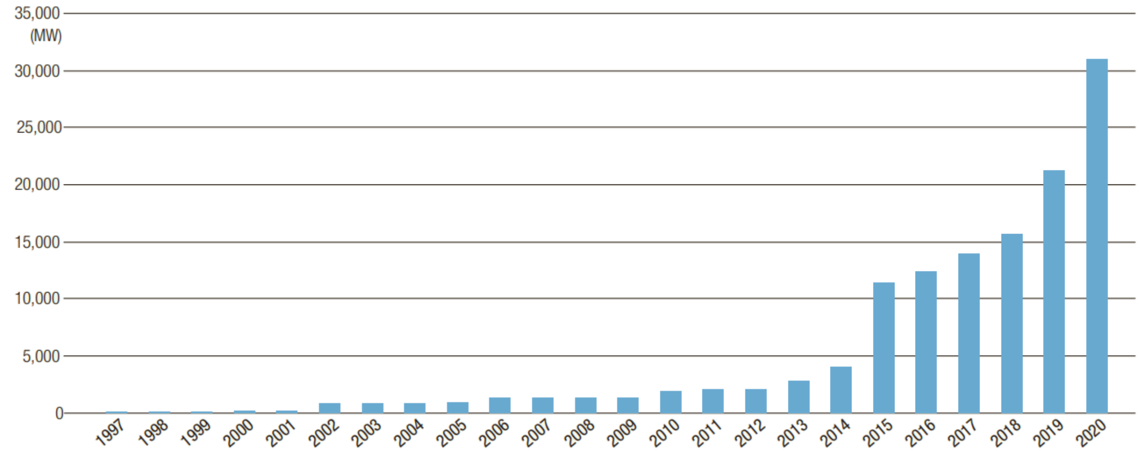
Figure 1: Cumulative new capacity of VSC2 HVDC in the world as of 2020



Source: Adapted from Nishioka, Alvarez, and Omori (2020)

Similarly, when green electrons are converted into green molecules, several options exist for their delivery to end consumers. Zero-carbon hydrogen and its derivatives can be transported in tanks by marine vessels or on land via rail or road (Patonia and Poudineh, 2022b and US Department of Energy, 2022). Furthermore, due to hydrogen's gaseous nature under ambient conditions, its transfer over extended distances through pipelines, akin to natural gas transport, has garnered considerable attention. While the total length of operational hydrogen pipelines worldwide currently stands at approximately 4,500 kilometres,[3] primarily located in Europe and North America, an estimated 30,300 kilometres of pipelines across 91 planned regional hydrogen pipeline initiatives are projected by around 2035 (Shell, 2022 and Rystad Energy, 2023).

The rationale underpinning this enthusiasm stems from the economic advantages of pipelines, which are typically the most cost-effective means to transport large quantities of gases such as methane over land. Pipelines offer lower cost per unit and higher capacity compared to other terrestrial transportation options (Bolonkin, 2009). Further cost reductions are expected through the repurposing of existing natural gas pipelines for hydrogen transport, which is estimated to account for only 10-35 percent of new construction expenses (DNV, 2022). Consequently, a combination of repurposed natural gas infrastructure and newly dedicated hydrogen pipelines is envisioned to evolve into an extensive hydrogen network, as exemplified by the 'European Hydrogen Backbone' in Europe (*Figure 2*).

While these ambitious initiatives have garnered substantial political support in leading economies[4] worldwide, their realization remains uncertain.[5] Additionally, questions persist about the range of applications where green molecules can economically substitute green electrons within the global net-zero landscape. In this context, this paper conducts a comparative analysis of key techno-economic characteristics between green hydrogen pipelines and HVDC lines for transferring green energy. It aims to elucidate the primary advantages, disadvantages, and conditions favouring one option over the other.

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[2] VSC (voltage source converters) are self-commutated converters to connect HVAC and HVDC systems using devices suitable for high power electronic applications (ENTSO-E, 2023)

[3] By comparison, the estimated combined length of all the major oil and gas trunk pipelines in the world is around 2.15 million km (Global Data, 2023)

[4] For instance, Germany and Belgium are planning to link their respective hydrogen pipeline networks by 2028 (Hydrogen Insight, 2023)

[5] For example, for a long period of time, planning to mostly rely on its own nuclear-derived 'pink' hydrogen production as well as LNG infrastructure, France deemed unnecessary the construction of a new hydrogen-ready gas pipeline connecting Spain to northern Europe (Clean Energy Wire, 2023)

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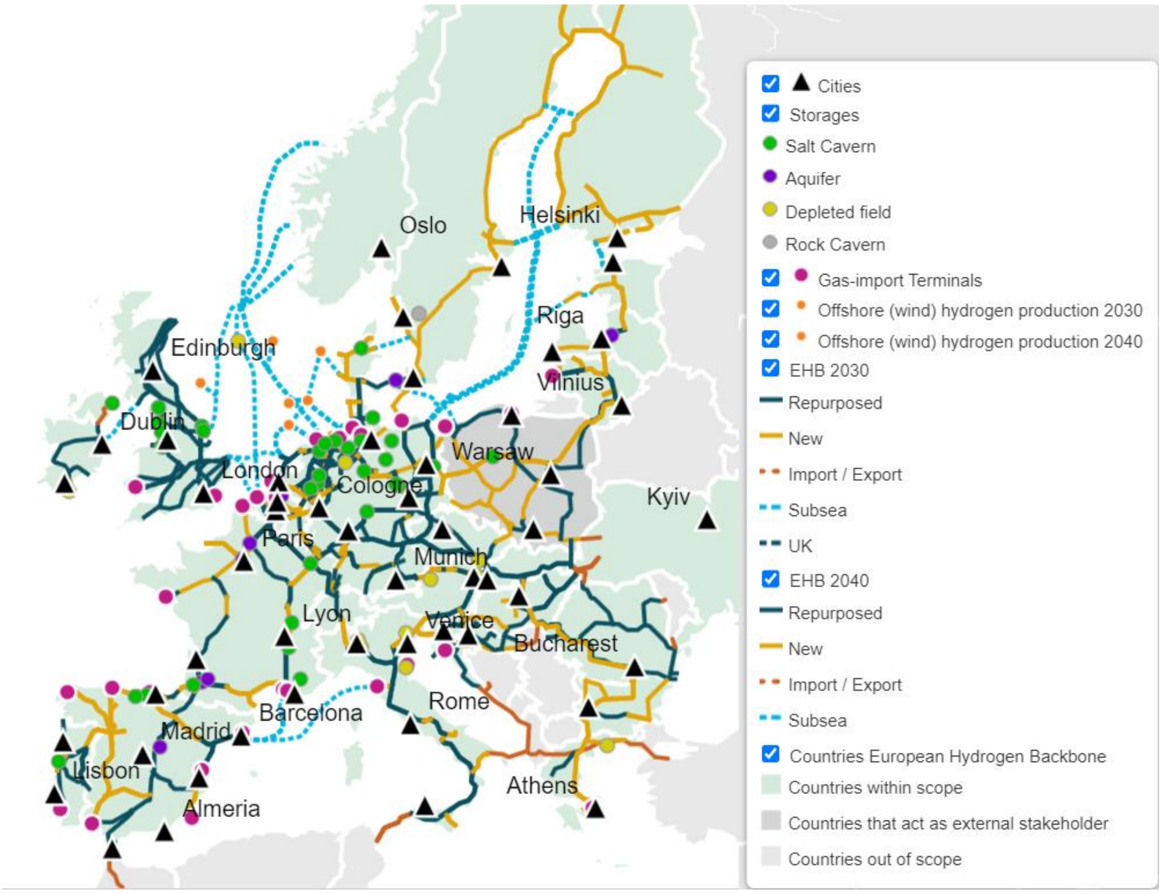
Figure 2: European hydrogen network expected by 2040



Source: Adapted from the European Hydrogen Backbone (2023)

The outline of the paper is as follows. The first part of Section 1 provides a comparison of the key technological aspects of hydrogen pipelines and HVDC lines. The second part of Section 1 then discusses the main costs and economic consideration associated with each of these options. Section 2, in turn, reviews what system-wide impacts, risks, challenges, and factors should be taken into account when considering their development. The final section provides concluding remarks.

1. Techno-economic characteristics of green energy transfer: HVDC lines vs. hydrogen pipelines

1.1 Technological aspects

HVDC lines

HVDC lines are not new in the delivery of energy across space. The first demonstration project transmitting electric power through direct current (DC) over long distance (57 km) was launched in Germany in 1882 (Guarnieri, 2013).However, despite having been known to industry for over a century, this type of energy transmission failed to gain global dominance. Instead, alternating current (AC) is used by most power transmission and distribution systems at the moment (Cence Power, 2022b). The vast majority of power plants generate AC and not DC[6] as the former generally allows for

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[6] In general, most power stations that use rotating devices (e.g. hydropower plants and thermal power plants) generate alternating current, whereas power stations with static components (e.g. solar power plants) generate direct current (Mondal,

increases and decreases in voltage and the ability to isolate an electrical load from the supply is easier than with DC, which makes it more ‘suitable’ for use in populated areas (ibid). In addition, it appears to be inherently safer to switch AC electricity on and off (ibid).

At the same time, HVDC lines have their own advantages, which the HVAC alternatives cannot match. This is particularly relevant to the delivery of large volumes of energy across space, since HVDC power lines can transport more power over greater distances with lower losses. Specifically, at distances exceeding 600-800 km on land, 50-95 km underground and 24-50 km underwater, HVDC lines are normally expected to be more efficient than HVAC lines (Reed et al, 2019). This is mostly because, unlike AC, DC is purely active power, which means that there are no reactive power losses[7] and it travels further than power with reactive components (Cence Power, 2022a).

In addition, because DC electricity has no frequency, the corona discharge[8] and the skin effect[9] do not affect it in the same way as they affect AC conductors, which ultimately lose almost three times more energy because of that effect (ibid). In order to mitigate the first problem, AC transmission lines use bundled conductors to increase their diameter, which reduces the corona effect (Omeje, 2020). Because HVDC lines do not face this challenge, fewer cables are needed in their case – DC transmission only requires 1-2 conductors per circuit, whereas the AC one needs a 3 phase circuit, which significantly reduces the cost of cabling HVDC lines (Daware, 2021). The skin effect of AC power, in turn, is normally addressed through increasing the thickness of each of the cables used so that they can transmit the required (effective) amount of power (Cence Power, 2022a). Since this problem does not apply to DC power, DC conductors can be thinner and thus use less conductive material such as copper (ibid).

Given the mentioned advantages of the DC transmission system for the delivery of large volumes of power over long distances, the number of HVDC projects in the world is estimated to grow further in the future. While an average HVDC line at the moment carries around 3-5 GW across some 500-1,500 km, the Changji-Guquan ultra-high-voltage direct current transmission line in China, the largest HVDC system built so far, is able to deliver 12 GW of power over a distance of 3,324 km (*Table 1*) (NS Energy, 2022). This, however, does not seem to be the limit, as more ambitious projects in the future are expected to surpass these numbers both in terms of length and transfer capacity, since they are often viewed as one of the best means of interconnection of different power grids with varying voltage and frequencies, which appears to be suitable for the integration of renewables.

On the other hand, despite the clear advantages that HVDC lines can bring, they also have their drawbacks. In particular, apart from the concerns of fire and shock hazards associated with equipment malfunctioning, land use and habitat disruption coupled with the visual impact on the landscape are often viewed as some of the key challenges of such projects (Wang, Li, and Guo, 2022). While each of these problems is likely to be common for HVAC transmission systems as well, one of the major factors discouraging investment in HVDC is the high cost of such initiatives (Acaroglu and Marquez, 2022). In fact, since each project is tailored to specific conditions and designed for individual requirements, whether it is for connecting intermittent renewables or long-distance delivery of power, converter stations and complex control systems that ensure stable and

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Chakrabarti, and Sengupta, 2020). With the exception of smaller-scale or specialised applications, most wind turbines also produce AC, which can then be converted to DC and back with a rectifier (Action Renewables, 2019)

[7] Reactive power is the quantity of unusable power that is developed by the reactive components that are present in AC systems due to the alternating behaviour of AC electricity (Cence Power, 2022a)

[8] The corona discharge is a term used to describe a phenomenon taking place when voltage increases above a certain threshold, and the air surrounding the conductor starts ionizing and generates sparks, which waste energy (Thierry, 2023)

[9] The skin effect is broadly defined as the tendency of AC current to distribute unevenly over the cross-section of a conductor so that the current density is highest near the surface of the ‘skin’ of the conductor and decreases exponentially towards the core (Kosak, Truhlar, and Richter, 2012). This means that the inner part of the conductor would then carry less current that the outer part, which would result in increased effective resistance (ibid)

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efficient operation are built individually for each HVDC line and thus are very expensive (Alam, Rahaman, and Dhali, 2022).

Table 1: Some key characteristics of HVDC lines and hydrogen pipelines

Characteristics		**HVDC lines**	**Hydrogen pipelines**[10]
Energy transfer capacity per project (GW)	***Current maximum***	~12	20-30
	Current average	3-5	<13.5
	Expected by 2030	>12	<40[11]
Length per project (km)	***Current maximum***	3,324	~1,000
	Current average	500-1,500	50-100
	Expected by 2030	>3,500	>1,000
Efficiency/energy losses per 1,000 km (%)		~3	~1
Longevity (years)		25-40	15-50
Flexibility		• Bi-directional power flow facilitates integration of intermittent renewables • Enable interconnection of different power grids with varying voltage and frequencies	• Can be used for storage and offer some flexibility for intermittent power sources • Can partially be integrated into natural gas system
Potential safety risks		• Electrical shock hazard • Fire and explosion risks due to generated heat • Malfunction of equipment causing either/both of the above	• Hydrogen embrittlement causing leaks and dispersion • Potential mismanagement of pressure • Fire and explosion risks due to high flammability and fast mixture with air
Potential environmental impact		• Land use and potential habitat disruption • Potential negative effects of electromagnetic fields on humans and animals • Equipment failure and system faults damaging flora and fauna (e.g. release of insulating fluids) • Visual impact on the landscape	• Land use and potential habitat disruption • Potential asphyxiation hazard in case of hydrogen leaks and oxygen displacement • Pipeline corrosion/ embrittlement and resulting risks and challenges • Visual impact on the landscape
Capital and operating costs		• High capital costs (terminal converter stations tailor-made and very expensive) • Relatively low operating costs	• High capital costs that can potentially be reduced (e.g. through conversion of natural gas pipelines) • High operating costs

Source: Adapted from Weimers (2011), Air Products (2012), Danish Energy Agency (2017), ABB (2018), Guidehouse Insights (2018), European Files (2020), S&P Global (2020), European Parliament (2021), Li et al (2021), Energy Futures Initiative (2022), Energy Post (2022), Global Data (2022), Hitachi (2022), NS Energy (2022), World Pipelines (2022), Gas Infrastructure Europe (2023), Hydrogen Insight (2023), NKT (2023)

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[10] These estimates do not consider the conversion of natural gas pipelines for the transport of hydrogen, which is likely to ultimately significantly increase these capacities while simultaneously reducing costs

[11] Although, just like in the case of HVDC lines, the maximum transfer capacity of the largest future hydrogen pipelines is hard to predict, this number signifies the maximum expected capacity of some of the largest announced projects (both repurposed natural gas projects and new H_2 pipelines)

In addition, while HVDC lines work well for point-to-point connection, integrating them into networks with multiple branches may pose significant barriers (Sass et al, 2018). This is primarily due to technical constraints and limitations associated with synchronization, overlays, communication, complex subsystem interactions and other challenges (ibid).

Hydrogen pipelines

Similarly, hydrogen pipelines do not represent a completely new technology for delivering H_2 molecules over distances. In fact, one of the first such systems was built in 1938, was later expanded and is still operating in the Rhine-Ruhr area of Germany to connect 25 chemical and petrochemical plants across a total combined distance of 875 km (Kirkwood and Williamson, 2022). In this context, as is common in most operational hydrogen pipelines, the choice of pipelines over alternative methods like road transport in tanks is primarily driven by economic considerations. This preference stems from the pipeline's ability to provide a reliable and consistent supply of substantial hydrogen volumes to the intended consumption point (ibid). However, while these economic criteria also hold true for natural gas pipelines, it's worth noting that their transmission infrastructure is considerably more extensive than that of hydrogen. Currently, the total length of natural gas pipelines is estimated to be approximately 555 times longer (Global Data, 2023).

One of the key reasons for the limited development and use of H_2 pipelines could be the fact that, at the moment, these pipelines mostly deliver hydrogen from the place of production to the points where it is consumed by specific sectors (such as oil refining or petrochemical industry) (Lee and Lee, 2022). These sectors typically use hydrogen as a feedstock to manufacture more complex products and not as a separate commodity that would have its own independent value and utilization (Air Liquide, 2023). As a result, while an average existing hydrogen pipeline transports around 13.5 GW of energy over a distance of up to 100 km, the largest and longest H_2 projects in operation are capable of delivering 20-30 GW across 500 kilometres (*Table 1*) (Shell, 2022 and Rystad Energy, 2023). In addition, the absolute majority of H_2 delivered by these pipelines (just like the absolute majority of all the globally produced hydrogen) is 'grey' as it is synthesised from fossil fuels (Lee and Lee, 2022). This obviously has to be changed in a net-zero carbon paradigm.

The high cost of construction of H_2 pipelines, which is estimated to be 10-68 per cent higher than that of natural gas pipelines, appears to be another reason why, in the situation when the demand for hydrogen is still not certain, investment in hydrogen delivery infrastructure is not as active as it could have been (Science Daily, 2015). In this context, various stakeholders, including governments, researchers, and energy companies, commonly argue that while the development of new H_2 pipelines is essential for scaling up hydrogen infrastructure to support a thriving H_2 economy, repurposing existing natural gas pipelines for hydrogen transport could expedite this process (Jayanti, 2022). Generally, it is estimated that utilizing existing natural gas grids for hydrogen transportation could be up to four times more cost-effective than constructing entirely new pipelines (Rystad Energy, 2023). However, it is essential to recognize that although this approach is technically feasible and economically viable, the key attributes of pipelines used for hydrogen delivery differ significantly from those designed for natural gas (*Table 2*).

As seen, the characteristics of H_2 itself make designing and operating hydrogen pipelines a more challenging undertaking than running natural gas pipelines. Among many reasons, this is due to the fact that, under ambient conditions, hydrogen has substantially lower volumetric energy density than natural gas (Pipeline Safety Trust, 2015 and Wang et al, 2022).[12] Because of this, at the same pressure, it takes a larger volume of H_2 to provide the same heating value as natural gas and also more energy is needed to pump the same amount of hydrogen as natural gas through a pipeline (ibid). Therefore, in order to make the piped volume economically attractive, hydrogen is normally compressed to 500-1,200 psi (or more), which usually represents higher compression indicators than those used for natural gas (*Table 2*).

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[12] The specific amount of additional energy required depends on several factors, including the hydrogen purity level, pipeline distance, and pipeline pressure

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Table 2: Some key characteristics of hydrogen vs. natural gas pipelines

Indicators		Hydrogen pipelines	Natural gas pipelines
Volumetric energy density of transported fuel under ambient conditions (kg/m^3)		0.09	0.717
Current total length in the world (km)		>5,209	>3,200,000
Maximum diameter of pipes currently used (cm)		20-122	142
Common diameter of pipes used (cm)		20-66	30-122
Typical pressure currently used (psi)[13]		1,000-5,000[14]	200-1,000[15]
Typical thickness of pipes (mm)	***High—pressure pipelines***	10-30	8-20
	Low-pressure pipelines	5-15	3-8
Average energy used for compression from ambient pressure to 500 bar (kWh/kg)[16]		3-10	0.3-0.8
Average spacing between compressor stations (km)		10-100	65-200

Source: Argonne National Laboratory (2008), Penn State Extension (2015), Pipeline Safety Trust (2015), Witkowski et al (2017), Offshore Technology (2018), IEA (2020), ArcelorMittal (2021), Energy Post (2022), Global Data (2022), Marfatia and Li (2022), Wang et al (2022)

In addition, hydrogen molecules are smaller than natural gas molecules (Power Engineers, 2021). That is why hydrogen can not only permeate solid metals potentially causing embrittlement but also leak more easily through pipelines (Bouledroua et al, 2020). To compensate for the latter in properly sealed pipelines, pressurisation of hydrogen to higher pressure levels is needed (Exponent, 2022). This, in turn, requires additional energy to maintain and puts greater demands on the durability and thickness of the pipes, as well as on the quality of the steel, which needs to be higher to safely sustain these conditions (*Table 2*). As a result, investors and operators are likely to incur additional costs.

Finally, the adjustment of natural gas infrastructure to hydrogen will most likely require the substitution of key equipment along the entire length of the repurposed pipelines. In particular, at the moment, most of the natural gas compressor stations operate either screw or reciprocating compressors that use a portion of the piped natural gas as their own fuel (Quincy Compressor, 2021). Although, with some efficiency losses and at smaller flow rates, reciprocating compressors could potentially be utilized for hydrogen as well, centrifugal compressors – a completely different type of compressor that runs on electricity – are more suitable for H_2 and gases at higher flow rates in general (Tahan, 2022). That is why repurposing parts of the natural gas transmission infrastructure for the delivery of hydrogen raises not only economic but also the technical issues of replacing compressors and finding a sustainable power source for their operation.

Nonetheless, these technical challenges, while significant, are unlikely to impede the progress of hydrogen infrastructure development. Ultimately, most of these challenges translate into additional costs, which, in many instances, still render the repurposing and operation of such energy infrastructure economically viable (Monsna, Illson, and Hussain, 2023). This is perhaps the reason

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[13] psi (pound per square inch) is the pressure that results when a 1-pound force is applied to a unit area of 1 square inch (IEEE, 2004). 1 psi is approximately equal to 6,895 pascals (Pa) (ibid)

[14] Existing hydrogen pipelines associated with industrial facilities such as oil refineries and chemical plants operate at pressures around 500-1,200 psi (Pipeline Safety Trust, 2015, Penev, Zuboy, and Hunter, 2019, Wang et al, 2022). However, the suggested pressures for long-distance pipelines used for cross-border hydrogen transport are expected to be 10-75 times higher (ibid)

[15] Natural gas transmission pipelines typically operate at pressures of 200-1,500 psi, which are stepped down further, to 0.25-200 psi, in natural gas distribution pipelines (ibid)

[16] These are general estimates and can vary based on various factors, e.g. the composition of the natural gas, the efficiency of the compression system, and the specific conditions of the compression process

why, in addition to ambitious plans for HVDC systems, many countries are actively considering the extensive expansion of hydrogen pipeline networks. Notably, the European Hydrogen Backbone stands as one of the most ambitious projects, championed by thirty-three energy infrastructure operators (see *Figure 2*) (BloombergNEF, 2023 and European Hydrogen Backbone, 2023).

Key components of the systems and the associated energy losses

As seen, both the delivery of electrons via HVDC lines and molecules via hydrogen pipelines require significant financial commitment. Apart from funding, other non-financial concerns such as safety, environmental impact, and flexibility should be considered when deciding which energy transfer option to prefer. In general, although both alternatives are similar in terms of durability, HVDC lines at the moment can boast longer power transmission reach while hydrogen pipelines can technically transfer more energy (*Table 1*). In this connection, in order to facilitate the development of green energy infrastructure, it would seem reasonable to either extend the length of hydrogen pipelines or construct HVDC lines with greater transmission capacity (or both).

At the same time, the complexity of each of these energy delivery systems significantly differs (*Figure 3*). This complexity is primarily associated with various components of the system which results in energy losses owing to the inefficiencies of each of these components. These inefficiencies and losses, in turn, result in additional costs. Here, although the direct transmission losses normally expected from HVDC lines are likely to be higher (up to 3 per cent per 1,000 km) than those of H_2 pipelines (around 0.5-1 per cent per 1,000 km), the losses associated with the conversion of electrons into molecules seem to be able to significantly reduce the potential attractiveness of the pipeline option[17] (*Table 3*) (Pickard, 2013 and Kanz et al, 2023).

In particular, if renewable power is used to generate green hydrogen that would then be pumped through a pipeline, the conversion of green electrons into green molecules will include several additional stages before the actual process of energy transmission of H_2 takes place. Specifically, if green hydrogen is supposed to be generated at sea by wind energy and then delivered by pipeline (option 'B' in *Figure 3*), a significant amount of energy that could have otherwise been delivered directly via the transmission lines (option 'A' in *Figure 3*) will be lost due to the inefficiencies of the components involved in the power-to-H_2 conversion (*Table 3*). Here, the inefficiencies of electrolysers resulting in 10-32 per cent of maximum losses[18] are likely to be accompanied by 5-15 per cent losses of AC/DC rectifiers and desalination units as well as up to 20-25 per cent of energy further lost by the stand-by battery and compressor (*Figure 3*). Although these losses of around 40.5 per cent or higher (compared to 8-18 per cent in the case of HVDC lines) could then be compensated for by extending the length of the H_2 pipeline so that lower direct energy transmission losses add up to the advantage of this form of energy transfer, determining whether green electrons even need to be converted into molecules seems reasonable. More specifically, a more fundamental question to ask in this respect is:

Do we need to deliver energy (in general) or hydrogen (in particular)?

If we definitely need to deliver hydrogen, then the energy transfer could combine both HVDC transmission with H_2 pipelines (option 'C' in *Figure 3*) and the losses associated with the transformation of electrons into molecules will be incurred at the far end of the delivery system – i.e. closer to the consumption site. In this case, some energy and costs could be saved if there is no need for desalination when green H_2 is produced from the available fresh water. In any case, however, it is clear that converting electrons into molecules will require greater complexity of the system. In this connection, to demonstrate how this complexity transforms into concrete losses, the following exemplary calculation exercise could be used.

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[17] On the other hand, over very long distances, the lower losses per 1,000 km will bring hydrogen pipelines closer to HVDC lines.

[18] Although Hysata claims to have created a capillary-fed electrolyser with 95 per cent efficiency (New Atlas, 2022), the average numbers for most electrolyser technologies are around 68 and 90 per cent (*Table 3*)

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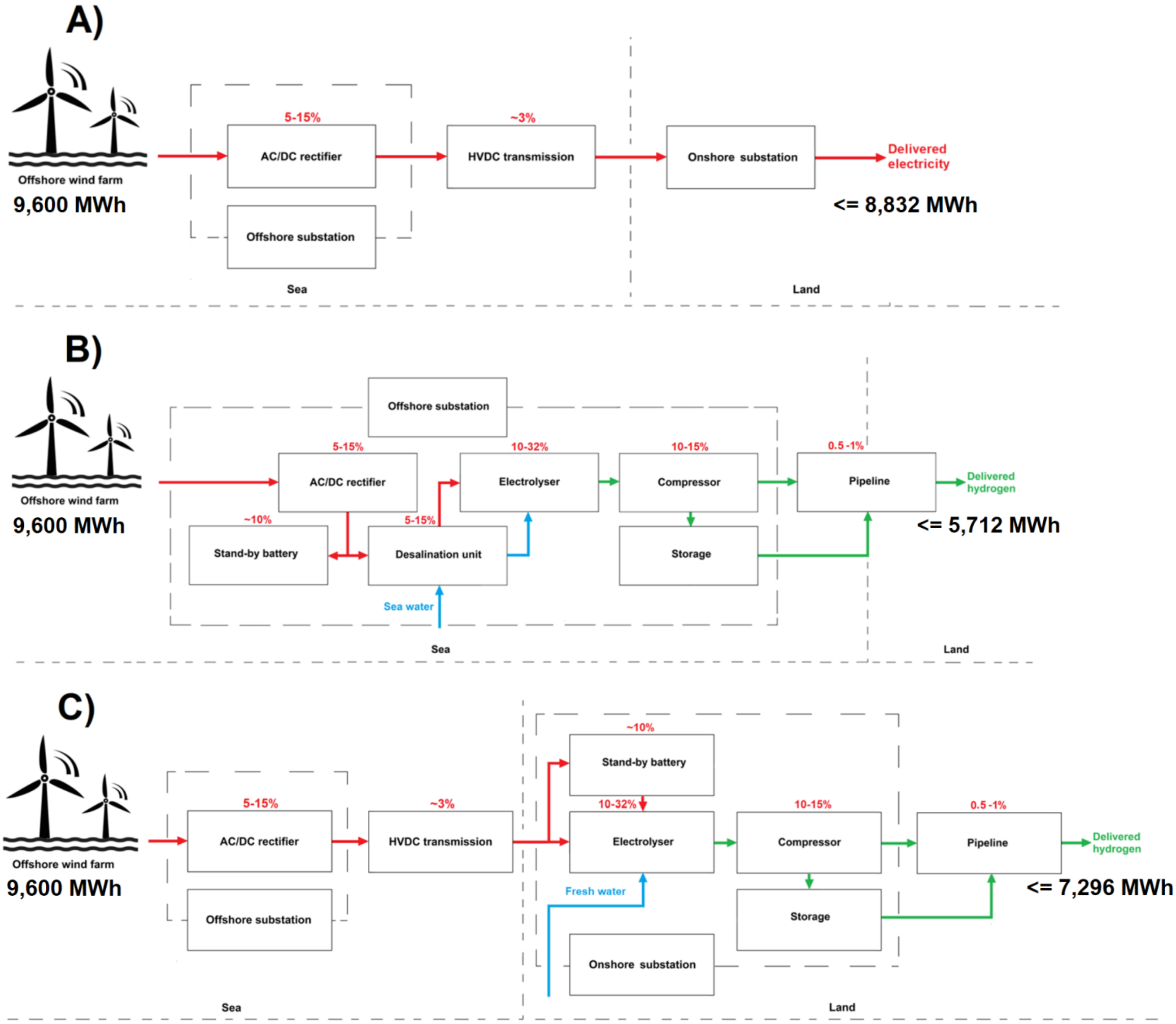
Figure 3: Key elements in the simplified exemplifying systems of energy transmission from offshore wind farms via HVDC lines (A) vs. hydrogen pipelines (B) vs. HVDC lines and hydrogen pipelines (C)



Source: Adapted from US Department of Energy (2019), Yan et al (2021), Ibrahim et al (2022), Giampieri, Ling-Chin, and Roskilly (2023).

Nowadays, offshore wind turbines typically have capacities ranging from 3 to 12 MW[19] (IRENA, 2022). With a turbine of 10 MW, and a conservative capacity factor of 40 per cent, we can estimate that each turbine daily generates around 96 MWh:

10 MW * 0.4 * 24 hours = 96 MWh per day

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[19] In 2023, China State Shipbuilding Corp. unveiled components for what would be the world's largest and most powerful wind turbine, an 18-MW unit with a 260-meter-diameter rotor (Power, 2023)

If we consider that an offshore wind farm consists of 100 turbines, the total energy produced in a day would be ~ 9,600 MWh.

Table 3: Estimates of approximate maximum energy losses along the transmission system for hydrogen pipelines and HVDC lines calculated for the 9,600 MWh of power generated for 24 hours by an offshore wind farm for a distance of 1,000 km

Key elements	Hydrogen pipelines			HVDC lines		
	Maximum losses		Left (MWh)	Maximum losses		Left (MWh)
	%	MWh		%	MWh	
AC/DC rectifier	5-15	480-1,440	8,160-9,120	5-15	480-1,440	8,160-9,120
Stand-by battery	~10	~960	7,200-8,160	n/a	n/a	n/a
Desalination unit	5-15	480-1,440	5,760-7,680			
Electrolyser	10-32	960-3,072	2,688-6,720			
Compressor	10-15	960-1,440	1,248-5,760			
Means of transmission (per 1000 km)[20]	0.5-1	48-96	1,152-5,712	~3	~288	7,872-8,832
Total	**40.5-88**	**3,888-8,448**	**1,152-5,712**	**8-18**	**768-1,728**	**7,872-8,832**

Source: Calculated by the authors based on the information adapted from Bulckaen (1992), Pickard (2013), Mohammad and Fuchs (2015), Bereiß et al (2019), Kumar and Himabindu (2019), Yan et al (2021), Groenemans et al (2022), Janowitz, D. et al (2022), Patonia and Poudineh (2022a), Yang (2022), Yu et al (2022), Giampieri, Ling-Chin, and Roskilly (2023), Kanz et al (2023), Linquip (2023), Olczak and Surma (2023).

Knowing this and the approximate maximum losses associated with each of the key components of the respective energy transfer systems (HVDC lines vs. hydrogen pipelines), we can estimate the total maximum ultimate losses (*Table 3*). Although Table 3 does not include the losses associated with the use of compressors that should be placed along the pipeline to pump the transported H_2 through, the maximum losses incurred at the key pre-pumping stages seem to be quite significant[21] (potentially, at least 40.5 per cent of the initial input energy).

For example, a 2 GW offshore wind farm[22] can generate 19,200 MWh per day if the capacity factor is 40 per cent:

10 MW * 0.4 * 24 hours * 200 turbines = 19,200 MWh per day

With losses of around 40 per cent (*Table 3*), this gives us approximately 11,520 MWh of energy (or around 346 tonnes of hydrogen)[23] that could be pumped through the pipeline on a daily basis. Though the pressure applied to hydrogen in the pipeline could vary (*Table 2*), at 100 bar (around 1,450 psi),

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[20] These calculations do not include energy losses associated with the use of hydrogen compressors that should be placed every 10-100 km along the transmission pipeline to keep the optimal pressure and pump the hydrogen through the system (depending on specific characteristics) (see *Table 2*)

[21] This, however, is not a 'fault' of the hydrogen pipelines themselves but rather a drawback of the very process of conversion. In fact, even if HVDC lines are used instead of H_2 pipelines to deliver energy to generate hydrogen later, the conversion of green electrons into green molecules will occur at the far end of the HVDC transmission – i.e. closer to the point of hydrogen consumption where comparable conversion losses will become inevitable (*Figure 3*). At the same time, with the green H_2 production taking place before its transportation by pipelines, the capacity of hydrogen pipelines may have to be adjusted to the scale of the green H_2 output, since it may not necessarily be of desirable volume (especially if some pieces of hydrogen infrastructure represent converted natural gas pipelines previously used for larger volumes of natural gas)

[22] At the moment, Hornsea 2, a wind farm with the total capacity of 1.4 GW that contains 165 turbines and is located in North Sea, is the largest offshore wind farm constructed to date (Engineering News-Record, 2022 and Ørsted, 2023).

[23] 1 kg of hydrogen has the energy value of about 33.3 kWh (Carbon Comment, 2021). Hence, 1 tonne (1,000 kg) of hydrogen will be equivalent to approximately 33.3 MWh, since 1 MWh = 1,000 kWh.

the daily amount for delivery would constitute approximately 44,359 m^3 of H_2 (see the calculations below).

1. At 100 bar (around 1,450 psi) and 20^{o}C, the density of hydrogen gas is approximately 7.8 kg/m^3 (Andersson and Grönkvist, 2019).
2. This means that 346 tonnes (or 11,520 MWh) per day would approximately be equal to the following amount:

346,000 kg / 7.8 kg/m^3 = 44,359 m^3 of H_2 per day

This, in fact, would mean that the pipeline delivering this hydrogen will be rather small – i.e. will have a rather small capacity. Even if we assume that the input into the pipeline is provided by 10 renewable power plants (solar and/or wind farms) with the combined capacity of 20 GW (i.e. 2 GW each), their total direct output with the 40 per cent capacity factor would only be 192,000 MWh per day. Here again, if the losses are around 40 per cent, the daily energy that will be converted into hydrogen will only be 115,200 MWh (or around 3,460 tonnes), which will give us around 443,590 m^3 of hydrogen compressed to 100 bar. Although this example is hypothetical, since 20 GW is currently several times greater than the total installed electrolyser capacity in the entire world,[24] and given how insignificant this volume would be for the transportation through the pipelines, it is questionable whether filling a pipeline with this amount of hydrogen will make economic sense in the foreseeable future.

By comparison, Linde's Gulf Coast hydrogen pipeline of 545 km that currently serves more than 50 refineries and chemical plants has the capability of supplying 32 million cubic feet (or around 906,941 m^3) per day (Hydrogen Council, 2022). This hydrogen, however, is not green. The Nord Stream 2 pipeline (which was claimed to be potentially suitable for conversion to hydrogen), was designed to deliver around 150.7 million cubic metres of natural gas on a daily basis (Offshore Technology, 2022). For reference, on average, this would constitute approximately 1.5 million MWh (or 1.5 TWh) and would then require at least 15,625 turbines of 10 MW each:

1.5 million MWh/96 MWh per turbine of 10 MW per day = 15,625 turbines

Interestingly, a recent report by Bellona estimated that producing enough green hydrogen for 12 of the 20 largest steel plants in the EU would require at least 85 GW of newly installed renewable energy generating facilities (Bellona, 2023). By comparison, this would be approximately equivalent of 56 copies of Hornsea 2, the world's largest offshore wind farm spanning an area of 462 km^2, and thus would need an area of around 25,872 km^2 (462*56 = 25,872), under the same climatic conditions (ibid). Needless to say, even for these actual steel plants located in Italy, the Netherlands, Belgium, Romania and Finland, the generation of the required amount of green H_2 would mean that these respective countries would have to install many more wind farms that they have done so far (ibid).

In this connection, the declared capacities of the world's most ambitious hydrogen pipeline projects look even more controversial, as most of these projects are supposed to become fully functional by the end of the next decade (*Table 4*). While these declared capacities are impressive, it is still unclear whether they will be delivered – i.e. whether these huge volumes of green hydrogen will be produced to then be pumped through these high-capacity pipelines. In principle, due to their high capital cost and relatively long lifetime, natural gas, oil, and other pipelines are normally reserved for high volume flows with stable and long-term demand of 15-30 years (S&P Global, 2020). For H_2 pipelines this is typical in the chemical and refining industries that are currently operating the bulk of installed pipeline capacity (ibid). In this respect, at low flow volumes, operating large pipelines is unlikely to be cost-effective (ibid).

In these circumstances, it seems reasonable to answer the following question:

Does it make sense to operate such hydrogen pipelines only for green hydrogen?

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[24] In 2020, the IEA estimated the global installed electrolyser capacity to be around 0.3 GW (IEA, 2021)

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Table 4: Top ten suggested hydrogen pipeline projects in the world by aimed capacity (as of 2022)

#	Project	Location	Aimed capacity (GW)	H_2 output (tonnes per year)	Power source (GW)	Expected length (km)	Planned use of H_2	Planned date of completion	Stage of development
1	***HyDeal Ambition***	Multiple sites across Western Europe	67	3.6 million	95 GW of solar	Not stated, but likely to be over 1,000	Deliver green H_2 across Europe	Before 2030	Early (project announced in 2021)
2	***Hyrasia One***	Steppes of western and central Kazakhstan	~20	~3 million	45 GW of wind and solar	~2,000	For export and/or local use	2024-2027	Very early (memorandum of understanding signed in 2021)
3	***Western Green Energy Hub***	Southeast Western Australia	28	<=3.5 million (H_2) or ~20 million (NH_3)	50 GW of wind and solar	~1,600	For multiple domestic and export markets	After 2028	Very early (data collection)
4	***AMAN***	Northern Mauritania	16-20	Not stated	30 GW of wind and solar	~1,500	Green steel, long-distance shipping, ammonia fertilisers domestically and internationally	Not stated	Very early (MOU)
5	***Oman (unnamed)***	Oman	14	Not stated	25 GW of wind (2/3) and solar (1/3)	~1,000	For sale on international markets	After 2028	Very early (project announced)
6	***Asian Renewable Energy Hub***	Pilbara, Western Australia	14	1.75 million (H_2) / 9.9 million (NH_3)	16 GW of onshore wind and 10 GW of solar	416	Green H_2 and green NH_3 export to Asia	2027-2028	Early (design and engineering)
7	***NorthH2***	Eemshaven, northern Netherlands	~10	1 million	4-10 GW of offshore wind	~1,000	To power heavy industry in the Netherlands and Germany	2040	Early (feasibility study)
8	***AquaVentus***	Heligoland, Germany	10	1 million	>10 GW of offshore wind	>2,900	General sale via a European hydrogen network	2035	Very early (project announced)
9	***HyEnergy Zero Carbon Hydrogen***	The Gascoyne region of Western Australia	8	~550,000	Wind and solar	>1,500	Green H2 and NH3 for 'heavy transport and industry', blending into local natural gas pipeline, and export to Asia	2030	Very early (project announced)
10	***Murchison Renewable Hydrogen Project***	Near Kalbarri, Western Australia	~3	~2 million	5.2 GW of onshore wind and solar	~2,500	Green H_2 and NH_3 for export to Asia	2028	Early stage (proposal developed)

Source: Adapted from Recharge (2021), Gascade (2021), Government of Western Australia (2021), Ammonia Energy Association (2022), Benhamou (2022), CSIRO (2022), CWP (2022), Hydrogen Insight (2022), Recharge (2022), Government of Western Australia (2023), Pipeline Technology Journal (2023), Province Resources Limited (2023), Western Green Energy Hub (2023).

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Short term balancing is a more acute problem in electricity grids compared with pipelines transporting gaseous substances. In the absence of reliable technological solutions for the large-scale, long-term storage of electric power, using hydrogen pipelines could potentially offer higher flexibility in this respect and a potential solution to mitigate the negative consequences of intermittency and seasonality of variable renewables and, in many cases, may appear to be more attractive from both technical and economic perspectives. However, for such a solution to be deployed solely for the purpose of transporting green hydrogen, it needs to be economically competitive with other forms of decarbonized flexible technologies, a condition that might be difficult to satisfy.

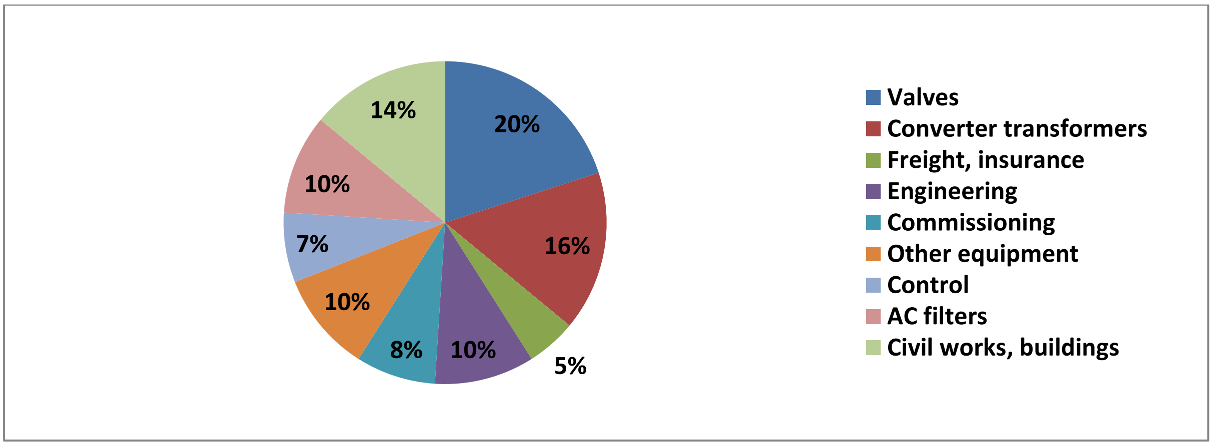
1.2 Economic aspects

HVDC lines

Just like other pieces of infrastructure, HVDC lines have various cost components, the significance and share of which varies from project to project, as each initiative is individual and serves specific purposes in a given environment (Csanyi, 2014). In this respect, power capacity and voltage, transmission medium, and specific environmental, safety and regulatory aspects all contribute to the expenses associated with these projects. Nevertheless, a typical cost structure of an HVDC project would look like the one represented by *Figure 4*. In general, because of the high cost of tailor-made terminal converter stations and other auxiliary equipment, the use of HVDC lines makes economic sense only for large quantities (over 20 MW) and long distances (over 600-800 km) of energy transmission (Rudervall, Charpentier, and Sharma, 2000). Otherwise, given the existing infrastructure and power system characteristics, alternating current would normally be more cost-efficient.

One of the most critical aspects, with a direct impact on the ultimate cost of any HVDC project, is the physical placement (location) of the lines that would deliver green electricity. Specifically, while one advantage of HVDC networks over HVAC alternatives is their significantly greater efficiency of power transmission under water or below ground, it is important to note that overhead lines are generally cheaper to construct and maintain (Reed et al, 2019). Typically, for the same distance and capacity, the total costs of underground cables, regardless of whether they are HVAC or HVDC, would be at least 1.5 times the costs of overhead alternatives. Furthermore, the cost of submarine cables would rise even further (Eurocable, 2011). In light of these cost considerations, it becomes imperative to align project investments with the economical carrying capacity of the chosen technology. This approach ensures both the extensive applicability of HVDC technology and the minimization of excessive and unnecessary expenses (Zhao et al, 2020).

Figure 4: Typical cost components for the construction of an HVDC project



Source: Adapted from Csanyi (2014) and Joseph et al (2018).

Simultaneously, when used for underground and underwater power transmission over extended distances, HVDC cables can emerge as a significantly more cost-efficient solution compared to HVAC systems. This cost advantage primarily stems from the inherent characteristics of direct current, as discussed in Part 1 of Section 1, which typically result in higher losses for HVAC transmission and

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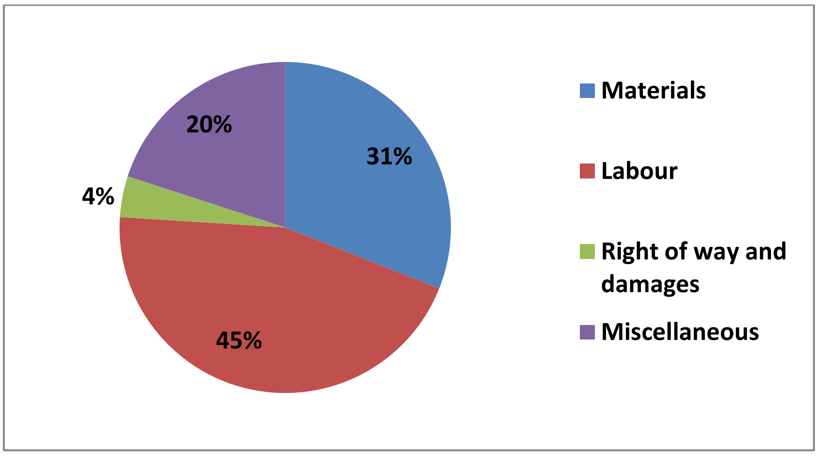
necessitate more intricate (and consequently, more expensive) cable designs (Wang et al, 2021). Since capacitance tends to increase with cable length, wire twisting, and the presence of a shield around the conductors—factors typically encountered in underground and submarine environments where alternating current would be employed—HVAC cables designed for long-distance transmission are likely to incur higher operational costs than their HVDC counterparts (ibid).

Hydrogen pipelines

Currently, as there are relatively few hydrogen pipelines and their length (both average and total combined) is significantly lower than that of natural gas pipelines (see *Table 2*), the analysis of the key cost components and indicators for such projects remains challenging and is usually based primarily on literature research rather than primary data obtained from real projects. That is why the uncertainty of cost levels for such projects is particularly high. At the same time, as there is some similarity in the physical characteristics of hydrogen and natural gas, many studies try to extrapolate the wealth of experience in constructing and operating the natural gas infrastructure and apply it to hydrogen so that the economic parameters of H_2 pipelines (such as capital and operating expenses) can be predicted and analysed (Khan, Young, and Layzell, 2021 and Semeraro, 2021). Following the logic of these and similar pieces of research, the key cost components of a typical pipeline project (including a hydrogen pipeline project) would broadly look as follows (*Figure 5*).

On the other hand, in absolute terms, hydrogen pipelines are usually at least 10-30 per cent more expensive to construct than natural gas pipelines (Timmerberg and Kaltschmitt, 2019). This is due to the more 'challenging' physical characteristics of H_2, stricter requirements for pipe materials to avoid such problems as hydrogen embrittlement, coupled with the additional costs of higher energy requirements for compressors as well as the installation of enhanced insulation and control valves, etc. (Khan, Young, and Layzell, 2021). However, repurposing some natural gas infrastructure may potentially significantly reduce the total expense by 65-90 per cent (see *Part 1 of Section 1*) (DNV, 2022). At the same time, most of such conversion initiatives at the moment still appear to be at either the research or testing phase (Cerniauskas et al, 2020).

Figure 5: Typical cost components for the construction of a pipeline project



Source: Adapted from Smith (2010) and Ulvestad and Overland (2012)

Similar to the importance of power transmitting capacity and voltage in the cost of HVDC projects, the diameter and pressure levels in hydrogen transportation via H_2 pipelines, appear to be crucial in determining the ultimate cost as they define the volume of the transferred gas as well as the energy consumed during this process. As seen in *Figure 6*, quite predictably, large pipeline diameters can allow for the delivery of greater volumes of hydrogen in more economically advantageous conditions and thus usually appear to be more cost-efficient than their alternatives (Danish Energy Agency, 2021 and Collis and Schomäcker, 2022). At the same time, as discussed in the previous section, from an economic standpoint, uneven flows of low quantities of transported gas are unlikely to make economic sense (ibid). In this connection, to make an H_2 pipeline project economically viable and competitive, it

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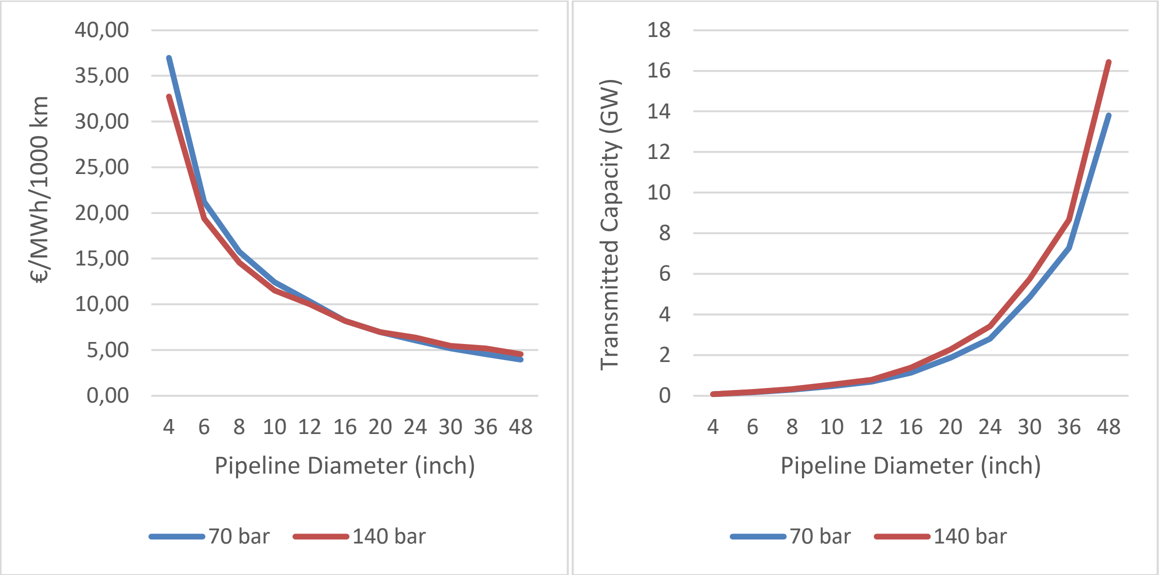
seems reasonable for its capacity and other characteristics to be adjusted to the specific requirements of demand and supply of hydrogen that could be created.

Figure 6: The impact of pipe diameters and pressure levels on the cost of delivered hydrogen and transmission capacity



Source: Adapted from Danish Energy Agency (2021) and Collis and Schomäcker (2022).

Finally, as in the case of HVDC lines, the length as well as physical location of hydrogen pipelines will impact the ultimate cost of such projects. In this respect, it is quite predictable that underground and submarine H_2 pipelines will be more expensive to construct and operate. Specifically, for identical projects, the cost of the underground ‘version’ would normally be around 1.5-2.5 times higher than the cost of its above-ground substitute,[25] and the cost of a submarine pipeline would be up to 2-5 times higher (Kaiser, 2017). Similarly, laying underground and underwater HVDC cables is costlier than above-ground lines because of the higher construction, installation, and maintenance costs owing to more expensive materials and design and more challenging geographical, environmental, and regulatory conditions (ibid). Here again, converting (repurposing) existing underground and submarine natural gas pipelines for hydrogen is widely expected to reduce the expenses associated with H_2 pipeline transportation.

Comparing the costs of HVDC and hydrogen pipelines

When it comes to the direct comparison of economic efficiency of HVDC lines and hydrogen pipelines, creating an objective analysis is challenging primarily due to the low number of the existing and operating H_2 pipeline projects, as well as lack of access to the data on their techno-economic features. On the other hand, there is a vast amount of research that models potential costs of each of these technological solutions based on specific assumptions regarding their main characteristics such as capacity, length, etc. Although these studies greatly differ in their method of analysis of the two technologies, the cost ranges for hydrogen pipelines identified by most of them appear to be more favourable (between 1.1 and 18.2 EUR/MWh/1,000 km) than those identified for the HVDC projects (2.3 to 90.1 EUR/MWh/1,000 km) (Hagspiel et al, 2014, Purvins et al, 2018, Welder et al, 2018). Since these ranges are quite significant and do not necessarily make the juxtaposition of the options easy, a visual representation of these costs for energy transport via H_2 pipelines and HVDC lines could be used to facilitate the comparison (see *Figure 7*).

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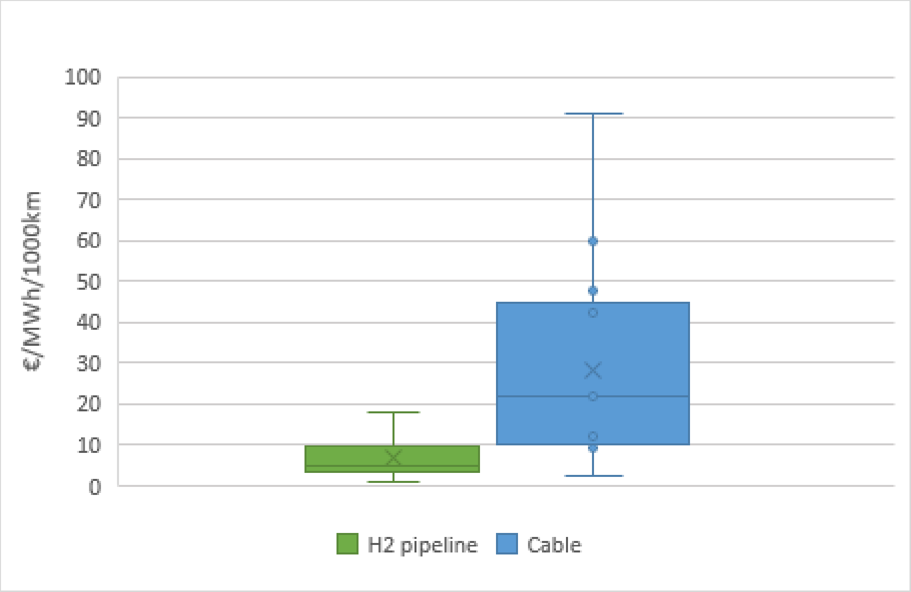
[25] To minimise safety risks, protect the pipeline from external factors, and reduce visual impact (especially in populated areas), the majority of existing pipelines are located underground (OECD, 2023).

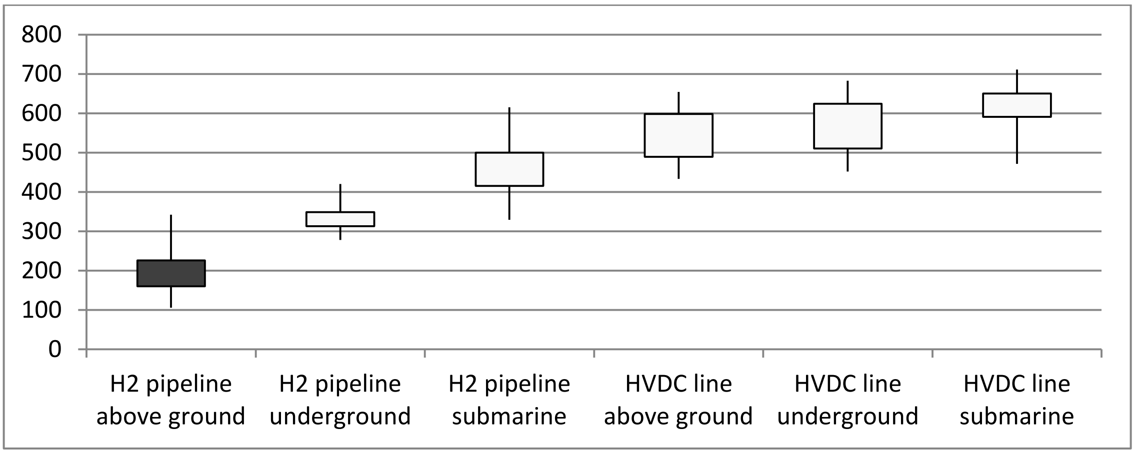
Figure 7: Specific cost ranges for energy transport by hydrogen pipelines and HVDC lines (EUR/MWh/1,000 km)



Source: Adapted from Saadi, Lewis, and McFarland (2018), Timmerberg and Kaltschmitt (2019), Brändle, Schönfisch, and Schulte (2020), Cerniauskas et al (2020), DeSantis et al (2021), European Hydrogen Backbone (2021), Hydrogen Council (2021), Semeraro (2021), Australian Pipelines and Gas Association (2022), Collis and Schomäcker (2022), Guisehouse (2022), European Hydrogen Backbone (2023), DNV (2023).

In general, as most of the comparative studies demonstrate, the cost drivers that would be applicable to both hydrogen pipelines and HVDC lines are the length of such projects, materials (for pipelines and cables), regulatory compliance (permitting costs, environmental impact assessments, etc.) and labour costs as well as environmental considerations such as the need to navigate a challenging system or a sensitive infrastructure. In addition, both options would be heavily affected by the cost of technology and specialized equipment (though this would be different for HVDC and H_2 pipelines), voltage levels/pressure of hydrogen and cable size/pipeline diameter. On average, however, it is estimated that investment costs for the overhead HVDC lines are likely to be almost twice as high as the investment expenses for above ground hydrogen pipelines, though the difference for the underground and submarine options is less significant (*Figure 8*).

Figure 8: Estimated average investment costs for HVDC lines and hydrogen pipelines (in EUR/MW/km)



Source: Adapted from Hagspiel et al (2014), Purvins et al (2018), Welder et al (2018), European Hydrogen Backbone (2021), and DNV (2023).

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At the same time, it should be noted that, unlike HVDC power transmission systems, hydrogen pipelines currently exist primarily as industry-owned infrastructure and have not yet been utilized for the transportation of large quantities of H_2 that would be comparable to those of regularly transported natural gas. In this respect, most of the existing studies and research models estimating the cost of hydrogen delivery by pipeline as well as the overall investment expenses associated with such projects are based primarily on the available information on natural gas pipeline projects. That is why, despite all the similarities of the two substances, cost models and comparisons appear to be rough estimates and may not always reflect the real situation. Each H_2 pipeline initiative will be unique, and hydrogen is likely to pose some specific and unexpected challenges that have not yet been dealt with, which will have an impact on the ultimate cost.

At the moment, a large amount of research focuses on identifying the impact of specific system factors on the cost of energy transmission. While each piece of research provides its own unique findings, many of them agree that capacity factor, power transmission capacity, and the total distance for energy delivery play the most important roles in reducing/increasing the overall cost of HVDC and hydrogen pipeline projects (Timmerberg and Kaltschmitt, 2019, Miao, Giordano, and Chan, 2021, and Semeraro, 2021). For instance, as demonstrated by Miao, Giordano, and Chan (2021), when the capacity factor for power/H_2 generation is increased from 10 to 50 per cent, cost reductions of 50-70 per cent per unit of energy per unit of distance in case of both energy transportation options (EUR/MWh/1,000 km) could be expected. Similarly, the increase of transmission capacity from 0.5 GW to 5 GW is likely to result in the overall costs per unit of energy per unit of distance being reduced by 33-66 per cent[26] (Miao, Giordano, and Chan, 2021). Finally, when it comes to the direct impact of the increase in distance of a specific HVDC power transmission or hydrogen delivery piece of infrastructure on the cost of such projects, this effect can usually be described by a linear dependence, though it is considered to be the least substantial of these three factors (ibid).

Following this rationale, increasing the capacity factor of power or hydrogen production, along with the overall transfer capacity, while optimizing the length of HVDC lines or hydrogen pipelines, can enhance the cost-efficiency of such projects. Consequently, larger volumes and stable flows of electrons or molecules contribute to the economic attractiveness of energy transportation initiatives. However, it is crucial to consider that power transmission capacity should align directly with both demand and supply. Investing in infrastructure capable of transferring greater energy volumes is sensible only when these quantities can be both generated and consumed effectively.

In this context, to maximize the benefits, it may prove advantageous to tailor specific pieces of energy delivery infrastructure to particular use cases. Moreover, achieving maximum energy delivery volume and flow stability is likely to necessitate the incorporation of energy storage components, such as batteries or hydrogen storage, into HVDC and hydrogen pipeline infrastructure elements. Alternatively, integration with a broader energy system might be warranted. For example, harnessing surplus power to produce hydrogen can enhance grid stability, while hydrogen infrastructure can complement the existing electrical transmission system, and vice versa.

2. Systems perspective and other factors to consider

The decision regarding whether to prioritize the transportation of green molecules or green electrons is influenced by a broader perspective, taking into account systemic factors such as the characteristics of economic growth in various global regions and the projected development of power and hydrogen markets in the future. While estimates for hydrogen demand in 2050 vary, ranging from 150 to 600 megatonnes (Mt)[27] (World Energy Council, 2021), it is evident that achieving climate targets with the assistance of hydrogen necessitates a substantial increase in its production and

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[26] However, existing literature and projects demonstrate that the current transmission capacity of HVDC lines in offshore and coastal areas usually does not exceed 2 GW, which can limit cost reduction (Siemens, 2023)

[27] This means that it is estimated to rise from around 3,135 TWh (or 95 Mt) at the 2022 level to around 4,950-19,800 TWh (150-600 Mt) by mid-century (IEA, 2023).

1 megatonne (Mt) of hydrogen is about 33 terawatt hours (TWh) (Gen H2, 2022) transmission capacity. Nevertheless, this emphasis on hydrogen should not diminish the importance of electricity. In fact, global electricity generation is projected to experience a significant surge of 91 per cent between 2020 and 2050[28] (Enerdata, 2023). Given the highly improbable scenario where most of this electricity is converted into molecules, there will continue to be substantial demand for HVDC projects.

While each of these energy transmission options boasts its unique advantages and presents certain drawbacks, it would be imprudent to regard them as competitors that should entirely exclude each other. As previously mentioned, both HVDC lines and hydrogen pipelines currently coexist and are likely to continue doing so in the foreseeable future, given the anticipated growth in the number of energy infrastructure projects involving each of these solutions.

In this context, beyond selecting the most suitable option for specific applications and energy delivery projects, it is beneficial to perceive these energy transmission alternatives not in isolation but as integral components of a larger, interconnected energy system. This perspective is essential because analysing isolated components of a complex mechanism often fails to provide decision-makers, including managers, business leaders, and policymakers, with sufficient information for optimal decision-making. The entirety of an energy system seldom behaves as simply as the sum of its constituent parts (Laimon et al, 2022).

In this light, adopting a systems thinking approach, inspired by the works of Forrester (1968), Bertalanffy (1969), Senge (1990), Meadows (2008), and others, implies that, alongside evaluating pure techno-economic characteristics, decision-makers should prioritize the examination of dynamics, interactions, and relationships among the various components within the broader energy ecosystem. This approach enables a deeper understanding of how changes in one part can reverberate across others and, ultimately, affect the entire system.

Here, one of the crucial determinants for deciding whether electrons or molecules should be actually transported is the initial purpose for the use of the delivered energy. In particular, if the end user represents an enterprise from the so-called ‘hard-to-abate’ sector for which the use of hydrogen is likely to be one of the very few solutions allowing for a comprehensive decarbonization (e.g. a steel or ammonia plant), delivering green electrons may only make sense to a place which would be closest to the consumption point where H_2 could be produced (and most likely stored) at the lowest cost.[29] If the energy system does not offer such a site, it would be more reasonable to transport hydrogen by pipeline all the way from where it is generated even though converting electrons into molecules would then be associated with significant losses (as described in *Section 1*). In any case, it is unlikely that applying a standardized one-size-fits-all approach would result in finding the most efficient solution for each specific case.

Another important factor to consider in this respect is the availability of already existing infrastructure. In this connection, the same argument of cost minimisation associated with repurposing or adjusting the existing natural gas infrastructure could become a decisive point in a country with a well-developed gas network (Lipiäinen et al, 2023). At the same time, although it may be less popular than adjusting natural gas pipes for hydrogen, HVAC transmission lines may also be converted into HVDC ones if the former, for instance, appear to be in excessive number and have a high risk of becoming stranded assets on a given territory[30] (Novoa and Rios, 2017). That is why the ease with which new components could be integrated into an already existing energy production and transfer infrastructure can have a substantial impact on the overall system costs and efficiency and, as a result, on the decision making. Because of these considerations one option can actually become more viable than the other.

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[28] With the global electricity demand in 2022 being around 25,500 TWh, the figure by 2050 is expected to be approximately 48,705 TWh (Statista, 2023)

[29] In these conditions, for instance, the availability of water for electrolysis as well as available storage locations may become a determining factor for the location of hydrogen production

[30] This could happen, for example, when power generation becomes more decentralised and some of the existing pieces of HVAC infrastructure are no longer needed

In addition to the ease of adjusting the already existing infrastructure pieces to the new needs, the entire path from the energy source to the end user should be taken into account. Just like it was represented by *Figure 3*, delivering electric power from its producer to the ultimate consumer would normally require fewer steps and intermediary elements than delivering hydrogen. This is so because, although battery or pumped hydro storage of electricity could potentially complement the system, a typical infrastructure path for green electrons would usually only include generation, transmission, and utilization. When it comes to green molecules, the situation gets significantly more complicated by the very fact that green H_2 should be first produced by green electricity. In this case, renewable power generation would then have to be followed by the power-to-H_2 conversion mechanism as well as the transformation of the generated hydrogen into a transportable and storable form (compression), as the transportation and storage stages will have to be gone through before hydrogen is decompressed prior to its final use by the consumer or power generator.

Apart from these considerations, risk factors and future-related uncertainties and concerns are also likely to play an important role in the process of choosing and preferring one solution over the other. For instance, if the decision makers anticipate that one of these technologies may become obsolete over time (or at least become obsolete faster than the other one) and hence may not be aligned with future trends,[31] they are likely to be less interested in its development. This could, in principle, be spurred by some new elements introduced into the energy system. This situation may resemble the one from the end of the nineteenth century when alternating current was competing with direct current and the advent of transformers simplified the use of AC and made DC a significantly less attractive option for the investors despite its unique features (Specht, 2019). Since at that time DC was perceived as a technology of less favourable commercial applicability in the long term, its further progress was hampered for almost a century.

In this connection, when making the decision on which technology to support, the investors would also need to consider how flexible each of these alternatives is in adapting to changing demands or technological advancements. The need for a long-distance energy delivery from an offshore wind farm via either HVDC lines or hydrogen pipelines could theoretically change with the rise of alternative concepts such as the so-called ‘multi-purpose offshore platform’ (Engie, 2021). This solution, in contrast to letting the energy be delivered to the end user located hundreds or thousands of kilometres away, could let the generated power be harvested and used locally for various purposes from aquaculture to desalination (ibid). Although this concept is unlikely to be applicable everywhere, in theory, it could significantly improve the efficiency of energy use, since the costs and losses associated with its transportation to the consumer placed far away will be minimised. As a result, it may decrease the investment attractiveness of long-distance energy transfer of both green electrons and green molecules.

Apart from that, other risks such as those associated with external factors of geopolitics are most likely come into play as they can have a significant impact on the feasibility and safety of both energy delivery options. Here, looking at the energy infrastructure management from today’s perspective on the on-going full-scale Russian invasion of Ukraine, dependencies on materials or technologies originating in a single country or region increases the risk of supply chain interruption. For instance, given that most of the world’s aluminium that is frequently substituting copper in HVDC lines is currently being produced by China and Russia, going from aluminium back to copper, the production of which is more evenly distributed around the globe, might be advantageous from a strategy standpoint (Gordonnat and Hunt, 2020 and Harbor Aluminum, 2023). Apart from that, planning the construction of energy delivery infrastructure should also consider potential conflicts of interests with neighbouring countries. In fact, apart from the high overall cost, such interstate political tensions appears to be one of the major reasons that key investors abandoned the Desertec project –

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[31] For instance, with repurposing an existing natural gas pipeline that has been in operation for several decades, the lifetime of the converted hydrogen pipeline will automatically be shortened (see *Table 1*)

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an20nitiativee that was supposed to enable the delivery of large quantities of solar power generated in Africa to Europe via HVDC lines[32] (Euractiv, 2013).

From a long-term perspective, susceptibility of each of these energy delivery options to natural disasters, sabotage, and failure has to be considered as well. While natural disasters are perhaps the hardest to predict and prevent of the three mentioned categories, sabotage and system failures can also take the network operators and managers by surprise and their consequences may dramatically affect the entire energy system for the years to come. In this context, Europe's forced rearrangement of natural gas supplies after the damage to the Nord Stream pipelines caused by presumably coordinated explosions may serve as a clear reminder of the importance of security provision for large-scale infrastructure projects (DW, 2022). That is why the solution with a better fallback mechanism that would allow the system to cope with failures and force majeure in a faster and more efficient way is also more likely to be preferred by investors over its competitors. In this connection, the question of how the preferred energy delivery option would contribute to or detract from the overall stability and reliability of the national or regional energy system would need to be addressed.

The presence of a mature and liquid market for the energy vector can make investment in one technology potentially more preferable than the other. Since a proper hydrogen market is currently almost non-existent, the development of H_2 infrastructure projects (including pipelines) seems to be happening primarily under the auspices of national governments. In addition, as seen in *Table 4*, even with significant enthusiasm, none of the major long-distance H_2 pipelines has gone farther than the early design and research stage. Electricity, despite all its challenges, already represents a relatively well-developed market. Also, power transmission systems, in general, and HVDC projects, in particular, are significantly more numerous at the moment. That is why, for a faster and more sustainable development of energy transportation initiatives (in a form of both molecules and electrons), further market improvement and maturity need to be achieved.

To expedite these market improvements, the presence of effective government policy mechanisms becomes crucial. These policies should not only incentivize the advancement of efficient energy transfer technologies and their associated vectors but also address and eliminate regulatory impediments that hinder progress. The absence of a regulatory framework for grid development and operation for each of these technologies can significantly undermine the overall system's feasibility. Therefore, establishing a comprehensive set of supportive regulations is essential to stimulate the adoption of these energy transfer technologies.

Finally, though they might seem to be less obvious, the issues of social acceptance of energy infrastructure pieces are likely to have a profound impact on their implementation. In fact, lack of societal support for private and public energy initiatives has often been one of the main causes of their termination or complete withdrawal from the agenda. This, for example, happened to the Atlantic Coast Pipeline – a natural gas infrastructure project that was cancelled after years of delay and litigation instigated by massive protests by local communities (Sierra, 2020). Similarly, in the late 1970s, the proposed CU Project – an HVDC transmission line initiative in Minnesota – spurred years of public unrest (Anderson, 2020). Although these civil actions were not successful and the project was implemented, the protests inspired the creation of a number of anti-powerline groups across the entire United States (ibid). That is why, if an energy delivery project needs to be realised, it should gain social licence to operate, which, in turn, includes supportive (or at least neutral) public opinion.

Conclusion

This paper has concentrated on two prominent concepts in decarbonized energy transmission through fixed infrastructure. It has examined high-voltage direct current (HVDC) transmission lines, a widely promoted method for conveying green electrons over long distances, and compared them with hydrogen pipelines, envisioned by many as essential for transporting green molecules across regions.

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[32] The investors failed to secure the support of the Spanish government for the undersea cable, as Morocco, the country's direct competitor in solar power generation, would then get direct access to the European power market (Hamouchene, 2023).

While both technologies can transfer substantial amounts of green energy over lengthy distances, they are often portrayed as competitors vying for limited decarbonization funding. Therefore, it was vital to evaluate the key techno-economic attributes of HVDC lines and hydrogen pipelines to discern their advantages, disadvantages, and the circumstances favouring one over the other.

Hydrogen pipelines, generally capable of transporting greater energy volumes, surpass HVDC lines in terms of capacity. However, existing hydrogen pipelines are usually much shorter than typical HVDC transmission lines, and HVDC projects are more numerous, especially for intercontinental energy transfer. Advocates of hydrogen pipelines favour expanding these networks to transport larger energy volumes compared to HVDC lines, capitalizing on the physical similarities between hydrogen and natural gas, potentially leading to cost savings.

Nonetheless, repurposing existing natural gas infrastructure for hydrogen is not universally feasible due to hydrogen’s unique characteristics, necessitating material upgrades and modifications throughout the pipeline. Challenges arise from the small size of hydrogen molecules, posing leak and embrittlement risks, and the increased energy required for compression compared to natural gas. These challenges translate to additional expense and potentially reduced attractiveness for hydrogen pipeline projects.

Despite these challenges, technical solutions exist for most cases, making the repurposing of natural gas infrastructure and construction of hydrogen infrastructure technically viable. However, the efficiency of green hydrogen production and its subsequent transportation presents another challenge. When hydrogen is produced from offshore wind farms and directly delivered via hydrogen pipelines, energy losses stemming from the power-to-hydrogen process may reach approximately 40 percent. This prompts a broader question: should end-users receive green electrons or molecules? For sectors that are hard to electrify, hydrogen transportation may be the preferred option, pending alternatives like carbon capture and storage (CCS).

Nevertheless, HVDC lines are not universally suitable for large-scale, long-distance green energy transmission. Hydrogen pipelines are generally considered more cost-efficient, particularly when both hydrogen generation capacity and pipeline transfer capacity are high. Stable hydrogen flow and large volumes enhance the economic attractiveness of pipeline projects. However, intermittent renewable energy sources like wind and solar power may not consistently generate sufficient green hydrogen, posing challenges for hydrogen pipelines. In such cases, hydrogen storage and the blending of green hydrogen with other hydrogen types can stabilize the flow.

Most comparisons between these two technologies are based on assumptions and models, as hydrogen pipelines are less numerous than natural gas pipelines. Therefore, further research may be necessary as the global hydrogen pipeline infrastructure develops.

In a broader context, viewing these technologies and projects in isolation is unproductive, as they will likely become integral parts of a complex energy system. They should not be seen as competitors but rather as complementary elements, each offering unique features.

While both HVDC lines and hydrogen pipelines are expected to proliferate, decisions about which technology to prioritize in the short term will depend on budget constraints and other factors. Factors like the availability of existing infrastructure, adaptability to new components, risk assessment, and market maturity will influence the choice. Social acceptance should also be considered, as public opposition can significantly impact project feasibility.

Considering all relevant factors, risks, and uncertainties might not always be feasible, but the complexity of the environment should not deter support for these projects. The challenges of climate change and decarbonisation are profound, and we may need an energy infrastructure capable of accommodating both green molecules and electrons.

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