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Introduction

Claudio Aranzadi

This 13th edition of *Energy and Geostrategy (E&G)* opens with an interview with Landon Derentz (vice president of the Atlantic Council). It also includes a geographically-focused paper authored by Joseph Colman ("Geopolitics of Energy: a View from Canada"); two papers analysing the current global context as it relates to primary energy resources, by Ignacio Urbasos ("Natural Gas Geopolitics in a New Order") and María del Mar Hidalgo ("The Geopolitics of Critical Minerals for the Energy Transition"); another two papers that examine two key energy sector technologies, authored by Sehila M. González de Vicente ("Fusion Energy") and Inmaculada Martínez ("Artificial Intelligence: the Strategic Catalyst for a Resilient and Decarbonised Energy Future"); and a paper on one of the most critical global energy infrastructures for the transport of gas and oil by Miguel Golmayo ("Energy Port Infrastructures: Pillars of Global Energy Security").

In our usual review of how global energy geopolitics have evolved since the previous edition of *E&G* up to this latest edition (beginning of 2026), much of our attention is, quite logically, given to the changes in the international order brought about by the foreign policy of the new US administration. The past year has supplied a remarkable surplus of information in this respect, though geostrategic uncertainties also continue to multiply. In this time, there have been significant changes in the traditional energy trilemma (competitiveness, security, sustainability): security (specifically, guaranteeing the supply of primary energy resources) has acquired greater relevance whilst global decarbonisation policy has not regained the necessary dynamism (the lack of results from COP30 is a key manifestation of this). Elsewhere, the global geopolitical climate has deteriorated (with an intensification of rivalries and the weakening of cooperation), the outlook for oil and gas markets has done an about-face, and we have witnessed a renewed emphasis on industrial policy as a key tool for promoting technological innovation and competitiveness for productivity and, more specifically, in the energy sector.

In the previous edition of *E&G*, it was pointed out that 'the Trump administration was causing a substantial change in the paradigm that underlay the conception of international relations configured in the post-war world: from the defence of a "Kantian" world, respectful of the law and subject to rules, to a "Hobbesian" vision where "might makes right", multilateralism and multilateral organisations are dismissed, and bilateral negotiations are explicitly adjusted to transactional considerations and relations of force'. The political initiatives, public statements, and the publication of the US government's 2025 National Security Strategy over the past year seem to confirm this diagnosis, which Canadian Prime Minister Mark Carney summarised at the Davos meeting in January 2026 by stating that we are witnessing not a transition but a rupture of the international order. It should not be forgotten, however, that the separation between the two paradigms in the order we are leaving

behind us was not particularly clear: rules were violated on numerous occasions, especially by great powers, given the inherent limitations of international law.

The prolific geopolitical analyst during the cold war (in addition to philosopher and sociologist), R. Aron (1984) pointed out that 'the natural state (or state of potential war) between States is essentially different from the state of societies within these States' / 'the interstate system, unlike the intrastate systems, is not subject to a central power, to a central agency of control' / 'States have not emerged, in their mutual relations, from their natural state. Otherwise, there would be no theory of international relations if they had'. M. Spektor (2026), deferring to M. Carney's words in the aforementioned forum, offers a more 'utilitarian' explanation of Western countries' acceptance of a system subject to rules they knew were hypocritical in their application: the system facilitated the stability and power of the United States and supplied the public goods on which other Western countries depended. This diagnosis, of course, does not call into question the superiority of the 'liberal order' subject to the rules of the last eight decades: stability did contribute to the reduction of geopolitical risk and the values that underlay the system have played the role of 'regulatory principles' and moral point of reference — indeed, any violation would at least entail reputational consequences via political sanctions.

The new international order, however, is still forming and the geopolitical scenario in a world not respectful of the rules and subject to the game of power balances is affected by a deep uncertainty that, in turn, is aggravated by the main actors (especially China) necessarily repositioning themselves in response to the structural changes in international relations provoked by the US. In this context, closer to the naked rivalry between states espousing a 'realist' vision than to the spirit of cooperation and respect for multilateral discipline typical of the liberal international order, modelling the behaviour of states in their foreign policy takes on greater relevance. Otherwise, any forecast would simply end up anticipating the results of a multidimensional clash of state 'black boxes' in an 'anarchic' world setting. The quality of this modelling will depend on its greater or lesser ability to simulate state behaviour in different circumstances, which requires the identification of a systematic pattern of behaviour that goes beyond pure factual description. One ingredient of this systematic pattern might be the hypothesis of rationality.

Mearsheimer and Rosato (2023) consider states to be normally rational actors when they elaborate and implement their foreign policy: that is, they 'base their policies on credible theories and adopt their decisions through a deliberative political elaboration process'¹. For these authors, the 'credibility of a theory is based on its assumptions, its causal logic, and its empirical validation' and 'a credible theory is not only based on realistic assumptions but must also be deduced from them by a logically consistent causal formulation'. This requirement of rationality is very close to that often used in

¹ As the authors themselves point out, this opinion goes against the emerging 'conventional wisdom' in the analysis of international relations. K. Yarhi-Milo (2023) makes a vivid critique of Mearsheimer and Rosato's book in which they present their theses, attributing to them a return to the old conceptual framework of 'realism' in whose vision states 'act rationally seeking to maximise their power and protect themselves against attacks in an anarchic world'.

economics, in which the individual who consistently maximises an objective function (or the mathematical expectation of the objective variable, in an environment with uncertainty) is considered as a rational actor. Of course, in geopolitical argumentation, we can dispense with the formalisms and heroic requirements that economic theory would require to define the 'internal consistency' of a rational choice (Sen 1998). It should be noted that, in both economic and geopolitical contexts, the use of 'rationality' as a normative criterion does not necessarily have an ethical connotation, nor does its assessment derive from the potential results of the supposed rational action. The objectives could be perverse and not achieved (e.g. in an unjust war that ends in defeat). (Sen 1998); Mearsheimer and Rosato 2023). The latter authors also add a requirement to define the 'rationality' of a state in a geopolitical context: the deliberation among those responsible for foreign policy through a robust and uninhibited debate which should foster an aggregation of individual positions that leads to a final decision.

How should the US government's new foreign policy be identified in accordance with the aforementioned criteria? The answer is hindered by the excessively open nature of Mearsheimer and Rosato's definition of 'rationality', but above all by the resistance to detach a strictly procedural concept of 'rationality' (as a coherent mechanism of argumentation and action to achieve an objective) from the substantive assessment of that objective and the subsequent verification of the results. Logically, the positions on the issue are multiple. When Martin Wolf (2026) affirms that 'with a US that is neither predictable nor linked by any fundamental principle of action beyond a few short-term gains, its credibility as a reliable partner and ally is being destroyed, perhaps permanently', he could hardly accept a qualification of US foreign policy as rational, all the more so as Trump himself explicitly boasts of his 'unpredictability'.

In E&G 2025, this claim was examined within the framework of what R. Nixon described as the 'madman theory'. McManus (2025) traces this theory back to Machiavelli's doctrine in 1517, which considered that in certain circumstances 'it is a very wise thing to simulate madness' and cites a list of politicians who supposedly followed this Machiavellian principle (Khrushchev, Saddam Hussein, Gaddafi, etc.) with normally unsatisfactory results. This seemingly irrational behaviour, however, would meet the criterion of rationality if used deliberately as a strategic device; indeed, the choice of a 'mixed strategy' in game theory can be perfectly rational. Nor could the historical failure of these strategic initiatives be alleged as a factor of irrationality if the criterion of rationality set out above is accepted.

Mearsheimer and Rosato's criterion of rationality for states (2023), however, reveals certain shortcomings. Firstly, as Yarhi-Milo (2023) points out, there is the subjective nature of the definition of 'credible theory'. The tariff policy imposed by the Trump administration was defined in E&G 2025, following Blinder (2019), as an action inspired by a bad idea (mercantilism) and the rejection of a good one (liberalism). But its proponents might consider such a protectionist policy, supposedly defending domestic jobs, as based on a 'credible theory'. A similar indeterminacy would affect the characterization of US energy and climate policy. The definition of

a strategy's rationality would depend on the chosen intellectual framework (an exogenous preference) and would, therefore, be weighed down by clear relativism. This would lead to the acceptance of various rational, 'conditional' alternatives depending on the economic or political conception chosen, as well as to discarding the equivalence between the concept of rationality and that of justifying one's behaviour. Yarhi-Milo also criticises the requirement for deliberation among policymakers through debate and without inhibitions, something that is difficult to control empirically, especially in authoritarian countries.

However, the definition of the rational behaviour of states from an instrumental perspective as the consistent maximization of a function as one's goal (regardless of its acceptability) does have analytical utility. This hypothesis of rationality of state actors is fundamental if the game theory framework is to be used, albeit analogically, to model geopolitical rivalry. The examination of the asymmetrical EU–US trade agreement is an example. The European strategy would resemble that of the 'coward' in a 'game of chicken' who chooses to yield instead of risking confrontation. This strategy can be perfectly rational (it corresponds to one of the three possible balances of the game) as long as the profit matrix considered is correct. Of course, it differs from China's strategy towards the US that eventually led to both parties yielding and reaching an optimal state of balance, although considering in this case a profit matrix corresponding to a 'game of reciprocity' (Binmore 2007, Binmore 2009). Even if we consider this comparison with caution (and theoretical tolerance)², it can be used to exemplify Europe's and China's different perceptions of the geopolitical landscape, both in terms of each country's power and the political capacity to withstand a confrontation. What this example helps illustrate is that each of the state actors involved would have behaved rationally (that is, trying to maximise their function in a consistent manner).

Of course, although the attribution to states of normally rational behaviour (without ethical connotations or references to results) may be useful for the analysis of the geopolitical environment and the forecast of its future evolution, it is nevertheless insufficient.

Firstly, as behavioural economics shows, the criterion of rationality of the mainstream of economic theory does not adequately represent the pattern of behaviour of individuals in their real economic and social coexistence (Bowles 2004). As Yarhi-Milo (2023) points out, foreign policymakers (and therefore governments) frequently act using heuristic procedures, but additionally, like all individuals, they are subject to limitations of the standard pattern of rationality due to the effect of loss aversion (beyond risk aversion), path dependence, etc. The problem presented by behavioural economics, however, is its lower formalised modelling potential compared to that offered by standard economic theory, although some authors such as D. Ariely (2008) affirm that 'our irrational behaviours are neither random nor absurd. They are systematic and, since they are repeated over and over again, they are

² Mark Blaug (2002) warns, even in the field of economics, of the descriptive and predictive limitations of game theory due to the inadequacies that can affect the realism and robustness of its models even within their formal rigour.

predictable'. But if this were true, we would have a systematic pattern of behaviour with the same predictive value as rationality, which seems doubtful.

Secondly, the modelling of the behaviour of states in their foreign policy beyond their rationality requires taking into account the conditioning that their political ideology and the institutional and intellectual framework left by history impose on the actions of governments.

Thirdly, Yarhi-Milo mentions factors such as the emotions and psychology of policymakers that can provoke deviations from the supposed rational behaviour of governments; these arguments are being used extensively to explain the current evolution of US foreign policy, although it seems doubtful that psychoanalysis can offer a solid basis for geopolitical diagnoses. On the other hand, any explanation of the future evolution of the system of international relations requires not only a modelling of the US government's behaviour pattern but also one of other relevant geopolitical actors as a response to the United States' strategic turnabout. Questions linger about China as well as Europe, which is still fumbling in its attempts to promote its strategic autonomy more assertively. There has been a breakdown in the equilibrium that characterised the postwar international order, but no other has yet been achieved.

Speaking strictly about energy, the new orientation of US foreign policy, embodied in the '2025 National Security Strategy' (The White House), reiterates the strategic centrality of the concept of 'energy dominance' that was already contemplated in the 2017 National Security Strategy of the first Trump era. The thesis of the 2025 National Security Strategy, presented in November 2025, was predictable given that it reflected the positions that collaborators from the Heritage Foundation (the 'think-tank' that inspired a good number of the Trump administration's initiatives) had insistently advocating for throughout the year. In July, D. Fuchtgott-Roth (2025) clearly explains the meaning of this strategy: 'The Trump administration's energy dominance agenda is not a mere economic policy but a strategic doctrine. Its objectives are clear. One: Ensure energy independence through the use of fossil fuels and nuclear energy. Two: Influence global energy prices. Three: Provide reliable and accessible energy to Americans and their allies. Four: Reduce reliance on China's green energy supply chain'. The wording of the 2025 National Security Strategy (NSS 2025) largely reflects the spirit of these words and marks a clear departure from the Biden administration's more climate policy-focused strategy. In pursuing a decarbonization policy, President Biden restricted oil and natural gas development and imposed regulations to fossil fuel production and infrastructure (I.E.A 2025 a).

This intellectual climate explains the changes in the concept of energy dominance in NSS 2025 with respect to NSS 2017, as indicated by Escribano, Lázaro, and Urbasos (2025). NSS 2025 declares that 'restoring American energy dominance (in oil, gas, coal, and nuclear) and reshoring the necessary key energy components is a top strategic priority'. Here, the exclusion of renewable energies is significant, something that did not occur in the 2017 National Security Strategy. On the other hand, it is clearly stated that 'we reject the disastrous "climate change" and "Net Zero" ideologies

that have so greatly harmed Europe, threaten the United States, and subsidize our adversaries'. This language represents a hardening of this Trump administration's climate scepticism with respect to the first Trump term and is consistent with the 2025 decision to leave the Paris Agreement.

As the International Energy Agency's World Energy Outlook (IEA 2,025 a) shows, this reorientation of US energy policy does not imply a halt to all decarbonisation options. The so-called 'One Big Beautiful Bill Act' of the Trump presidency accelerates the elimination of tax credits for wind and solar photovoltaic energies as well as for electric vehicles, whilst promotes domestic production of oil and gas. However, it expands tax deductions for CO₂ capture, nuclear energy, biothermal energy, bioenergy, and battery storage technologies. Regardless, the US is now the world's leading producer of oil and natural gas and a net exporter of both, so preserving this position as the axis of its energy dominance is a strategic imperative not only in terms of competitiveness but also as a guarantee of national security.

In the long term, however, in the IEA's current policies scenario (CPS), by 2050 US oil and gas consumption would be similar to its current consumption, with hardly any substitution of petroleum products in transport and a limited substitution of natural gas in industry and electricity generation. The strategic central role of fossil fuels would be maintained in the long term, therefore, and, in the scenario indicated, the reduction of CO₂ emissions in 2050 would be only 9% in a country like the United States that is the world's second largest emitter (12% of total emissions in 2024) (IEA 2025 a).

In China, the world's leading emitter of CO₂ (33% of total emissions in 2024), another fossil fuel — coal — plays a fundamental role in ensuring energy supply security given the high degree of self-sufficiency of this fuel: domestic coal production in 2024 accounted for 94% of consumption (IEA b). China is a highly electrified country with the expectation of maintaining, especially in the medium term, sustained growth in electricity demand. According to the IEA in its CPS scenario, the weight of coal in electricity generation (58% in 2024) will trend downwards (36% in 2035 and 21% in 2050), given its enormous program to expand renewable and nuclear generation capacity, but in the medium term (2035) the volume of electricity generation with coal will remain approximately stable. In fact, there are 200 GW of coal-fired generation capacity currently under construction. This investment has been justified for the purpose of incorporating CO₂ capture technology and for the contribution of these plants to backing up the growing renewable capacity (the IEA itself recognizes that, for this function, the alternative of new coal plants will have cost advantages in relation to natural gas plants). In this scenario, although the IEA foresees a reduction in coal demand for the steel and cement industries, a significant reduction in CO₂ emissions can hardly be expected in the medium term.

The case of India (third largest emitter with 8% of total emissions in 2024), although on a much lower scale, has similarities with China in terms of its dependence on coal. Like China, its degree of self-sufficiency is very high (domestic production represents 82% of consumption) and it foresees a strong increase in its renewable and

nuclear electricity generation capacity, but preserving its coal generation capacity in the medium term. As in China, the weight of coal power generation is significantly reduced in the 2035 horizon (falling from 74% in 2024 to 46% in 2035), despite experiencing an increase in volume. (IEA 2025 a, 2025b).

The security imperative has therefore become a central determining factor in the long-term maintenance of a high dependence on fossil fuels for the top three CO₂-emitting countries (China, the US, and India), which together also account for 53% of global emissions. It is true that only the United States has explicitly formulated an 'energy dominance' strategy focused on fossil fuels, but it is enough to recall the intensity with which both China and India argued to illustrate their position in the terminological dispute of previous COPs (defending the 'phase down' against the 'phase-out' with respect to the elimination of coal). It can also be argued that, in the long term for China (by far the largest current emitter), the expected sharp demographic decline will contribute to correcting the weight of its emissions (which would go from 33% today to 25% in 2050). However, on this horizon, India, which follows the reverse trend, represents a significant counterweight (it would go from 8% of total emissions in 2024 to 12% 2050), slightly surpassing the US, which would maintain 11% of total emissions in 2050.

All these data correspond to the IEA's Current Policies Scenario (CPS). (IEA a) and, as the agency itself warns, should not be considered a forecast. Yet they must be taken into account, firstly, to recall the long-term geopolitical relevance of the global cycle of resources–production–trade–consumption of fossil fuels; and, secondly, to enrich the reflection on the challenge posed for global climate policy by the strategic role attributed to fossil fuels in the security policies of the main CO₂ emitters.

In fact, in the year since E&G's last publication, the international framework in which climate policy is developed has worsened. Global warming is a negative global externality and therefore requires a global cooperative policy to address it. It can hardly be considered that progress has been made in this regard, with the abandonment by the US of the Paris Agreement, its exit from the IPCC and the UNFCCC, and its proposals of the N.S.S. 2.025; nor, of course, with the escapism strategy of China, the first issuer, who would be responsible for assuming the leadership role in the context of climate scepticism in US energy policy. Nor does it seem that the cooperative climate has prevailed over the conflicts of interest at COP 30 in Brazil, where the variety of issues discussed (Henderson 2.025) has been accompanied by a web of debates in which the most common outcome has been the absence of commitments (in relation to the mitigation policy) or the repetition and limited reliability of execution of others already assumed (e.g., in the financing policy). In this sense, media attention has focused on the impossibility of reaching a consensus in the final statement, relating to the establishment of a 'road map' for the process of 'transition away' from fossil energies that was approved at COP28, at the same time as the global goal for 2035 of tripling renewable capacity and doubling efficiency. The solution adopted has been, as in other issues, to refer the debates to forums parallel to the COP as a method to deal with the absence of unanimity.

Probably, however, the most defining feature of the character of COP 30 is pointed out by Henderson (2025), who points out that 'it is the first time that the United Nations has implicitly recognized that the objective of limiting the temperature increase to 1.5 °C may not be achieved', something that the scenarios of the International Energy Agency have shown with increasing alarm in recent years. In the conference's final statement, 'Mutirão Global' (United Nations, 22 November, 2025), it is recognized that 'limiting global warming to 1.5 °C with no or limited overshoot requires deep, rapid and sustained reductions in global greenhouse gas emissions of 43 per cent by 2030 and 60 per cent by 2035 relative to the 2019 level and reaching net zero carbon dioxide emissions by 2050'. It likewise notes that 'significant collective progress towards the Paris Agreement temperature goal has been made, from an expected global temperature increase of more than 4 °C according to some projections prior to the adoption of the Agreement to an increase in the range of 2.3–2.5 °C and a bending of the emission curve based on the full implementation of the latest nationally determined contributions'. However, it is noted that 'this is not sufficient to achieve the temperature goal'. These quotes from COP30's 'Mutirão Global' are enough to confirm the scepticism of the parties to the conference regarding the possibilities of meeting the temperature limitation objectives set out in the Paris Agreement.

The long-term evolution of CO₂ emissions reflected in the IEA's Current Policies Scenario (PSC) confirms the scepticism regarding compliance with the Paris Agreement expressed in the 'Mutirão Global' of Brazil's COP30. It is true that this scenario can be considered as the most pessimistic of the scenarios presented by the agency (IEA 2025 a) and that, in general, the commitments of the new nationally-determined contributions (NDC) must involve stricter climate policies. However, it should also be borne in mind that the authorship of the NDC presented by the US corresponds to the Biden presidency, and that the foreseeable medium-term evolution of emissions in this country will show an upward deviation as a consequence of the new energy and climate policy of the Trump presidency.

In the IEA's CPS scenario, a temperature increase of 2.9 °C would be reached by the end of the century, the result of maintaining a high dependence on fossil fuels to cover the global energy demand. In the long term, global oil demand would maintain an increasing trend from 100mb/d in 2024 to 105mb/d in 2035 and 113mb/d in 2050; (OPEC 2,025), raising these figures to 113.3mb/d in 2030 and 123mb/d in 2050; global natural gas demand would register a significant growth (30% in 2050 compared to 2024) and global coal demand would experience, after a peak before 2030, a limited drop (-20% in 2050 compared to 2024). Covering this demand would require a 6% increase in the global supply of fossil fuels (oil, gas, coal) between 2024 and 2050. In the same period, there would be a sharp increase in the supply of decarbonized energy (117%), though insufficient to significantly correct the flow of emissions that would remain practically constant (falling by 1%), (IEA 2025 a).

Although the above figures should be considered with caution, they are indicative of the pending challenges of global climate policy. Firstly, it shows that a strong increase in renewable (and nuclear) capacity is not enough to steer the energy system

towards an emissions path compatible with the objectives of the Paris Agreement, unless dependence on fossil fuels is significantly reduced. As such, despite the agreement at COP28 in Dubai to triple renewable energy capacity and double energy efficiency improvements by 2030 (an agreement supported by the IAE and IRENA), the euphoria that followed this agreement can be considered a mirage in terms of guaranteeing the world reaches climate policy targets. It is also true that, in this a scenario, such an expansion of renewable capacity would be difficult to achieve. The global supply/production of renewable energy would increase by 71% through 2035 and would only multiply by 2.6 by 2050 (IEA 2025 a)³. Even so, given the long-term evolution of fossil fuel demand, the result would be a high level of 'stranded investments' in addition to a foreseeable non-compliance with climate objectives. Secondly, it must be taken into account that climate warming is a function of the concentration of greenhouse gases in the atmosphere (a 'stock' variable) and that, therefore, the temporal profile of the convergence towards a situation of net-zero emissions is fundamental. Delays in this process will require additional efforts in subsequent phases and even the application of higher-capacity carbon sinks. Thirdly, the prospect of a notable deviation of temperatures from Paris Agreement targets makes adaptation and damage coverage policy a central ingredient of climate policy (something COP30 considered), although a potential 'moral hazard' effect that could weaken mitigation policy must be prevented.

The temporal profile of CO₂ emissions described, clearly incompatible with the long-term decarbonisation objectives of climate policy, corresponds, as already mentioned, to a scenario (the IEA's CPS scenario) defined by the continuity of the policies currently applied. It is therefore unlikely, since it would imply the total absence of new corrective policies of global scope, but is still an indicator of the consequences of the lack of ambition in climate policy. But it is also a sign of the uncertainties that affect energy markets in the medium and long term and the evolution of the geopolitical balances of power, whose dynamics will be conditioned by the greater or lesser intensity of decarbonisation policies implemented in the future to correct the continuing scenario we have just examined. The year 2025 has certainly offered some signs of uncertainty in forecasts of the future evolution of oil and gas markets.

On the one hand, the past year has made it possible to clearly illustrate the imprecise causal relationship between geopolitical risk and oil market prices that was already identified in E&G 2024, where this phenomenon was analysed by Ferrari, Lappe, and Rößler (2023), who examined the historical evolution of an indicator of geopolitical risk (Caldara and Iacoviello's Global Geopolitical Risk Index) and oil prices, as well as the reaction of the oil markets to specific events such as the 11 September, 2001 attacks, the Russian invasion of Ukraine in February 2022, or the

³ The IEA (IEA 2025 c) evaluates the commitment of the COP28 agreement at 11,000 GW of renewable capacity by 2030. Taking into account the new NDCs (and those submitted since 2015), the IEA estimates that it would reach 1,635 GW. However, it sees NDCs as underrepresenting governments' current plans. The IEA's analysis of existing policies, plans, and estimates for 189 countries brings the capacity figures to 8,350 GW.

terrorist attack on Israel on 7 October, 2022. As these authors point out, 'geopolitical shocks can have an impact on oil prices through lower economic activity or higher risks to commodity supply.' Ultimately, geopolitical risk would influence the evolution of oil prices through its effect on market fundamentals (costs, net demand, and stocks) which, in turn, also depend on factors other than geopolitical risk.

This assertion is confirmed by Cano's examination of the evolution of oil prices in 2025 (2025), which points to the existence of spikes (e.g. those caused by geopolitical events such as Biden's sanctions on Russia at the beginning of the year or the Iran–Israel conflict in June), quickly followed by a return to moderate prices consistent with a context of oversupply in the market. Cano's conclusion is as follows: '2025 suggests a change in the way in which geopolitical risk has been reflected in oil prices. Geopolitical events continue to condition short-term volatility, but strong supply growth and high stocks have limited the persistence of the price response. As a result, oil prices have become increasingly anchored to underlying supply–demand expectations, with geopolitical risk influencing through short-term volatility rather than a sustained price direction'.

Conversely, the forecasts for the evolution of oil and natural gas markets in the medium term reflect considerable uncertainty. Concerning oil, the IEA report (IEA 2025 d) containing medium-term forecasts (2030) points out this uncertainty ('turbulent times for oil markets' due to trade and geopolitical tensions), highlights significant changes in the structure of the global market, and detects a growing concern for safety whilst anticipating a market profile with excess supply. The forecasts of global demand are similar to those of the continuing scenario previously examined (105.5 mb/d) but in a market in which the leading countries radically reduce their influence. In the 2015–2024 period, the US accounted for 90% of the increase in global supply (a result of the sharp increase in unconventional oil production) and China accounted for 60% of global demand. In the period up to 2030, China would notably moderate its demand (largely reflecting the expansion of electric vehicles) and the US would increase its production, but not by the amount of the last decade. The IEA also foresees a softer market, since it anticipates 5.1 mb/d in production growth for that period (mainly in the US and Saudi Arabia), clearly higher than the expected increase in global demand (2.5 mb/day) and somewhat prefigured by the decision of OPEC+ in May 2025 to end its supply containment policy.

However, the IEA itself, in a subsequent report (IEA 2025 e) on the implications of the productivity decline in oil and gas wells (the annual rate at which well production declines), emphasizes a supply risk which, if not corrected by the necessary investment process, could cause serious imbalances (due to excess demand) in oil and gas markets. The AIE suggests different options to address this correction: 'investment in existing wells to slow the decline and/or boost production; discovery and development of new conventional and unconventional resources; or reduction in demand'. The potential effect of the decline in oil and gas supply is significant: the 'natural' rate of decline (if all investment were halted) would be in oil by 8% per year in the next decade (global production would be reduced by that percentage) and in natural gas by 9% per year.

It is significant to note that the IEA (IEA 2021) indicated that the profile of global demand for crude oil in the net-zero emissions scenario (75 mb/d in 2030 and 23 mb/d in 2050) would not require the exploration of new resources nor more wells than those whose development has already been approved. With regard to natural gas, no new operations would be required beyond those currently being developed. As in the oil sector, there is overlap in the natural gas sector between the aforementioned concern about the effects on global production of the decline of existing wells and the medium-term forecast of a market with a tendency to oversupply. M. Fulwood (2026) points to an expected growth in the supply of liquefied natural gas of around 50% between 2025 and 2030, after a tense market period from 2020 (COVID pandemic) to 2025.

The gap between the scenario corresponding to a policy of continuous decarbonisation (such as that represented by the IEA's CPS scenario) and that corresponding to the application of rigorous climate policy (net zero emissions by 2050) is so wide that it raises new uncertainties, not only in terms of the effects of climate warming but also in relation to the medium and long-term evolution of relevant economic variables such as prices and investments in the energy sector. It is enough to point out as an example the hypotheses of oil price evolution in both scenarios used by the IEA (in the CPS scenario, prices would be \$89/b in 2035 and \$106/b in 2050; in the net zero emissions scenario, they would be \$33/b in 2035 and \$25/b in 2050).

As for investments, as has been pointed out, the distance is not only quantitative but qualitative. Whilst in the zero net emissions scenario, new investments in 'upstream' oil and gas would cease, in the 'continuing' scenario the risk to supply, imposed by the decline of existing wells, could require significant investments in new oil and gas production capacity, both conventional and unconventional. The risk of 'stranded investments' in this context of uncertainty is high, not only in the oil and gas sectors, but also in decarbonised technologies (renewable and nuclear). This scenario of uncertainty is further exacerbated by the effect of new factors that amplify geopolitical risk (tariff wars, the increasing use of energy as a means of punishment, the reinforcement of foreign policies to guarantee the supply of primary energy resources and critical minerals, etc.). Ignacio Urbasos, in his paper in this issue of E&G, conducts an in-depth analysis of the new geopolitical determinants of the global natural gas market that have replaced the predominant pattern in the preceding liberal order.

Over the period since the previous edition of E&G, new challenges and uncertainties have emerged regarding the medium and long-term future evolution of the geopolitical energy scenario, but the centrality of industrial policy (and within it, of technology policy) has also been reactivated to face them. This reactivation was already examined in last year's E&G, but it has experienced fundamental support with the International Monetary Fund's publication of its 2025 World Economic Outlook, which devotes one of its three chapters to industrial policy. The IMF's traditional doctrine gave structural reforms (of an essentially horizontal nature, that is, without prioritizing sectors or companies) the central role in the microeconomic

accompaniment of policies of growth and macroeconomic balance. However, in the aforementioned 2025 World Economic Outlook, the FMI, although still showing its preference for structural reforms, explicitly expresses its support for a well-designed industrial policy: 'Industrial policy has returned to the centre of policy debate. If well designed and targeted to address production-side market failures, it can improve economic outcomes at sectoral and aggregate levels. The experience of countries such as Korea illustrates that carefully crafted subsidies, aligned with clear objectives and implemented within a sound institutional framework, can catalyse structural transformation'. (IMF 2025 a).

Governments use a wide range of instruments in the implementation of industrial policy: subsidies, tax write-offs, advantageous credit conditions, contributions of public capital, price regulations, public procurement, promotion of public infrastructure, trade protectionism, etc. Criticisms of industrial policy have focused on its financial cost (in those measures that involve a contribution of public funds), but above all on the distortion in the allocation of resources that the action of governments would cause, with respect to that which would derive from market signals, especially through their 'picking winners' (sectors or companies benefiting from industrial policy measures), which public authorities would undertake based on information inferior to that provided by the free market. This sceptical view of industrial policy has been predominant in academic circles over the past few decades. The 1992 Nobel Prize in Economics, Gary Becker (1985), who, representing the most radical opinion, stated that 'the best industrial policy is none at all', was already cited in the previous edition of E&G. Recently, however, two other famous academics, Daron Acemoglu (Nobel 2024) and Philippe Aghion (Nobel 2025) make a nuanced defence of technological and industrial policy, respectively.

Acemoglu (2023) not only defends the need for technological policy that corrects the tendency to underinvest in innovation by individuals and companies but also justifies (when there are negative externalities, significant differences in the margins of alternative technologies, or processes of 'path dependence') policies to redirect technological evolution, correcting the trajectory that would induce 'the incentives of benefit, competition, or reputational concerns of researchers'.

Aghion (2016) and Aghion, Antonin, Bunuel (2020) point out that 'the question is not to give a "yes" or a "no" to industrial policy; it is rather how to rethink the governance of industrial policy to make it more compatible with competition and, more generally, with growth through innovation'. In support of this position, they offer a wide range of arguments along the same lines as Acemoglu (negative and positive externalities, 'dependence on the path', economies of coordination, etc.), and even include where to intervene in the tax due to the economic and social priorities of the government (for example, climate policy) as a criterion for selecting sectors. Although both authors distance themselves from the traditional policies of 'picking winners', it seems difficult that the policies they propose can be implemented without applying a significant degree of selectivity.

The correct design of industrial (and technological) policy is fundamental for the energy sector because it allows the traditional trilemma of energy policy (competitiveness, sustainability, security) to be addressed more efficiently, minimising the intensity of the 'trade-off' between these objectives. It seems clear, for example, that technological innovation can have a cross-cutting positive impact on all of them if the choice of the portfolio of technologies to be promoted is the right one. In this regard, it is useful to examine China's experience. Chinese industrial policy has intensively used practically all the aforementioned instruments in a directional and selective strategy in relation to the sectors and technologies to be promoted. García-Macia, Kotary and Tao (2025) (IMF 2025) quantify the fiscal cost of Chinese industrial policy measures at 4% of GDP and estimate the effect of the distortion in the allocation of resources caused by this policy on a reduction in factor productivity of 1.2% and GDP of 2%. These figures could characterise Chinese industrial policy as high-cost for the nation's treasury and generating inefficiencies. But it should be noted that the aforementioned analysis does not consider the impact of industrial policy on correcting market failures or disseminating knowledge that would have positive effects on productivity. In addition, it must be taken into account that the selection of which sectors and technologies to support has enabled China, for example, to reach global leadership in production and technologies central to decarbonisation policies (solar panels, batteries, electric vehicles, etc., in the field of renewable energies and remarkable advances in the learning curve of nuclear power generation).

On the other hand, China's leadership in renewable technologies has been largely the result of this combined directional–selective strategy in the choice of sectors to be promoted, with very strong competition between companies in the chosen sector: this is broadly the recipe for industrial policy advocated by Aghion (2016) and Aghion, Antonin and Bunel (2020). China's leadership in decarbonising products and technologies is also an example of the transversal impact of technology policy on the objectives of the energy trilemma, with positive effects on competitiveness (exports and reduction of the cost of electricity generation), sustainability (contribution to decarbonisation), and security (less dependence on external energy supply). Similarly, it is a challenge for Chinese technology policy to advance in the learning curve of CO₂ capture technology as a means of minimising its strong dependence on coal-fired power generation on CO₂ emissions.

The Chinese experience illustrates some relevant aspects that characterise the industrial and technological policies applied to achieve the objectives of the energy trilemma, minimising the 'trade-off' amongst them. First of all, it illustrates how the achievement of the objectives is accompanied by costs and that the cost–benefit balance is difficult to determine. Secondly, it shows the idiosyncratic nature of industrial policies (IMF 2025): their design and application depend on the political and institutional characteristics of each country and on specific advantages, as is the case in China with the scale of an economic space that allows it to advance more quickly in the learning curve of new technologies and to take greater advantage of technological externalities and coordinated economies. Thirdly, it seems clear that, within the framework of geopolitical interactions, industrial policies approach the

different objectives of the energy trilemma according to different balances of the rivalry–cooperation binomial. Competitiveness and security policies respond to an imperative of rivalry (competitive advantages or security guarantees are sought against others), whilst sustainability policies (decarbonisation) pursue (and require) global collaboration. Although, as has been pointed out, there are factors, such as technological innovation, that can have a cross-cutting positive effect for the achievement of all the objectives of the energy trilemma, in the new international order it is difficult to achieve a satisfactory global balance of rivalry and cooperation between states.

In the European Union, industrial and technological policies with an impact on the energy sector are taking a path different from both China's directed strategy and US climate scepticism. The EU is a multi-state political entity and, therefore, its governance is clearly unique. Its decision-making processes are slower than those adopted by state leadership and deliberation on the policies adopted is more complex and subject to debate: this certainly makes the EU a model for compliance with the requirements of rationality in the behaviour of states postulated by Mearsheimer and Rosato (2023) (adoption of decisions through the deliberation of policymakers through a robust and uninhibited debate). However, the difficulty of reaching unanimity among 27 Member States (and the Eurosceptic nature of some governments) will increasingly require turning to decision-making instruments of variable geometry that the EU has already used (such as the monetary union, the Schengen Area, reinforced cooperation, or voluntary coalitions). This uniqueness of the EU's governance explains to a large extent the limited assertiveness of its strategic autonomy and, as former high representative J. Borrell pointed out, the resistance to exercising its power in numerous geopolitical conjunctures. Europe is the world's leading trading power, but in the negotiation of the trade agreement with the US it has maintained, as already pointed out, the 'weaker' attitude in a 'game of chicken' (if the game theory analogy is accepted).

The Letta and Draghi reports (examined in E&G 2025) have inspired the European Commission's industrial policy road map over the course of 2025 with initiatives such as the 'Competitiveness Compass' (European Commission 2025 a), the 'Clean Industrial Deal' (European Commission 2025 b), and the 'Industrial Decarbonisation Acceleration Act', which the European Commission must present in 2026 (and has already dealt with notable controversies). The three pillars of European industrial policy, initially proposed by Draghi in his report (and also included in the 'Competitiveness Compass'), are: reducing the innovation gap with the US, the elaboration of a joint decarbonisation and competitiveness plan, and the promotion of security/strategic autonomy by reducing external dependence. As also stated, the European strategy fits perfectly with new 'conventional wisdom' regarding industrial policies defined by the FMI and the Nobel laureates in economics D. Acemoglu and Ph. Aghion, as it proposes a balanced combination of horizontal structural reforms with selective sector-based initiatives.

Included among the horizontal structural reforms proposed are the expansion of the single market (with a special emphasis on the capital market), the correction of

current regulatory fragmentation, and progress towards administrative simplification and debureaucratisation, as well as the proposal of a '28th legal regime', that is, the establishment of a kind of virtual 'off-shore' area that 'would simplify the applicable rules and reduce the cost of bankruptcy, including relevant aspects of commercial, bankruptcy, labour, and tax law' (Competitiveness Compass. E.C. 2025 a). But at the same time, European industrial policy proposes a selective action focused on certain sectors and technologies (defence, energy and new digitization and decarbonisation technologies) that requires the definition of 'strategic sectors' to be supported and, therefore, responds to a logic of vertical intervention close to that of the 'picking winners', although Draghi (2024) rejects this characterisation. The aversion to the label of defender of the 'picking winners' strategy is quasi-generalised even, with nuances, in those such as D. Acemoglu and Ph. Aghion whom accept a certain degree of selectivity in industrial policy.

European industrial policy, on the other hand, more completely minimises the 'trade-offs' between the objectives of the energy trilemma. As has already been pointed out, the US figures its 'energy dominance', one of its keys in its national security strategy, in its leadership position in the global supply of oil and natural gas and, in addition, it doctrinally rejects the fundamentals of decarbonisation policy, which not only affects its domestic energy policy but also its behaviour in relation to global climate policy (abandonment of the Paris Agreement).

As for China, despite its plans for massive expansion of its decarbonised generation capacity (renewable and nuclear) and taking full advantage of its domestic and international leadership in decarbonised technologies, it still foresees a strong dependence on coal, which, given its high degree of self-sufficiency in this resource, is a strategic security factor.

For Europe, in contrast, being poor in primary energy resources and highly dependent on the outside for the supply of fossil fuels, the requirement of decarbonisation (sustainability) is also a security imperative. Therefore, unlike the aforementioned expected long-term evolution of CO₂ emissions in China and the US, which is clearly incompatible with the objectives of global climate policy (if current policies are not corrected), the European Union's targets (a 55% reduction in emissions by 2030 and a 90% reduction by 2050) are consistent with the imperatives of global decarbonisation policy. This is reflected in the terms of the commitment ('Nationally Determined Contributions') presented at COP 30 (European Council 2025) and in the aggregation of Member States' National Energy and Climate Plans (NECPs) (European Commission 2025 c), which reflect the trajectory to meet these targets in the medium and long term.

The ambition of the European Union's climate policy has been criticised first of all due to Europe's small share of global emissions (6%) when compared to those of China (33%) and the US. (12%) and, secondly, for the use of domestic resources to benefit 'free riding' countries that would take advantage of the global impact resulting from the European effort. However, Bilan and Känzig (2025) state in their work that sufficiently broad unilateral decarbonisation, especially in economies of a certain size,

can lead to a domestic benefit (avoided damage in the economy considered) greater than the cost of reducing emissions and that, according to their estimates, a unilateral decarbonisation of 86% in the US and 84% in Europe would lead to a positive cost–benefit balance in both economies.

As we have seen, European industrial policy contemplates a more intense containment of the trade-off between security imperatives and those of decarbonisation than would result from the application of industrial policies in the US and China. This does not logically entail the elimination of the traditional trade-off of energy policy (competitiveness, security, decarbonisation). In fact, as the debates around the draft of the 'Industrial Decarbonisation Acceleration Act' show, new dilemmas appear when taking into account the context of geopolitical rivalry that affects not only international trade, but also technological control and, more generally, competition between industrial policies. The competitiveness and decarbonisation plan as a whole, on which Draghi insists in his report and which is a key pillar of European industrial policy, is undoubtedly the most characteristic trade-off.

It is true that this trade-off is relativised with the incorporation technological innovation as a pillar of this policy (with positive effects on all the goals of the energy trilemma). This is especially the case if, in the selection of sectors and technologies, the 'social cost' of emissions is taken into account (updated damage of a marginal emission of CO₂); if the mitigation cost overrun (emission reduction) is lower than the 'social cost', the incorporation of decarbonisation technology is a rational choice based on cost-benefit analysis (of course, this would involve selecting the optimal portfolio of decarbonization technologies based on their respective costs and risks).

As already noted in last year's edition, the quantification of the 'social cost' of emissions has received numerous criticisms for the precision and robustness of the estimates (which have also been extraordinarily varied). It is likewise unnecessary to quantify the mitigation costs of the different technologies, since it is necessary to take into account positive externalities (e.g. the dissemination of knowledge), and the expected schedule of maturation and progress in the learning curve. But even so, the qualitative consideration of both variables is a useful guide for the selective allocation of resources by industrial policy.

More controversial is the inclusion in European industrial policy, as seems to be deduced from the information on the draft of the Industrial Accelerator Act (IAA Act), of concepts such as 'European preference' or 'local European content' in the mechanisms for awarding public purchases or in the conditionality for the authorisation of non-EU direct investments in strategic sectors (technology transfer requirements, percentage of added value, and European shareholding majorities, etc.). This would enshrine the centrality of the notion of 'strategic sector' in industrial policy, something that is consistent with the new 'conventional wisdom' but which opens a new margin of discretion in its designation.

Authors such as García, McWilliams, Poitiers, and Tagliapietra (2025), who accept the new conception of industrial policy ('it must concentrate resources where Europe has competitive potential' but 'also promote healthy competition so that companies

have incentives to innovate'), criticise, however, the logic of 'European preference'. Although they accept the restrictions imposed on foreign products or investments for security reasons (e.g., to avoid excessive dependence on a single supplier or investor), they consider some restrictive requirements incompatible with WTO rules or commitments with countries with which free trade agreements exist. On the other hand, they believe that this selective strategy can prevent the exploitation of the structure of international comparative advantages and induce inefficiencies in the supply chains of exporting companies. These authors, therefore, advocate maintaining decarbonisation as a selective criterion, but disapprove (except for security reasons) of the application of 'European preference' requirements.

In this discussion, two different logics confront each other. On the one hand we have a strictly free trade approach that would make it possible to leverage the cost advantages of the most competitive countries to import necessary inputs into European industry at low prices. On the other hand is an approach close to that of the 'nascent industry' policy, aimed at configuring an industry that, with temporary protections, could become competitive in the medium term, thus shielding it from the abuse of a dominant position by potential quasi-monopoly suppliers (as was the case with European support to Airbus in aeronautical construction). This duality of approaches is reflected in some current proposals, which suggest applying the first of them to the solar panel industry and the second to the configuration of a European battery supply chain. Of course, there are mixed approaches that are also aimed at installing production activities in Europe in collaboration with international technological leaders through joint ventures that incorporate technology transfer and European human resources.

It seems logical that, in the current context of geopolitical rivalry, European industrial policy would adopt pragmatic and non-doctrinal criteria, firmly applying the principle of reciprocity. After all, US industrial policy (without using that name) has traditionally used public procurement policy (especially from the US Department of Defense) to support its own industry. Additionally, and as has been pointed out, China has employed a whole battery of public aid to achieve technological leadership in a series of sectors, among which are decarbonisation products and technologies (in this case, causing, in addition, an excess of generating capacity of an extremely aggressive foreign commercial strategy). European industrial policy must contemplate the demands of international collaboration (especially in the field of climate policy that faces a global negative externality), but also effectively address its reaction in areas of rivalry in which the best response is not necessarily that which would correspond to the ideal of a unified, homogeneous, and harmonious world.

The papers included in this issue of Energy and Geostrategy offer extensive information on factors of great relevance to anticipate the medium and long-term evolution of the geopolitical scenario of energy. Joseph Colman, in his paper 'Geopolitics of Energy: a View from Canada', makes a detailed presentation of Canada's position in global energy geopolitics. This issue is of notable interest today, given the changes in that position caused by trade and political tensions with the US, the gestures of moving closer to Europe and the renewed interest in the Arctic (new

transport routes, access to primary resources, military challenges, etc.): a geographical area in which Canada plays a central role. Colman's paper underscores the specific characteristics that explain Canada's uniqueness in the context of energy geopolitics: geological and geographical factors, historical development of energy infrastructures, but above all the enormous dependence on the US. As the author points out, 'At the core of this question is Canada's unusually close economic and security integration with the United States, and how geography, economics, and demographics overdetermined the integration of their energy systems'. The author, who underlines 'the Carney government's renewed ambition to position Canada as an "energy superpower"', explores in this context 'avenues for energy diversification: eastward toward Europe, westward toward the Indo-Pacific, and northward into the Arctic', although he considers that 'the Indo-Pacific emerges as the most credible medium-term option for diversification'.

This issue of E&G includes two papers on the geostrategy of primary energy resources, one relating to natural gas and the other to critical minerals. Ignacio Urbasos, in the first of these, 'Natural Gas Geopolitics in a New Order', offers a decades-long panoramic view of the evolution of natural gas geopolitics before focusing his attention on the rupture of the international liberal order that, the author states, had led to the creation of 'an interconnected and relatively efficient market, regulated by multilateral institutions and operated mainly by companies, in which complex interdependence seemed to have displaced geopolitics.' Urbasos considers the European Union as the laboratory of this liberal paradigm as, in the decade of the 1990s it 'began the long and complex process of deregulating, harmonising, and integrating the energy markets of its Member States'. These markets were traditionally dominated by state monopolies that governed their internal dimension, with consumers, and external, with suppliers. This liberal order, oriented towards a more liberalised and globalized market, would have also replaced a framework characterised by long-term contracting, price indexation with reference to oil prices, destination clauses and a greater role of remote transport by pipeline. It had also included, as Urbasos points out, a significant increase in LNG supplies and the technological incorporation of 'fracking' that led to the United States' ascent to global leadership in the sector.

The author points to the date of 24 February, 2022, with the Russian invasion of Ukraine, as the most significant moment of the rupture of the liberal order, since 'Europe's energy security architecture collapsed and, with it, natural gas became the centre of great power competition'. In this new geopolitical context, says Urbasos, 'the new rules of the game are the instrumentalisation of interdependence, fragmentation, and geopolitical alignment. The winners are the great powers, capable of imposing their interests, and the losers are those who banked everything on a rules-based order, cooperation, and integration. The new gas order reflects the emerging realist order that is replacing the liberal order: geoeconomics now prevail over the paradigms of interdependence and integration.

The second paper dedicated to the analysis of the geopolitics of primary energy resources is by Maria del Mar Hidalgo, author of 'The Geopolitics of Critical Minerals

for the Energy Transition'. In this comprehensive study, Hidalgo explores the specific features of the type of primary resources (critical minerals such as copper, lithium, nickel, cobalt, and rare earths) that the development of decarbonised technologies now requires following a long period of energy dependence on the extraction of hydrocarbon resources such as coal, oil, and gas. As Hidalgo points out, 'the shift from a fossil fuel-intensive to a mineral-intensive energy system introduces new structural vulnerabilities, stemming not so much from its geological scarcity, but from the extreme concentration of production, processing, and manufacturing in a small number of countries'. The author indicates that 'The high concentration of production and, above all, refining — with China as the clearly dominant actor — turns critical minerals into instruments of geopolitical power. Although the disruption of the supply of critical minerals in the energy sector would not have short-term consequences, its long-term effects would imply slowing down the energy transition and preventing the fulfilment of climate objectives'. However Hidalgo's paper warns that 'no strategy based exclusively on the opening of new mining exploitations can solve the bottlenecks in the short term, due to long development times, price volatility, and regulatory and social uncertainty. In this regard, recycling, the circular economy, technological innovation, and the replacement of materials emerge as indispensable pillars to reduce the pressure on the primary supply, although their contribution will remain limited in the short term. The energy transition therefore requires far-reaching industrial planning, accompanied by public financing mechanisms, investment support, and risk management that stabilise strategic mineral markets'.

Also included in this issue of E&G are two papers on two technologies, nuclear fusion and artificial intelligence, with different maturation processes and commercial exploitation horizons, but with enormous long-term disruptive potential in the energy sector. Even today, both authors point to the contribution of artificial intelligence in the advances that fusion technology research is recording.

Sehila M. González de Vicente, author of the paper 'Fusion Energy', in addition to offering in the Appendix a solid technical introduction to this technology, breaks with a quasi-secular scepticism regarding the possibilities of 'nuclear fusion' being part of the energy mix in a given horizon. The author recognizes that the technology's process of maturation is still in a pre-industrial phase but, at the same time, she presents a series of technical milestones that have revitalised confidence in the future of fusion energy, which has resulted, beyond public initiatives (such as ITER), in a sharp increase in private investments. As the author points out, 'in 2025 more than 50 private companies were dedicated to the development of fusion technologies, with an accumulated investment close to \$10 billion since 2021)'.

González de Vicente explains the technological challenges and analyses the milestones that have marked the revitalization of nuclear fusion research: 'The development of fusion energy requires an exceptional level of technological sophistication. For a fusion reaction to produce net energy, it is necessary to achieve what is called 'plasma ignition', a state in which the fusion process itself is self-sustaining. Achieving this involves heating plasma to temperatures of hundreds of millions of degrees Celsius, confining it using extremely intense magnetic fields, and

maintaining these conditions long enough for the energy produced to exceed the energy invested. This milestone was first reached in December 2022, in an experiment at the Lawrence Livermore National Laboratory in the US, marking a historic turning point in the scientific credibility of fusion as an energy source'. But González de Vicente adds a second fundamental factor: 'the advancement of enabling technologies — from new materials to advanced computing capabilities — that significantly reduce the technical and economic barriers that have historically existed'. Although 'nuclear fusion' technology shares with 'nuclear fission' the decarbonised character and the elevated firmness in electrical system operation, the former has an advantage over 'fission' technology due to the lower environmental impact of its waste and the greater accessibility of the fuels used. As the author points out, 'fusion fuels — mainly hydrogen isotopes — are widely available: deuterium is extractable from seawater and tritium will self-generate within the fusion systems themselves'.

In the second paper on technological content, Inmaculada Martínez, author of 'Artificial Intelligence: the Strategic Catalyst for a Resilient and Decarbonised Energy Future', offers a broad overview of the technological progress in AI in recent decades and its current state (still subject to a strong development drive of increasing complexity), as well as the solutions that AI provides to the new requirements of the evolution of the energy sector, especially the electricity sector: fundamental in the decarbonisation process and where, in addition, the data centres required by AI will represent a significant demand shock. The author details the process of scaling this technology: 'artificial intelligence (AI) has evolved from what in past decades was developed through statistical models and scenario planning towards high-performance computing (HPC) and the training of algorithmic machine learning models during the 2000s. But this almost linear trajectory has recently been challenged by advanced AI models that have disrupted technological innovation in the energy sector with models beyond the mathematical algorithms of structured data'.

As Martínez points out, 'Today, AI is already more than a technology. It works as a system of systems that encompasses the different types of advanced AI, such as generative, agentic, deep learning, and frontier models — foundation models, large language models, multimodal models, emerging capabilities, and state of the art — forming an interdependent ecosystem that is joined by the universe of data to be processed, the software and hardware that are used to carry out this task, as well as the processing semiconductors that are required to execute the actions required in energy management and distribution'.

On the other hand, the author considers that 'AI in 2026 has two aims to be achieved: the creation of a new value framework in innovation beyond high-performance computing, and ensuring it is safe, not only from a perspective of ethics and data governance guarantees, but that AI can be considered trustworthy. That is, technically appropriate for its intended use, and standardised and certified for use in industrial sectors and in society'. The author explains the contribution of AI as a tool in different areas of the energy sector, pointing out, like González de Vicente, its application in the developments of innovation in nuclear fusion technology and also mentioning the oil and gas sector (which would have used supercomputing

abundantly in the past). But, logically, the paper devotes more attention to AI's role in the electricity sector, where the growing sophistication of energy and capacity markets, the intelligence requirements of networks that must increasingly incorporate distributed resources of variable generation and storage, and system operation with increasingly complex demands, define a field of application of AI of enormous amplitude. Martínez also highlights the specific challenges posed by AI, which is rapidly evolving, for efficient and safe regulation, subject to increasing and little-known risks such as those induced by agentic AI.

As for the paper by Miguel Golmayo, author of 'Energy Port Infrastructures: Pillars of Global Energy Security', makes a detailed analysis of the security challenges associated with hydrocarbon port loading and unloading centres as fundamental infrastructures in the maritime transport of oil and gas but which, as Golmayo points out, have usually been neglected by the public attention focused preferably on other strategic points in maritime routes commonly known as 'chokepoints' (the Panama Canal, the entrances to the Red Sea, the Strait of Gibraltar, the Strait of Malacca, the Bab el-Mandeb Strait, etc.). The author points out that, however, the strategic substitutability of ports is lower than that of maritime routes (which offer alternatives). In addition, he emphasizes that other specific features, such as the concentration of energy facilities in their surroundings and the location of populations in their vicinity, add a potential vulnerability greater than that of other infrastructures, 'especially in a context of growing threats of all kinds, physical and cyber terrorism, geopolitical tensions, extreme natural events, armed conflicts, etc.'. The author explains in detail the specific risks of port infrastructures that play a crucial role in oil, gas, and petroleum product logistics. With respect to oil, it names Rotterdam in Europe, Houston in the US, Ras Tanura in Saudi Arabia, and Singapore in Asia. As for LNG, he highlights Ras Laffan in Qatar, Sabine Pass in the US, Sines in Portugal, Yamal in the Russian Arctic, Dahel in India, Incheon in South Korea, and Yokohama in Japan.

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Interview with Mr. Landon Derentz, vice president, energy and infrastructure, senior director and Morningstar Chair for Global Energy Security at the Atlantic Council Global Energy Center

In a dialogue within the framework of an institution such as the Atlantic Council, it is almost obligatory to begin this interview by asking for your view on the future of the transatlantic bond between Europe and the United States, both in its military and in its economic, commercial, and energy dimensions

The transatlantic relationship remains foundational to U.S. and European security and prosperity, even as it is clearly under strain. That should not be surprising. The institutions, economic assumptions, and security frameworks that defined the partnership over the past eighty years were built for a very different geopolitical and technological moment. What we are seeing now is less a breakdown of the bond than a renegotiation of how it should function going forward. In many cases, the challenge is not that these institutions failed, but that they were designed for a different era and are struggling to adapt as geopolitical competition, technological change, and industrial policy reassert themselves.

Even among policymakers in Washington who are skeptical of aspects of the European Union, there is still a broad recognition that the United States is more effective when it works with Europe. As Secretary of State Marco Rubio suggested at the Munich Security Conference this year, disagreements across the Atlantic are not evidence of permanent divorce; they are signs of two mature partners adjusting to a changing world. The United States is prepared, if necessary, to act alone, Rubio said in his address, but it is America's "preference and it is our hope to do this together with you, our friends here in Europe," he underscored.

Today's tensions stem less from a weakening of the partnership than from a growing recognition that many pillars of the post-war system need renewal to remain effective in a more competitive and less predictable world. Institutions such as the United Nations, International Monetary Fund, World Bank, and NATO remain essential to global order, but their influence depends on their ability to adapt with greater speed and realism. The current U.S. posture — including terse economic tactics and confrontational rhetoric around Greenland — has undeniably jolted Europe. Yet over the longer arc, this shock may prove constructive.

A more capable European defense posture, including serious movement toward higher defense spending, strengthens NATO rather than weakens it. Our defense industrial bases remain deeply intertwined; one need only examine the supply chains behind the F-35 Lightning II to see how mutual reliance already defines transatlantic security.

Energy policy reflects a similar dynamic. The pursuit of an energy transition remains the focus of most countries, but it is constrained by the reality that fossil fuels still underpin system stability, affordability, and industrial competitiveness. Climate action must therefore proceed in a way that does not erode the strategic position of Europe and the United States vis-à-vis competitors such as China, which continues to

leverage conventional energy at scale as a tool of geopolitical influence.

Recent U.S. policy shifts — including withdrawal from the UNFCCC process, departure from the Paris Agreement, and reconsideration of the EPA’s Endangerment Finding (the 2009 legal determination that greenhouse gases threaten public health, forming the basis of federal climate regulation) — should be understood not as the end of transatlantic climate cooperation but as part of a longer recalibration.

Over time, the United States and Europe will still need to align on energy security, industrial policy, and climate risks, because none of those challenges are manageable alone.

What features, in your view, distinguish the energy policies implemented in Europe from those applied in the United States? And what would you recommend to promote an energy policy in Europe that supports improving the competitiveness of its productive structure?

The most fundamental distinction between European and American energy policy begins with geography. The United States benefits from a large and diverse domestic resource base — oil, natural gas, coal, nuclear potential, and significant renewable capacity — which gives policymakers more flexibility in balancing affordability, security, and industrial competitiveness. Europe operates under tighter geological and physical constraints. Greater import dependence has pushed European policy toward diversification, efficiency, and managing exposure to external suppliers.

A second difference lies in the innovation ecosystem that supports the energy system. The United States tends to move more quickly from research to deployment, supported by deep capital markets and the integration of public research institutions such as the Department of Energy’s national laboratories. That structure allows the United States to pursue multiple technological pathways simultaneously, from advanced nuclear and fusion to geothermal, and storage systems. Europe has strong research capacity of its own, but innovation often advances more unevenly across member states, reflecting differences in national policy priorities.

For Europe, maintaining an affordable and reliable energy system while preserving industrial capacity will require a pragmatic approach to resources and supply chains. Where indigenous resources exist, they should be used strategically. Continued natural gas production in the North Sea, for example, can provide stability and complement LNG imports — including from the United States — as Europe manages long-term supply risks.

Europe should also prioritize energy technologies whose supply chains can be anchored largely within the continent and strategic partners. Nuclear energy is a clear example: it provides firm power, supports electrification, and reduces exposure to external energy suppliers in ways that intermittent sources alone cannot, especially to the degree clean energy supply chains rely on China. Strengthening domestic manufacturing and fuel-cycle capabilities around these technologies would contribute directly to competitiveness.

Finally, improving energy competitiveness will depend not only on fuel choices but on institutional agility. Both Europe and the United States face regulatory systems that were designed to improve environmental performance but now risk slowing infrastructure development, grid expansion, and manufacturing needs at a time when energy demand is rising. Europe's response to the energy crisis following Russia's invasion of Ukraine showed that faster action is possible. Germany's rapid construction of LNG import terminals demonstrated that when energy security becomes urgent, permitting and investment barriers can be overcome – that mentality needs to be more pervasive in all efforts to push back on deindustrialization.

Increasingly, energy policies prioritize security over the requirements of sustainability, competitiveness, and affordability. What consequences do you foresee?

It is not so much that energy policy is suddenly prioritizing security over sustainability, affordability, or competitiveness. Rather, policymakers are rediscovering something that had been easier to overlook during the post-Cold War period of relative geopolitical stability: energy systems are always shaped first by security considerations. For many years, stable trade flows and seemingly predictable supply chains allowed governments to assume that market efficiency and environmental goals could advance without major strategic tradeoffs. That premise is increasingly difficult to reconcile with global affairs today.

Russia's invasion of Ukraine demonstrated how quickly energy dependence can become a strategic vulnerability. At the same time, the concentration of critical mineral supply chains — particularly in China, which accounts for a majority of global processing capacity for many key materials — underscores that the transition to new energy technologies does not eliminate geopolitical risk; it shifts where those risks sit. Together, these developments force governments to refocus on how energy infrastructure, fuel supply chains, and technology inputs fundamentally underwrite national resilience.

Another factor reinforcing this shift is the outlook for demand. Electricity consumption is rising across advanced economies, driven by electrification, digital infrastructure, reshoring of manufacturing, and demographic trends in some regions. The expansion of artificial intelligence alone is expected to add meaningful load growth in the coming decade. As demand rises, the political pressure to ensure reliability and affordability intensifies, making it harder for governments to narrow their energy options too quickly.

The likely consequence is not the abandonment of sustainability goals, but a more pragmatic approach to them. Conventional fuels will remain part of the system longer than many projections assumed, particularly where they support grid stability or industrial competitiveness. At the same time, countries are likely to invest more heavily in securing supply chains for next-generation technologies — from critical minerals to advanced nuclear and storage systems — often through partnerships among allies and trusted suppliers.

In practical terms, this points toward a more security-conscious energy system overall: one in which diversification, redundancy, and domestic capacity carry greater weight in policy decisions.

The Arctic has become a first-order geopolitical factor, and its importance will intensify as climate warming progresses, with the opening of new maritime routes and access to new mineral resources. How would you describe the most relevant short-, medium-, and long-term impacts?

The Arctic is moving from a peripheral strategic space to a core geopolitical arena. What is changing is more than simple access to resources or shipping lanes, with the focus increasingly on the degree to which states view the region as central to national security, supply chains, and long-term energy security.

In the near term, the most visible impacts are security driven. As seasonal ice retreats the region is becoming more navigable, Arctic states and their allies are prioritizing having an active presence and infrastructure deployment rather than pure commercial expansion. Russia has treated the Arctic as a strategic priority for years, reinforcing military installations and emphasizing control over the Northern Sea Route, while China is becoming more active through investment, research activity, and shipping ambitions. That dynamic is pushing NATO members and partners to pay closer attention to the Arctic, including through new exercises and coordination efforts such as Arctic Sentry, because inaction risks ceding influence in the region to adversaries.

Over the longer horizon, the Arctic's importance will increasingly be tied to resources and strategic positioning. The region likely holds substantial hydrocarbons and mineral deposits, though large-scale extraction currently remains costly and technically demanding. What matters in the nearer term is that the expectation of future access is already shaping how countries position themselves in anticipation of what may become viable decades from now.

For firms already operating in Arctic environments, that early experience carries strategic value. Companies such as Repsol, with operations in Alaska and familiarity with the region's regulatory, environmental, and dynamics with indigenous populations, are likely to be better positioned over time than newcomers attempting to enter the Arctic as conditions evolve.

The IEA highlights a reactivation of nuclear power generation projects worldwide, but the new 3rd-generation reactors still face cost-overrun issues. What is your opinion on the technological challenges and the need to advance along the learning curve for these reactors to become competitive?

Cost overruns in new nuclear projects reflect how the industry manages complexity, financing risk, and execution. Whether we are talking about large light-water reactors or small modular reactors (Gen III+ or Gen IV), nuclear construction requires long timelines, highly specialized components, and regulatory stability over decades. When supply chains slip, regulatory requirements shift, or political backing

weakens, costs escalate quickly because delays compound over such long construction periods.

Design maturity is another persistent issue. Nuclear reactor projects require the design to be fully finalized prior to construction. Even small engineering adjustments made during construction can cascade into significant cost overruns. Developers of next-generation reactors are trying to simplify designs and standardize components precisely to reduce this risk, but the industry is still early in that transition.

Ultimately, the competitiveness of new nuclear depends on moving from first-of-a-kind projects to repeat deployment. First-of-a-kind plants inevitably carry higher costs because investors price in construction risk, regulatory uncertainty, and untested supply chains. The challenge for policymakers is therefore less about proving the technology works and more about creating conditions that allow multiple units to be built so that learning effects, standardization, and financing confidence can bring costs down over time.

Ensuring the supply of critical minerals is a key factor in the development of decarbonization policy. What is your opinion on the changes in global supply chains that this implies, and what impact do you believe it may have on geopolitical balances?

Ensuring the supply of critical minerals is less about decarbonization alone than about strategic autonomy in a world where supply chains are increasingly used for geopolitical leverage. The shift we are seeing is not toward self-sufficiency, which is unrealistic, but toward resilience — the ability to make strategic choices, even when under stress.

China's dominance explains why this shift is happening. It controls roughly 60 percent of global critical mineral production and about 85 percent of processing capacity, including close to 90 percent of rare earth refining. That concentration matters more than geology alone, because the most important chokepoints often sit downstream in refining, component manufacturing, and magnet production. In practical terms, a disruption in processing capacity can halt entire industries, from electric vehicles to advanced defense systems, regardless of where the raw materials are mined.

The consequence is that global supply chains are reorganizing along two parallel tracks. First, countries are trying to diversify production and processing through alliances with partners such as Australia, Canada, and Argentina. Second, governments are investing heavily in domestic capacity for refining, recycling, and component manufacturing — not to replace global markets, but to ensure they are not wholly dependent on a single supplier.

This restructuring is already reshaping geopolitical balances. Minerals are increasingly viewed as strategic assets, and supply relationships are becoming tools of influence. China has demonstrated a willingness to use export controls on materials such as gallium, graphite, and rare earth elements, reinforcing the perception that mineral supply chains now sit alongside energy and semiconductors as instruments of

state power.

At the same time, China's scale may ultimately create incentives for the rest of the world to innovate around these dependencies. Efforts to develop substitute materials, reduce rare earth intensity in magnets, expand recycling, and redesign supply chains are accelerating precisely because concentration risks are so high. In that sense, China's dominance may prove both a short-term vulnerability and a long-term catalyst for diversification.

The likely outcome is a more fragmented but also more resilient system, in which supply chains are shaped as much by alliances and strategic priorities as by cost alone. Critical minerals are no longer just inputs to clean energy technologies; they are becoming central to how states think about industrial policy, defense readiness, and geopolitical leverage.

What is your view on the impact of artificial intelligence on energy policies?

Artificial intelligence is likely to affect energy policy first as a demand story, not a technology story. The rapid expansion of data centers, digital infrastructure, and advanced manufacturing is already accelerating electricity consumption in advanced economies after years of relatively flat demand. That shift is forcing policymakers to confront a structural reality: meeting near-term load growth requires new generation capacity, stronger grids, and faster infrastructure deployment.

In the short term, AI therefore acts as a catalyst for policy decisions that might otherwise have taken years. In the United States, it has sharpened attention on transmission bottlenecks, grid stability, and permitting reform, because the scale and speed of projected electricity demand leave little room for slow build-outs. It also raises affordability risks. If infrastructure investment and supply expansion do not keep pace with demand, consumers will feel it in higher power prices, which can quickly translate into political pressure.

Over the longer term, AI could help improve the efficiency of energy systems themselves. Advanced modelling, predictive maintenance, grid optimization, and accelerated materials discovery all hold potential to improve reliability while lowering costs. But those benefits are conditional. They only matter if the system has sufficient capacity to support the demand surge in the first place.

What, in your opinion, are the causes of China's leadership in key areas of decarbonization technologies?

China's leadership in key decarbonization technologies is less the result of a sudden technological breakthrough than of decades of deliberate industrial strategy. Beijing invested early in upstream resources, downstream processing, and manufacturing scale at a time when many Western economies were comfortable outsourcing resource-intensive industries. That combination — geology, patient capital, and policy coordination — allowed China to build vertically integrated supply chains across batteries, rare earth magnets, solar components, and grid equipment.

A critical factor has been China's dominance in mineral processing rather than mining alone. Controlling roughly 85 percent of global processing capacity for many critical materials gives Chinese firms leverage across the entire value chain, from raw inputs to finished technologies. Western firms initially contributed to this rise through joint ventures and technology transfer, but China steadily built domestic technical expertise and restricted foreign participation once capabilities matured.

China also benefited from regulatory and financing structures that supported long investment horizons and large-scale deployment. The result is not just cost competitiveness, but manufacturing ecosystems that are difficult to replicate quickly. Rebalancing that advantage will require time, coordination among allies, and a focus on rebuilding processing, not just mining capacity.

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Chapter One

The geopolitics of natural gas facing a new order

Ignacio Urbasos

Abstract

Under the international liberal order, natural gas became fully integrated into globalisation through the expansion of the LNG market, increased transnational investment, the consolidation of international energy governance institutions, and the liberalisation of the sector in much of the world. This process gave rise to an interconnected and relatively efficient market, regulated by multilateral institutions and operated mainly by companies, in which complex interdependence seemed to have displaced geopolitics. Russia's invasion of Ukraine and the subsequent instrumentalisation of natural gas represent a definitive break with this paradigm. Since then, geopolitical logic has prevailed over commercial interests, eroding fundamental pillars of the liberal order such as the use of the dollar and the US financial system, respect for arbitration mechanisms, and the protection of transnational investments. The result is an increasingly fragmented market in which energy flows respond more to geopolitical alignment than to criteria of economic efficiency. This new natural gas order is characterised by the instrumentalisation of interdependence, greater fragmentation, and increased volatility, reflecting the advance of a more competitive and openly realist international order.

Keywords

Geopolitics, natural gas, international order, realism, interdependence.

THE GEOPOLITICS OF A NEW GAS ORDER

UNITED STATES

- THE UNITED STATES HAS BECOME THE WORLD'S LARGEST GAS EXPORTER.
- THE EU IS ITS MAIN DESTINATION, TOGETHER WITH ITS ASIAN ALLIES: JAPAN, SOUTH KOREA AND TAIWAN.
- UNDER THE LOGIC OF 'ENERGY DOMINANCE, TRUMP HAS USED GAS EXPORTS TO OBTAIN GEOPOLITICAL CONCESSIONS.

CHINA

- A DECADE AGO, CHINA WAS POSITIONED TO BE A HUGE MARKET FOR US GAS.
- HOWEVER, CHINA HAS IMPOSED TARIFFS IN RESPONSE TO THE TRADE WAR INITIATED BY TRUMP.
- CURRENTLY, CHINA IS THE MAIN MARKET FOR RUSSIAN GAS, AND THIS TRADE IS EXPECTED TO INTENSIFY IN THE COMING YEARS.
- FOR CHINA, RUSSIAN GAS IS CHEAPER THAN OTHER ALTERNATIVES AND IS TRADED IN YUAN, REDUCING ITS EXPOSURE TO THE WESTERN FINANCIAL SYSTEM.

EUROPEAN UNION

- UNTIL 2022, THE EU WAS THE MAIN MARKET FOR RUSSIAN GAS. SINCE THEN, IMPORTS FROM RUSSIA HAVE FALLEN BY 90% AND ARE EXPECTED TO BE PHASED OUT COMPLETELY BY 2028.
- AS PART OF THE GEOECONOMIC WAR, THE EU HAS SEIZED RUSSIAN ASSETS IN EUROPE AND IMPOSED SANCTIONS ON ITS ENERGY COMPANIES, BREAKING WITH DECADES OF ENERGY INTEGRATION.
- CURRENTLY, NORWAY AND THE UNITED STATES ARE THE EU'S MAIN GAS SUPPLIERS.

RUSSIA

- FOLLOWING THE INVASION OF UKRAINE, RUSSIA HAS ATTEMPTED TO SHIFT ITS GAS EXPORTS FROM THE EU TO CHINA.
- RUSSIA HAS BUILT A SHADOW FLEET OF LNG TANKERS TO TRANSPORT GAS FROM THE ARCTIC TO CHINA, DEFYING WESTERN SANCTIONS.
- WITH THE CONSTRUCTION OF THE POWER OF SIBERIA 2 GAS PIPELINE, RUSSIA WILL BE ABLE TO REDIRECT RESERVES THAT WERE PREVIOUSLY DESTINED FOR EUROPE TO CHINA.



LNG TERMINALS IN THE EU

- OPERATING
- OPERATING AND WITH EXPANSION PLANNED
- UNDER CONSTRUCTION
- PROJECTED



Source: Gas Infrastructure Europe

LNG TERMINALS IN RUSSIA

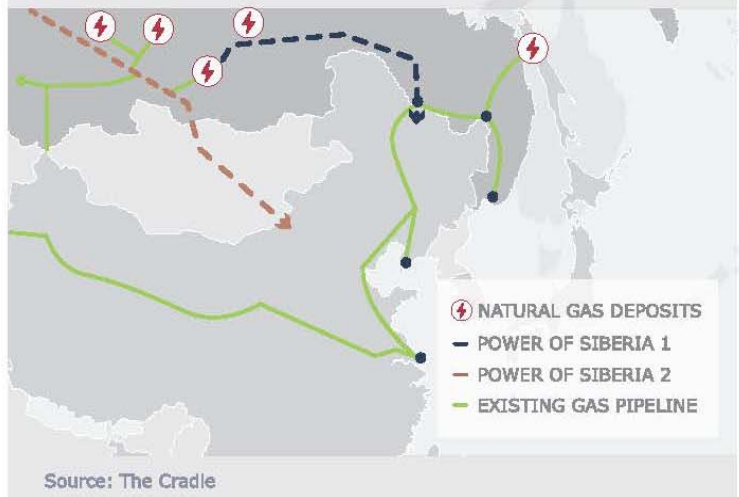
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| 1 SAKHALIN-2 | 4 YAMAL LNG, IV LINE | 6 ARCTIC LNG 2 | ● OPERATING |
| 2 YAMAL LNG | 5 PORTOVAYA LNG | 7 UST LUGA LNG | ● UNDER CONSTRUCTION |
| 3 CRYOGAS-VYSOTSK | | | |



RUSSIA-EUROPE GAS PIPELINES



RUSSIA-CHINA GAS PIPELINES



Introduction

It is clear in the year 2026 that the international system's transition away from the liberal order that had characterised the post-Cold War era is in full swing. The end of the United States' unipolar moment is accompanied by profound transformation in the relationships between states with the return of great power competition, the instrumentalisation of interdependence, a zero-sum revisiting of the globalisation process, and, ultimately, the return of an eminently realist order (Mearsheimer, 2019).

Energy has always been at the heart of geopolitical struggles. However, the mirage of a hegemonic liberal order seemed to offer a path of cooperation thanks to the consolidation of new energy governance frameworks and the benefits associated with complex interdependence (Keohane and Nye, 1973; 1987). After the fall of the Soviet Union, the energy industry underwent an accelerated process of globalisation driven by market liberalisation, the privatisation of state-owned companies, and technological advances, with the Energy Charter Treaty standing out as the pinnacle of multilateralism (Westphal, 2006). Deregulation allowed private players to enter sectors once controlled by state-owned monopolies and, with the end of the Cold War, a whole new landscape of opportunities opened up to transnational investors. Hydrocarbon trading, taking place mainly in dollars, emerged as the keystone of hegemony for the US, who, in exchange for guaranteeing free commerce and maritime security, enjoyed the 'exorbitant privilege' of issuing the global currency (Priest, 2012). The financialisation of commodity markets brought energy commerce to new heights of complexity as traders and futures markets proliferated. With the appearance of new emerging markets, especially China, international trade of oil, natural gas, and coal increased rapidly. This, together with the construction of new infrastructures, generated new flows of energy that overran the old patterns of an export-oriented global south and a consumer-focused global north.

Natural gas stood out as a paradigm case of this inclusion of energy and its geopolitics in globalisation from a liberal standpoint. Major gas projects were undertaken by international consortiums, thousands of kilometres of gas pipelines were built across multiple countries, and many believed in the transformational power of energy integration through gas, from North Africa and the southern cone of South America to relations between the European Union (EU) and Russia. Technological development achieved the feat of normalising the transport of natural gas by ship, liquefying it to $-162\text{ }^{\circ}\text{C}$ and regasifying it at the destination, making consumption of natural gas possible in countries such as Japan and South Korea: true energy islands located thousands of kilometres from the nearest natural gas reserves. As opposed to oil, natural gas was considered safer in geopolitical terms due to the inexistence of a large cartel such as OPEC that could manipulate prices or episodes marked by its instrumentalisation for geopolitical purposes, as had occurred with the oil shock of the 1970s (Goldthau and Witte, 2010). Additionally, in the context of decarbonisation, natural gas took on a central role as a 'bridge' energy vector, a backup for renewables, and a cleaner fossil fuel in terms of both greenhouse gas emissions and air pollution (Gürsan and de Gooyert, 2021).

However, on 24 February 2022, when Russian troops invaded Ukraine, Europe's energy security architecture collapsed and, with it, natural gas became the centre of great power competition. The Russian invasion of Ukraine permanently transformed the geopolitics of natural gas, and its use as a tool of coercion by Moscow, combined with the subsequent Western response in the form of sanctions and confiscations, has ushered in a new gas order aligned with international reality.

1 Background: the liberal mirage in an expanding market

Before the invasion of Ukraine, the gas market had emerged as the energy paradigm of liberal hegemony. Technological advances and liberalisation had taken it from being a highly regulated and relatively regionalised market and placed it in the globalised world. We can identify three major catalysts in this process: the EU's regulatory development, the transformative effect of the LNG market's US-led expansion, and transnational investments through multinational companies.

1.1 The EU as a laboratory for the liberal paradigm

With the end of the Cold War and the peak of liberal hegemony in the 1990s, the European Union began the long and complex process of deregulating, harmonizing, and integrating the energy markets of its Member States. These markets, traditionally dominated by state monopolies. Beginning with the first gas directive in 1998, the EU took its initial steps toward market liberalization, gradually incorporating external suppliers into its regulatory framework and exemplifying the Brussels Effect in global energy governance. By unbundling monopolies and giving third parties access to infrastructures, the Second and especially the Third Energy Package flexed the EU's regulatory muscles, forcing union suppliers such as Russia, Norway, Algeria, and Qatar to adapt to the regulatory requirements imposed by Brussels in exchange for access to the world's largest and most lucrative gas market (Westphal, 2006). A paradigm case is that of Gazprom: after several arbitration losses, the company had to concede on essential points such as price formation and the structure of its European subsidiaries, thereby accepting the EU *acquis* in energy matters (Stern, 2015).

This liberalisation sped up the creation of a profound web of interdependence between the EU and its suppliers which, supposedly, was based on the principles of the free market and the rule of law. During this process, foreign companies acquired stakes in European gas market assets such as storage and trading activities, making these companies part of Europe's domestic market and giving them access to the economic benefits of the entire value chain. Gazprom, for example, before 2022 was not only the top gas supplier to the EU but also the primary operator of underground gas storage on European soil, operated one of the largest gas retailers, and was a shareholder of some of the continent's most important gas pipelines (Jirušek and Kuchyňková, 2018). The EU's approach to energy security attempted to guarantee international market efficiency (Chester, 2010) as opposed to the traditional

geopolitical focus on physical access to resources. The expectation was that, through efficient markets run by private enterprises according to clear rules, energy flows would be depoliticised to the benefit of efficiency, a win-win mindset would prevail and thus disincentivise any instrumentalisation of interdependence (Escribano, 2011).

1.2 The globalisation of gas through LNG

Traditionally, natural gas trading has mostly taken place on a regional scale, with markets concentrated around areas of production or nearby regions, due largely to the high costs of transport. For decades, the most efficient and preferred means of transporting gas over long distances was by pipeline, an option that is subject to significant geographic, economic, and geopolitical limitations. By the 1960s, the technology already existed for cooling natural gas and transforming it into liquefied natural gas that could be transported by sea, similar to crude oil. However, the energy and capital-intensive liquefaction, transport, and regasification process has been much more costly. As a result, no single global natural gas market existed and transactions remained largely regional, with marked price differences between regions depending on the specific conditions of supply and demand.

However, the last 25 years have seen the LNG market experience unprecedented growth and transformation, driven by the same liberal paradigm of business competition and deregulation. The sector has gone from being a space with limited exportation—dominated by three countries: Algeria, Indonesia, and Malaysia—to a much more diversified system with two major exporters, Qatar and Australia, with the especially significant addition of the United States and Russia in the last decade (Mañé-Estrada and Albinyana, 2023).

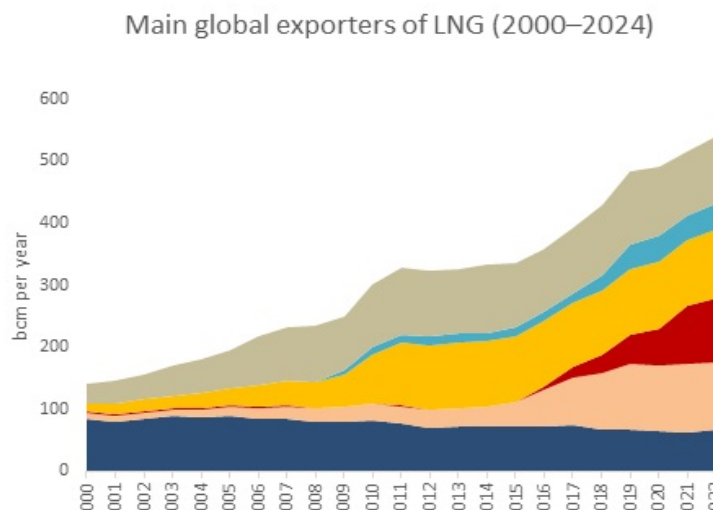


Figure 1. Source: Statistical Review of World Energy (2025).
Bcm = billion cubic metres of natural gas.

As opposed to the oil market, where maritime transport dominated for decades and in 2024 accounted for nearly 77% of international commerce (US EIA, 2024), LNG made up only 27% of the natural gas market in 2000 and had never exceeded 47% before the invasion of Ukraine. From today to the end of the decade, new LNG export capacity, mainly from the United States, Qatar, and Canada, will consolidate this trend by increasing available capacity by more than 50%, whilst no significant growth is expected in gas by pipeline (IEA, 2025).

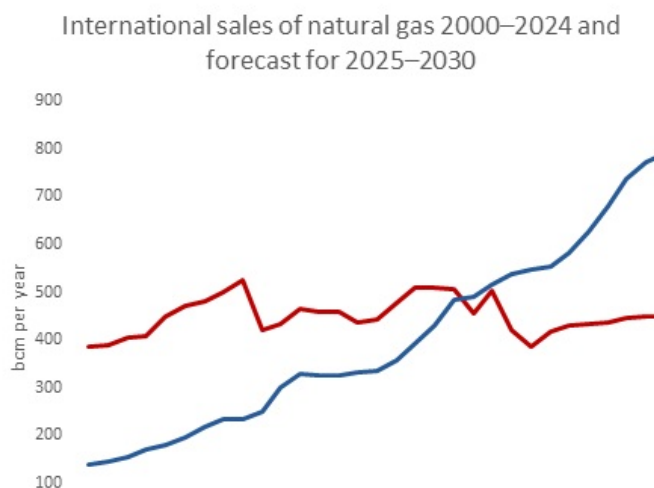


Figure 2. Source: Statistical Review of World Energy (2025), IEA (2025).

At the same time, LNG operations themselves have evolved towards greater flexibility for both buyers and sellers, bolstering the interdependence of gas markets through a process of 'deregionalisation' (Mañé-Estrada, 2022). Traditionally, the LNG business had been based on long-term contracts, generally between 20 and 25 years, which was necessary to finance investments in liquefaction plants and regasification terminals from both a sales and a purchasing perspective. These contracts would usually include strict destination clauses through which the selling party would guarantee a volume of gas per contract which offtakers were required to receive at one or several specified terminals. As such, these contracts worked according to the same logic as gas pipeline contracts, creating veritable maritime corridors that, due to their characteristics, operated like virtual pipelines.

When the United States burst onto the scene as a gas superpower thanks to the fracking revolution (Bros, 2012), it had a transformative effect on how the international gas market operated. LNG contracts signed a decade ago with US-based terminals introduced disruptive innovations into a traditionally rigid market in which long-term contracts dominated. According to Tagliapietra (2022), this contract flexibility is based on two main factors. First, the disappearance of destination clauses, which allows buyers to select the final market for gas purchased. The second factor is the rise of aggregators or 'portfolio players', energy companies that combine volumes of LNG from various sources for redistribution among their customers as needed, whether fixed term contracts or on the spot market.

The percentage of contracts with flexible destination clauses went from 34% on average from 2015 to 2017 to 64% from 2018 to 2020, mainly driven by the sudden appearance of US LNG projects which are also prevalent in new contracts signed in this decade (Tagliapietra, 2022). This contract framework has favoured the growing 'petrolisation' (Mañé-Estrada, 2022) of the gas market: flows are increasingly influenced by market trading and opportunism based on the evolution of different global price indexes and with new intermediaries gaining a larger role in spot market transactions, which now make up about 40% of operations (IGU, 2024) as opposed to the traditional preference for long-term markets.

This is where Title Transfer Facility (TTF), the Dutch virtual trading point, has consolidated its position as the key European benchmark whilst Henry Hub has done the same in the United States, the same way that Brent is for European oil what West Texas Intermediate (WTI) is for oil in North America. TTF offers a liquid and transparent price signal that competes with its Asian counterpart, JKM, emulating for gas the short-term market operations of crude oil (Heather, 2021). Gas indexes have made it possible to 'decouple' natural gas prices from crude oil, which was practised extensively in the industry until the liberalisation of the European market and the arrival of LNG from the United States. The result has been a market that is much more interconnected than in the past. Consequently, spikes in LNG demand in Asia due to a cold spell can attract to that region shipments that traders or portfolio players control all over the world, forcing European operators to offer higher prices to ensure supply. The result is a reconfiguration of the gas market from fragmentation to interconnection, with greater levels of volatility and exposure to geopolitical events but also a notable increase in liquidity and flexibility.

1.3 The transformative capability of transnational investments

The great transformations in the international gas market have taken place through the actions of major multinational companies, both public and private, and their transnational investments. As opposed to the oil sector, more characterised by resource nationalism, the 21st century's major LNG exporters—Qatar, Australia, Russia, and the United States—have developed their capabilities, each with its own peculiarities, in models that are relatively open to the participation of international capital. There are paradigmatic examples of these investment flows: France's TotalEnergies holds shares in four major LNG exporters; US major ExxonMobil is present in the United States, Australia, and Qatar; whilst QatarEnergy, despite being a state-owned company, combines investments in Qatar and the US with long-term supply agreements signed with Australian firms. The natural gas value chain's greater technological complexity incentivised states with natural gas reserves to open their markets to foreign investment whilst the lower resource rent associated with natural gas undercut the resource nationalism that was endemic to oil politics in the last century (Xu *et al.*, 2024).

The major gas pipelines developed over the past decades were likewise driven by international consortiums focused on balancing interests and mitigating geopolitical risk. The Maghreb–Europe gas pipeline, passing through Algeria, Morocco, Spain, and Portugal, was promoted by shareholders that included, in its different sections, at least one entity from each of the states involved. As for the Nord Stream pipeline, it included Gazprom as well as major gas-consuming European utilities. Despite the new international reality that has affected both pipelines, and the fact that the integration of business interests was ultimately insufficient to prevent geopolitical weaponization, at the time of their construction both were considered projects that would generate spaces of shared prosperity, emulating the spirit of economic cooperation that had inspired the European Coal and Steel Community (Hernando de Larramendi & Thieux, 2025).

2 Natural gas turns into a geoeconomic weapon

The Russian invasion of Ukraine destroyed the main commercial flow of natural gas, forcing an unprecedented reconfiguration of the gas market and sparking a price crisis that continues today, though it has abated. This rupture in the Russian–European natural gas by pipeline market has given rise to new gas corridors both on land and by sea, in addition to the appearance of new vulnerabilities, dependencies, and possible chokepoints. This confrontation between Russia and the West has not taken place exclusively on the military plane, as geoeconomics and specifically energy have been central in this crisis.

The EU and the United States have attempted to damage the Russian economy through asset seizures and sanctions on the Russian Federation's largest companies, whilst Russia has responded with equivalent measures against Western assets under Russian sovereign control (Urbasos, 2025). These sanctions have fragmented a gas market that, over the past decades, had experienced rapid convergence in terms of commercial, technological, regulatory, and investment exchanges.

Specifically, the gas pipelines that linked Russia to Europe were the clearest symbol of Moscow's status as a fossil energy superpower and its ability to project this power towards the EU (Bros et al., 2012). Managing this geopolitical dimension had been historically complicated for EU Member States and for European cohesion, as each maintained divergent interests and perspectives (Urbasos, 2024). Through effective trade diplomacy, Gazprom had succeeded in promoting new pipelines such as TurkStream and Nord Stream, which allowed it to get around certain less-than-friendly transit countries, mainly Ukraine and Poland. As such, Russia ended up building a transport network with capacity far beyond the needs and true potential of Europe–Russia exchange.

Russia's weaponization of this dependency therefore cast doubt on one of the pillars of liberal economic theory: the premise that economic interdependence contributed to peace. The major European powers, with Germany at the forefront, had placed their bets on gas interdependence with Russia as a mechanism to create a 'cushion of

interests' capable of containing any hypothetical geopolitical tensions. The idea espoused by Berlin since the fall of the Soviet Union that economic and energy interdependence between the EU and Russia would coax the latter towards the tenets of liberal democracy was decisively discredited on 22 February 2022 (Steimberg, Urbasos, and Escribano, 2025). In terms of energy, the main victim of this 'liberal illusion' (Barbieri, 2009) was the bilateral flow of natural gas between Russia and the EU, a multibillion-euro market that stretched through an extensive network of gas pipelines, intermediaries, storage infrastructures, and long-term contracts.

As a consequence, if in 2021 Russian gas pipelines had supplied 38.5% of EU gas imports, thus securing a dominant position in numerous captive markets, (Henderson and Chyong, 2023), after the invasion—and resulting from the sabotage to Nord Stream and the closing of the Ukrainian and Polish corridors—by 2025 Russian gas via pipeline accounted for only 5% of EU imports. In economic terms, this commercial relationship went from a value of over \$50 billion in 2021 to less than \$3 billion in 2025 (Raghunandan, 2025). At the end of 2025, the EU agreed to a definitive road map to end these imports. Not one Russian gas molecule is expected to reach the European market by the end of 2027.

The rupture of this market has wrought a transformative effect on the global economy. With the loss of Russian gas, especially following the halt in supply and subsequent sabotage of the Nord Stream pipelines, EU businesses scrambled to locate new gas suppliers and found an alternative in LNG which, although more expensive, was much quicker and more modular than the traditional supply by pipeline to the continent. The transition towards a mixed pipeline–LNG European market materialised in a matter of months: in 2021, liquefied gas represented 21% of imports and by the second quarter of 2025 had reached 44%. This transformation has turned the EU into the world's largest importer of LNG, absorbing all the new supply available on the international market, at times supplanting developing countries, and creating new energy corridors that have reconfigured the geography of natural gas. On the EU's new gas map, Russia has been replaced by greater volumes by pipeline from Norway but especially by LNG from the United States.

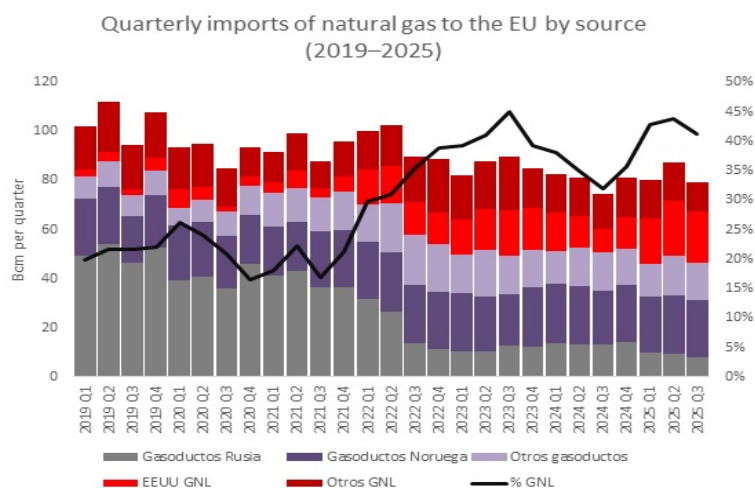


Figure 3. Source: Bruegel (2026)

The war in Ukraine has not just turned the international gas market on its head: it has also meant the dismantling of the arbitration system that had regulated disputes between European and Russian energy companies for decades. The recent court rulings related to the shutting off of the gas supply via Nord Stream and Russia's requirement that gas payments be made in roubles have handed down very different decisions, though the consequences have been especially burdensome for a Gazprom ordered to pay millions in compensation. To avoid further adverse rulings and the execution of their sentences, Russia has turned to its national courts to prevent its companies from complying with the decisions of foreign arbitration courts whilst imposing sanctions on European companies that attempt to use these mechanisms to obtain compensation (Urbasos, 2024).

Meanwhile, both Russia and various European countries have begun nationalising energy assets for strategic purposes, eroding decades of confidence and cross-investment. This process has contributed to the collapse of the institutional framework that was the bedrock of international gas commerce based on free market principles. This evolution in which state sovereignty takes precedence over shared norms and the interests of non-state players such as companies fits with what literature on the subject identifies as a return to neo-Westphalian logic (Esteban, 2025). According to this neo-Westphalian reasoning, the energy system would tend to build itself around sovereign states with primacy over individual rights, including those of juridical persons, and over supranational institutions. In addition to the erosion of the arbitration system, another manifestation of this shift has been the EU's own withdrawal from the Energy Charter Treaty in 2024 upon considering it to be a governance instrument designed for a liberal energy order and based on fossil fuels that has become outdated. Likewise, the United States' and Qatar's outright rejection of the EU Methane Regulation and the EU's Corporate Sustainability Due Diligence Directive (CS3D) are proof of states' growing reticence when it comes to yielding their sovereignty with regard to energy governance.

3 Geopolitical realignment

The end of the liberal gas order built according to the logic of interdependence has given way to a new formula in trade relations that prioritises geopolitical alignment and supply security over economic efficiency or diversification. This new model tends to reinforce the role of great powers, particularly the United States and China, who are capable of projecting their energy preferences over their respective areas of influence.

The clearest example of this emerging paradigm is the transatlantic convergence of natural gas flows towards the EU which, following the Russian invasion of Ukraine, has absorbed over 60% of US liquefied natural gas exports (US EIA, 2025). Since the start of its LNG exports in 2016, the United States has prioritised guaranteeing that the European natural gas market remain open. Washington has traditionally viewed with scepticism the relationship between the EU and Russia with regard to gas: as

early as the 1980s, the Reagan Administration used sanctions in an attempt to prevent the construction of a network of gas pipelines intended to supply the Western European market for the first time in what constituted an energy extension of Willy Brandt's *Ostpolitik* (Forsberg, 2016).

This opposition intensified following Russia's illegal annexation of Crimea in 2014 and was again expressed in response to the 2015 decision to build Nord Stream 2. The US Congress later passed the Protecting Europe's Energy Security Act (PEESA), introducing sanctions against the companies involved in the gas pipeline's construction. At the same time, the first Trump Administration actively promoted US LNG exports to Europe, rebranding it as 'freedom gas' (Jong, 2023).

With the Russian invasion of Ukraine in 2022 and the subsequent European gas crisis, purchases of US LNG increased sharply. This was, in large part, a response to market dynamics, but such purchases were also politically incentivised by the Biden Administration through the creation of the EU–US Task Force on Energy Security, which contributed to coordinating supply and stabilising the European market (Steimberg, Urbasos, and Escribano, 2025).

Since Trump's arrival, LNG has also found a place on the neomercantilist agenda that Washington has imposed on the rest of the world. In one of the most striking provisions of the latest trade agreement between the EU and the United States, Brussels committed to acquiring up to \$750 billion in US energy products, including LNG, oil, and nuclear fuel, between 2026 and 2028. Though these figures are essentially unattainable due to their magnitude, they clearly illustrate the extent to which geopolitics is shaping the configuration of new energy flows. A similar example is that of the investment and purchase commitments of US natural gas made by Japan, South Korea, and Taiwan to placate Washington's trade demands and keep US defence commitments intact.

This is where natural gas exports have become a central component of US foreign policy. Each administration has used this ability differently, from the Biden Administration's emphasis on contract flexibility and supply security to Trump's inclusion of gas in trade negotiations. Regardless, the underlying logic has remained the same: the US seeking to consolidate its position as a key supplier to its allies, thus turning fossil fuels into an instrument of international influence that can bolster its superpower status. Following this logic, the United States' security strategy for 2025 is clear in its definition of the new doctrine of energy dominance: 'Expanding our net energy exports will also deepen relationships with allies while curtailing the influence of adversaries, protect our ability to defend our shores, and—when and where necessary—enables us to project power' (White House, 2025).

This is how the United States has become the world's number one natural gas exporter, whether by pipeline mainly to Mexico and Canada or as LNG. This new energy power projection is focused on US allies—the EU, the UK, Japan, South Korea, and Taiwan—which since 2022 have absorbed about 80% of United States LNG exports. As a result, these economies have developed a new strategic dependence with regard to the United States alongside the traditional security and defence

dependence.

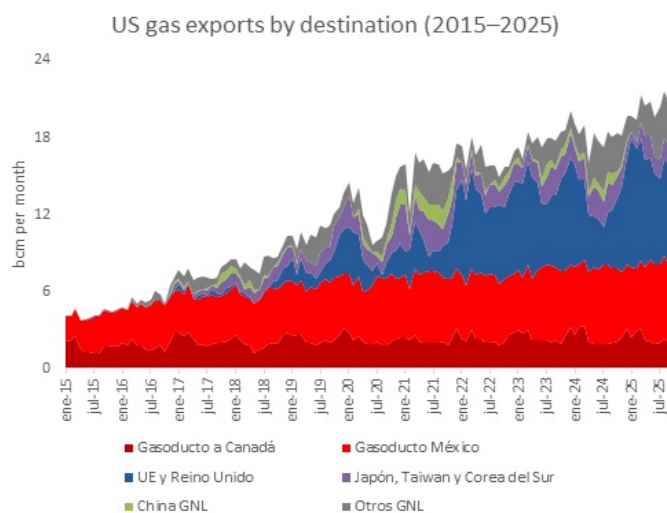


Figure 4 Source: US EIA (2025).

On the other side of the Pacific, a similar geopolitical realignment can be observed. Attracted by the contract flexibility of US LNG and the rapid growth of domestic gas demand, starting in 2016 Chinese energy companies began to take an interest in this supply. However, the trade war launched by the first Trump Administration in 2019 completely interrupted imports, as Beijing identified oil and gas from the US as politically sensitive goods and decided to exercise pressure through targeted tariffs (Corbeau and Downs, 2025).

Trade negotiations in 2020 and 2021 incentivised the signing of numerous long-term supply contracts by Chinese companies, leading to a new upturn in purchases. However, the progressive deterioration of bilateral relations during the Biden Administration and, most importantly, the return of Trump and his onslaught of tariffs led Beijing to reactivate its tariff retaliation on US LNG, slashing imports back down to zero. Despite this, China still faces a strategic dilemma: contracts signed between 2021 and 2023, which began to take effect in 2025, make up six times the volumes imported from the US in 2024 or a third of Chinese LNG imports that same year. This, combined with the growing geopolitical instrumentalisation of gas flows, has sparked concern amongst the Chinese political elite regarding a possible dependence on US LNG and its potential implications for Chinese energy security. All indications point to the persistence of economic tensions between both powers and that China will continue reaching for tariffs on US hydrocarbons as a means of exercising pressure, thereby intensifying the fragmentation of the global gas market.

	Seller	Buyer	Annual volume (bcm)	Term (years)
2018	Cheniere	PetroChina	1.7	25
2021	Cheniere Energy	ENN	1.2	13
		Sinochem	2.5	18
		Foran	0.4	20
	Venture Global	Sinopec	5.6	20
		UNIPEC	1.4	3
		CNOOC	2.8	20
		CNOOC	0.7	3
2022	Energy Transfer LNG	ENN NG	2.5	20
		ENN Energy	1.3	20
		China Gas	1	25
	NextDecade	ENN	2.1	20
		China Gas	1.4	20
		Guangdong Energy	2.1	20
	Cheniere Energy	PetroChina	2.5	25
2023	Venture Global	China Gas Holdings	1.4	20
		China Gas Holdings	1.4	20
	Cheniere	ENN	2.5	20
		Foran	1.2	20
			35.8	

Table 1: LNG contracts between Chinese buyers and US projects. Source: Adaptation¹ of Corbeau and Downs (2025).

In response, China and Russia have developed a closer relationship around energy, with natural gas at the centre of this symbiosis. In 2025, both countries signed a historic agreement to increase natural gas trade through existing pipelines and to build a new gas pipeline, Power of Siberia 2. This gas pipeline will be the equivalent of Nord Stream in terms of capacity and will connect, for the first time, the gas reserves in western Siberia with the Chinese market starting in 2030. These are the same reserves that traditionally supplied the European market and which, since 2022, Gazprom has been unable to trade internationally (Median and Yermakov, 2025). According to Gazprom CEO Alexey Miller, exports will be delivered via 30-year contracts in roubles and yen, and for a lower price than that traditionally paid by Europe², yet another example of geopolitics taking precedence over trade interests (ibid.).

China sees the construction of this pipeline as a decisive step towards reducing its US imports of LNG as well as its dependence on a financial and trade architecture dominated by Washington, all by relying on Russia as an alternative trade partner.

¹ Note on methodology: some volumes or dates have been simplified and are subject to future updates.

² In 2025, China's state-owned CNPC purchased gas from Gazprom at an average price of \$6.5/mmbtu, 45% lower than the average of the EU's gas benchmark, the TTF, in the same period. Gazprom had sold in Europe under various formulas that were often closely pegged to the TTF.

For Russia, in 2025 China became the primary destination for its gas exports for the first time, taking over a position traditionally held by the EU. We can add to this that, when Russian LNG imports to the EU end in 2027, China can be expected to also become its main receiving market, redoubling Russia's growing dependence on the Chinese market to monetise its natural gas reserves. This process confirms the rupture of the Eurasian market in two, with Russian gas reserves rerouted to China as a new geoenergy space takes shape in which geopolitics prevails over commercial interests.

4 The fragmentation of value chains

Since 2014 but most notably starting in 2022, G7 countries have applied successive rounds of sanctions against the Russian natural gas sector with the aim of curbing export income and restricting access to technology and financing that could support its development.

The most relevant financial measures have been the seizing of Russian foreign assets, especially those of Gazprom in the EU, and the freezing of the Central Bank of Russia's international reserves. At the same time, energy companies such as Gazprom Neft, Surgutneftegas, Novatek, and Rosneft—in addition to banks specialised in servicing the gas sector such as Sberbank and Gazprombank—have been designated sanctioned entities by the US, the EU, and the UK. These companies have excluded from the Western financial system, including international payment systems such as SWIFT³, thereby limiting their access to the US dollar or the euro in international transactions.

These measures have broken a prevailing dynamic in place since the fall of the Soviet Union, and a core element in the consolidation of the liberal order, in which practically all international natural gas market transactions took place through the SWIFT system and in dollars (or in euros for transactions between Gazprom and European companies). The sanctions imposed following the invasion of Ukraine have uprooted this system and forced Russia and its customers to seek alternative payment methods. Specifically, Moscow and Beijing have intensified their 'bilateral monetary cooperation' in line with a narrative of 'democratisation of the international financial system', establishing a system of mixed transaction in roubles and yuan that excludes the dollar and the euro as currencies of use (Kluge, 2024).

Since 2022, Russia has eliminated both currencies from its hydrocarbon exports to India, China, and Turkey, whilst loans from Chinese banks to Russian energy project developers are extended mainly in yuan. As for gas, following the first financial sanctions in March 2022, Moscow began demanding payment in roubles from its European and Asian customers. Various European companies complied, and the Asian companies linked to the Sakhalin-2 LNG project gradually adopted a mixed model using roubles, yuan, yen, and won, depending on the national currency of each buyer. Beyond Russia and as a collateral effect of sanctions, this tendency has also

³ SWIFT (Society for Worldwide Interbank Financial Telecommunication) is a global secure messaging network used by banks and financial institutions to standardise information exchange and payment orders, thus facilitating international money transfers.

spread to the LNG market, which had traditionally operated in dollars. In 2023, the Abu Dhabi National Oil Company (ADNOC) and China's CNOOC finalised an LNG transaction supplied by TotalEnergies and paid in yuan (LNG Prime, 2023), one of the first international LNG transactions to take place outside the US financial system.

Another significant effect of sanctions has been the rupture in the natural gas sector's technological value chain. Until 2022, this was a highly globalised market with few players and extremely specialised value chains. One paradigm case would be two projects in the Arctic developed by the Russian company Novatek—first Yamal LNG and later Arctic LNG 2—alongside a consortium of international companies. Both projects became symbols of innovation in Arctic engineering, the result of the combined efforts of companies such as France's Technip, the Japanese firms JGC and Chiyoda, and Germany's Linde, which develop breakthrough solutions for liquefaction in conditions of extreme cold or on permafrost soil. No less noteworthy were the cutting-edge icebreaking LNG tankers built by Daewoo Shipbuilding in South Korea with hulls designed in Finland.

However, this dense network of technological interdependence fell apart with the Western sanctions imposed in 2022. The withdrawal of the projects' European, Japanese, and South Korean partners limited Novatek's access to their engineering and equipment, forcing the company to find domestic solutions whilst reaching out to Chinese and Iranian suppliers to resume project construction. For the first time, Russia has developed technological solutions historically controlled via patents and technical expertise by Western, Japanese, or South Korean companies. The result has been a deep fragmentation of the global LNG value chain, proving that sanctions have not only altered trade flows but have also dismantled the cross-border technological ecosystems that had sustained the sector's rapid growth in recent decades.

A third transformation has been the appearance of a nascent LNG shadow fleet (Urbasos, 2025). As opposed to the crude oil market, where smuggling and transit of cargo subject to sanctions by uninsured vessels or ships of opaque ownership has been a regular practise for decades, the LNG market had never seen a similar phenomenon. LNG tankers are much more valuable and technically complex, not to mention that their operation is limited to a reduced number of specialised and often multinational companies. The LNG market is also significantly smaller: there are nearly 8,000 oil tankers as opposed to only 772 LNG tankers in service, built and maintained in but a dozen shipyards, and operated and insured by a handful of companies. We can add to this that most shipyards, shipowners, insurance companies, and LNG terminals are controlled by Western companies or which have a strong international presence. This explains why Iran, with its extensive experience in evading sanctions and smuggling petroleum, has never successfully developed LNG export projects despite sharing the enormous South Pars/North Dome field with Qatar and from where QatarEnergies exports about 20% of the world's LNG.

When the United States and the EU decided to sanction Arctic LNG 2 in 2024, prohibiting any transactions that could contribute to its development, the measure seemed especially forceful as it was expected that no operator from the sector would

be willing to run the risk of secondary sanctions that could exclude them from the international financial system and its global transactions. Construction on Arctic LNG 2 ground to a halt for several months following the withdrawal of the international engineering consortium responsible for the project. Only Russian companies, with the technical assistance of Chinese engineers, remained on site to attempt to finish the project.

The events of 2025, however, revealed the limits of this strategy. At the end of August, Russia partially completed the project and China received its first shipment from Arctic LNG 2. This operation, repeated in the following weeks, marked a turning point in the effectiveness of sanctions: never before had a project designated as a sanctioned entity by the United States managed to execute commercial operations (Urbasos, 2025). Additionally, the LNG tankers used in transport were likewise subject to Western sanctions, resulting in the first case of what would become an LNG shadow fleet analogous to the well-established crude oil counterpart (Muñoz Abad, 2025). Oil tanker shadow fleets are one of the main tools used by Iran, Venezuela, and Russia to operate in the oil market despite sanctions. Their final destination is often China, which has developed a complex of independent refineries in the province of Shandong used to purchase sanctioned oil at a discount (Velázquez, 2024). This parallel oil trade structure entails significant environmental risks, as shadow fleet ships are usually uninsured by recognised firms, are not as well maintained, and are generally much older. This is why the emergence of an LNG shadow fleet would break with the 'exceptionality' of a sector accustomed to operating under strict legality and maximum operating standards.

Altogether, this triple transformation—the dedollarisation of natural gas commerce, the creation of new technology value chain parallel to Western knowledge, and the emergence of an LNG shadow fleet—point to a future marked by the fragmentation of the international gas market provoked by and, at the same time, despite international sanctions. The fact of the matter is that this fragmentation of the gas value chain is not an exception but rather part of the deglobalisation and reshoring of the value chains that now seem to dominate the new global geoeconomic space. The new gas order reflects the realist order that is replacing the liberal order, with geoeconomics prevailing over interdependence and integration (Mearsheimer, 2019; Farrell and Newmann, 2025).

5 Towards a new gas order

This analysis has attempted to present the transformations that took place under the liberal international order in the natural gas sector, specifically its inclusion in globalisation through the expansion of the LNG market, transnational investments, and the deregulation process promoted by Brussels, which ultimately spread to other suppliers. These processes, independent of one another but with the principles and values of the liberal paradigm in common, brought about an interconnected and highly efficient market. It seemed that institutions had replaced geopolitics and that businesses operated the market according to the maximisation of profit in lieu of states

that operated according to calculations of power. The result was a wide community of exporters and importers who shared rules, technology, knowledge, and, ultimately, a cushion of common interests that created a complex interdependence that would create common benefits and dynamics of cooperation.

Though it is clear that this gas order had begun to erode well before 2022, it was in February of that very year when it became evident that geopolitics would hold dominion over commercial interests and that the liberal paradigm of complex interdependence had largely been a mirage. The liberal and multilateral institutions that had been the foundation of the international gas market were first casualties of the geoeconomic warfare waged on the sidelines of the Ukrainian front between the West and Russia. We have already mentioned several of them in this analysis, such as the use of the dollar and the euro as trade currencies, SWIFT system payments, transnational investments, flows of technology, and the internal arbitration system.

The end of a liberal order for natural gas has given way to a markedly fragmented scenario in which geopolitics determines trade flows with greater intensity than economic efficiency. The clearest consequence of this new reality is the rupture of the gas trade between the EU and Russia and its replacement with growing LNG flows between Europe and the United States. Washington has not hidden the geopolitical facet of its gas exports, spelling them out in its most recent National Security Strategy as yet another instrument of power projection towards rivals and allies alike. Energy flows are no longer mere commercial transactions: they now require geopolitical alignment and, if necessary, strategic acquiescence. Reflecting a neo-Westphalian logic, the main players are no longer multinational companies but sovereign states and their interests.

The other great transformation in the geopolitics of natural gas is the consolidation of the energy alliance between Russia and China. Following the loss of its European market, Russia has had little other choice than to accept the harsh conditions imposed by China for access to its market. Gazprom has needed to adapt to the deadline and terms set by Beijing for the construction of the Power of Siberia 2 gas pipeline, a project that will permanently reconfigure global gas flows as it reroutes to China the reserves supplied to Europe until 2022. China stands out, alongside the United States, as one of the main winners of this transformation. Russian gas is not only cheaper than the alternatives but is also purchased in yuan, contributing to the Chinese strategy of eroding the dollar and Western hegemony in financial markets. Beijing can also now recalibrate the decisions of its gas companies between 2021 and 2022, when they signed numerous long-term supply contracts with LNG export terminals in the United States. The fact that these contracts were signed so recently illustrates the speed of the changes taking place and speaks to how an instrument that could improve relations between Beijing and Washington, LNG trade, is seen today in China as a potential threat to its supply security. This is the new reality of gas geopolitics.

The EU, as well as Russia, is poised to be one the biggest losers in this new scenario and must now adapt to a reality that does not match its multilateral and regulatory nature. Both the EU and its Member States must recalibrate their supply security strategies, keep watch for the appearance of new dependencies, and maintain a solid

and lasting diversification strategy. The EU must remain committed to the energy transition but it cannot, as it has attempted since the publication of the European Green Deal, ignore that energy diplomacy also requires securing the supply of fossil fuels such as gas, which will remain a central part of its economy at least through 2050.

Just as it is difficult to predict precisely what kind of international system will inherit the remnants of the liberal order, the same is true of the geopolitics of natural gas. We are relatively sure of what is being left behind, but uncertainty persists regarding what is to come. This analysis has attempted to outline some possibilities⁴. The first is that, in the future, the instrumentalisation of interdependence will become the norm for trade flows, financial services, and access to technology. Second is that fragmentation, used as a mechanism of protection against this instrumentalisation, will undo part of the globalisation and integration process that has defined the last few decades. The third is that, in contrast to the relative stability in prices and flows that characterised the natural gas market for a good part of the liberal order, we will see greater episodes of volatility and trade disruptions, hindering investors' ability to anticipate future supply and demand balances.

The new rules of the game are the instrumentalisation of interdependence, fragmentation, and geopolitical alignment. The winners are the great powers, capable of imposing their interests, and the losers are those who banked everything on a system based on rules, cooperation, and integration. The new gas order reflects the emerging realist order that is replacing the liberal order: geoeconomics now prevail over the paradigms of interdependence and integration.

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⁴ Though it has been decided to exclude it from this analysis, the energy transition will have a transformative effect on the geopolitics of natural gas. It will reduce part of demand in developed countries, but may also produce new consumers in the developing world. The way in which they will interact the new geopolitics of gas and its role as a vector in the transition is beyond the scope of this study.

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*Communications, 11(1), 1–*Xu, D., Dou, S., Zhu, Y., & Cheng, J. (2024).
Resource nationalism: The intersection of politics and economics. *Humanities
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Chapter Two

The geopolitics of critical minerals for the energy transition

Maria del Mar Hidalgo García

Abstract

The energy and digital transitions are driving up demand for minerals containing lithium, cobalt, rare earth elements, nickel, and copper, among others. The imbalance between supply and demand for these minerals—as well as their processed products—is creating a new geopolitic of resources where control and supply of these materials are becoming key factors in economic power, strategic competition, and national security.

Access to these critical minerals is becoming increasingly complex. China's dominance in production and processing, the rise of protectionism, and export controls are contributing to the profound geopolitical disruption of these mineral markets. In this context, in addition to encouraging the opening of new mines, it is essential to reconfigure industrial policies and foster international alliances with like-minded countries to ensure resilient and diversified supply chains for these critical minerals.

Regarding a potential disruption in the supply of raw materials in the energy sector, although it would not have immediate short-term consequences, its effects would be felt in the long term, impacting the future development of clean energy and the achievement of decarbonization goals.

Keywords

Critical minerals, lithium, rare earth elements, decarbonization

GEOPOLITICS OF CRITICAL MINERALS IN THE ENERGY TRANSITION

THE ENERGY TRANSITION IS AN EXTRACTIVE TRANSITION

- THE ENERGY TRANSITION IS NOT ONLY TECHNOLOGICAL AND CLIMATIC, IT IS ALSO:

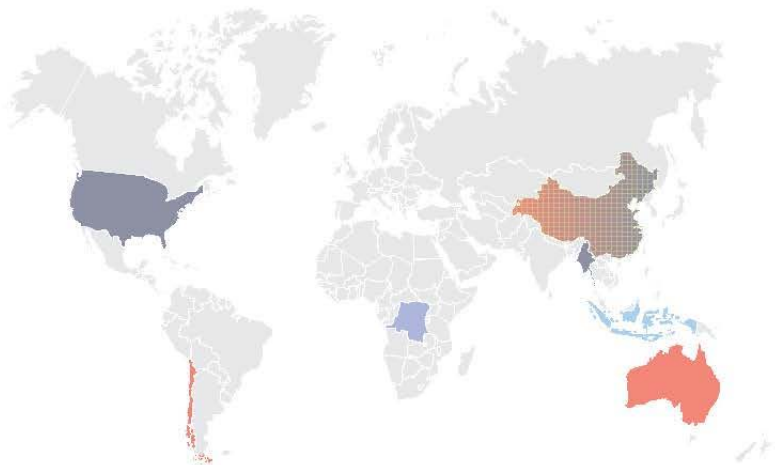


- RENEWABLE ENERGIES, ELECTRIC VEHICLES, DIGITALIZATION, AND DEFENSE DEPEND ON CRITICAL MINERALS:



FAST-GROWING DEMAND AND CONCENTRATED SUPPLY

- DEMAND FOR MINERALS FOR CLEAN ENERGY **WILL TRIPLE** BY 2040.
- MINING PRODUCTION IS CONCENTRATED IN A FEW COUNTRIES:



- NICKEL**
- COBALT**
- LITHIUM**
- RARE EARTH ELEMENTS**
- LITHIUM+REE**
- REFINED STRATEGIC DOMAIN OF CHINA**
- ~90%** OF RARE EARTH REFINING
- ~70%** OF THE PROCESSING OF ENERGY MINERALS

RISKS TO THE GLOBAL SUPPLY DISRUPTIONS OF CRITICAL MINERALS



1 MINERAL CONTROL = NATIONAL SECURITY

- ENERGY, DEFENCE, AI AND DIGITALISATION COMPETE FOR THE SAME MINERALS.
- CHINA-US RIVALRY REDEFINES MARKETS: LESS ECONOMICS, MORE GEOPOLITICS.
- CRITICAL MINERALS ARE NOW A STRATEGIC ASSET.



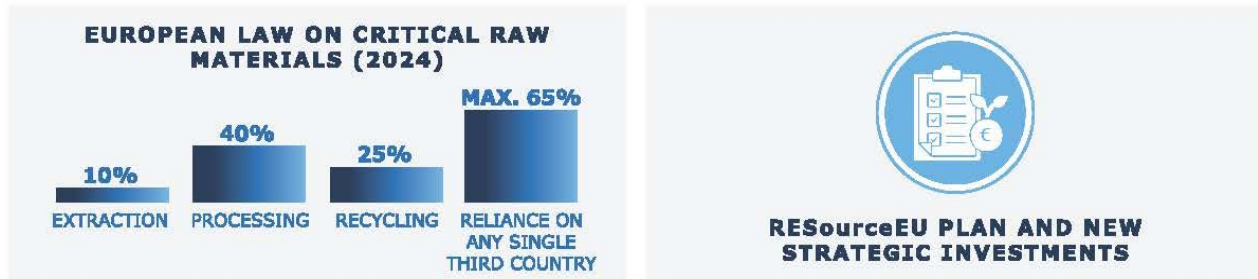
2 PROTECTIONISM AND CONTROLS

- INCREASING EXPORT BANS, TARIFFS AND NATIONALISATIONS.
- INTRODUCTION OF ACCESS TO MINERALS AS CURRENCY OF EXCHANGE IN CONFLICT RESOLUTION PROCESSES (E.G. IN UKRAINE).

RISK MITIGATION



EUROPEAN UNION RESPONSE



SPAIN AND CRITICAL MINERALS

- **7 STRATEGIC EU PROJECTS** ARE LOCATED IN SPAIN.
- **CHALLENGES:** SOCIAL ACCEPTANCE, ENVIRONMENTAL SUSTAINABILITY.
- **MINERAL RAW MATERIALS ACTION PLAN 2025-2029.**
- **KEY MINERALS:** SEE MAP.



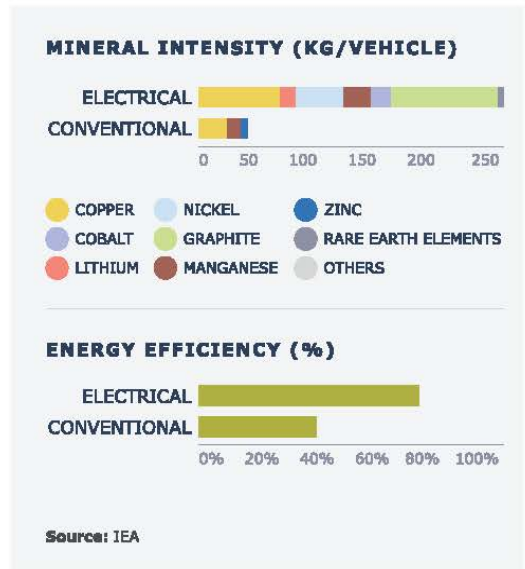
LI LITHIUM
 CU COPPER
 NI NICKEL
 CO COBALT
 W WOLFRAM
 PGM PLATINUM GROUP METALS

RARE EARTH PRODUCTION AND RESERVES

PRODUCTION		RESERVES
US	41.600 41.600	1.900.000
AUSTRALIA	16.000 13.000	5.700.000
BRAZIL	140 20	21.000.000
MYANMAR	43.000 31.000	NA
CANADA	- -	830.000
CHINA	255.000 270.000	44.000.000
GREENLAND	- -	1.500.000
INDIA	2.900 2.900	6.900.000
MADAGASCAR	2.100 2.000	NA
MALAYSIA	310 130	NA
NIGERIA	7.200 13.000	NA
RUSSIA	2.500 2.500	3.800.000
SOUTH AFRICA	- -	860.000
TANZANIA	- -	890.000
THAILAND	3.600 13.000	4.500
VIETNAM	300 300	3.500.000
OTHERS	1.440 1.100	NA
TOTAL	376.000 390.000	90.000.000

● 2023
 ● 2024

TRANSPORT - VEHICLES



Introduction

Since the Industrial Revolution ushered in the era of carbon-based resources, much of the global energy supply has depended on extracting large amounts of hydrocarbons such as coal, oil, and gas. However, in the 21st century, climate policies and the quest for energy independence are making energy systems electrified, digitalised, and interconnected, with a great impact on energy security. Whereas before the debate on renewable energies focused on the costs of technology and the challenges of integration, now the debate focuses on how to promote and integrate them to be a fundamental component of the energy sovereignty and security of many nations in order to significantly reduce the risk of disruptions in energy supply.

From electric vehicles to solar panels and wind turbines, the deployment of clean energy technologies is advancing rapidly and is heavily dependent on critical minerals such as copper, lithium, nickel, cobalt, and rare earth elements¹. This boom in renewable energy sources - which are developing at a faster rate than any other fuel in history - means that we are witnessing not only an energy transition but also an extractive transition.

The imbalance between their supply and demand, the high concentration of their production and processing, as well as the possible disruption of their supply chains mean that some of these minerals -or more precisely certain metals contained in mineral forms- are considered critical because they are also essential not only for the energy and digital transition, but also for the defence and aerospace sector.

Mineral markets are being affected by the adoption of policies imposed for reasons of national security. The main consequence is that access to these critical minerals is altering the economic and geopolitical balance worldwide, helping to shape a very complex landscape framed in the strategic rivalry between China and the US. In this context, minerals and their supply chains have become a geopolitical weapon.

In the specific field of renewable energies, the International Renewable Energy Agency (IRENA) considers that although critical minerals could potentially become weapons, the effect of such disruption would be limited. It could slow the deployment of clean energy technologies, but it is unlikely to cripple entire energy systems. However, this view is only part of the reality as continued access to strategic minerals has become a matter of national security due to their use in emerging technologies in the digital and defence fields.

Many of the minerals needed by the energy, digital, and defence sectors are common and this opens up great uncertainties both from a supply and demand standpoint. By becoming the centre of commerce and hegemonic disputes between China and the United States, the renewable energies sector may be the one that is most affected in the long term.

¹ Rare earth elements are a group of 17 metals that are essential to modern technology. They are used from smartphones and electric vehicles to wind turbines, fighter jets, and missile guidance systems. Their unique magnetic, luminescent, and conductive properties make them irreplaceable in high-performance electronics and clean energy applications.

In this context, it is necessary to analyse the challenges of the energy transition from the point of view of the requirements for the use of critical minerals. The increase in demand, the concentration of supply, protectionist and tariff policies, the exploitation of new spaces, or the social and environmental issues of mining are factors that can undermine the transition to economies away from the use of fossil fuels. Without proper management, the growing demand for critical minerals risks perpetuating dependence on raw materials, exacerbating geopolitical tensions and environmental and social challenges².

1 Toward an extractive transition

The dependency risks and supply dynamics of critical minerals differ fundamentally from those of fossil fuels, due to their very different characteristics and patterns.

Since 2010, there has been a 50% increase in the average amount of minerals needed for a new power generation unit, according to a report by the International Energy Agency (IEA). By 2040, demand for minerals to generate cleaner energy will have tripled. Essentially, the energy transition “means a shift from a fuel-intensive to a material-intensive system.”³

The current notion of energy security revolves around continuous access to energy sources. In the case of the EU, the war in Ukraine has highlighted its energy vulnerability due to its high dependence on fossil fuels from Russia and the repercussions on the economy and competitiveness of the Union. Therefore, **in the short term**, the repercussions of a fossil fuel disruption are much greater on energy security than the disruptions in the supply of the minerals needed to construct renewable energies since the technologies already built could continue to function for decades. Therefore, the risk associated with disruptions in the supply of critical materials is lower than the risk associated with disruptions in the supply of fossil fuels in the short term.

A second aspect is that trade in critical materials is many orders of magnitude lower in value than trade in fossil fuels. Fossil fuels reached a value of Generate huge rents Oil and gas exports alone represented a value of USD 2 trillion in 2021, while the market for minerals related to renewable energies (lithium, cobalt, rare earth elements, nickel, and cobalt) reached a value of 96 billions dollars⁴. Unlike oil, most critical materials are not widely traded on exchanges. Although this limits opportunities to hedge against price volatility, it allows commodity *traders* to play a key role in matching producers and consumers.

The third difference lies in the recycling rate. Fossil fuels are consumed while the

² <https://www.un.org/en/climatechange/critical-minerals>

³ <https://www.mining-technology.com/features/mining-energy-transition-minerals/?cf-view>

⁴ <https://www.irena.org/Digital-Report/Geopolitics-of-the-Energy-Transition-Critical-Materials>

elements incorporated in renewable energies can reach a high recycling rate. The average life is also very different, fossil fuels disappear when used while the average life of the usefulness of minerals used in energy installations is around 10-30 years.

Regarding the comparison between mineral and fossil fuel reserves, it should be mentioned that there is no shortage of reserves for energy transition minerals. From 2013 to 2022, the summaries of the US Geological Survey (USGS) reveal that, together, the known reserves of cobalt, lithium, and nickel are increasing, as are the known reserves of other critical minerals, so the global supply of critical minerals is, to some extent, elastic, but it is true that capacities for obtaining and refining are more limited compared to fossil fuels. This uncertainty in supply could slow down the transition to renewable energies due to the lack of investment in the minerals market, which is much more opaque than that of fossil fuels and much more risky.

All these factors imply that in order to move towards decarbonisation and compliance with climate objectives, progress must also be made in an updated approach to energy security, different from that used with fossil fuels. In this way, the risks associated with investing in projects to obtain the critical minerals needed for renewable energies can be minimised. In 2021, the International Energy Agency (IEA) identified an imminent lack of coordination between the demand for critical minerals and their availability. The IEA's findings helped governments and companies around the world to develop strategies and investments in critical minerals.

2 Growing demand and concentrated supply

According to the IEA report "*Renewables 2025. Analysis and forecasts 2025*", renewable energy will account for almost 45% of electricity generation by 2030, going from 9,900 TWh in 2024 to 16,200 TWh in 2030. According to the aforementioned report, solar PV energy alone accounts for more than 60% of this increase, followed by wind with 32%. Regarding global AI-related electricity demand, the initial exponential growth will become more linear over time, reaching 11% of electricity demand by 2060⁵.

This increase in renewable energies continues to drive growth in demand for certain metals. According to the International Energy Agency (IEA) report "Global Critical Minerals Outlook" published in 2025, lithium demand increased by almost 30%, maintaining the strong increase observed in 2023 and significantly exceeding the 10% annual growth rate recorded in the 2010s. The demand for nickel, cobalt, graphite, and rare earth elements increased by 6% to 8% in 2024. Copper also experienced solid demand growth of around 3%, surpassing the pace of the previous two years to reach 12 million tonnes. The rapid expansion of investment in power grids in China was the main driver of demand growth during those two years. Electric vehicles will also remain one of the biggest catalysts of metal demand, as they use four times more

⁵https://www.dnv.com/energy-transition-outlook/2025/?utm_source=google&utm_medium=search&utm_campaign=eto_2025_download/&gad_source=1&gad_campaignid=23088436235&gclid=EAIaIQobChMI-eTPtIPtkQMVsch5BB0cyTu1EAAYASAAEgLUSPD_BwE

copper than their internal combustion counterparts. For this reason, for example, copper consumption in electric vehicles is expected to increase from 200,000 tonnes in 2020 to 3.4 million tonnes in 2035, representing an average annual growth rate of 14% between 2025 and 2035⁶.

In the IEA's Stated Policies Scenario (STEPS), demand for lithium will quintuple by 2040, while demand for graphite and nickel will double. The demand for cobalt and rare earth elements is also growing strongly, increasing between 50% and 60% by 2040⁷.

Despite this high demand, there are probably enough critical minerals in the Earth's crust to cover the global need. But the reality is access to them can be very complex. Some critical minerals, like aluminium and palladium, have stable reserves on land that can meet global demand through 2050 and probably beyond. For others, such as copper, nickel, and cobalt, the reserves currently found may be insufficient, so a combination of more exploration, technological advances, and economic incentives will be needed to increase supply⁸.

If historical growth rates in the supply of strategic minerals were increased by a factor of 3 to 4, developments in the energy sector by 2050 would remain largely unaffected. However, this increase would still be insufficient to supply the materials needed for large capacity expansions in the short term, resulting in a slower rate of electrification and greater use of fossil fuels in some sectors⁹. In particular, copper and nickel markets could face material deficits in the mid-2030s, while lithium supply remains concentrated in only a few countries¹⁰.

More than 60% of the global demand for critical minerals is met through international commerce, underlining the deep structural interdependence between producing and consuming economies as clean energy deployment accelerates¹¹. Even in a well-supplied market, dependence on a small number of suppliers increases vulnerability to shocks and disruptions with the risk of slowing the energy transition. For example, if there were a disruption in the supply of graphite, the price would increase tenfold, the average prices of battery packs worldwide would increase by 45%, substantially reducing the competitiveness of the companies that use them¹². Battery prices already vary considerably by region, with average prices in 2024 much higher in the United States (30%) and Europe (50%) than in China. A steep rise in graphite prices would further widen the price gap between new electric vehicles sold in the United States or Europe and those sold in China, making them nearly twice as expensive in the United States and 75% more expensive in Europe¹³.

⁶ <https://www.mining.com/over-60-of-critical-minerals-demand-met-through-global-trade-ief/>

⁷ Global Critical Minerals Outlook 2025 – Analysis - IEA

⁸ Qiu Y. et al. The impacts of material supply availability on a transitioning electric power sector. Cell Reports Sustainability, October 2024.

⁹ Schulze K. et al. From fossil fuels to metals and minerals: Navigating global resource challenges in the energy transition, Cell Reports Sustainability, Volume 1, Issue 10, 2024,

¹⁰ https://www.ief.org/_resources/files/reports/a-critical-minerals-enabled-energy-future.pdf

¹¹ Ibid.

¹² <https://www.iea.org/commentaries/growing-geopolitical-tensions-underscore-the-need-for-stronger-action-on-critical-minerals-security>

¹³ Ibid

Therefore, the main current problem related to the supply of critical minerals is their high concentration - far more than fossil fuels - in both production and processing. Indonesia accounts for more than half of the world's nickel supply, the Democratic Republic of the Congo produces about 70% of cobalt. Lithium mining continues to be dominated by Australia, Chile, and China, which together accounted for more than three-quarters of global production in 2022. This concentration in production is far from ending in the short/medium term since around 75% of the projects planned for refined lithium, nickel, and cobalt, and more than 90% for battery quality graphite projects, are being developed in the three main current producers¹⁴.

As for the rare earth element metals group, the main producers were China, the United States, and Canada. It must be highlighted the considerable increase in production from Nigeria and Thailand¹⁵.

	Mine production ^a		Rt
	2023	2024	
United States	41,600	45,000	1
Australia	¹² 16,000	¹² 13,000	¹³ 4
Brazil	140	20	2
Burma	¹² 43,000	¹² 31,000	
Canada	—	—	
China	¹⁴ 255,000	¹⁴ 270,000	44
Greenland	—	—	1
India	2,900	2,900	6
Madagascar	¹² 2,100	¹² 2,000	
Malaysia	¹² 310	¹² 130	
Nigeria	¹² 7,200	¹² 13,000	
Russia	2,500	2,500	3
South Africa	—	—	
Tanzania	—	—	
Thailand	¹² 3,600	¹² 13,000	
Vietnam	¹² 300	¹² 300	3
Other	1,440	1,100	
World total (rounded)	376,000	390,000	>91

Figure 1. Principal producers and reserves of rare earth elements. Source: USGS

While the production of critical minerals may seem somewhat diversified, this advantage fades when it comes to the refining and processing of these minerals, where China occupies a clearly dominant position. China's position is based solely on scale and control throughout the supply chain, rather than on geological abundance or crude ore extraction. China refines about 90% of rare earth element group metals. It also refines 19 of the 20 key energy-related minerals, with an average global market share of around 70%. For many high-demand minerals such as lithium, nickel, and cobalt, China's extraction share is only 10-30%, but its share in refining and processing is between 60% and 70%¹⁶. Currently, China produces 99% of battery graphite, over 60% of lithium chemicals, 40% of refined copper, 70% of refined cobalt, and over 80% of processed rare earth elements¹⁷. Currently, there are only five rare earth element refineries outside China in operation, under construction, or in the process of reactivation. These refineries are located in the USA, Malaysia, France, Estonia, and Australia.

With regard to manufactured material, China alone represents an 80% share in the

¹⁴ Global Critical Minerals Outlook 2025 – Analysis - IEA

¹⁵<https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-rare-earths.pdf>

¹⁶<https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality>

¹⁷<https://www.mining-technology.com/features/a-deep-dive-into-chinas-role-as-critical-mineral-monolith/>

different stages of solar panel manufacturing¹⁸, including raw material processing and polysilicon production¹⁹. China produces two-thirds of the world's electric vehicles (EVs), 85% of battery cell productions, 90% of cathode production capacity, and 98% of anode materials globally. It leads the production of solar panels, wind turbines, and hydrogen electrolyzers and dominates the entire graphite anode supply chain from start to finish²⁰. The numbers are staggering.

By controlling all stages, China has built the quasi-monopoly that underpins its dominance in global clean energy manufacturing. This dominance is the result of a state policy designed with the long term in mind. Since the 1980s, Beijing has supported early investment in mineral extraction and processing, provided subsidies to both state-owned and private companies in mining, refining, and production of magnet materials or batteries, and applied more flexible environmental standards than countries such as the United States and Australia.

Specifically, China's rise as a powerhouse in the rare earth elements sector has been a product of global specialisation. China increased rare earth element production from approximately 31,000 metric tons in 1994 to 270,000 metric tons in 2024. During this period, Chinese suppliers offered lower prices than US producers thanks to state support, lower environmental standards²¹, and cheaper labour²², which led to the cessation in 2002 of the activity of the US Mountain Pass mine, which until then was recognised as the cornerstone of global production of rare earth elements, constituting the richest and most reliable source in the world²³.

The importance of critical minerals for China has driven an acceleration of Chinese investment in the mining sector, both domestically and internationally, securing foreign mining assets in developing countries through the Belt and Road Initiative (BRI), in Africa and Latin America. Chinese-backed entities have invested nearly \$57 billion in mineral projects in 19 countries²⁴. China's investment in metals and mining, through its Belt and Road Initiative (BRI), reached a record \$21.4 billion in 2024, a 10% increase over 2023²⁵. This ensures that raw materials flow into the Chinese refining industry, reinforcing its role as a global mineral processing centre.

In recent years, China has acquired significant African mining assets, including the Khoemacau copper mine in Botswana (2023), the Goulamina lithium mine in Mali (2024), and the Ngualla rare earth element mine in Tanzania (2025). In many African

¹⁸ <https://www.energynews.es/amenaza-fotovoltaica-china-controla-el-46-de-la-capacidad-mundial-y-el-80-del-mercado-de-paneles/>

¹⁹ IEA (2022), Solar PV Global Supply Chains, IEA, Paris <https://www.iea.org/reports/solar-pv-global-supply-chains>, License: CC BY 4.0

²⁰ <https://www.mining-technology.com/features/a-deep-dive-into-chinas-role-as-critical-mineral-monolith/?cf-view>

²¹ Earth processing is very polluting as it generates radioactive waste.

²² <https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-rare-earths.pdf>

²³ <https://mpmaterials.com/history/>

²⁴ Escobar, B., Malik, A. A., Zhang, S., Walsh, K., Joosse, A., Parks, B. C., Zimmerman, J., & R. Fedorochko. (2025). Power Playbook: Beijing's Bid to Secure Overseas Transition Minerals. Williamsburg, VA: AidData at William & Mary

²⁵ <https://theoregongroup.com/investment-news/chinas-mining-investments-under-belt-and-road-initiative-hit-record-high-in-2024/>

countries right now, it is Chinese companies that exploit these resources, not the country itself.

In African countries, investment has focused on the creation of new lithium supply chains, where, of the seven lithium assets in Africa that are expected to start production by 2027, five have at least 50% equity ownership by Chinese companies²⁶. China's BYD - the world's largest manufacturer of electric vehicles - is involved in six African lithium mines, securing enough raw materials until 2032²⁷.

China's advantage in critical minerals cannot be explained solely by state support to the mineral extraction and processing sector. It is the result of a vertical industrial policy developed decades ago in which an effort is made to integrate all the sectors involved from education, research, industry, and the strategic objectives of defence capabilities. In the case of electric vehicles, Beijing expanded subsidies to consumers and required foreign companies to enter into joint ventures with domestic car manufacturers.

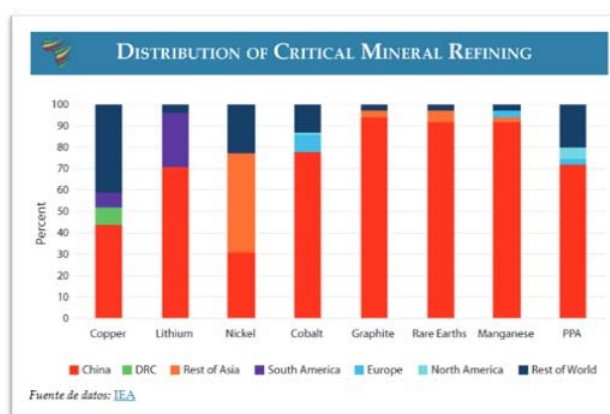


Figure 2. Distribution of refined mineral production by country. Source: <https://africacenter.org/spotlight/china-africa-critical-minerals/>

This high concentration of production and processing of critical minerals from China creates vulnerabilities in the supply chain that transcend the economic realm to move into the geopolitical realm.

To study this vulnerability, the N-1 assessment²⁸ used in natural gas markets and energy systems can be applied. Conducting this assessment in the context of critical minerals to examine what the system looks like when the largest supplier is excluded from global supply and demand balances, nickel, cobalt, and graphite appear to have sufficient supply globally.

However, if the largest supplier and its demand (China for lithium, cobalt, and graphite; and Indonesia for nickel) is excluded, the remaining N-1 supplies would fall significantly below the N-1 demand. For cobalt and graphite, the remaining supplies would cover only 25-30% of N-1 demand in 2035, totally insufficient to cover mineral needs in the renewable energies sector. The N-1 supply covers 55% of N-1

²⁶<https://www.mining-technology.com/features/a-deep-dive-into-chinas-role-as-critical-mineral-monolith/?cf-view>

²⁷ <https://africacenter.org/spotlight/china-africa-critical-minerals/>

²⁸ The remaining supply after excluding the largest supplier is known as N-1 supply.

demand for nickel, but the proportion could be much lower if supplies of battery-grade nickel sulphate, mainly from China, are also disrupted. For lithium, the gap is less pronounced, but the remaining N-1 supply still covers only 60% of N-1 demand. This emphasises that even where the global balance is reasonably well-supplied, critical mineral supply chains can be highly vulnerable to supply shocks, whether from extreme weather events, trade disruptions, or geopolitics²⁹.

3 Mineral markets: less economics and more geopolitics

China has long understood the strategic value of its dominance in rare earth elements production. As reflected in Deng Xiaoping's 1992 quote, "The Middle East has oil, China has rare earths," China recognised several decades ago the value of these minerals as geopolitical assets. Since 2017, it has gradually strengthened its control over rare earth elements and other critical minerals, imposing licensing and regulatory requirements, limiting foreign companies' access to mining, processing, and related technology.

On the other hand, the defence sector and the digitalisation of economies, where AI plays a fundamental role, need certain minerals, many of them also necessary for the energy sector. For example, electric vehicles and wind turbines require the same specialised magnets as ship propulsion systems and guided missile actuators.

This sectoral competence depends to a large extent on the priorities that certain countries have. For the US, as reflected in the National Security Strategy 2025 and the Pax Silica Initiative, the binomial of economic security-national security seems to be indissoluble. In this case, access to the strategic minerals necessary from the point of view of defence and technological development, will mark to a greater extent the policies and initiatives that the Trump Administration carries out to relocate its supply chains and minimise its dependence on China. For China, its priority is to position itself in the global market as a leader in the export of products for the energy transition, but also encouraging the development of technology in other areas such as defence and AI.

The competition between both powers to gain global hegemony constitutes a risk for the secure and sustainable access of the strategic minerals necessary to carry out the energy transition towards renewable energies. In this complex geopolitical context, preventing a power from having access to critical minerals may be prioritised over free trade, thereby contributing to mineral markets being managed by geopolitics from a national security perspective.

3.1 Increased export controls

China has repeatedly used its "quasi-monopoly" in strategic minerals as a geopolitical tool, especially in 2010, when it halted exports to Japan following the collision between a Chinese fishing vessel and a Japanese Coast Guard vessel near the

²⁹ <https://www.iea.org/commentaries/growing-geopolitical-tensions-underscore-the-need-for-stronger-action-on-critical-minerals-security>

Senkaku Islands, causing the price of rare earth elements to skyrocket up to tenfold³⁰.

In 2023, China imposed new licensing requirements for gallium and germanium exports. Gallium exports fell from almost 6,900 kilograms in July to zero in September, and germanium shipments dropped from about 8,000 kilograms to just 1 kilogram. According to 2022 production quotas, this effectively eliminated about 60 percent of global germanium supply and 90 percent of gallium supply from international markets³¹, disrupting chip and defence supply chains and demonstrating Beijing's ability to weaponise export licenses. In December 2024, China banned the export of gallium, germanium, and some other materials to the United States. Additional export control announcements followed in February 2025 on a variety of materials, including tungsten, tellurium, bismuth, indium, and molybdenum, key minerals used primarily in defence and high-tech applications. On 9 October, 2025, China expanded export controls including holmium, erbium, thulium, europium, and ytterbium as well as associated mining and processing technologies.

However, the implementation of these new restrictions and controls was suspended for a year after negotiations with Trump on 30 October. A few days later, China announced that it was suspending other long-standing restrictions, such as a ban on the export of gallium and germanium to the United States. The United States then suspended the application of the Affiliates Rule for a year³² in addition to making other concessions related to the sale of certain chips to China. These negotiations make it clear that minerals, critical and in particular rare earth elements, are a very effective geopolitical tool.

By controlling its exports, China could thus disrupt the global supply chains of a number of strategically important sectors, such as energy and automotive, but also defence and aerospace. China's dominance in the processing of critical minerals has allowed it to reduce prices below any comparable level, increasing the rest of the world's dependence on Chinese exports of these minerals.

These actions show that mineral markets are increasingly governed by geopolitics and less by the economy. This change is a reflection of the new global geopolitical paradigm in which the order established after World War II is breaking down. An example of this is the loss of multilateralism as a tool to resolve international disputes. While in 2010, the US, Japan, and the EU were able to complain to the WHO about rare earth element export restrictions following the Senkaku Islands incident, there is currently nothing that can be done when export restrictions are made on the grounds of national security. And this is the game changer.

³⁰ Kang Y. et al. Navigating geopolitical risks: The impact of the Senkaku/Diaoyu Islands dispute on global rare earth markets and diversification strategies, *Resources Policy*, Volume 106, 2025,

³¹ <https://www.reuters.com/world/china/china-exported-no-germanium-gallium-aug-due-export-curbs-2023-09-20/>

³² The "Affiliates Rule" refers to a US Department of Commerce (BIS) regulation that expands the Export Administration Regulations (EAR) by subjecting non-U.S. companies that are 50% or more owned by entities included in the Entity List or MEU List to the same licensing requirements, with the goal of closing loopholes and preventing diversion of US technology.

This situation means that in recent years there has been an increase in export restrictions on certain goods, with a considerable increase in those that affect strategic minerals. Export controls pose unique challenges compared to other trade controls. Although, like tariffs, they are often part of broad diplomatic negotiations, export controls are often driven by national security concerns. Consequently, governments sometimes implement export restrictions unilaterally and immediately, generating a lot of uncertainty for companies³³.

The largest number of export restrictions between 2019 and 2023 related to the minerals needed for the energy transition were imposed by countries such as the Democratic Republic of the Congo, Mongolia, India, Burundi, and Zambia. These restrictions mainly target key minerals such as copper (notably in the Democratic Republic of the Congo, Mongolia, Zambia, and Argentina), molybdenum (Mongolia), and a group of high-tech or strategic minerals such as gallium, germanium, indium, niobium, tantalum, and vanadium (especially in Burundi and Ethiopia). Zinc has also been subject to restrictions, especially in India, Burundi, and Ethiopia³⁴.

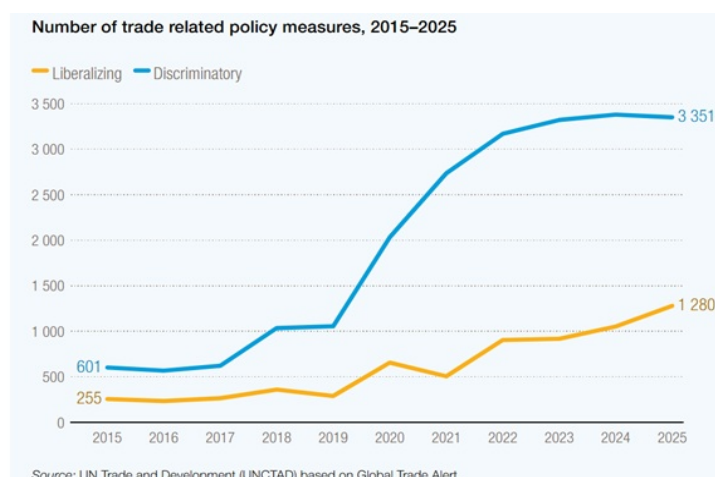


Figure 3. Number of trade policies 2015-2015. Source: UNCTAD

3.2 Promoting protectionism

Recent supply chain disruptions have led many countries and regions to seek a relocation of supply chains for greater strategic autonomy and to reduce dependence on potential adversaries. As countries move to protect their national security and energy independence, critical minerals have become the protagonists in policymaking in strategic sectors. The main objectives of these policies are to encourage strategic industries to relocate or establish new operations in their countries of origin (reshoring), in nearby regions (nearshoring), or in trusted allied nations (friendshoring)³⁵. These measures disrupt global flows and are indicative of how state

³³ <https://www.mckinsey.com/capabilities/geopolitics/our-insights/restricted-how-export-controls-are-reshaping-markets>

³⁴ <https://sdgpulse.unctad.org/critical-minerals>

³⁵ <https://www.irena.org/Digital-Report/Geopolitics-of-the-Energy-Transition-Critical-Materials#page-4>

policy can redirect supply.

According to estimates from the International Energy Forum (IEF), the number of critical minerals policies issued since 2020 nearly doubled the combined total of the previous two decades, with countries increasingly turning to strategic planning, export controls, and domestic processing mandates to protect supply chains. To cite some examples, Indonesia, with 21% of the world's nickel reserves and 37% of the mining production of this metal, has been progressively restricting exports. In 2020 it banned the export of nickel ore to force local smelting, attracting heavy investment in refineries. Zimbabwe has restricted chromium exports to boost processing in the country and the Philippines has passed a bill to ban the export of unprocessed nickel ore by 2030 to promote domestic processing³⁶. And in Latin America, Chilean President Gabriel Boric has taken steps to nationalise his country's lithium industry, which accounts for 26% of global reserves³⁷.

In recent months, the Trump Administration has made efforts to reduce US dependence on Chinese supply, launching initiatives to fund domestic mining projects, streamlining permits, and partnering with allies to diversify the supply chain. Within months, the Trump Administration has rewritten the rules of US trade policy. It has imposed general tariffs on almost all countries, starting at 10% and increasing to 50%. Taxes on a number of products, such as steel, aluminium, cars, and auto parts, have further raised these trade barriers. At an average effective rate of about 18%, US import taxes are now the highest in nearly a century³⁸. These actions will change the position of the United States in the world economy, detaching the country, at least in part, from global supply chains.

In recent years, support for new critical mineral projects in the US has been carried out based on purchase agreements between car manufacturers and national mineral extraction companies. General Motors (GM), for example, made a \$650 million equity investment in Lithium Americas, gaining exclusive access to Phase 1 production from a new mine in Thacker Pass, Nevada³⁹. This agreement would have supported GM's choice to receive consumer tax incentives for domestically produced electric vehicles.

The Trump Administration has taken another step and focused its attention on policies to increase mineral supply, including import tariffs, deregulation, and direct federal investment through the Department of Defence. The March 2025 Executive Order on “Immediate Measures to Increase American Mineral Production”⁴⁰ established the “National Energy Dominance Council,⁴¹” expanded the list of critical

36 https://legacy.senate.gov.ph/press_release/2025/0203_escudero1.asp

37 <https://cncls.cl/estrategia-nacional-del-litio-impulso-para-chile/>

38 <https://www.infobae.com/america/mundo/2025/08/07/los-impuestos-a-las-importaciones-en-estados-unidos-alcanzaron-el-mayor-nivel-en-casi-cien-anos/>

39 <https://www.greencars.com/es-us/noticias/gm-invierte-650-millones-de-dolares-en-la-produccion-de-litio>

40 <https://www.whitehouse.gov/presidential-actions/2025/03/immediate-measures-to-increase-american-mineral-production/>

41 Among the Council's functions is to advise the President on improving permit gaining, production, generation, distribution, regulation, transportation, and export processes for all forms of US energy, including critical minerals.

minerals to include uranium, copper, potash, and gold, and directed agencies to expedite permits and mobilise funding. In April 2025, a second Executive Order launched a marine minerals strategy, directing the Bureau of Ocean Energy Management (BOEM) and the National Oceanic and Atmospheric Administration (NOAA) to inventory deposits of nickel, cobalt, copper, manganese, titanium, and rare earth elements, and apply for fast-track permits for exploration and mining on the US outer continental shelf. It also calls for strengthening national refining capacity, integrating seabed minerals into national security planning, and partnering with allies to develop seabed resources responsibly, countering Chinese influence.

In mid-July 2025, the US Department of Commerce intervened in the natural graphite market, imposing a 160% tariff on Chinese graphite anode active material⁴². On 30 July, the Administration announced a 50% tariff on imports of copper products and copper-intensive products, with additional actions to require that 25% of copper ores, scrap, and concentrates produced in the United States be sold domestically⁴³.

In addition to tariffs, Trump's strategy also includes subsidies for the production and processing of strategic minerals. This would be especially important in industries where markets have failed, such as the battery industry where Chinese subsidies have increased battery manufacturing capacity to the point of far exceeding total global demand. It seems that Trump seeks to play by the same rules using an unusual pragmatism in Western democracies. In addition, the Mine of the Future initiative provides nearly \$100 million in funding to accelerate research, innovative mining technologies, and commercialisation⁴⁴. Also, Donald Trump, using the Defence Production Act of 1950, signed in March 2025 an executive order aimed at immediately increasing US production of critical minerals such as uranium, copper, potash, and gold, among others.

In July, the Department of Defence (DOD) signed a collaboration agreement with MP Materials for a vertically integrated operation from rare earth element extraction to magnet production, known as a “mine to magnet” strategy. The agreement includes capital investment by the DOD; a guaranteed agreement to purchase 7,000 metric tons of rare earth element magnets per year, just over 40 percent of US demand for these materials in 2020, and at a guaranteed price approximately twice the 2025 market price. This action should reduce the United States' dependence on China when the plant comes into operation in 2028⁴⁵.

For its part, the EU is also moving towards greater protectionism with the approval of the Critical Raw Materials Act with the aim of establishing a secure and reliable value chain of critical minerals for the bloc. It establishes dependency on a single

⁴² <https://source.benchmarkminerals.com/article/chinese-aam-imports-into-the-us-face-160-tariff-following-antidumping-investigation-ruling>

⁴³ <https://www.whitehouse.gov/presidential-actions/2025/07/adjusting-imports-of-copper-into-the-united-states/>

⁴⁴ <https://www.energy.gov/articles/energy-department-announces-actions-secure-american-critical-minerals-and-materials-supply>

⁴⁵ <https://mpmaterials.com/news/mp-materials-announces-transformational-public-private-partnership-with-the-department-of-defense-to-accelerate-u-s-rare-earth-magnet-independence>

supplier country at 65% percent and encourages mining, processing, and recycling in Europe.

3.3 International initiatives of like-minded geopolitical groups: friendshoring

China's partnerships through its Belt and Road Initiative, which supports infrastructure development primarily in developing and emerging economies, have been instrumental in dominating mineral processing⁴⁶.



Figure 4. Location of operational mines abroad that contain critical minerals as a main product, owned by US or Chinese companies. 2023. Source: <https://mine.nridigital.com>

That's why the United States and its allies are turning to friendshoring, which consists of building supply chains through trusted partners. This approach is being promoted through a series of alliances and agreements at the multilateral and bilateral levels. These agreements between governments provide positive signals in the marketplace and leverage political support that catalyse more private investment and ensure projects get from announcement to production.

From the multilateral point of view, the initiatives framed in the G7⁴⁷ and the G20⁴⁸ stand out, as well as the Minerals Security Partnership (MSP) created in 2022. This initiative is an international cooperation mechanism to expand diversification and trade in mineral supply. Much of the MSP's focus has been on promoting corporate and political transparency in mineral-rich developing countries, including policies in support of environmentally and socially sustainable mining practices. Proof of this is the Lobito corridor initiative in West Africa.

⁴⁶ <https://www.wri.org/insights/critical-minerals-explained>

⁴⁷ <https://www.consilium.europa.eu/media/rwkj3dls/minerals-en.pdf>

⁴⁸ <https://www.iied.org/critical-minerals-reflections-g20-leaders-summit>

But it is the bilateral framework where more progress is being made among like-minded countries to secure critical mineral supply chains and counter China's dependence. Although it involves global diversification on a smaller scale, these bilateral partnerships can bring mutual benefits in a more agile and efficient way. For example, in 2010, prices for some rare earth elements rose significantly for fear that China was restricting its supplies due to an unrelated dispute with Japan. Japan contracted Australia for additional extraction of these materials, established an agreement with Malaysia for new processing capacity, promoted mineral recycling, and funded research on rare earth element alternatives. Over the past decade, Japan's dependence on Chinese rare earth elements has fallen from 90 to 60 percent⁴⁹.

In this regard, it is worth mentioning the agreement between the US and Australia and those recently signed with Japan, Malaysia, and Thailand. We must also mention the peace agreements that Trump is reaching with certain countries in the resolution of conflicts that, although not like-minded, have critical mineral resources. Such is the case with Ukraine or the Republic of the Congo.

But perhaps Trump's most promising bet is the recently announced Pax Silica Initiative, with which he aims to establish partnerships with countries that contribute to strengthening their independence from China in certain strategic materials and advance technological development. At the moment, the initiative is a statement of shared principles-still without an implementation mechanism-on which future cooperation will be based. The first to join the initiative were: Japan, Australia, Singapore, South Korea, United Kingdom, and Israel. Qatar and the United Arab Emirates have since joined, and India is likely to join in the coming weeks. It cannot be ruled out that in the future Trump will invite other countries to become part of it. What is most significant about this Initiative is that it is the first time that countries are organised around computing, semiconductors, minerals, and energy as shared strategic assets.

Both the EU and Canada have been left out of this initiative for now, despite the fact that Canada has deposits of more than half of the minerals on the US critical list, including lithium, graphite, nickel, cobalt, copper, and rare earth elements. It is the only western nation with all the raw materials needed for advanced electric vehicle batteries. Canada is proactively expanding its capacity for mining and processing. For example, its 2022 Critical Minerals Strategy seeks to accelerate exploration, streamline the granting of permits, and expand domestic processing.

All these multilateral agreements are reinforced by collaborations that move between the government and business sectors. These include, for example, the new joint venture between the US Department of War, the company MP Materials, and the company Maaden, which is 67% owned by the Public Investment Fund of Saudi Arabia. The aim is to build a rare earth element refinery in Saudi Arabia. This partnership represents a critical step toward balancing the global rare earth element supply chain and is aligned with US economic and national security interests. Under

⁴⁹ <https://www.rusi.org/explore-our-research/publications/commentary/japans-responses-chinas-supply-chain-dominance#:~:text=Japan%20empowered%20the%20Japan%20Organization,from%2095%25%20to%2060%25.>

the agreement, the Department of War will fully fund 49% of the US side, while MP Materials will provide the technical expertise; Maaden will retain the remaining 51% of the stake⁵⁰.

Saudi Arabia offers a very favourable regulatory landscape. It has introduced a modern regulatory framework to accelerate the development of its mining sector and support its broader ambitions in critical minerals set out in Vision 2030. In 2021, Saudi Arabia enacted the Mining Investment Law, a set of sweeping reforms aimed at attracting investment and streamlining processes in the mining industry. Mining licenses in Saudi Arabia can be obtained in 180 days, in stark contrast to the United States, where it normally takes between 7 and 10 years to obtain the necessary permits to put a mine into operation⁵¹.

For its part, the EU under its Global Gateway strategy⁵² has launched projects related to access to critical minerals, among which it is worth highlighting those signed with several countries such as Zambia, Namibia, Ghana, Kazakhstan, and the Democratic Republic of the Congo with its contribution to the development of the Lobito corridor⁵³.

In view of all these initiatives, what is perceived is a mosaic of government and business relations with similar geopolitical objectives and interests. However, some authors point out that what is missing is an institution capable of coordinating policies, mediating disputes, and promoting responsible resource management. The idea of an International Materials Agency (IMA) — proposed by the UN's International Resource Panel and, more recently, by the Global Investor Commission on Mining 2030 — offers precisely that mechanism. Just as the International Energy Agency (IEA) was created in response to the oil shocks of the 1970s, an IMA would offer a platform for cooperation between governments and industry, reinforcing data transparency and equitable access to mineral resources crucial to the energy and digital transition⁵⁴.

4 New exploitations vs. recycling

Increasing the supply of materials is vital to meet the future demand for materials in the energy sector. This increase can be done by expanding the primary or secondary supply. Primary supply could be increased by expanding the extraction and processing of critical minerals. Regarding secondary sources, recycling could contribute significantly to diversifying sources of supply to prevent the vulnerabilities generated by the excessive dependence on exporting countries.

⁵⁰ <https://es.marketscreener.com/noticias/mp-materials-y-el-departamento-de-guerra-de-ee-uu-se-asocian-con-maaden-para-desarrollar-una-refine-ce7d5ed9d98ff325>

⁵¹ <https://www.arabnews.com/node/2223726/business-economy>

⁵² This initiative was launched in 2021 to compete with China's New Silk Road and boost infrastructure development in Latin America, Southeast Asia, and Africa. In four years, more than €306 billion has been mobilised, and it is likely to exceed €400 billion by 2027.

⁵³ https://international-partnerships.ec.europa.eu/policies/global-gateway/climate-and-energy_en?page=2

⁵⁴ <https://www.theparliamentmagazine.eu/news/article/europes-chance-to-lead-on-critical-minerals>

4.1 Primary supply of critical minerals

In terms of primary supply, resources are classified based on geologists' confidence in the existence and size of deposits. They become reserves when economic extraction is possible under current technical and market conditions. The border between the two is fluid, as it is subject to many factors, including raw material prices, infrastructure, regulatory frameworks, political decisions, technological innovation, and even the existence of security and conflict situations that may affect the extraction zone.

Ten years ago, 50% of all known rare earth element deposits were in China. Today, that figure has dropped to 34%⁵⁵, indicating the interest placed in the exploration of new ones in recent years. Earlier this year, Sweden discovered the largest rare earth element deposits in Europe⁵⁶, and between 20 and 40 million tonnes of lithium was recently found in a volcanic crater along the Nevada-Oregon border⁵⁷, making it potentially the largest deposit in the world. And regarding cobalt, for example, Australia has the second largest reserves, with around 15% of the world's total, with a production to date of only 2%.

By the end of the next decade, there is reason to expect additional discoveries that deepen the understanding of the various potential sources of supply⁵⁸. However, explorations to find new deposits are very expensive and can be considered a lost fund if satisfactory results are not obtained, constituting the first barrier to encourage investments in the mining sector.

Although the demand for critical minerals can increase dramatically in just a few years, increasing supply by putting a new mine into operation usually takes a decade or more. This gap between rapid technological adoption and slow resource development puts governments and businesses under constant pressure to secure new sources of supply. Addressing these risks requires both short-term responses and long-term industrial planning.

The main problem for the opening of new deposits is the great uncertainty surrounding their profitability. In this regard, public-private collaboration and the support of state financing is essential if we are to move towards a secure supply chain related to renewable energies and avoid dependencies on third countries and especially China.

Prices of some minerals have swung sharply over the past decade, driven less by supply and demand fundamentals than by strategic behaviours, whether by China's dominance in supply chains or by export controls and protectionist measures. Price should not be the engine used to start up new deposits. If this is the only factor, diversification of supply will not be possible for certain minerals.

⁵⁵ <https://www.goldmansachs.com/insights/articles/resource-realism-the-geopolitics-of-critical-mineral-supply-chains>

⁵⁶ <https://lkab.com/en/press/europes-largest-deposit-of-rare-earth-metals-is-located-in-the-kiruna-area/>

⁵⁷ <https://www.earth.com/news/worlds-largest-lithium-deposit-lies-under-a-supervolcano-in-the-us/>

⁵⁸ <https://www.goldmansachs.com/insights/articles/resource-realism-the-geopolitics-of-critical-mineral-supply-chains>

For example, in 2022, Jervois opened the only US cobalt mine in Idaho, only to close it the following year when prices plummeted. Between May 2022 and May 2025, cobalt prices fell by 59.5%. This sharp drop coincided with China Molybdenum Company Limited (CMOC) nearly doubling its annual cobalt production in 2024, reaching record production levels even as market prices fell more than 60 percent⁵⁹.

This situation indicates that government investment in shares provides an avenue for the necessary capital and reduces risks for companies. Price support mechanisms and other policy tools will also be able to make strategic mining projects viable for national security.

With regard to investments in developing and mineral-rich countries, foreign direct investment plays a key role in helping resource-rich countries build local refining and processing capacities and move up the mineral value chain. The energy transition offers developing economies a great opportunity to boost development by moving up the value chain of critical minerals⁶⁰.

Recently, new regions are emerging as hotspots in the competition for mineral resources. They have large underdeveloped reserves and are attracting geopolitical interest. Their importance as sources of critical minerals gives these areas additional strategic importance. This is the case of the Arctic, deepwaters, or space mining.

Greenland has deposits of 39 of the 50 minerals included in the US critical minerals list. These include earth elements, graphite, platinum group metals, and niobium. Greenland's REE reserves are approximately 1.5 million metric tons, close to the US total. If developed, these reserves could cover a large portion of global demand⁶¹. Both the United States and China have shown interest in Greenland's resources in recent years, but now Trump has gone a step further by seeking to annex this huge island.

4.2 Secondary supply

Emerging technologies for recycling and recovering critical raw materials are not yet sufficiently developed to meet current demand. Their large-scale industrial implementation requires technological, environmental, and economic validation.

Current recycling levels vary significantly by material. Steel, aluminium, and copper are commonly recycled, with average rates above 60%, so there could be large volumes of secondary supplies of these materials available to replace a portion of their primary production and relieve pressure to further expand their supply chains. In contrast, other materials, such as lithium, graphite, and rare earth elements, are rarely recycled (1% recycling rate), mainly due to the lack of considerable flows at the end of their useful life.

In the long term, there is great potential to improve recycling rates for these materials as a growing number of contemporary energy infrastructures reach the end

⁵⁹ <https://source.benchmarkminerals.com/article/cobalt-price-slump-hits-first-new-us-cobalt-mine-in-decades>

⁶⁰ <https://sdgpulse.unctad.org/critical-minerals/>

⁶¹ <https://www.csis.org/analysis/greenland-rare-earths-and-arctic-security>

of their useful life⁶². Therefore, proactive actions are also needed to support the R&D of waste management measures and recycling technologies for these materials, so that they are available and can be scaled up to manage the increasing volumes of energy technologies at the end of their useful life that will be needed in the future.

The most convenient thing is that the entire life of the product -from its design to the end of use- is carried out from a point of view of subsequent recycling and circularity. Many products today are not designed for easy material recovery. They are often created with functionality and production costs in mind rather than sustainability. For example, some products contain adhesives or coatings that further complicate material recovery. The lack of clear design standards for recycling exacerbates the problem, making the transition to a circular economy even more complicated⁶³.

4.3 Replacement

Technological advances can drive the reduction of the intensity of the use of critical minerals and their replacement, thus alleviating the impacts of a possible shortage of materials supply in the future related to strategic minerals. Technological innovation that reduces the intensity of material use in energy technologies such as solar PV, wind, and battery storage is already underway. Replacements of materials and technologies are also being carried out, such as the abandonment of permanent magnet-based wind turbines and the adoption of vanadium redox flow batteries. While these strategies could reduce the demand for supply-constrained materials such as Li, Co, and rare earth elements, they could increase the demand for other materials due to replacement of technologies and materials (e.g., increased demand for Na or V due to replacement of lithium ion batteries for sodium or vanadium ion redox flow batteries, or replacement of Cu for Al in wires). Thorough assessments of these trade-offs are essential to ensure a sufficient supply of alternative materials should such replacements occur⁶⁴.

5 EU's response to critical minerals

The EU is gradually trying to strengthen its autonomy in strategic sectors such as clean energy and artificial intelligence through a strategy of diversification and reduction of the risks of excessive interdependence with other countries (de-risking), but avoiding commercial decoupling with them (decoupling), which would imply deglobalisation with enormous economic costs for member states.

To this end, the European Critical Raw Materials Act, approved by the EU in 2024, sets the goal of achieving the local extraction of 10% of the critical materials

⁶² Yang Qiu, 1,2 et al. The impacts of material supply availability on a transitioning electric power sector <https://doi.org/10.1016/j.crsus.2024.10022>

⁶³ Ries, Lena & Wartzack, Sandro & Zipse, Oliver. (2023). Creating Sustainable Products: The Road to Circularity. 10.1007/978-3-031-42224-9_5.

⁶⁴ Yang Qiu et al. The impacts of material supply availability on a transitioning electric power sector, Cell Reports Sustainability. Volume 1, Issue 10, 2024, <https://doi.org/10.1016/j.crsus.2024.10022>

that the bloc needs by 2030 and reaching 40% of the processing, in addition to covering 25% of the demand with recycling and not depending on a single supplier by more than 65%.

In compliance with this law, the EU has approved 47 projects of interest that will have advantages for their implementation, mainly in the streamlining of the permits necessary to carry them out. Of these, 7 are in Spain.

Recently, the Commission has proposed a new Action Plan called RESourceEU to accelerate the diversification of supply through concrete financing, market monitoring, and risk mitigation instruments. The RESourceEU Action Plan will accelerate the deployment of raw materials projects in Europe and partner countries.

The Commission is prioritising strategic projects with the potential to rapidly reduce EU dependencies. To achieve this, the Commission is mobilising close to €3 billion in EU funding over the next 12 months for critical raw materials projects. The Commission is also expected to propose simpler permits for critical raw materials in order to enable the rapid deployment of the projects, while respecting EU environmental, social, and governance standards.

Funding remains an important bottleneck for projects along the entire value chain of critical raw materials. In recent years, the Commission and Member States have supported critical raw materials projects, for example through the Innovation Fund or the Just Transition Fund. Neo Performance Materials' rare earth element magnet plant in Narva, Estonia - construction of which began in 2023 - has been one of the first beneficiaries of the EU's Just Transition Fund. Its production capacity in Phase 1 is 2,000 annual tonnes, with plans to subsequently expand it to 5,000 annual tons⁶⁵.

The InvestEU guarantee has also helped implementing partners such as the EIB to finance projects. Some Member States have also started to create specific funds for critical raw materials. But more action is needed and that is why the RESourceEU Plan is fundamentally focused on funding. The Commission will unlock support through direct aid through EU grants and mobilise support by channelling investments.

Within this RESourceEU Plan, the EU aims to create the European Critical Raw Materials Centre in 2026. This centre will provide strategic oversight that will enable the EU to ensure European industries' access to critical raw materials, while ensuring resilience and sustainability. It will develop robust information on critical raw material value chains and primary and secondary markets, which will serve as a basis for national and EU strategies on investment, storage, and joint procurement.

A Raw Materials Mechanism will also be established within the framework of the EU Energy and Raw Materials Platform, which will act as a contact search tool, allowing the aggregation of demand and facilitating the joint private purchase of strategic raw materials.

In addition, the Commission, together with Member States, will also launch a pilot

⁶⁵ https://ec.europa.eu/regional_policy/whats-new/panorama/2025/09/17-09-2025-green-jobs-local-roots-global-reach-the-baltic-sea-region-road-to-innovation_en

project for the storage of critical raw materials to create an effective approach to raw material reserves, focusing on logistical and financing challenges to improve industrial resilience.

The RESourceEU Plan will also accelerate raw material diplomacy by deepening and expanding the EU's strategic partnerships with resource-rich and related countries, and strengthening cooperation in multilateral fora. The Commission, Member States, and partner countries will continue to implement the already existing strategic partnerships established through the Global Gateway strategy by accelerating support to projects in third countries through technical assistance, guarantee, and blended financing instruments. Following the Memorandum of Understanding with South Africa, the Commission will also initiate negotiations with Brazil to support joint projects, local value creation and employment, and stricter ESG (Environmental, Social, and Governance), research, and innovation standards throughout the value chain⁶⁶.

The RESourceEU Plan urges Member States that have not yet done so to establish one-stop contact points and ensure that they function efficiently, in order to help set clear deadlines for the granting of permits and reduce risks for project promoters. With a view to improving the regulatory framework, the Commission will present a proposal on accelerating the granting of environmental permits, which will include provisions to accelerate the granting of permits for critical raw material projects.

A very important aspect is that the EU must ensure that foreign investment brings real added value to the single market and is in line with our economic security objectives. Taking into account the strategic nature of the value chain of critical raw materials, the Commission will integrate the strategic projects as 'projects or programmes of Union interest' under the Foreign Direct Investment Regulation, which will provide greater control over foreign investment in the EU critical raw material value chain for security reasons. To further safeguard strategic projects, the Commission will also restrict the participation of non-reciprocal foreign entities, including Chinese-controlled entities, in EU-funded research.

6 Mining in Spain and critical minerals

As demand for renewable energies continues to rise, the mining sector faces significant challenges and opportunities to meet the demand for critical minerals needed while addressing environmental concerns and adopting technological advancements.

Spain is a country with a mining tradition and can play a prominent role due to its geodiversity and the existence of minerals considered critical. In this context, Spain can contribute extractive and mineral processing capacity to the domestic market and the EU. In fact, 7 of the 45 EU priority projects have been awarded to Spain. Seven of these projects have been awarded to Spain, with mines located in Extremadura, Galicia, Andalusia, and Castilla-La Mancha. In Extremadura, the mines of

⁶⁶ https://ec.europa.eu/commission/presscorner/detail/es/ip_25_2755

Aguablanca (Badajoz) and Las Navas (Cáceres) will be used to extract minerals for batteries, while tungsten, a key mineral for the aerospace and defence industry, will be extracted in La Parrilla (Cáceres), an activity that will also take place in Abenójar (Ciudad Real). In Doade (Ourense) lithium will be extracted, and in Andalusia projects will be developed to obtain minerals through circular economy.

Selected projects will be able to benefit from financial support from the European Commission, Member States, and various institutions, in addition to a more streamlined permit processing process. In this regard, the maximum period for the granting of mining permits will be reduced to 27 months, while that of transformation and recycling will be 15 months, compared to the five or ten years that the process used to last.

<p>Doade mine Located in Galicia, the Doade mine is the only approved lithium mining exploitation in the region. Managed by Recursos Minerales de Galicia, S.A., the project involves the construction of an underground mine and a treatment plant for the minerals extracted in the Doade-Beariz area (Ourense).</p>
<p>Las Navas mine Lithium Iberia, S.L. is leading this project, which focuses on open-pit lithium extraction in the area of Dehesa Boyal de las Navas, in Cáceres. This deposit is in an ecologically sensitive location, being located between the SPAs (Special Protection Areas for Birds) of Monfragüe and Canchos de Ramiro - Ladronera, within the Natura 2000 Network.</p>
<p>La Parrilla mine Located between the Extremaduran municipalities of Almoharín and Miajadas, the La Parrilla mine has received the support of the European Commission for its reopening. Iberian Resources Spain seeks to extract tungsten, a critical metal with applications in the technology and defence industry, as it is used in the manufacture of components for home appliances, cars, and even military equipment.</p> <p>The approved exploitation model is an integrated project that will combine extraction with mineral processing, which is a strategic advantage by reducing dependence on third countries in the tungsten supply chain.</p>
<p>Aguablanca mine Located in Monesterio (Badajoz), the Aguablanca mine focuses on the extraction of a variety of strategic minerals such as nickel, copper, cobalt, platinum, palladium, and gold. This exploitation, managed by Rio Narcea Recursos S.A., had already operated open pit in the past, but the new project proposes an underground exploitation, with the aim of minimising its environmental impact.</p>
<p>El Moto mine This deposit located in Ciudad Real, managed by Abenójar Tungsten S.L., focuses on the extraction of tungsten and gold. After 14 years of research and obtaining environmental and mining permits, the project has been approved with an exploitation concession for 90 years.</p>
<p>CirCular Project Unlike the other projects, the CirCular Project, promoted by Atlantic Copper SLU, does not consist of a mining exploitation, but of an innovative metal recycling plant. This facility, located in Huelva, will have the capacity to process up to 60,000 tonnes of electronic and electrical waste per year, allowing the recovery of valuable materials such as copper, gold, silver, platinum, and palladium</p>
<p>Las Cruces PMR Project Cobre Las Cruces S.A.U. is leading this ambitious project in the Iberian Pyrite Belt, which covers areas of Badajoz, Huelva, and Seville. It is an underground mine that will exploit a new polymetallic deposit located beneath the one that was exploited between 2009 and 2020.</p> <p>In addition to extraction, the project includes the construction of the world's first polymetallic refinery, which will produce copper, zinc, lead, and silver using a technology patented by the company.</p>

Figure 5. Projects of strategic interest to the EU in Spain. Source: <https://elperiodicodelaenergia.com/del-litio-al-cobre-los-siete-proyectos-mineros-que-transformaran-espana/>

Spain faces a profound paradox: it has remarkable geological potential, recognised by the European Union with the designation of these seven strategic projects for the

continent's autonomy, but lacks a unified state vision for its mineral resources⁶⁷.

In compliance with the European Critical Raw Materials Act, Spain has presented the National Mining Exploration Program 2025-2029. The problem is that it neither has a clear budget nor depends entirely on the Government, since the competences in mining matters are transferred to the autonomous communities. Perhaps the most relevant novelty introduced by the new action plan is the approval of a new Mining Law.

The Mining Law in force is from 1973 and was a boost for mining, addressing the need for this activity to be developed looking for a balance with some protection of environmental values. A possible reform would offer the opportunity for mining activity to be more sustainable, integrated into the circular economy, and committed to the fight against climate change⁶⁸.

Current and future mining faces social and environmental challenges in general terms and specifically in Spain. Sustainability and the reduction of environmental impact are identified as the main challenges of mining in Spain in an opinion study carried out by Knauf⁶⁹ in which it is concluded that there is a significant gap between the reality of modern mining and the perception that society has. In the study, 63% of respondents consider that mining is an industry that should be boosted in Spain, but 8 out of 10 respondents believe that it does not have enough government support.

Almost half of Spaniards (49%) do not have a clear opinion on how they would react if a mining project were developed near their locality, which shows that the perception of mining in Spain is still complex and, in many cases, there is a great lack of knowledge. 57% of Spaniards believe that it generates employment and development in these areas, while 22% consider that it has an overall economic impact. This positive view on its economic contribution, however, coexists with a significant lack of knowledge about the real scope of its labour impact, 8 out of 10 Spaniards do not know that mining generates more than 320,000 quality jobs in the Spanish mining regions.

Regarding the environmental impact, it is worth mentioning that solutions are being offered to make mining production compatible with sustainable environmental management. In this regard, it is worth mentioning the techniques that allow the development of exploitations with a minimum impact, even fully integrating them into the landscape, generating new ecosystems. An example of this is the UCM Geomorphological Restoration Group led by José Francisco Martín Duque.

With regard to the social impact, it is necessary to have the participation of local communities and interest groups so that the mining activity benefits the local population. It is also important that the mining project be accompanied by other projects in the value chain. From research in universities to the implementation of

⁶⁷ VAN DEN HURK, Arnoldus M. La Nueva Geopolítica del Siglo XXI: La Doctrina TESIS como Pilar de la Soberanía Mineral y la Seguridad Nacional de España. Documento de Opinión IEEE 102/2025.

⁶⁸ Carlos Ramírez Sánchez-Maroto | 28 November, 2023. Actualidad Jurídica Ambiental, no. 139 DOI: <https://doi.org/10.56398/ajacieda.00348>

⁶⁹ <https://knauf.com/es-ES/knauf/sobre-knauf/noticias/estudio-mineria>

production systems. In this way, the generation of "clusters" contributes to improving the development of populations and generate wealth over the long term, even when mining activity has ceased.

The United Kingdom's strategy on critical minerals offers a very interesting vision since it faces the challenge of increasing its own mining capacity by associating it with its own industry, and even proposes an industrial renaissance through the mining, processing, and recycling of minerals⁷⁰.

Conclusions

The future of green technology depends on sustainable supplies of critical minerals. For this reason, the global energy transition cannot be understood only as a technological or environmental change, but as a profound geoeconomic and geopolitical transformation marked by a growing dependence on these minerals.

The shift from a fossil fuel-intensive to a mineral-intensive energy system introduces new structural vulnerabilities, stemming not so much from its geological scarcity, but from the extreme concentration of production, processing, and manufacturing in a small number of countries. In this context, energy security is no longer exclusively associated with access to energy sources and becomes dependent on complex, long mineral supply chains that are highly exposed to political and strategic risks.

This chapter highlights that while the global supply of critical minerals might be sufficient to sustain the energy transition, the real challenge lies in stable access to these resources. The high concentration of production and, above all, refining - with China as the clearly dominant actor - turns critical minerals into instruments of geopolitical power. Although the disruption of the supply of critical minerals in the energy sector would not have short-term consequences, its long-term effects would imply slowing down the energy transition and preventing the fulfilment of climate objectives.

Export controls, trade restrictions, and state-led industrial policies are transforming traditionally economically driven markets into national security issues, weakening multilateralism and increasing geoeconomic fragmentation.

The strategic rivalry between the United States and China acts as the backbone of this new mineral geopolitics. As China consolidates its leadership through vertical integration of value chains and a long-term global investment strategy, the United States and its allies are opting for policies of reindustrialisation, selective protectionism, and friendshoring to reduce critical dependencies. These dynamics, although aimed at strengthening national resilience, run the risk of slowing the deployment of clean technologies, raising the costs of the energy transition, and generating new tensions between climate objectives and security and defence imperatives. The absence of effective global governance of critical minerals remains

⁷⁰ <https://www.gov.uk/government/publications/uk-critical-minerals-strategy/vision-2035-critical-minerals-strategy>

one of the main weaknesses of the current international system

Faced with these limitations, the document shows that no strategy based exclusively on the opening of new mining exploitations can solve the bottlenecks in the short term, due to long development times, price volatility, and regulatory and social uncertainty. In this regard, recycling, the circular economy, technological innovation, and the replacement of materials emerge as indispensable pillars to reduce the pressure on the primary supply, although their contribution will remain limited in the short term. The energy transition therefore requires far-reaching industrial planning, accompanied by public financing mechanisms, investment support, and risk management that stabilise strategic mineral markets.

The energy transition will only be viable if it is accompanied by a strategic, responsible, and cooperative management of the critical minerals that make it possible. In this regard, the European Union's response reflects an attempt to balance between strategic autonomy and economic openness, betting on diversification, de-risking, and strengthening internal capacities without resorting to a complete decoupling from global trade. Initiatives such as the European Critical Raw Materials Act and the RESourceEU Plan represent important advances.

Finally, the case of Spain illustrates both the opportunities and the challenges of this new scenario. The existence of critical mineral resources and the inclusion of several strategic projects in the European framework place the country in an important position within the EU value chain. However, the development of sustainable mining that is socially accepted and aligned with climate objectives requires a profound update of the regulatory framework, greater coordination between administrations, and a real integration of mining in a circular economy vision.

Chapter Three

Fusion energy

Sehila M. González de Vicente

Abstract

Fusion energy, a natural process that powers the Sun and sustains the planet's climatic and biological systems, has become a first-order scientific challenge and a key strategic asset in global geoeconomic competition. Replicating this mechanism on Earth requires highly demanding conditions from both a scientific and technological standpoint. This was achieved for the first time in 2022 at the National Ignition Facility in the United States.

Renewed interest in fusion responds to two structural dynamics: the progress of critical enabling technologies —advanced materials, superconductivity, artificial intelligence and high-performance computing— and the growing demand for firm, decarbonized and scalable energy to sustain highly electrified and digitalised economies.

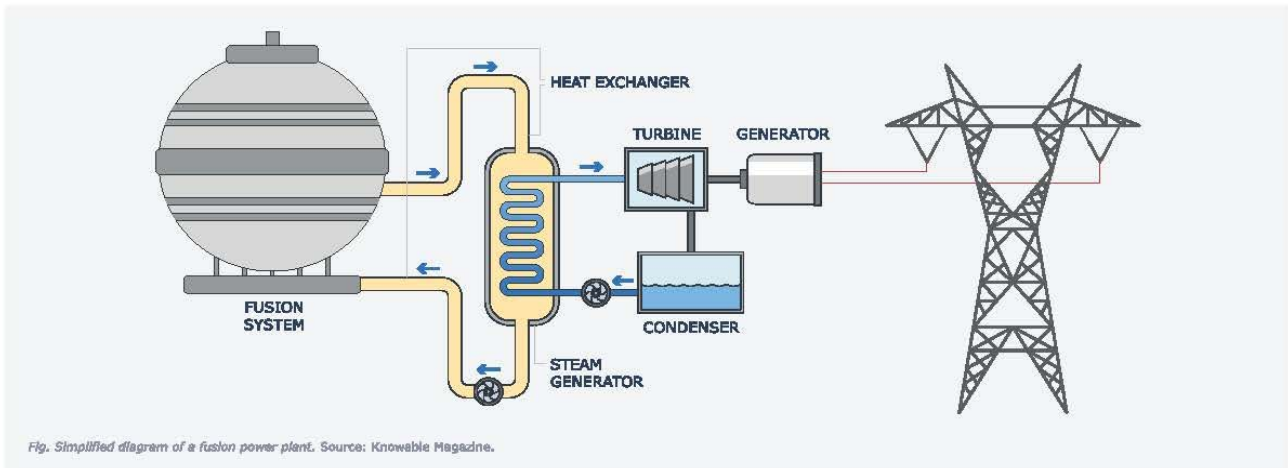
In 2025, more than 50 private companies were engaged in the development of fusion technologies, with cumulative investment approaching 10 billion dollars since 2021. Strategic advantage will be determined by industrial leadership, advanced manufacturing capacity and the coherent integration of public policy, regulation, financing and human capital. Countries that succeed in translating scientific leadership into productive capacity will consolidate their position in the new global energy order.

Keywords






Fusion energy, Energy transition, Energy sovereignty, Enabling technologies, Energy geopolitics, Technological competition.

FUSION ENERGY

FUSION ENERGY IS NO LONGER JUST A MATTER OF ADVANCED PHYSICS, BUT A STRATEGIC VECTOR OF ECONOMIC, INDUSTRIAL AND TECHNOLOGICAL POWER, WHOSE EVOLUTION WILL HAVE MAJOR IMPLICATIONS FOR ENERGY GEOPOLITICS IN THE COMING DECADES.



ADVANTAGES OF FUSION ENERGY

-  **CLEAN AND EMISSION-FREE:** FUSION REACTIONS DO NOT PRODUCE CO₂ OR OTHER POLLUTANTS ASSOCIATED WITH THE COMBUSTION OF FOSSIL FUELS.
-  **STABLE AND RELIABLE ENERGY:** PROVIDES CONTINUOUS AND STABLE ENERGY SUPPLY, 24 HOURS A DAY, COMPLEMENTING INTERMITTENT RENEWABLE ENERGIES SUCH AS SOLAR AND WIND POWER.
-  **INTRINSIC SAFETY:** NO RISK OF CORE MELTING, GUARANTEEING A HIGH LEVEL OF OPERATIONAL SAFETY.
-  **LOW-LEVEL WASTE:** GENERATES LOW-LEVEL, SHORT-LIFE RADIOACTIVE WASTE, WHICH SIMPLIFIES ITS MANAGEMENT.
-  **FUEL ABUNDANCE:** DEUTERIUM, EXTRACTED FROM WATER, AND TRITIUM OFFER THE POTENTIAL FOR VIRTUALLY UNLIMITED RESOURCES.

TWO STRUCTURAL FACTORS CONVERGE TO PLACE FUSION AT THE CENTRE OF THE CONTEMPORARY ENERGY DEBATE:

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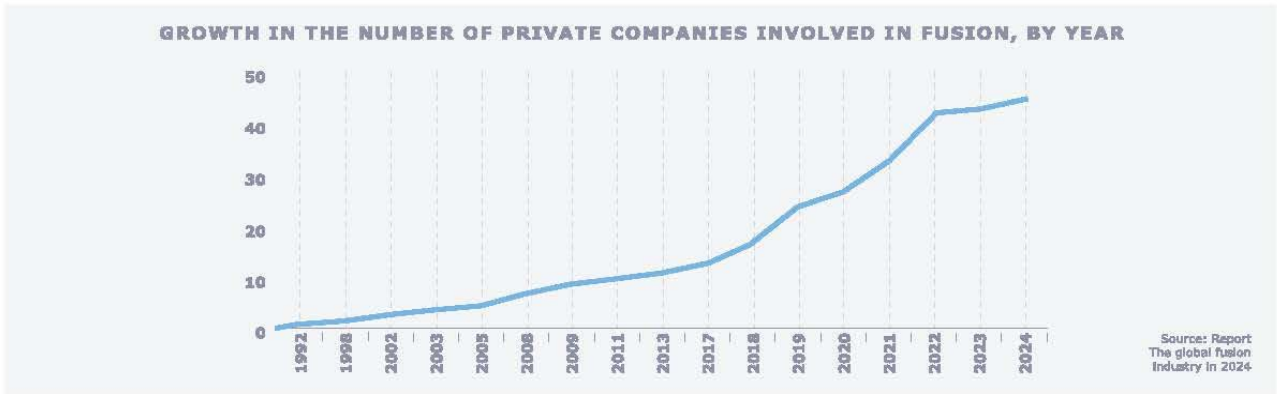
ADVANCES IN ENABLING TECHNOLOGIES
-FROM NEW MATERIALS TO
ADVANCED COMPUTING CAPABILITIES-

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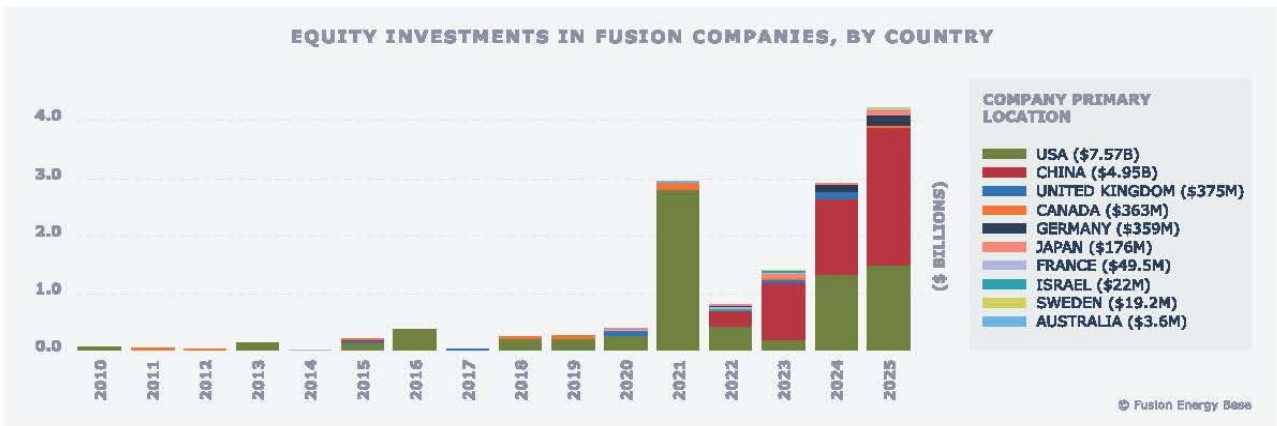


**GROWING NEED FOR RELIABLE,
DECARBONISED AND SCALABLE
ENERGY SOURCES**

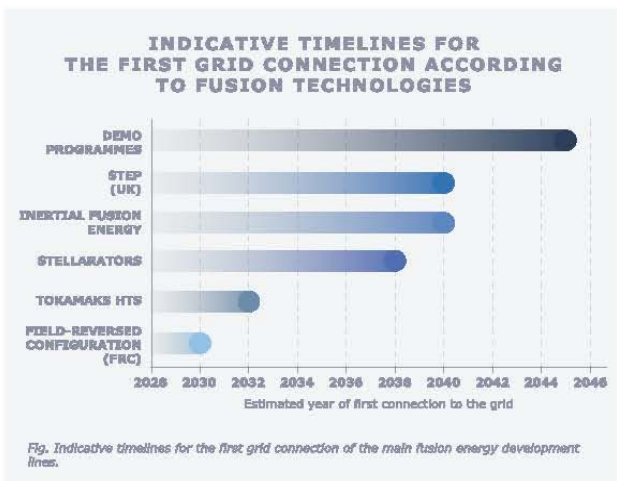
THERE ARE MORE THAN 50 PRIVATE COMPANIES AROUND THE WORLD DEVELOPING VARIOUS FUSION CONCEPTS.



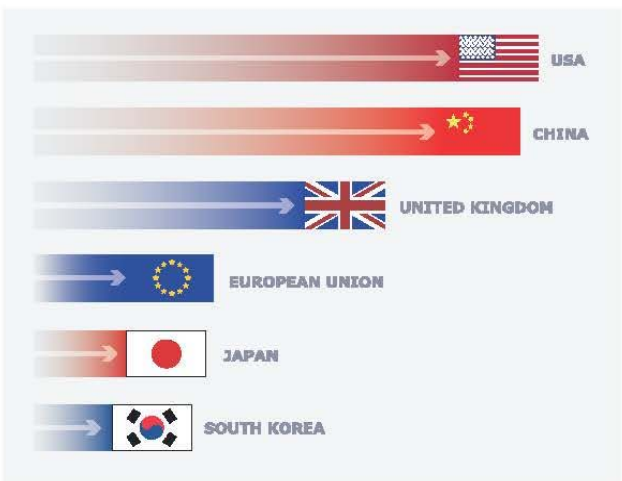
FINANCING OF PRIVATE INITIATIVES: WITH AN ANNUAL GROWTH OF 178% COMPARED TO THE PREVIOUS YEAR AND A TOTAL INVESTMENT OF NEARLY US \$10 BILLION SINCE 2021.



DEADLINES FOR GRID CONNECTION



THE GLOBAL RACE TOWARDS LEADERSHIP IN FUSION ENERGY



Introduction

1 Fusion Energy: innovation, energy sovereignty and global competitiveness

Energy has always been a central pillar of geopolitics. Control over energy resources, technologies, and supply chains has shaped international relations, economic development, and national security for over a century. From coal and oil to natural gas and nuclear fission, each major energy transition has reconfigured global power balances, created new dependencies, and redefined strategic influence. In the context of the twenty-first century—marked by climate change, geopolitical fragmentation, and rapid technological acceleration—fusion is increasingly viewed not merely as a scientific ambition, but as a potential strategic asset with profound geopolitical implications.

Fusion energy occupies a unique position in the global energy landscape. Unlike fossil fuels, it promises near-zero operational carbon emissions; unlike renewable energy sources, it offers the prospect of continuous, dispatchable power independent of weather or geography; and unlike nuclear fission, it carries intrinsically different safety characteristics and long-term waste profiles. These features place fusion at the intersection of climate policy, energy security, industrial strategy, and technological sovereignty. As a result, fusion is emerging as a subject of strategic interest for governments before its commercial deployment.

By 2025, fusion has reached a critical inflection point. Decades of publicly funded research—epitomized by large international programmes such as ITER—have been complemented and increasingly challenged by a rapidly expanding private fusion sector. Scientific milestones, including sustained high-performance plasma operation, ignition-relevant results in inertial fusion, and advances in high-temperature superconductors, have shifted fusion from a distant promise to a pre-industrial technology under active strategic consideration¹ This transition fundamentally alters the way fusion must be understood within energy context: no longer solely as a long-term research endeavour, but as an emerging component of energy systems and industrial competition.

From a geostrategic perspective, fusion's most distinctive attribute is its potential to decouple energy production from traditional resource geopolitics. Fusion fuels—primarily isotopes of hydrogen—are widely available, with deuterium extractable from seawater and tritium potentially bred within fusion systems themselves. While tritium availability represents a near- and medium-term strategic constraint, the long-term vision of self-sustaining fuel cycles contrasts sharply with the geographically concentrated reserves of oil, gas, and critical minerals that dominate today's energy geopolitics. If realised at scale, fusion could significantly reduce exposure to fuel price

¹ National Academies of Sciences, Engineering, and Medicine. *Bringing Fusion to the U.S. Grid*. Washington, DC: The National Academies Press, 2021.

volatility, supply disruptions, and coercive energy diplomacy 2.

At the same time, fusion introduces new strategic dependencies that differ from those of previous energy systems. Rather than fuel access, geopolitical advantage is likely to be determined by leadership in advanced manufacturing, materials science, superconducting technologies, digital control systems, and high-performance computing. In this sense, fusion aligns closely with broader strategic competition in deep technologies, where energy, digitalisation, artificial intelligence, and advanced materials increasingly converge. Countries that succeed in mastering these enabling technologies—and in translating scientific leadership into industrial capability—stand to gain not only energy security, but also economic and technological influence. Leadership in fusion will depend not only on technical breakthroughs, but on the ability to integrate policy, regulation, finance, workforce, and industry into coherent national and regional strategies.

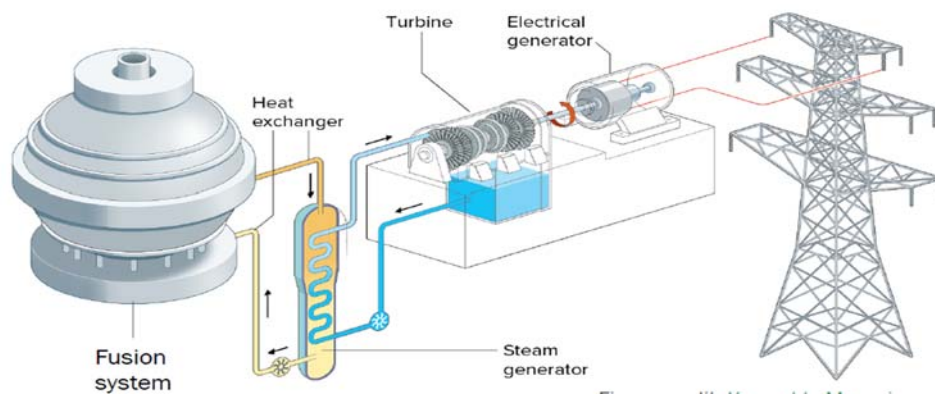


Figure 1. Simplified diagram of a fusion power plant. Source: Knowable Magazine.

The strategic relevance of fusion must also be understood within the context of global decarbonisation. As countries pursue net-zero commitments, limitations in existing energy technologies have become increasingly apparent. Variable renewables require large-scale storage and grid reinforcement; nuclear fission faces political, regulatory, and waste-related challenges in many regions; and carbon capture technologies remain uncertain at scale. Fusion is therefore increasingly framed by policymakers as a potential “firm, clean power” option capable of complementing renewables in future low-carbon systems ³ This framing elevates fusion from a scientific curiosity to a potential pillar of long-term climate and energy strategies.

Also, fusion energy has the potential to play a transformative role in meeting the rapidly expanding demand for electricity over the coming decades. As societies electrify transportation, industry, and buildings, and as new digital technologies—especially artificial intelligence (AI) and data centres—drive unprecedented increases in power consumption, energy systems will need significantly larger, reliable, and low-carbon baseload capacity. Global electricity demand is projected to continue rising strongly through mid-century, with scenarios indicating that total demand may

² World Energy Outlook 2023. IEA, Paris, 24 de octubre de 2023.

³ European Commission (2023) – State of the Energy Union 2023.

increase by more than the equivalent of adding a country the size of Japan’s consumption each year through the late 2020s, driven by electrification and digital growth⁴. Growth in electricity consumption could more than double between 2023 and 2050 as electrification expands into new sectors, with emerging demand centres such as AI and cloud computing significantly shaping future load patterns, including forecasts of data centre demand doubling by 2030 to nearly 1 000 TWh per year due to AI and related technologies⁵. By providing firm power that can operate around the clock without the variability of wind or solar, fusion could help ensure grid stability and support the energy system backbone required to satisfy the growing global appetite for firm sources of electricity.

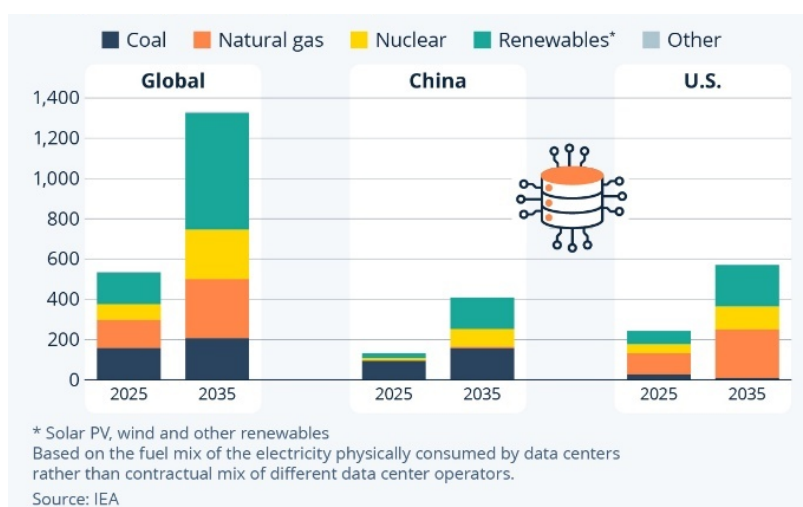


Figure 2. Electricity generation to supply data centres (in TWh)⁶.

The rise of private fusion companies further reshapes the strategic landscape. Unlike previous generations of nuclear technology, fusion commercialization is being pursued through venture-backed firms operating across multiple jurisdictions. This introduces new questions regarding intellectual property, export controls, regulatory alignment, and state support. Governments are now confronted with strategic choices: whether to act primarily as funders of research, as market shapers through regulation and procurement, or as active partners in commercialization. These choices will influence not only domestic energy outcomes, but also international competitiveness and alliance structures.

In this context, fusion energy matters for geostrategy not because it will immediately transform the global energy mix, but because decisions taken in the 2020s will determine who controls the knowledge, infrastructure, standards, and industrial capacity underpinning fusion’s future deployment. As with previous energy transitions, early strategic positioning is likely to yield long-term advantages. Understanding fusion through a geostrategic lens is therefore essential to navigate an

4 IEA, World Energy Outlook 2025.

5 McKinsey Global Energy Perspective 2024; IEA, Energy and AI.

6 <https://www.statista.com/chart/34295/data-centers-electricity-generation-source/>.

increasingly complex, competitive, and decarbonising global energy system.

2 State of Fusion in 2025: From Research to Pre-Industrial Phase

By 2025, fusion energy has reached a stage where scientific research and engineering development increasingly overlap with early industrial strategy and commercialization planning. After decades of basic plasma physics research and critical investments in large international facilities, fusion is no longer viewed purely as a long-term scientific goal. Instead, it occupies an intermediate phase in which key technologies are being validated, multiple prototype concepts are under construction, and an emerging private sector is positioning for eventual deployment.

2.1 ITER and Public Fusion Programmes

At the forefront of the public effort remains the International Thermonuclear Experimental Reactor (ITER), the largest scientific infrastructure ever built to pursue controlled magnetic fusion. Located in Cadarache, France, ITER is designed to demonstrate the physical and technological feasibility of producing net energy from fusion reactions, aiming for a ten-fold energy gain ($Q \approx 10$) in deuterium-tritium operations in 2039⁷.

The goal of ITER is to operate at 500 MW (for at least 400 seconds continuously) with 50 MW of plasma heating power input. No electricity will be generated at ITER, and it will be an experimental machine. The ITER Tokamak will be the largest ever built, with a plasma volume of 830 cubic metres, and a major radius of 6.2 m.



Figure 3. Image: Drone view of the ITER tokamak and construction site. 14-05-2025 - Photo: ITER Organization/EJF Riche.

ITER is funded and will be operated by seven member parties: China, the

⁷ <https://www.iter.org/sites/default/files/media/2025-11/exe-ra-2024-ok-web.pdf>.

European Union (EU), India, Japan, Russia, South Korea and the United States. Switzerland participated through Euratom and F4E until 2021, though it is expected to rejoin in 2026 following subsequent negotiations with the EU. ITER also has technical cooperation agreements with Australia, Canada, Kazakhstan and Thailand⁸.

The ITER project's design process began with a conceptual phase in 1988, following the idea's launch in 1985, with the final design approved in 2001, though detailed engineering continued, leading to the formal agreement to build it in 2007 and construction starting in 2013.

ITER has experienced multiple schedule delays and cost increases. Initial projections suggested that ITER construction would be completed in 2016, with the first experiments beginning in 2020, at a total cost of \$10 billion (adjusted for inflation).

In 2016, the construction schedule was extended to 2025, with full operation expected by 2035, adding an additional \$5.2 billion (adjusted for inflation) to the total cost. In July 2024, ITER announced that the facility would not be fully operational until 2039 and would with a final cost of \$22 billion⁹.

ITER's continuing construction and component delivery—such as the installation of massive niobium-tin superconducting magnets—underscore both the technological scale and the persistent timeline challenges of fusion research. Despite periodic schedule adjustments and budget escalations, ITER's progress provides very useful information about components manufacturing, quality control, assembly phase issues, etc as well as the set up of an incipient fusion supply chain.

In parallel with ITER, regional programmes such as EUROfusion in Europe¹⁰ coordinate research and design work toward a post-ITER device (often referred to as DEMO) that would exemplify a practical electricity-producing fusion plant. These programmes extend beyond pure plasma science into materials science, breeding blanket systems, tritium fuel cycles, and component testing, all essential to bridge the gap between experimental devices and industrial power plants.

2.2 Materials Validation and Infrastructure Development

A core technical bottleneck remains the behaviour of materials under intense neutron irradiation and high heat fluxes. Fusion energy systems produce neutron spectra and fluxes not routinely encountered in fission reactors or conventional power plants, making materials qualification an international priority.

One strategic initiative in 2025 is the IFMIF-DONES project in Spain¹¹, an accelerator-based high-flux neutron source designed to test candidate materials for future fusion reactors. Spain, the European Commission, and international partners have committed hundreds of millions of euros to its construction and operation,

⁸ <https://www.iter.org/about/iter-members>.

⁹ <https://www.congress.gov/crs-product/R48362>.

¹⁰ <https://euro-fusion.org/>.

¹¹ <https://ifmif-dones.es/>.

reflecting the broader focus on materials readiness as a prerequisite for having an operating fleet of fusion power plants.

2.3 Private Sector Momentum and Diversification

Historically, fusion research was dominated by public institutions and multilateral collaborations like ITER. However, by 2025, private fusion ventures have grown in number, ambition, and funding. Fusion Industry Association 2025 report 12 indicates that over 50 private companies worldwide are active in developing diverse fusion concepts, from compact tokamaks and field-reversed configurations to alternative confinement systems and laser-driven approaches.



Figure 4. Distribution of fusion start-ups in 2025. Source: Fusion Industry Association 2025 report.¹²

Investment data from the Fusion Industry Association show a surge in funding to these private efforts, reaching record annual growth — a 178 % increase over the prior year — with total investments nearing \$10 billion since 2021. While capital requirements remain high, this influx of private funds demonstrates both confidence in fusion’s prospects and strategic interest from commercial and institutional investors alike. Venture capital, strategic corporate investors, and increasingly sovereign and institutional actors are shaping the sector. The report notes a shift from early speculative funding toward larger, milestone-based investment rounds tied to demonstrable technical progress.

¹² <https://www.fusionindustryassociation.org/fusion-industry-reports/>.

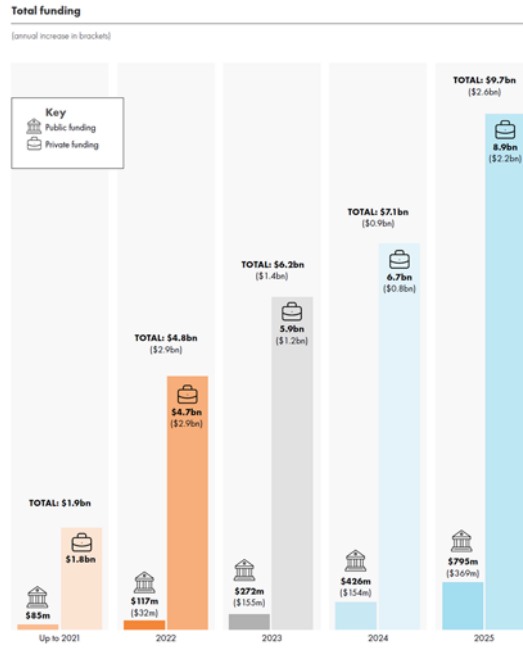


Figure 5. Total funds allocated to the development of fusion.
Source: Fusion Industry Association 2025 report.¹²

In the following table the top-5 best-capitalised fusion energy startups in 2025 are listed:

Company	Total Funding (approx.)	Headquarters	Fusion Concept / Technology	Major Prototype / Project	Top 3 Known Investors
Commonwealth Fusion Systems (CFS)	~\$3.0 billion+	Devens, Massachusetts, USA	High-field Tokamak (HTS magnets)	SPARC & future ARC power plant	Breakthrough Energy Ventures; Eni; Google; Temasek
TAE Technologies	~\$1.3 billion+	Foothill Ranch, California, USA	Field-Reversed Configuration (FRC)	Copernicus / Da Vinci (planned)	Google; Chevron; (Pre-merger) Rusnano (historic/legacy)
Helion Energy	~\$1.03 billion	Everett, Washington, USA	Magneto-inertial / FRC fusion	Polaris prototype	Sam Altman; Reid Hoffman; Peter Thiel's Mithril Capital Management
Pacific Fusion	~\$900 million	Fremont, California, USA	Pulsed electromagnetic / inertial fusion tactic	Electromagnetic pulse fusion prototype (milestone-driven)	Not fully disclosed / milestone-based (lead investors not yet widely published)

SHINE Technologies	~\$778 million	Janesville, Wisconsin, USA	Neutron testing & isotope support for fusion readiness	Test & isotope production facilities	Energy Ventures Group; Disruptive Technologies; Nucleation Capital
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Table 1. Summary of the top-5 best-capitalised fusion energy startups in 2025

One high-profile example is TAE Technologies, a company developing alternative fusion concepts that has partnered with the UK Atomic Energy Authority to commercialise auxiliary technologies such as neutral-beam systems, which have applications in medicine and industry on shorter timescales, and in December 2025 merged with Trump Media & Technology Group in all-stock transaction valued at more than \$6 billion¹³.

2.4 Technological maturity level and outstanding challenges

Fusion still faces the need of technological developments. Net electricity production and continuous operation have not yet been achieved. Materials testing, fuel cycle integration — particularly tritium breeding and handling — and cost-effective manufacturing at scale remain major challenges.

The next decade will be decisive in transforming fusion from an experimental quest into an industrial programme capable of delivering real energy solutions.

Artificial intelligence (AI) can significantly accelerate the development of fusion energy by addressing some of the most complex, data-intensive, and time-critical challenges in many critical aspects in the deployment of fusion power plants. From real-time plasma control using reinforcement learning and neural networks to actively manage plasma shape, position, and stability, to achieve RAMI (Reliability, Availability, Maintainability, Inspectability) targets in future fusion power plants by improving and optimizing fuel cycle, tritium management, and Operations.

2.5 Timelines to Grid Connection

Fusion energy development follows multiple parallel timelines, largely determined by the chosen confinement concept, development approach, and balance between physics risk and engineering complexity. Rather than a single “fusion date,” the field is characterized by a portfolio of pathways with different risk–reward profiles:

2.5.1. Public DEMO Programmes (ITER-based Tokamaks)

Public programmes anchored in ITER and followed by DEMO machines represent the most conservative and physics-validated pathway. These efforts

¹³ <https://tae.com/trump-media-and-technology-group-to-merge-with-tae-technologies/>.

prioritize full demonstration of plasma performance, tritium breeding, materials qualification, and regulatory acceptance before grid connection.

- Strengths: High confidence in physics, strong international governance, regulatory credibility
- Limitations: Long timelines, difficult to integrate innovations, complex international coordination, large machines, high capital intensity
- Indicative grid connection: ~2045–2050

2.5.2 Tokamak-based start-ups using high-field, high-temperature superconducting magnets (e.g. CFS, Tokamak Energy)

High-field tokamak startups leverage advances in high-temperature superconductors (HTS) to significantly reduce machine size and accelerate iteration cycles. These companies aim to bridge public science and private delivery by de-risking key physics while compressing engineering timelines.

- Strengths: Strong physics basis, faster iteration than ITER-class machines, smaller machines, agile approach
- Limitations: Materials lifetime, tritium systems, integration
- Indicative grid connection: ~2035

2.5.3. Field-Reversed Configuration (FRC) Approaches (e.g. Helion, TAE)

FRC-based concepts pursue compact, pulsed, and often semi-aneutronic designs, sometimes bypassing steam cycles through direct energy conversion. These approaches prioritize speed and simplicity, accepting higher physics risk.

- Strengths: Potentially faster path, smaller machines, lower capital cost
- Limitations: Plasma stability, repetition rate, and net electricity still unproven
- Indicative grid connection: ~2031–2033

2.5.4. Stellarator-based Start ups (e.g. Proxima Fusion)

Advanced stellarator concepts aim to exploit inherently stable plasma configurations combined with modern computational design and advanced manufacturing. While physics is well established, engineering complexity remains high.

- Strengths: Intrinsic plasma stability, steady-state operation
- Limitations: Manufacturing complexity, limited operational experience at scale, less mature concepts than tokamaks

- Indicative grid connection: ~2037

2.5.5. Inertial Fusion Energy (IFE) (e.g. Xcimer Energy)

IFE builds on ignition breakthroughs but faces challenges in repetition rate, target fabrication, and energy efficiency. While scientifically promising, engineering gaps remain before power plant operation.

- Strengths: High power density potential, separation of driver and chamber
- Limitations: Industrial scalability, cost, and system integration
- Indicative grid connection: ~2040

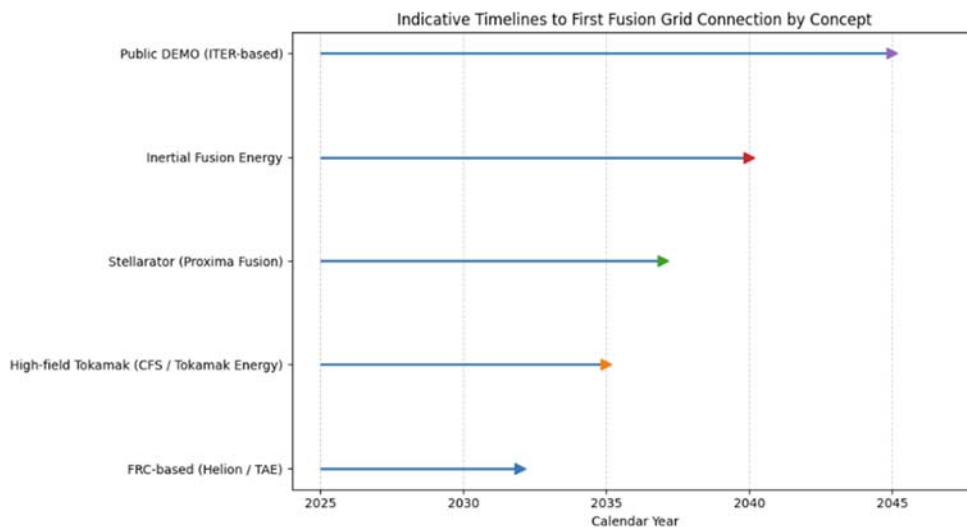


Figure 6. Indicative timelines to first grid connection for major fusion energy development pathways. Dates reflect expert consensus estimates based on current technology readiness, announced roadmaps, and system integration challenges. Arrows indicate first-of-a-kind grid-connected demonstrators, not full commercial deployment.

3 A key element for Fusion Energy Deployment: Regulation

As fusion energy moves toward prototype demonstration and early commercial deployment, regulation becomes one of the most critical non-technical determinants of success. The regulatory framework governing fusion will shape not only safety outcomes, but also investment decisions, siting of facilities, pace of deployment, and long-term industrial competitiveness.

Fusion developers are now designing facilities intended to connect to the grid, supply electricity markets, and operate under commercial conditions. These systems must be licensed, insured, financed, and accepted by the public. In this context, regulation must strike a careful balance: it must ensure protection of workers, the public, and the environment, while remaining proportionate to the actual risk profile

of fusion technologies.

History shows that regulatory misalignment can significantly delay energy transitions. Overly conservative frameworks increase costs, lengthen timelines, and discourage private capital. Conversely, clear, predictable, and risk-informed regulation can accelerate learning-by-doing, foster innovation, and anchor new industrial ecosystems. For fusion energy—where multiple technology pathways are advancing in parallel—regulatory clarity is now a strategic necessity rather than a future concern.

3.1 Fundamental Differences Between Fusion and Fission

The case for a distinct regulatory approach for fusion is grounded in fundamental physical and operational differences between fusion and nuclear fission systems.

Fission reactors rely on controlled chain reactions, which require complex engineered systems to manage reactivity, decay heat, and accident scenarios. Fusion reactions, by contrast, are inherently self-limiting. The fusion process ceases immediately if precise plasma conditions are not maintained, eliminating the possibility of runaway reactions. There is no possibility of chain reaction.

Fission plants contain large inventories of fissile material that must be safeguarded over decades. Fusion systems operate with very small quantities of fuel, primarily deuterium and tritium. Tritium presents radiological and environmental hazards, but it does not pose the same proliferation or long-term security risks as fissile materials. For example, Tritium half-life is 12.32 years.

Fission produces high-level radioactive waste requiring isolation for millennia. Fusion produces no fission products; its waste consists mainly of neutron-activated materials, many of which decay to low-level waste within decades. This distinction has major implications for waste classification, disposal pathways, and long-term liabilities.

Credible accident scenarios for fusion are dominated by localized releases of tritium or activated dust, rather than large-scale off-site radiological releases. As a result, emergency planning requirements for fusion facilities are fundamentally different from those for fission reactors.

3.2 Why Fusion Regulation Must Be Specific

Given fusion's distinct risk profile, regulation should focus on hazard-based oversight rather than reactor-centric licensing. Key regulatory domains include:

- Management of radioactive materials (especially tritium)
- Occupational radiation protection
- Environmental releases
- Conventional industrial safety

This approach aligns fusion regulation more closely with particle accelerators and research facilities than with nuclear power reactors.

Fusion technologies will mature through a sequence of increasingly integrated prototypes. Regulation must therefore be adaptive, allowing lessons learned from early facilities to inform subsequent requirements. Overly prescriptive rules at early stages risk freezing designs prematurely and increasing costs without commensurate safety benefits.

Private investment now plays a central role in fusion development. Regulatory uncertainty directly translates into higher financing costs. Clear licensing pathways, defined timelines, and regulatory stability are essential to mobilize the scale of capital required for fusion deployment.

3.3 Impact of regulatory frameworks on the deployment of fusion technologies

Regulatory frameworks increasingly function as tools of industrial policy.

Proportionate regulation enables faster licensing, earlier grid connection, and rapid learning.

Overly conservative regulation delays projects, increases costs, and drives developers to more favorable jurisdictions.

Early regulatory leadership allows countries to shape international norms and standards, reinforcing long-term competitiveness.

Countries that move first to establish fusion-appropriate regulation are more likely to attract prototype facilities, supply chain investment, and skilled talent—key ingredients of a future fusion industry. This is somehow reflected in the emerging fusion industry distribution, being US the leader.

3.4 Status of Fusion Regulation in Key Jurisdictions

United States

The United States has taken the most explicit steps to define fusion-specific regulation. Fusion facilities are regulated under a byproduct materials framework rather than as fission reactors.

Key milestones include:

- 2009: NRC affirms jurisdiction over fusion
- 2019–2022: Congressional direction via NEIMA
- 2023: NRC decision to regulate fusion under 10 CFR Part 30
- 2024: ADVANCE Act codifies fusion as particle accelerators under federal law

This framework enables faster licensing while maintaining safety and environmental protections.

United Kingdom

The United Kingdom has taken one of the most proactive and explicit approaches in the world to develop a regulatory regime that is proportionate to the actual risk profile of fusion energy, avoids unnecessary hurdles, and provides clarity and confidence for both public and private developers. This regulatory strategy is now embedded in statute, supported by formal consultations, and linked directly to national planning policy — a combination that gives the UK a strong first-mover advantage. This approach supports national initiatives such as STEP and positions the UK as a global fusion hub.

One of the UK’s defining regulatory innovations is the explicit exclusion of fusion facilities from the traditional nuclear licensing regime under the Nuclear Installations Act 1965. The UK government has legislated to ensure that fusion facilities are not automatically regulated as “nuclear installations”, reflecting their very different hazard profile compared to fission reactors. This legal change provides important clarity and proportionality for fusion developers.

Fusion energy facilities do not require a nuclear site licence under the Nuclear Installations Act. They are therefore not regulated by the Office for Nuclear Regulation (ONR) in the same way as fission reactors. Instead, fusion facilities will continue to be regulated primarily by the Environment Agency (EA) and the Health and Safety Executive (HSE).

European Union

In policy and regulatory development, the EU is actively working toward a dedicated fusion strategy that could lead to a more structured regulatory environment in 2026, reflecting growing recognition of fusion’s potential role in the future energy mix. Stakeholders, including policymakers and industry groups, have called for clearer, harmonised regulatory principles that distinguish fusion from nuclear fission) regulation to provide certainty for investors and developers. The European Parliament and the Commission are engaging in consultations and planning to embed fusion within broader industrial and net-zero frameworks (for example, discussions about its categorisation under the Net Zero Industry Act), but detailed licensing rules for commercial fusion facilities remain in early stages of development or under discussion rather than fully codified across the EU.

In summary, fusion regulation in the EU is evolving from foundational research governance toward emerging policy initiatives aimed at enabling future commercialisation, but a comprehensive, specific regulatory regime for fusion power plants does not yet exist — it is anticipated as part of upcoming EU strategy and legislative planning.

Nordic states (Finland, Sweden, Denmark and Norway)

Finland stands at the forefront of fusion regulation readiness in the Nordic countries, driven by its planned overhaul of nuclear law and clear statutory treatment of fusion under radiation regulation.

Finland is taking a proactive stance toward fusion regulation and broader nuclear law reform.

In June 2025, the Finnish Government sent a draft revision of the Nuclear Energy Act out for public comment. The proposal represents a major overhaul of a law that had been in force for more than 35 years and has been amended repeatedly. The reforms aim to modernise the framework, make it more innovation-friendly, and bring it into alignment with current technological and legislative realities. Fusion research and experimental use of fusion reactors would not fall under the Nuclear Energy Act governing fission facilities. Instead, such activities are clearly stated to be regulated under the Radiation Act. This distinction reflects the regulatory reality that fusion's hazard profile and operational needs differ from conventional nuclear reactors.

The Radiation and Nuclear Safety Authority (STUK) will serve as the licensing authority for activities regulated under radiation law, while facilities involving fission reactions will continue to be regulated under nuclear facility law. The draft restructuring separates decisions on radioactive waste and safeguards from technical safety matters, allowing for modular licensing and clearer governance. The revised Act is scheduled to enter into force on 1 January 2027 if approved.

Sweden was identified as next in readiness. Its existing nuclear legislation already explicitly includes fusion reactors, but those laws are heavily oriented around fission-based regulatory requirements. This means that Sweden's rules can be applied to fusion, but developers may need to navigate comprehensive fission-focused conditions that are not optimised for fusion's distinctive hazard and risk profile.

Both Denmark and Norway were noted to have older nuclear regulatory frameworks that do not specifically mention fusion energy. This creates political and procedural uncertainty for fusion projects, as the absence of explicit fusion references can delay clarity in licensing pathways. Neither country has yet adopted fusion-specific statutory language or strategies to make their legal environment particularly attractive for fusion development¹⁴.

Japan

Japan's nuclear legal architecture was built around fission: reactor licensing, nuclear fuel material controls, and site regulation. The most important consequence for fusion is definitional: fusion devices are not "reactors" under the legal meaning used for fission regulation, so the main fission-focused statute (the Reactor Regulation Act /

¹⁴ Framework of siting criteria and initial assessment for siting the Novatron 3 facility in Nordic region, <https://static1.squarespace.com/static/634d70f7acf00f3d7942848e/t/68f5cc3af2297812c492e052/1760939066885/VTT+report.pdf>.

reactor framework under the Atomic Energy Basic Act structure) does not automatically map onto fusion facilities. The practical result is that Japanese fusion machines have been handled under the radioisotope / radiation-generating device paradigm rather than the fission “reactor” paradigm.

Japan’s fusion devices (especially research-scale machines) have typically fit into regulation governing radioisotopes and radiation-generating equipment, for example JT-60SA, the largest operating tokamak in the world, which has been regulated as a plasma generation device under the radioisotope/radiation framework.

Under existing law, fusion devices can be regulated as radiation generation devices, but the present framework has limitations for commercial-direction fuel cycles—especially tritium. Using tritium as fuel would require changes/updates so that tritium-fuelled plasma generators can be accommodated appropriately.

Japan’s nuclear regulator (NRA) has been increasingly explicit that it is tracking emerging technology trends, including R&D in fusion, as part of its forward-looking work on radiation hazard prevention regulation.

China

China’s biggest recent regulatory milestone is a Ministry of Ecology and Environment (MEE) notice titled “Notice on Matters Concerning the Radiation Safety Management of Fusion Devices”, dated April 2025. China’s institutional structure places nuclear and radiation safety regulation under the Ministry of Ecology and Environment (MEE), including the national nuclear safety administration functions. The 2025 fusion notice explicitly assigns MEE responsibility for radiation safety permitting and indicates regional supervision stations conduct day-to-day oversight/inspection.

The 2025 notice does is effectively declare fusion devices in-scope of the radiation safety regulatory system and provide a fusion-specific classification and administrative pathway for permits/EIA coordination.

China’s fusion framework is explicitly moving toward graded/classified regulation (a familiar approach in China’s radiation device management). The 2025 notice and associated presentations describe fusion devices being grouped along lines such as: plasma physics experimental devices, deuterium–tritium fusion experimental devices, and fusion energy application devices being then managed according to corresponding risk and regulatory handling.

This is significant because DT experiments and “application devices” are precisely where tritium inventories, activated materials, and industrial interfaces become dominant safety drivers—so a one-size-fits-all rule set would either overburden low-hazard experiments or under-specify higher-hazard systems.

China’s official messaging around the 2025 notice emphasizes that fusion does not map neatly to traditional fission reactor supervision, and that the regulator is pursuing science-based regulation and development of a fusion regulatory standards system.

Dimension	Nuclear Fission	Fusion
Reaction behaviour	Self-sustaining chain reaction	Self-limiting
Fuel inventory	Large fissile inventories	Small quantities (D–T)
Proliferation risk	High	Very low
Waste type	High-level, long-lived	Activated materials, shorter-lived
Accident potential	Large off-site consequences	Localized, limited
Emergency planning	Extensive	Limited, site-specific
Appropriate regulation	Reactor-based licensing	Hazard-based oversight

Table 2. Fusion vs Fission: Regulatory-relevant differences

Country / Region	Regulatory Approach	Status
United States	Byproduct material / accelerator	Defined, codified
United Kingdom	Proportionate, fusion-specific	Defined, evolving
European Union	National-level approaches	Fragmented
Finland	Proportionate, fusion-specific	In progress
Japan	Adapted nuclear framework	Gradual adaptation
China	Integrated national oversight	Centralized, state-led

Table 3. Status of Fusion Regulation by Country (2025)

4 Enabling technologies for fusion: the key role of artificial intelligence, high performance computing and quantum computing

The physics and engineering of fusion present extraordinary complexity: plasmas at hundreds of millions of degrees must be generated, confined, and sustained; materials must endure intense heat and neutron loads; reactors must operate reliably as industrial power plants. Every facet of this challenge involves multiscale, nonlinear, high-dimensional physics that are far beyond the reach of human intuition or traditional experimentation alone.

Fusion devices involve tightly coupled, nonlinear phenomena spanning orders of magnitude in space and time: turbulent plasmas, superconducting magnets, neutron-irradiated materials, tritium fuel cycles, power conversion systems, and real-time control.

Historically, progress in fusion was constrained by experimental iteration speed. Design choices were validated by building machines, operating them for years, learning from failure, and then constructing the next generation. This approach is not compatible with the timescales required for industrial deployment.

This is why the integration of artificial intelligence (AI), high-performance computing (HPC), and emerging quantum computing into the core of fusion

development workflows is a game changer. These technologies allow fusion to move from a hardware-limited paradigm to a computation-accelerated engineering discipline, compressing decades of learning into years.

4.1. High-Performance Computing and Integrated Simulation Frameworks

Predictive simulation of fusion plasmas requires solving nonlinear kinetic and magnetohydrodynamic equations across immense scale separations^{15,16,17}. Traditional experimental iteration cannot match the breadth of parameter space that HPC models can traverse. Exascale computing capability is now recognized as a requirement for capturing turbulent transport, edge–core coupling, and electromagnetic effects with fidelity nearing experimental conditions¹⁷.

A recent collaboration between Commonwealth Fusion Systems, NVIDIA, and Siemens demonstrates how modern AI-enabled simulation libraries and digital engineering tools can compress fusion design cycles further.

According to CFS, the combination of NVIDIA’s AI and simulation SDKs (such as cuQuantum, cuFFT, cuBLAS, and TensorRT) with Siemens’ Xcelerator digital twin tools enables GPU-accelerated plasma physics solvers that leverage thousands of GPU cores to shave months off simulation time; AI-assisted surrogate models that replace expensive numerical kernels with learned approximations without significant loss of fidelity; and End-to-end digital engineering workflows that connect plasma simulations with finite-element structural and electromagnetic analyses directly in Siemens’ environment.

By harnessing GPU-accelerated simulation stacks, CFS reports orders-of-magnitude speedups compared to CPU-only workflows, enabling more design iterations within the same calendar time and improving the fidelity of *end-to-end plant performance predictions* (including magnets, structural loads, and integrated plasma behaviour)¹⁸.

4.2 Artificial Intelligence: from control to design optimization

AI is now embedded across the fusion innovation stack, not just in isolated research projects.

AI for plasma control

Deep reinforcement learning and other machine-learning methods have been

¹⁵Jenko, F. et al., Electron temperature gradient driven turbulence. *Physics of Plasmas*, Vol. 7, pp. 1904–1910 (2000).

¹⁶Chang, C. S. et al., Whole-device modelling of plasma transport in fusion plasmas. *Physics of Plasmas*, Vol. 24, 055503 (2017).

¹⁷Birdsell, J. et al., Exascale computing and fusion energy sciences. *Journal of Physics: Conference Series*, Vol. 1258, 012006 (2019).

¹⁸[How NVIDIA AI and simulation libraries and Siemens tools can accelerate fusion energy | The Tokamak Times.](#)

shown in academic research to outperform classical controllers in maintaining plasma shape and suppressing instabilities^{19, 20}. These methods are viable for plant-scale systems only if embedded within computational frameworks that can train on simulated data and then generalize to new operational conditions.

AI is being used to

Predict disruption precursor signatures, avoiding costly plasma terminations; optimize real-time magnet coil control strategies using models trained on simulated and experimental data; and inform control system architecture for future devices where human-tuned feedback loops are impractical.

These capabilities are essential because disruption avoidance and active stability control directly influence machine availability — a critical economic parameter for fusion power plants^{19,21}.

AI-accelerated design and surrogate models

AI also drives rapid prototyping of designs. Neural networks serve as surrogate physics models, capturing complex dependencies (e.g., turbulence transport coefficients, stability margins) at a fraction of the compute cost of full solvers^{22,23}.

This approach has been integrated with Siemens' digital twin environment, enabling: fast evaluation of candidate designs within a coherent digital engineering workflow, Multi-objective optimization across performance, cost, and manufacturability, as well as exploration of unconventional design concepts that would be impractical to test physically.

Such surrogate models — trained on HPC-generated datasets and cached for real-time evaluation — enable iterative design loops that compress what once took months into days or hours.

Type One Energy builds directly on decades of stellarator optimization research, where acceptable confinement and stability are achievable only through large-scale numerical optimization of three-dimensional magnetic configurations^{24,25,26}. Without modern HPC, commercial stellarator development would be infeasible.

¹⁹ Degraeve, J. et al., Magnetic control of tokamak plasmas through deep reinforcement learning. *Nature*, Vol. 602, pp. 414–419 (2022).

²⁰ Kates-Harbeck, J. et al., Predicting disruptive instabilities in controlled fusion plasmas through deep learning. *Nature*, Vol. 568, pp. 526–531 (2019).

²¹ van Milligen, B. P. et al., Machine learning control for tokamak plasmas. *Nuclear Fusion*, Vol. 62, 056019 (2022).

²² Bishop, C. M., *Pattern Recognition and Machine Learning*. Springer, 2006.

²³ Sanchez, R. et al., Gyrokinetic turbulence simulations with reduced models. *Nuclear Fusion*, Vol. 59, 056014 (2019).

²⁴ Hirshman, S. P., Whitson, J. C., Steepest-descent moment method for three-dimensional equilibrium calculations. *Physics of Fluids*, Vol. 26, pp. 3553–3568 (1983).

²⁵ Landreman, M., Paul, E. J., Magnetic fields with precise quasisymmetry for plasma confinement. *Physical Review Letters*, Vol. 128, 035001 (2022).

²⁶ Helander, P. et al., Stellarator and tokamak plasmas: a comparison. *Plasma Physics and Controlled Fusion*, Vol. 54, 124009 (2012).

Similarly, Thea Energy relies on computational optimization to explore magnetic configurations and operational regimes that would require prohibitively long experimental campaigns.

Other good example is Proxima Fusion that is involved in the project “AI for Fusion Engineering”, backed by Germany’s Federal Ministry of Education and Research, with partners at Forschungszentrum Jülich, the Technical University of Munich, and the University of Bonn. The focus of this project is on using geometric machine learning and deep learning to address the complex geometry problems inherent in stellarator design — learning to predict and optimize plasma behavior and field quality much faster than existing numerical methods alone can.

4.3 AI applied to materials and components for fusion

Fusion materials must simultaneously withstand: high neutron fluence, extreme thermal loads, and chemical and mechanical stresses.

AI is used to accelerate materials discovery and lifetime prediction by learning complex nonlinear responses to irradiation and thermal gradients. Studies have shown that AI-assisted materials screening can reduce experimental search spaces by orders of magnitude compared to trial-and-error methods²⁷.

4.4 Digital twins: continuous learning through data and simulation

Digital twins represent a synthesis of HPC, AI, and industrial simulation tools. In fusion, digital twins ingest real-time diagnostics, match them to physics models, and predict future states of the system.

Scientific work on digital twins in fusion demonstrates that such systems can forecast disruptions before they occur, evaluate multiple control trajectories in real time, and provide operators with actionable insight into machine health and performance^{28,29}.

For example, the Siemens-accelerated digital engineering environment used by CFS extends these ideas into an industrial context, where digital twins are core operational tools for pilot plants and future commercial reactors. By linking plasma simulators, structural analysis, and control models into a single virtual prototype, the workflow ensures that design decisions account for the full physics and engineering context, reducing lower-order surprises during construction and commissioning¹⁸.

4.5 Quantum computing as an emerging enabling technology

²⁷ Butler, K. T. et al., Machine learning for molecular and materials science. *Nature*, Vol. 559, pp. 547–555 (2018).

²⁸ Pankin, A. et al., Toward digital twins for fusion reactors. *Fusion Engineering and Design*, Vol. 146, 140–146 (2019).

²⁹ Rea, C. et al., Disruption prediction and avoidance in tokamaks using real-time data. *Fusion Science and Technology*, Vol. 74, pp. 1–13 (2018).

Even as AI and HPC drive the near-term fusion agenda, quantum computing is positioned as a long-horizon technology for problems that scale combinatorially or involve complex quantum chemistry.

Examples of domains where quantum methods could eventually surpass classical approaches include: strongly correlated materials modeling, Plasma–surface interaction calculations with full quantum fidelity, and optimization problems with exponentially large search spaces^{30,31}.

In practice, quantum computing is expected to be integrated via hybrid quantum–classical workflows, where quantum subroutines accelerate specific kernels within a larger HPC + AI pipeline. While practical quantum advantage in fusion remains an open research frontier, early engagement ensures that fusion R&D is ready to exploit it as hardware matures.

4.6 Computational technologies as catalysts for the development of fusion

The integrated impact of AI, HPC, and simulation ecosystems tools allows:

1. Design acceleration — Digital exploration replaces slow experimental sequences, enabling rapid convergence on viable power plant configurations.
2. Risk mitigation — Predictive models highlight failure modes early in design, reducing costly rework.
3. Operational reliability — AI-based control and digital twins improve uptime, extending component life and controlling degradation.
4. Capital efficiency — Fewer physical prototypes and targeted experiments reduce cash and time expenditures.

5 Global Power Dynamics in Fusion Development

Fusion has moved decisively from a long-horizon scientific ambition into the domain of strategic technology competition. While no commercial fusion power plants are yet operating, the scale, structure, and direction of investment reveal that major powers increasingly treat fusion as a determinant of future economic strength, energy security, and technological sovereignty. Fusion is now discussed alongside semiconductors, artificial intelligence, and advanced manufacturing as a platform technology with far-reaching spillover effects.

Unlike previous energy transitions, fusion development is unfolding during a period of systemic geopolitical rivalry. Governments are no longer funding fusion solely as a public-good scientific endeavor; they are embedding it within national industrial strategies, security doctrines, and long-term competitiveness agendas. As a result, the fusion landscape reflects divergent political economies: market-driven

³⁰ Preskill, J., Quantum computing in the NISQ era and beyond. *Quantum*, Vol. 2, 79 (2018).

³¹ McArdle, S. et al., Quantum computational chemistry. *Reviews of Modern Physics*, Vol. 92, 015003 (2020).

experimentation in the United States, state-coordinated planning in China, science-led but fragmented governance in Europe, and supply-chain positioning by advanced manufacturing economies such as Japan and South Korea.

This sub chapter describes fusion through the lens of power and value capture, focusing not on who achieves fusion first, but on who controls the industrial ecosystems, intellectual property, supply chains, and standards that will determine long-term geopolitical advantage if fusion reaches commercial maturity.

5.1 United States: Fusion as Industrial and Strategic Leverage

The United States has adopted a fusion development model intends to combine federal risk absorption with private-sector execution. Public funding, primarily through the U.S. Department of Energy (DOE), supports foundational plasma science, materials research, and enabling technologies, while private companies drive system design, construction, and commercialization.

Federal signalling accelerated markedly after 2022. The Department of Energy’s (DOE) Fusion Energy Sciences (FES) program, historically focused on plasma science, was repositioned through the DOE Fusion Science and Technology Roadmap to emphasize pilot plants, grid relevance, and supply-chain readiness. Annual federal fusion spending now stands at approximately USD 800–900 million across DOE offices, including FES, Advanced Research Projects Agency–Energy (ARPA-E), and inertial fusion programs at the National Nuclear Security Administration. When ancillary infrastructure, high-performance computing, and materials programs are included, effective public investment exceeds USD 1.2 billion per year.

Crucially, this public base has catalyzed unprecedented private capital. Since 2018, U.S.-based fusion startups—such as Commonwealth Fusion Systems, Helion Energy, TAE Technologies, and Zap Energy—have collectively raised an estimated USD 6–7 billion in private funding. These investments are not merely speculative; they are structured around hardware milestones, power purchase agreements, and defense-adjacent applications in some cases. The Genesis mission announced in 2023³², which framed fusion as a near-term strategic priority, served as a deliberate signal to markets and allies that fusion sits alongside AI, semiconductors, and advanced manufacturing in the U.S. strategic competition framework. It has to be mentioned that the need of energy sources to power AI, quantum computing, and autonomous systems is mentioned explicitly in the US National Security Strategy document released in November 2025 “The United States must at the same time invest in research to preserve and advance our advantage in cutting-edge military and dual-use technology, with emphasis on the domains where U.S. advantages are strongest. These include undersea, space, and nuclear, as well as others that will decide the future of military power, such as AI, quantum computing, and autonomous systems, plus the energy

³² <https://www.whitehouse.gov/presidential-actions/2025/11/launching-the-genesis-mission/>.

necessary to fuel these domains”³³.

Fusion is increasingly embedded in U.S. narratives of strategic competition, particularly with China. Congressional reports and executive strategies link fusion to broader priorities in AI, advanced manufacturing, energy independence, and national security. Fusion is treated as a platform capability whose enabling technologies — high-field magnets, power electronics, control software, advanced materials — reinforce U.S. leadership across multiple sectors. The implicit logic mirrors that of AI: dominance accrues to those who industrialize first, not necessarily those who discover first.

The U.S. advantage lies in its ability to translate laboratory success into scalable firms. National laboratories provide validation, while private companies assume engineering risk. This model privileges speed and optionality over centralized certainty. However, it also embeds vulnerability: fragmented efforts could duplicate infrastructure, and private timelines may clash with grid realities. Still, as of 2025, the U.S. remains the only jurisdiction where fusion is treated explicitly as both a future energy backbone and a pillar of strategic power projection.

Commercialization pathways in the United States are deliberately pluralistic. Magnetic confinement, inertial fusion, magneto-inertial hybrids, and alternative concepts are all funded to varying degrees, reflecting a strategic preference for portfolio competition. This contrasts sharply with the single-architecture bets of earlier decades. The DOE’s milestone-based public–private partnership programs, funded at roughly USD 50–75 million per award over several years, are designed less to “pick winners” than to de-risk multiple pathways until grid-relevant performance metrics emerge.

From an industrial-policy perspective, fusion is increasingly aligned with re-shoring agendas. Advanced manufacturing techniques—additive manufacturing of vacuum vessels, domestic production of REBCO superconducting tape, and neutron-tolerant alloys—are framed as dual-use capabilities with spillovers into aerospace and defense. Several fusion firms maintain active relationships with the Department of Defense, particularly around pulsed power, compact reactors, and space propulsion. While these programs are modest in budgetary terms, they reinforce the perception of fusion as a strategic technology rather than a purely civilian one.

Strategic signaling also extends internationally. U.S. officials increasingly reference fusion in bilateral technology dialogues with allies, positioning American firms as preferred partners for future demonstration plants. This has the effect of locking in standards and intellectual property norms early. The United States’ relatively permissive regulatory stance—fusion is regulated separately from fission, with lighter licensing burdens—further enhances its attractiveness as a development hub, accelerating talent inflows from Europe and Asia.

Despite these constraints, the U.S. model reflects a strategic calculation: fusion leadership will be secured by those who integrate science, capital markets, and

³³ <https://www.whitehouse.gov/wp-content/uploads/2025/12/2025-National-Security-Strategy.pdf>.

industrial execution faster than rivals. In this framing, early commercial demonstration—even at high cost—confers geopolitical advantage by anchoring supply chains and shaping global expectations. The United States is therefore less concerned with achieving perfect economic fusion in the first instance than with ensuring that, when fusion becomes viable, its firms, standards, and alliances define the field.

5.2 China: Fusion as Technological Sovereignty

China's fusion strategy is best understood through the lens of state-driven technological sovereignty. Fusion is embedded within a broader doctrine that prioritizes long-term control over foundational technologies, even when near-term economic returns are uncertain. Unlike market-led models, China's approach emphasizes continuity, infrastructure accumulation, and alignment with national planning cycles.

China's fusion program is embedded in long-term national science and technology planning. Public funding for fusion is estimated at \$1.2–1.7 billion per year, exceeding recent U.S. federal allocations and characterized by high stability and continuity. This funding supports flagship projects such as EAST (Experimental Advanced Superconducting Tokamak) and CFETR, which is positioned as a bridge between experimental devices and a future power plant. Unlike ITER, these facilities are nationally controlled, enabling faster iteration and tighter integration with domestic industry.

Fusion development is led by state institutions rather than venture-backed startups, reflecting China's preference for centralized coordination over entrepreneurial diversity.

Fusion is explicitly framed as part of China's technological self-reliance agenda. Mastery of superconductors, tritium breeding, and high-heat-flux materials is treated as strategically equivalent to semiconductors or aerospace engines. This framing justifies sustained investment despite long timelines, insulating fusion programs from short-term political cycles.

The civil–military dimension is also significant. While China publicly emphasizes peaceful energy applications, fusion-relevant research overlaps with military interests in pulsed power, directed energy, and compact power sources. The doctrine of military–civil fusion ensures that advances in one domain are rapidly transferred to the other, amplifying strategic returns on investment.

Internationally, China leverages fusion participation to shape norms while retaining strategic autonomy. Its engagement in ITER provides access to global scientific networks, yet parallel national programs ensure that critical knowledge does not remain externally dependent. Talent development is systematic, with fusion expertise cultivated across universities, state laboratories, and industrial research centres.

5.3 United Kingdom: Fusion as a National Industrial Bet

The United Kingdom stands out as Europe's most strategically assertive fusion actor. Fusion is framed not merely as science but as a national industrial mission, aligned with energy security, regional development, and post-Brexit technological identity.

Governance is centred on the UK Atomic Energy Authority (UKAEA), which functions not only as a research body but as a project developer and industrial anchor.

The UK's flagship initiative, the STEP (Spherical Tokamak for Energy Production) programme, aims to deliver a grid-connected fusion prototype in the early 2040s. Unlike ITER or DEMO, STEP is explicitly designed as: a power-producing facility, a first-of-a-kind industrial demonstrator, a catalyst for domestic supply-chain development.

West Burton, located south of the city of Sheffield, has been selected as the site for STEP, lending credibility to the project while also serving as a catalyst for a nationwide public engagement campaign across the United Kingdom to raise awareness and understanding of fusion energy³⁴.

The UK has committed £410 million in new funding in 2025, bringing total fusion commitments into the multi-billion-pound range³⁵. While smaller than ITER-scale spending, UK funding is directed at commercialization outcomes.

Equally important is regulatory positioning. The UK has established a bespoke fusion regulatory framework, deliberately avoiding classification of fusion facilities as nuclear fission reactors. This regulatory clarity is a strategic asset, enabling faster deployment and attracting private companies. Part of this strategy has focused on creating a hub for fusion companies in the Culham Campus where UKAEA is located, 'The Fusion Cluster', including a programme on workforce creation for fusion technologies.

UK also signed with US a major strategic partnership to accelerate fusion development, focusing on R&D, knowledge sharing, and skills in November 2023³⁶. This agreement has been reinforced under the Technology Prosperity Deal (TPD) signed in September 2025 focusing on combining expertise, resources, and AI to speed up commercial fusion, using shared research, test facilities, and aligning regulations for abundant, clean energy. These partnerships aim to integrate AI for advanced simulations, coordinate experiments, and foster private sector investment to accelerate the development of fusion power plants, creating jobs and boosting energy security³⁷.

³⁴ <https://stepfusion.com/west-burton/>

³⁵ <https://www.gov.uk/government/news/25-billion-for-world-first-prototype-fusion-energy-plant>.

³⁶ <https://www.gov.uk/government/news/uk-and-us-form-major-partnership-to-accelerate-global-fusion-energy-development>.

³⁷ <https://www.whitehouse.gov/presidential-actions/2025/09/memorandum-of-understanding-between-the-government-of-the-united-states-of-america-and-the-government-of-the-united-kingdom-of-great-britain-and-northern-ireland-regarding-the-technology-prosperity-de/>.

5.4 Europe: Scientific Leadership Without Industrial Sovereignty

Europe occupies a paradoxical position in global fusion dynamics. It retains unmatched scientific credibility through ITER and a dense network of national laboratories, yet struggles to convert this leadership into industrial leverage. The European fusion ecosystem has been shaped by decades of multilateral governance, risk aversion, and public-sector dominance—an architecture optimized for scientific consensus rather than strategic speed.

ITER remains the centerpiece. With a total projected cost exceeding EUR 20 billion over its lifetime, ITER has anchored Europe’s role as the world’s primary convener of fusion science. Complementing ITER is the European roadmap toward DEMO, a demonstration power plant envisioned for the 2040s. The EU’s annual fusion-related spending, including Euratom programs and national co-funding, is approximately EUR 1–1.2 billion, making Europe’s public investment comparable in scale to that of the United States.

ITER represents a triumph of international collaboration and engineering capability. However, it also illustrates Europe’s structural challenge: large-scale scientific leadership does not automatically translate into industrial dominance. ITER is not designed as a power plant, nor as a commercialization vehicle.

Yet this investment profile reveals a structural imbalance. Funding is heavily weighted toward large facilities and long timelines, with limited mechanisms for rapid industrial spin-out. European private fusion startups exist—particularly in Germany—but they operate at a fraction of the capital intensity seen in the U.S.

Europe’s fusion ecosystem is fragmented across EU institutions, national laboratories, and a relatively small private sector. Annual public fusion spending across the EU is estimated at €0.8–1.0 billion, dominated by ITER-related commitments. Private fusion investment remains modest at €1–1.5 billion cumulatively, a fraction of U.S. levels.

Company	Approx. funds raised / capitalization	Fusion concept (brief)	Country	Main investors / supporters
Marvel Fusion	€400M	Laser-driven inertial confinement (short-pulse lasers / target implosion)	Germany (Munich).	EQT Ventures, Siemens Energy Ventures, EIC Fund, Tengelmann, Bayern Kapital and others.
Proxima Fusion	≈€200M	Quasi-isodynamic stellarator (magnetic confinement variant focused on steady operation).	Germany (Munich origin; links to Max-Planck IPP).	Cherry Ventures, Balderton Capital; UVC Partners, DTCE, redalpine, others.

Focused Energy	≈ €175M	Laser-based inertial fusion (engineering prototype and integrated design).	Germany / US (dual US-German operation; active in Germany).	Strategic tie-ups with RWE, state of Hesse; private investors tied to US and EU funds.
Renaissance Fusion	≈ €61.5M	Compact stellarator / magnetic confinement with HTS magnets and liquid-metal walls (materials focus).	France	Led by funds including Crédit Mutuel Impact and participation by climate/VC investors.)
Gauss Fusion	€10m grant from Germany's Federal Ministry of Education and Research (BMBF)	Tokamak / megaproject ambitions (plans for large “GIGA” commercial plant).	Germany.	Public (BMBF) and venture supporters; industrial partnerships being developed.
Novatron Fusion	≈ €18M	Mirror / alternative magnetic confinement (Swedish research spin-out).	Sweden.	Axon Partners Group, together with St1 and a consortium of investors, Santander InnoEnergy Climate Fund

Table 4. List of European fusion start ups as December 2025. Data provide is indicative but not exhaustive.

This fragmentation limits Europe’s ability to align funding, regulation, and industrial strategy³⁸. Geopolitical consequence is a growing risk of scientific leadership without industrial sovereignty.

5.5 Japan and South Korea: Key capabilities in the supply chain

Japan and South Korea exert influence in fusion development less through system integration than through dominance of enabling technologies. Both countries possess world-leading capabilities in superconductors, precision manufacturing, and advanced materials—capabilities that are indispensable to any fusion architecture.

Japan’s annual public fusion spending is estimated at USD 400–500 million, supporting devices such as JT-60SA and extensive materials research. Japanese firms dominate segments of the high-temperature superconductor supply chain and ultra-

³⁸ A Fusion Engine for Growth: A European Industrial Strategy for Fusion Energy, <https://www.catf.us/resource/fusion-engine-growth-european-industrial-strategy-fusion-energy/>.

precise components, positioning the country as a critical supplier regardless of which fusion concept prevails. This supply-chain leverage constitutes a form of strategic power that does not require ownership of full reactor systems.

South Korea follows a similar pattern. With annual fusion-related investment of approximately USD 300–400 million, centered on KSTAR and industrial R&D, Korea integrates fusion development into its broader advanced manufacturing strategy. Large business conglomerates participation ensures rapid translation of research into producible components, reinforcing Korea’s role as an indispensable manufacturing partner.

Other actors, including Switzerland and Italy, occupy niche positions in vacuum technology, cryogenics, and diagnostics.

Region / Country	Annual Public Fusion Funding (approx.)	Cumulative Public Commitments	Private Fusion Investment (cumulative)	Dominant Funding Model	Strategic Implications
United States	\$0.8–1.5 bn / year (high volatility)	~\$25–30 bn historical (incl. labs)	\$8–9 bn (≈50–55% of global private capital)	Federal R&D + VC-backed startups	Industrial leadership, rapid iteration, strong IP capture but vulnerable to federal budget swings
China	\$1.2–1.7 bn / year (stable)	~\$20–25 bn (est.)	\$4–5 bn (mostly state-linked)	State-directed public programs	Long-term sovereignty, infrastructure depth, slower but resilient progress
European Union (EU-27)	€0.8–1.0 bn / year (ITER + R&D)	€45–50 bn (ITER lifecycle)	€1.0–1.5 bn	Public megaprojects, limited VC	Scientific leadership, weak industrial capture risk
United Kingdom	£250–400 m / year	£2–3 bn (incl. STEP program)	£700 m–1 bn	Hybrid public + private	Europe’s most commercialization-oriented fusion policy
Japan	\$300–500 m / year	~\$6–8 bn	<\$500 m	Public R&D + industry supply chains	Supply-chain leverage (magnets, materials)
South Korea	\$200–400 m / year	~\$4–6 bn	<\$300 m	Public R&D	Manufacturing and component leadership
France (national)	~€250–350 m / year	Included in ITER total	<€300 m	Public nuclear institutions	Engineering depth, weak private fusion sector
Germany	~€200–300 m / year	~\$2–3 bn	€300–500 m	Public science + startups	Stellarator leadership, unclear commercialization path

Canada	<\$100 m / year	~\$0.5–1 bn	\$500–700 m	Private-led (General Fusion)	Startup-driven niche leadership
Australia	<\$50 m / year	<\$500 m	<\$200 m	Research- focused	Materials, mining, niche science
UAE / Middle East	<\$50 m / year	<\$500 m	<\$200 m	Strategic investment / hosting	Geopolitical positioning, not tech leadership

Table 5. Summary of Fusion investments and business/government approach per country

Appendix: 1. What is Fusion Power?

The possibility of obtaining energy from nuclear fusion reactions was first raised in the 1920s. In 1926, the British astrophysicist Arthur Eddington suggested that the processes responsible for the enormous energy emitted by stars must be linked to the fusion of light nuclei into heavier ones. This hypothesis opened a new field of research that encouraged scientists from different countries to study both nuclear physics and the mechanisms that govern stellar interiors, laying the foundations of fusion as an energy source.

The first experimental step towards reproducing these processes on Earth was taken in 1932 at the University of Cambridge. Ernest Rutherford and his team managed to induce fusion reactions in the laboratory, observing the interaction between deuterium nuclei. These experiments not only confirmed the possibility of merging light nuclei but also allowed the identification of new nuclear products such as helium-3 and tritium. Rutherford underscored that, although each fusion event released a significant amount of energy, the low probability of these reactions occurring implied a negative overall energy balance.

A few years later, in 1938, Hans Bethe developed a detailed theoretical framework to describe the nuclear reactions responsible for energy production in stars. By calculating the interaction probabilities of different reactions, Bethe proved that stellar energy comes from a complex chain of fusion processes that, over time, transform hydrogen into helium and subsequently into heavier nuclei. This work conclusively verified fusion as the fundamental mechanism of energy of the observable universe.

In the early 1950s, the accumulated knowledge on the physics of light nuclei fusion allowed the development of quantitative criteria to evaluate its viability as an energy source in terrestrial devices. In this context, John Lawson established the well-known Lawson criterion, which defines the minimum conditions necessary to obtain net energy in a confinement fusion system. These conditions depend on the plasma temperature, the density of particles, and the time during which the energy remains confined. Thus, the temperature to be reached by that machine had to be about 10 keV (100 million degrees Celsius), with an electron density of $n_e \sim 10^{20} \text{ m}^{-3}$ and a confinement time of $\tau_E > 1.5 \text{ s}$. Reaching the density was relatively easy. Temperature seemed to be a difficult task, but several methods have managed to reach

and even exceed this value. However, the real challenge would be the confinement time of the energy.

During this period, researchers began exploring different experimental configurations to replicate fusion on Earth. In 1950, Soviet scientists Andrei Sakharov and Igor Tamm proposed the concept of the tokamak, a device based on the magnetic confinement of plasma in a toroidal shape. Soon after, in 1951, Lyman Spitzer presented the alternative concept of the stellarator in the United States. Although the stellarator initially attracted much scientific interest, the experimental advances led by Lev Artsimovich in the Soviet Union showed that the tokamak offered better performance in terms of confinement, which led to its widespread adoption. Temperatures on the order of the kiloelectronvolt were reached for the first time in those devices.

The 1950s were also marked by a change in the political context of fusion research. The 'Atoms for Peace' conferences, organised by the International Atomic Energy Agency in 1955 and 1958, promoted international cooperation in the peaceful use of nuclear energy. As a result, fusion research was officially declassified, facilitating scientific exchange and accelerating technological progress.

A major breakthrough occurred in 1968, when Soviet tokamaks simultaneously reached unprecedented high temperatures and confinement times. These results consolidated the tokamak as the dominant configuration in fusion research, a position it still holds today as the most advanced concept from an experimental perspective.

In the 1970s, it became clear that the development of fusion would require efforts on an international scale. In Europe, this conviction led to the design of the Joint European Torus (JET) in 1973. The construction of this facility, which would become the largest operational experiment in magnetic confinement, was completed in 1983 in the United Kingdom, where it achieved its first plasmas that same year and established a global benchmark in plasma physics.

At the same time, the idea of a truly global project to demonstrate the scientific and technological feasibility of fusion began to take shape. This initiative crystallised in 1985, during the Geneva summit between the superpowers, when the ITER project was formally proposed. After more than two decades of negotiations, ITER was established in France in 2007 with the aim of demonstrating the sustained production of fusion energy under conditions close to those of an industrial plant.

Meanwhile, national programs — especially in Europe, China, Japan, South Korea, the United Kingdom, and the United States — continued to make progress in key areas such as plasma physics, neutron-subjected materials, and related technologies. Since the 2010s, the emphasis has begun to shift gradually from scientific demonstration to commercial feasibility and pilot plant design.

The most recent results reinforce this perception. In 2021, JET set a new record by producing 59 megajoules of fusion energy, surpassing its own 1997 record. Soon after, in December 2022, the National Ignition Facility in the United States achieved for the first time a net energy gain in an inertial confinement fusion

experiment, reaching a $Q_{\text{scientific}}$ factor (gain) greater than unity. These milestones do not yet entail a commercial application, but they do confirm that the fundamental physical principles are validated.

Currently, about 130 experimental fusion devices are in operation, construction, or in the planning phase worldwide, along with multiple demonstration plant designs and pilot reactors. This collection of advances places fusion in a critical transition: traditionally considered a long-term scientific aspiration, it is beginning to emerge as a technological option with real implications for energy systems.

Fusion reaction

A nuclear fusion reaction is a phenomenon in which two low-mass atomic nuclei fuse to form a higher-mass nucleus, a process that is accompanied by a significant release of energy. This mechanism contrasts with nuclear fission, in which heavy nuclei are fragmented into lighter ones to produce energy.

Nuclear fusion is governed by the strong nuclear force, the fundamental force that holds protons and neutrons together within the atomic nucleus. For two nuclei to merge, they must come close enough for this force to overcome the electrical repulsion between protons, which have a positive charge. At extremely small scales, strong nuclear force dominates electrostatic repulsion, allowing nuclei to merge.

The released energy in a fusion reaction has its origin in the mass difference. The nucleus resulting from the fusion has a slightly lower mass than the sum of the masses of the initial nuclei. This difference is transformed into energy in accordance with the principle of mass–energy equivalence formulated by Albert Einstein, expressed by the equation $E=mc^2$.

In conceptual terms, various combinations of light nuclei can lead to fusion reactions with potential energy application. Hence, any of the reactions indicated in the following table could serve as a basis for the design of a fusion system for energy production, provided that the physical and technological conditions necessary for its control and use are met.

No.	Reaction	Products
1	D + T	${}^4\text{He}$ (3.5 MeV) + n (14.1 MeV)
2	D + D	T (1.01 MeV) + p (3.02 MeV) (50%) ${}^3\text{He}$ (0.82 MeV) + n (2.45 MeV) (50%)
3	D + ${}^3\text{He}$	${}^4\text{He}$ (3.6 MeV) + p (14.7 MeV)
4	T + T	${}^4\text{He}$ + 2 n + 11.3 MeV
5	${}^3\text{He}$ + ${}^3\text{He}$	${}^4\text{He}$ + 2 p
6	${}^3\text{He}$ + T	${}^4\text{He}$ + p + n + 12.1 MeV (51%) ${}^4\text{He}$ (4.8 MeV) + D (9.5 MeV) (43%) ${}^4\text{He}$ (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV) (6%)
7	D + ${}^6\text{Li}$	2 ${}^4\text{He}$ + 22.4 MeV
8	p + ${}^6\text{Li}$	${}^4\text{He}$ (1.7 MeV) + ${}^3\text{He}$ (2.3 MeV)
9	${}^3\text{He}$ + ${}^6\text{Li}$	2 ${}^4\text{He}$ + p + 16.9 MeV

10	$p + {}^{11}\text{B}$	$3 {}^3\text{He} + 8.7 \text{ MeV}$
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Table 1. Possible fusion reactions for energy production. Source: Fusion Physics, IAEA.

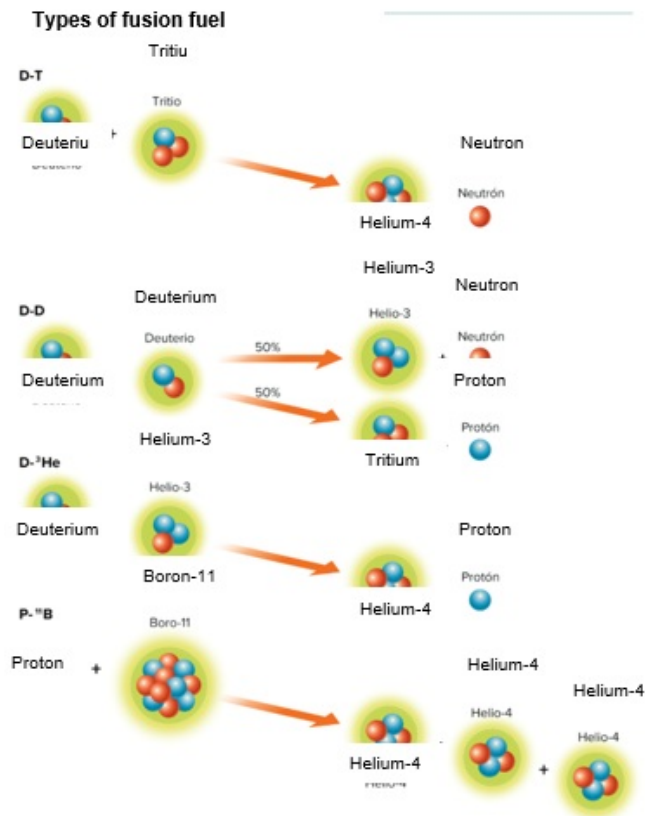


Figure 1. Illustration of the fusion reactions mentioned in Table 1. Source: Infographic/Knowable.

The fusion reaction between deuterium and tritium (D–T) is the most widely used in current fusion device designs, as it presents the highest probability of reaction at relatively 'low' temperatures compared to other possible fuel combinations. Its cross section reaches a maximum around 100 keV, while other alternative reactions require significantly higher temperatures and, even so, have lower fusion probabilities. This difference explains why the vast majority of fusion reactor concepts under development rely on the D–T cycle.

As previously indicated, the energy feasibility of fusion is conditioned by the Lawson criterion, which establishes the minimum requirements for a fusion system to produce more energy than it consumes. This criterion acts as a fundamental reference for the design and evaluation of fusion machines, as it allows us to identify the physical limits that must be exceeded in order for fusion to become a useful energy source.

Lawson's criterion is structured around three key variables:

- Temperature (T): the plasma — an extremely hot ionised medium — must reach very high temperatures so that the fuel nuclei have enough kinetic energy to overcome their electrostatic repulsion and fuse.
- Density (n): the concentration of fuel ions in the plasma must be high enough to increase the frequency of collisions and, with it, the rate of fusion

reactions.

- Energy confinement time (τ): the plasma must be confined at the required temperature and density for a sufficient time interval for the total number of reactions to generate a positive energy balance.

These three parameters are usually combined into a single parameter known as the Lawson triple product ($nT\tau$), which serves as an indicator of the degree of proximity of a fusion experiment to energy balance and net gain. Achieving high values of this product entails a precise adjustment between heating, density, and confinement, which is one of the main scientific and technological challenges of fusion.

The ultimate goal is to bring the plasma up to the ignition regime, in which the energy released by the fusion reactions themselves is sufficient to compensate for energy losses, especially those due to radiation. At this point, the system can sustain the reaction without significant external inputs, marking the threshold towards a net production of fusion energy.

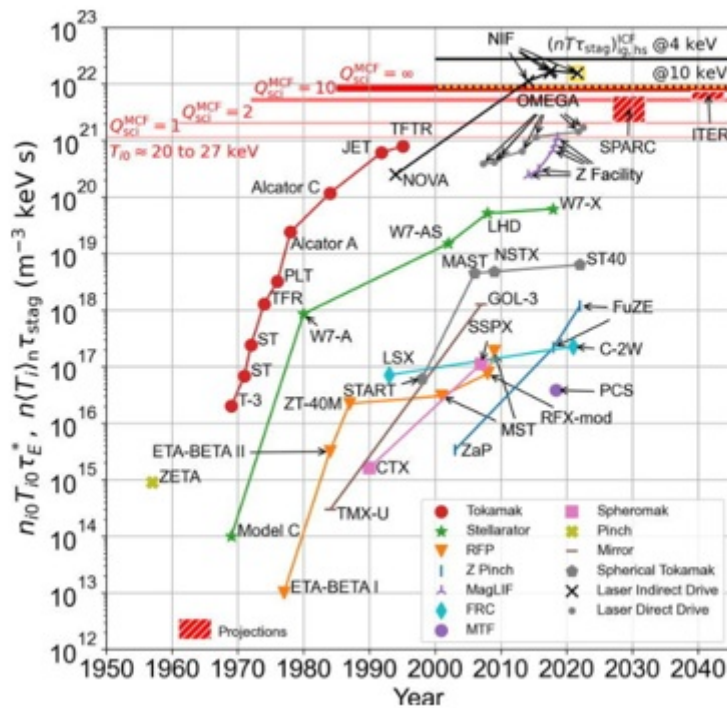


Figure 2. Advances towards the break-even point and fusion energy gain of different experimental fusion machines according to Lawson's criterion. Source: Phys. Plasmas 32, 112106 (2025).

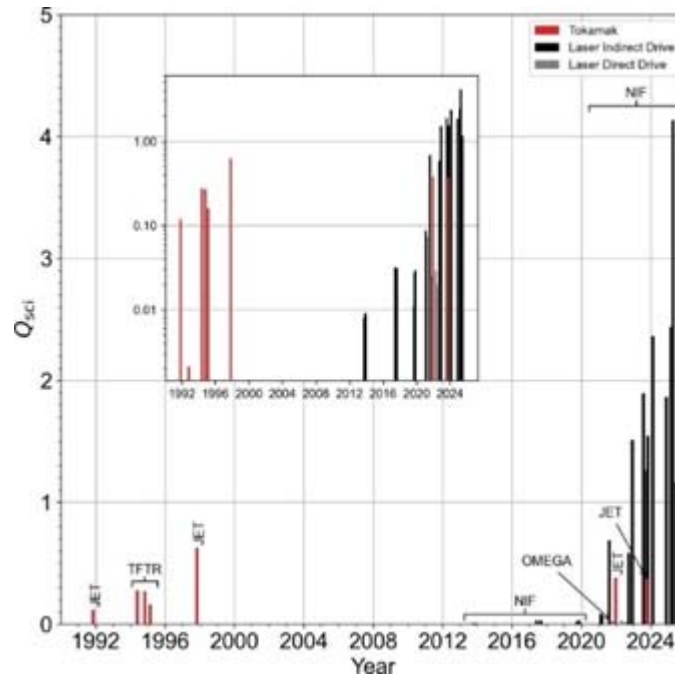


Figure 3. Graph of actual results versus date of D–T fusion experiments. Source: *Phys. Plasmas* 32, 112106 (2025).

Main technological approaches

There are currently multiple technological proposals aimed at obtaining energy through nuclear fusion. Although they differ significantly in their design and operating principles, they all share a common goal: to reach an operating regime capable of generating net energy in an efficient and controlled manner.

Most of these approaches rely on two major strategies for handling plasma, the medium in which fusion reactions occur. On the one hand, magnetic confinement systems use strong magnetic fields to contain and stabilise plasma at high temperatures. On the other hand, inertial confinement methods use extremely fast pulses via lasers or electric currents to compress the fuel to conditions where fusion can take place before the plasma expands.

There are also hybrid concepts that combine elements of both approaches, known as Magneto–Inertial Fusion, which seek to take advantage of each technique. To date, the greatest experimental milestones in terms of fusion energy produced have been achieved mainly in two types of devices: inertial confinement systems and tokamaks, which represent the most mature configuration within magnetic confinement.

From an experimental point of view, other alternatives are being developed alongside these main approaches. Though less advanced, they nevertheless present potentially attractive characteristics. These include concepts such as the Z-pinch, which, although still in early stages of development, continues to evolve and offer potential advantages in design simplicity or scalability.

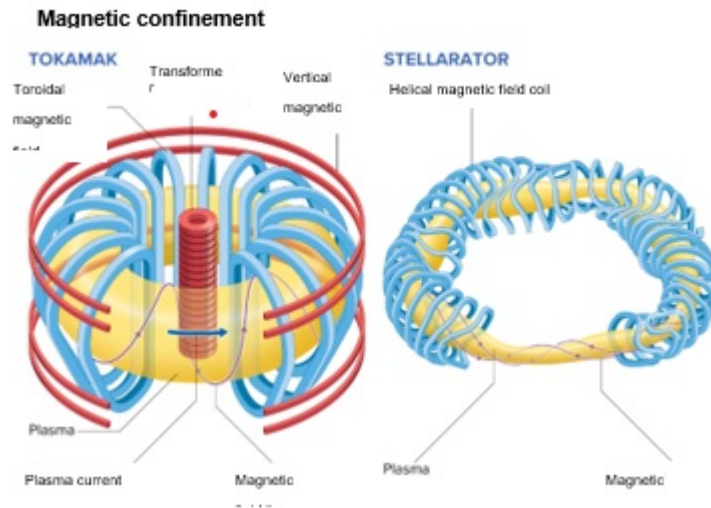


Figure 4. Magnetic confinement fusion machines: tokamak (left) and stellarator (right). Source: Infographic/Knowable.

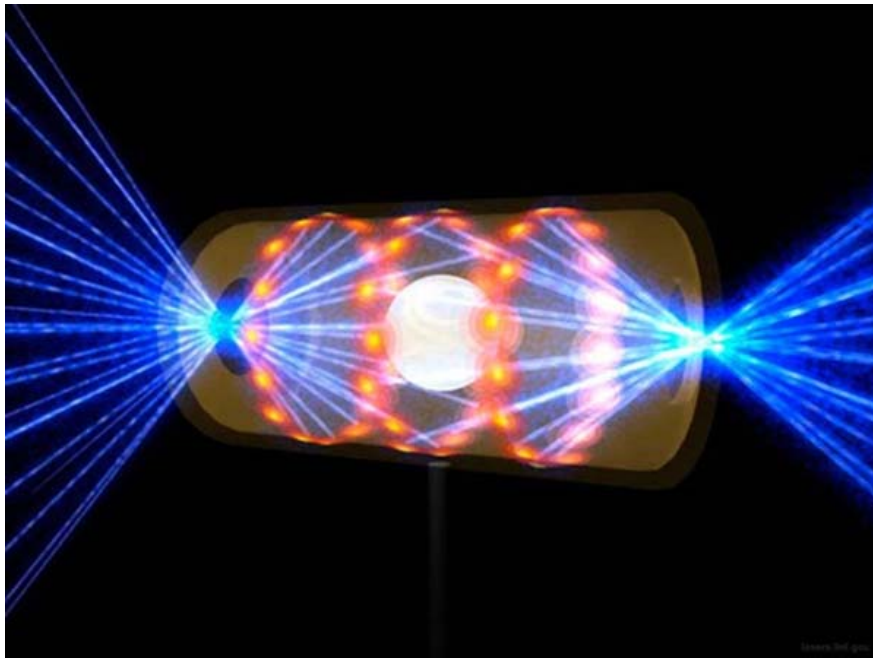


Figure 5. National Ignition Facility (USA). Experimental machine based on the concept of inertial fusion in which the installation's laser beams enter through the openings located at both ends of a hohlraum where the fusion fuel is located, in this case D-T. Source: Lawrence Livermore National Laboratory.

There are still major technical challenges that must be solved before fusion can become an operational energy source. The generation and control of plasmas subjected to extreme temperatures and pressures places very stringent demands on current technological systems. The difficulty of keeping the plasma stable for long periods and of limiting the energy losses associated with radiation and thermal transport processes are added factors that negatively impact the overall performance of the system. Likewise, the availability of materials capable of withstanding the intense neutron flux, high thermal loads, and mechanical stresses of a fusion reactor environment is a critical factor in ensuring its continued operation and long-term economic viability.

However, recent advances indicate that sustained progress is taking place. Improvements in magnetic confinement schemes, particularly in configurations such as tokamaks and stellarators, have increased both plasma stability and energy confinement times. In parallel, inertial confinement fusion, based on the rapid compression of the fuel by high-power laser systems, continues to show relevant results in the experimental field. Additionally, alternative fuel cycles are being explored, such as those based on proton and boron reactions — which, although presenting greater technological challenges, could lead to fusion reactions with reduced waste and potentially more favourable operational characteristics.

For a complete description of the physical principles that govern fusion energy and the technological implications that they entail, the following reference material is recommended:

- Principles Of Fusion Energy: An Introduction To Fusion Energy For Students Of Science And Engineering. A.A. Harms, D.R. Kingdon, K.F. Schoepf, G.H. Miley. ISBN-13: 978-9812380333.
- Fusion: Introduction to the Physics and Technology of Magnetic Confinement Fusion. Weston M. Stacey. ISBN-13: 978-0471880790.
- Fusion Physics. IAEA. https://wwwpub.iaea.org/MTCD/Publications/PDF/Pub1562_web.pdf
- Fundacion Innovacion Bankinter - [Future Trends Forum](https://www.fundacionbankinter.org/ftf-informes/fusionforward/) Energía de fusión <https://www.fundacionbankinter.org/ftf-informes/fusionforward/>

Chapter Four

Artificial intelligence: the strategic catalyst for a resilient and decarbonised energy future

Inmaculada Martínez Rubio

Abstract

Artificial Intelligence in 2026, paving the way to 2030, has evolved from a technological tool to an indispensable strategic catalyst for addressing the challenges of the energy sector. From its initial achievements in optimizing energy efficiency, AI is propelling us toward scenarios of exponential innovation that will enable a sustainable roadmap. AI will contribute to producing, managing, and distributing energy more effectively than other technologies, transforming the energy sector into a decentralized environment. Its potential encompasses robust and scalable solutions where 21st-century Advanced AI—Generative, Foundational Model, and Agentic AI—will create a new paradigm in how energy responds to the challenge of global digitalization. AI in the next five years will not only be regulated but will also adopt industry standards and be surrounded by cybersecurity far superior to anything seen in the past, combining AI with quantum encryption to protect critical infrastructure and sustain mission-critical operations. AI in 2026 is thus presented as a fundamental long-term capability, integrating technology, talent and solid governance to make the most of its potential in a responsible manner.

Keywords

Decarbonization, Energy Sustainability, Cybersecurity, Energy Efficiency, Critical Governance.

ENERGY AND STRATEGY

CYBERSECURITY AND SYSTEM RESILIENCE



**COUNTERACTING
SOCIAL ENGINEERING
DRIVEN BY AI**



**PREVENTION OF 'SIDE
MOVEMENT' WITH
MICROSEGMENTATION**



**DEFENCE AGAINST
'DATA POISONING'**

BENEFITS FOR POWER PLANTS (2025)

FEATURE	IMPACT ON SAFETY	STATE OF THE INDUSTRY IN 2025
FOCUSED ON IDENTITY	PREVENT STOLEN PASSWORDS FROM CAUSING BLACKOUTS	STANDARD FOR ALL NEW EU AND US NETWORK PROJECTS
CONTINUOUS MONITORING	DETECTS 'INSIDER THREATS' OR COMPROMISED AI IN REAL TIME	INTEGRATED WITH DEEPMIND-STYLE ARTIFICIAL INTELLIGENCE MONITORS
ASSUMING A BREACH IN CYBERSECURITY	THE SYSTEM REMAINS FUNCTIONAL EVEN DURING AN ACTIVE ATTACK	REQUIRED BY NERC CIP AND NIS2 REGULATIONS
MINIMUM PRIVILEGE	EMPLOYEES ONLY SEE WHAT THEY NEED TO DO THEIR JOB	REDUCE INTERRUPTIONS RELATED TO HUMAN ERRORS BY APPROXIMATELY 40%

THE ENVIRONMENTAL FOOTPRINT OF AI



**ALGORITHMIC
'SLIMMING'
TECHNIQUES**



**HARDWARE:
THE TRANSITION
TO THE EDGE**



**CONSCIOUS
CARBON
FOOTPRINT
PROGRAMMING**



**THE ENERGY
TAX OF
'REASONING'**



**THE DEPLOYMENT
OF GREEN AI**

SUMMARY

TECHNIQUE	POTENTIAL ENERGY SAVINGS	STATUS (END OF 2025)
MIX OF EXPERTS (MOE)	~90% REDUCTION	STANDARD IN NEW FRONTIER MODELS
QUANTISATION (1 BIT/ 2 BITS)	4X - 8X REDUCTION	RAPIDLY ADOPTED FOR MOBILE AI
AI IN THE DEVICE (EDGE)	100X - 1,000X	INTEGRATED INTO MOST NEW CONSUMER ELECTRONICS PRODUCTS
CARBON-CONSCIOUS PROGRAMMING	~30% CARBON REDUCTION	MANDATORY UNDER MANY CORPORATE ESG POLICIES

IMPACT OF LARGE VS. SMALL MODELS (2025)

METRICS	LARGE GENERAL MODEL (E.G.: GPT-4)	SPECIFIC MODEL FOR SMALL TASKS (E.G.: MISTRAL/SLM)
ENERGY CONSUMPTION	HIGH	90% LOWER
WATER COOLING	~500 ML FOR EVERY 10-50 CONSULTATIONS	SCARCE
INFRASTRUCTURE	MASSIVE HYPERSCALE DATA CENTRES	LOCAL 'EDGE' DEVICES / NPU
LATENCY	SUPERIOR (CLOUD-DEPENDENT)	REAL TIME

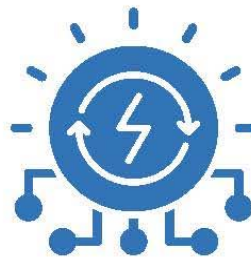
ARTIFICIAL INTELLIGENCE

EVOLVING FROM HIGH-PERFORMANCE COMPUTING TO AI



HPC COMPARED TO AI

HPC	AI
BASED ON SPEED AND FORCE BRUTE CALCULATIONS	FOCUSES ON SIMULATING INTELLIGENCE AND LEARNING PATTERNS
FOCUSED ON SOLVING LARGE AND COMPLEX COMPUTATIONAL PROBLEMS AS QUICKLY AS POSSIBLE	SIMULATES HUMAN INTELLIGENCE, ALLOWING MACHINES TO REASON, LEARN, PERCEIVE AND MAKE DECISIONS
PREDEFINED DETERMINISTIC ALGORITHMS THAT EXECUTE INSTRUCTIONS EXACTLY AS THEY WERE PROGRAMMED	NON-DETERMINISTIC ALGORITHMS THAT LEARN FROM DATA AND MAKE PREDICTIONS OR CLASSIFICATIONS
A PRECISE NUMERICAL RESULT OR A HIGH-RESOLUTION SIMULATION IS OBTAINED	A LEARNED MODEL IS CREATED TO PREDICT A RESULT THAT IS DIFFICULT TO CALCULATE USING OTHER METHODOLOGIES
HPC SIMULATIONS REQUIRE HIGH COMPUTATIONAL COSTS FOR REPEATED EXECUTION FOR UNCERTAINTY ANALYSIS	BETTER ADAPTED TO CURRENT CHALLENGES IN THE FIELD OF UNCERTAIN AND NON-LINEAR SITUATIONS
REQUIRES AN EXPLICIT PHYSICAL EQUATION	LEARN AND ADAPT FROM COMPLEX, CONFUSING AND INCOMPLETE OPERATIONAL DATA



THE ROLE OF AI IN THE ENERGY SECTOR IN THE 21ST CENTURY

FUNDAMENTAL AI METHODOLOGIES	TECHNOLOGIES THAT ENHANCE AND AMPLIFY THE DEPLOYMENT AND USE OF AI
MACHINE LEARNING (ML)	DIGITAL TWINS
DEEP LEARNING (DL)	IoT AND SENSOR NETWORKS
GENERATIVE AI (GenAI)	EDGE COMPUTING
AGENTIC AI	5G AND 6G CONNECTIVITY
WORLD MODELS	BLOCKCHAIN

1 Executive summary: The AI Imperative

The energy sector is at a pivotal moment, grappling with the complexities of decarbonization, decentralization of power generation, and exponential growth in electricity demand. In this context, artificial intelligence (AI) has evolved from what in past decades was developed through statistical models and scenario planning towards high-performance computing¹ (HPC) and the training of algorithmic machine learning models during the 2000s. But this almost linear trajectory has recently been challenged by advanced AI models that have disrupted technological innovation in the energy sector with models beyond the mathematical algorithms of structured data². This trajectory has made AI a powerful tool with a strong strategic imperative to face the challenges of the energy sector and forge more efficient, sustainable, and resilient solutions.

1.1 Key drivers of the AI energy revolution

AI's growing role is directly linked to the fundamental changes that are transforming the energy industry. These drivers are not isolated. Rather, they form a feedback loop that makes AI a necessity that cannot be postponed, as market competition is demonstrating that it is not only a viable solution, but oftentimes the only solution.

1.1.1 Decarbonisation

The global commitment to a low-carbon future has led to a dramatic increase in renewable energy sources, such as solar and wind. These sources are inherently variable and intermittent, introducing unpredictability into the power grid that traditional static management methods cannot deal with. AI is essential in managing this variability by forecasting renewable energy production and balancing supply and demand, facilitating greater penetration of clean energy and carbon footprint reduction.

1.1.2 Decentralisation and digitalization

The proliferation of distributed energy resources, such as rooftop solar panels, microgrids, and battery storage systems, is decentralising power generation and creating a complex, multi-directional flow of energy. This change requires an intelligent, highly digitalised grid that can manage vast amounts of data in real time

¹ HPC stands for high-performance computing.

² The distinction between structured and unstructured data is critical to modern data management, storage, and analytics, especially with the rise of advanced AI. The main difference lies in the presence or absence of a predefined data model or schema. Structured data is not just numbers; it usually includes text (and dates, times, currency, etc.) that can be perfectly stored in a traditional database. Unstructured data can contain numbers, but they are often difficult to extract without special and complex AI/ML (NLP/Computer Vision) tools to analyse.

to ensure stability. AI provides the only scalable solution to process this data and automate the complex supply-and-demand management tasks in these modern smart grids.

1.1.3 Electrification

Accelerated electrification of the economy, particularly with the growth of electric vehicles (EVs) and energy-intensive data centres, is putting unprecedented pressure on existing grid infrastructure. This surge in demand requires a new level of intelligence for network optimization and load management. AI is critical to forecasting these new load profiles and adjusting distribution to prevent blackouts and ensure reliability³.

1.2 Understanding AI and its transformative power

Today, AI is already more than a technology. It works as a system of systems that encompasses the different types of advanced AI, such as generative AI⁴, agentic AI⁵, deep learning AI⁶ and frontier models⁷ — foundation models, large language models, multimodal models, emerging capabilities, and state of the art⁸ — forming an interdependent ecosystem that is joined by the universe of data to be processed, the software and hardware that are used to carry out this task, as well as the processing semiconductors that are required to execute the actions required in energy

3 Top 10 applications of AI in the energy sector | FDM Group, 26 August, 2025

4 Generative AI is a type of artificial intelligence that uses deep learning models trained with massive datasets to create content in response to the user's request. Unlike traditional AI, which only classifies or analyses existing data, generative AI learns the underlying patterns and structures of its training data to autonomously produce understandable results such as text, images, audio, video, or software code. This capability lets it empower human creativity and automate complex content generation tasks.

5 Agentic AI refers to advanced systems that display autonomy and an ability to act, meaning they can set their own sub-goals, plan a sequence of actions, execute them using various tools, and adapt to changing environmental conditions to achieve an overall goal with minimal human intervention. Unlike generative AI, which creates content reactively (for example, drafting a report on demand), agentic AI is a proactive executor that coordinates multiple steps and systems (for example, drafting a report, archiving it in the database, updating a dashboard, and e-mailing the summary to a team).

6 Deep learning is a specialised subfield of machine learning that uses complex, multi-layered computer models, called deep neural networks, to analyse data. The term 'deep' refers to the structure of the network, which consists of numerous interconnected hidden layers that process information hierarchically, similar to the human brain. This architecture allows the model to automatically learn increasingly abstract and complex features from raw and unstructured data (such as pixels in an image or words in a sentence) without the need for explicit human programming for feature extraction, allowing it to excel at sophisticated tasks such as language translation, image recognition, and autonomous driving.

7 'Frontier models' is a collective term for the most advanced, large-scale, general-purpose AI systems in existence today that push the boundaries of artificial intelligence capabilities. These models are typically foundation models, trained with massive amounts of data and computation, and are characterised by their ability to perform a wide variety of complex tasks in different domains (such as reasoning, coding, and text, image, and audio generation) with cutting-edge performance. Because of their unprecedented scale, they often exhibit emerging capabilities that were not explicitly programmed and, therefore, imply the potential for social impact, whether positive or dangerous.

8 'State of the art', sometimes abbreviated as SOTA, refers to something that is the latest and newest in development.

management and distribution. However, this technological infrastructure could not be executable if it lacked the greatest competitive attribute: human intervention specialised in data analysis, inference, and cognition modelling, and the contribution of professionals in the energy sector who can evaluate the value provided by AI as an operating and execution system. Alongside specialised human capital, business protocols and processes created specifically for AI to execute its potential now emerge with greater relevance.

Thus, the future of the sector in the second quarter of the current century now appears increasingly dependent on the contributions that AI makes and, convinced of its ability to produce, manage and distribute energy in a way that is superior to other technologies, it is committed to radically transform an industry of traditional and static systems into one of dynamic, intelligent, and proactive networks and operations⁹, overcoming mindsets and attitudes of the past and charting a new road map of transcendental vision towards a transmuted, enhanced, and superior energy sector.

Given this panorama of opportunities and potential, it should be noted that, since the 1960s, data analysis and high-performance computing have made the energy sector one of the most innovative and transformative industries. AI did not 'arrive' at this sector unexpectedly, as has been the case in other sectors, but was sought in research and development processes as a tool that would allow a technological leap from high-performance computing (HPC) to address the kinds of challenges that have emerged in recent decades and to which HPC does not fit as a viable solution.

Whilst traditional AI has provided enormous advances in automation, detection, prediction, and expanded its reach to unstructured data — the words, images, and videos that must be extracted and reclassified — this AI of operational efficiency is not the advanced, autonomous, and dynamic AI in its cognition that we find impossible to compare with traditional AI, as the former's learning and execution have revealed its development of multidimensional thinking. This new and advanced AI not only seeks to reduce costs or improve operational efficiency, but also endeavours to create solutions to challenges that, in the recent past, the energy sector resigned itself to accepting as impossibilities because human beings and the technologies of that time did not cope with their complexities, such as controlling plasma in fusion to generate energy (one of the fundamental challenges faced by fusion energy for more than 70 years and among the keys to making it commercially viable, as mentioned in chapter III of this book¹⁰). This is a creative AI that seeks to learn on its own, manage

9 The Emergence of AI in the Energy Sector - The Energy Consortium, https://theenergyconsortium.ca/assets/pdf/Emergence_of_AI.pdf

10 Since the first attempts to build nuclear-powered machines in the late 1940s, scientists have been stuck in a cycle of creating stellar energy on Earth through nuclear fusion, only to see this possibility vanish in milliseconds because the plasma became unstable. In the 1950s, scientists observed this phenomenon in the first fusion devices that were built, in which the plasma twisted and curled, touching the walls and cooling instantly. Between 1990 and 2010, machines such as JET (UK) and TFT (USA) managed to produce fusion energy but were only able to hold it for seconds. The controls were based on rigid mathematical calculations that could not react quickly enough to the chaotic nature of the plasma. In 2022, DeepMind and the Swiss

itself autonomously, and where the human contribution is fundamental in accepting its results or rejecting them. The domain where humans can still execute advanced AI control lies in the choice of data to be processed, the formulation of hypotheses and strategies on how a model can be trained, and the assurance that the model is safe and trustworthy. That is why, in the last five years, we've begun talking about technically sound and scalable AI, because its developments are being oriented towards huge industrial sectors of vital importance to humanity.

AI in 2026 has two aims to be achieved: the creation of a new value framework in innovation beyond high-performance computing, and the assurance that it is safe, not only from a perspective of ethics and data governance guarantees, but that AI can be considered trustworthy: that is, technically appropriate for its intended use, and standardised and certified for use in industrial sectors and in society. Beyond regulatory requirements, which obey government policies regarding market controls and goals for societal well-being - still falling short in demanding that AI can be certified just like other advanced systems in other high-risk industries such as aerospace, it should be noted that AI is a system in continuous development, versatile and in constant evolution, and therefore it has been very complex and challenging in these years of the birth of advanced AI to create both absolute and immutable regulations and certification standards. However, it is important to observe that, since mid-2024, agencies such as ISO and IEEE have pursued this objective, making great progress in seeking standardisation that can be implemented in the next two years as an acceptable way to mollify some countries' rejection of regulation as the only solution to the detriment of innovation.

1.3 Evolving from High-Performance Computing to AI

High-performance computing (HPC) has a long history in the oil and gas industry, though it is far from exclusive to the sector. The transition to a modern, data-intensive power grid has made HPC equally indispensable for utilities, renewable energy developers, and grid operators around the world. HPC is a crucial and growing technology across the energy sector and it has managed to solve enormous challenges. However, advanced AI has now begun development in the sector parallel to other tools, but with superior capabilities and more adaptable to contexts in which HPC has not offered an absolute solution or has made it necessary to continue using past computing paradigms.

HPC in the oil and gas industry (traditional approach)

The oil and gas industry was an early commercial adopter of high-performance computing (HPC) and has pushed the boundaries of supercomputing for decades. Its

Plasma Center demonstrated that AI could 'learn' the behaviour of simulated plasma and then control the current flowing through the magnets generated by the magnetic field responsible for plasma confinement and stability, a revolutionary development.

use is mainly concentrated in the upstream segment (exploration and production).

Application	Purpose
Seismic data processing	HPC processes the huge datasets generated by seismic surveys to create high-resolution 3D and 4D subsurface images. This helps geoscientists accurately identify the location of oil and gas deposits and how they evolve over time.
Reservoir simulation	HPC runs complex mathematical models to simulate the behaviour of fluids (oil, gas, water) within a reservoir. This is essential for optimising drilling locations, predicting production rates, and maximising hydrocarbon recovery.
Computational fluid dynamics (CFD)	Modelling of fluid flow in pipelines, refineries, and drilling equipment to ensure safety and improve efficiency.
Materials science	Accelerating the design and testing of new materials (e.g., alloys, polymers) needed for equipment operating in extreme well or deepwater environments.

HPC in the electricity sector (the new frontier)

In the power sector, HPC is essential to managing the complexity of the modern smart grid and integrating variable renewable energy sources.

Application	Purpose
Renewable energy forecasting	High-performance computing (HPC) runs advanced weather and atmospheric models (such as computational fluid dynamics or CFD) to predict production from intermittent sources, such as wind and solar farms. This is crucial to maintaining grid stability.
Grid and power flow analysis	Performs complex and laborious calculations, such as optimal power flow (OPF) and power flow (PF) analysis, in near real-time. This helps operators ensure grid reliability, prevent outages, and minimise power losses, especially on extensive, interconnected grids.
Climate modelling and resilience	HPC simulations model the impact of extreme weather events (e.g., hurricanes, heat waves) on physical grid infrastructure, helping utilities plan for resilience and predict maintenance needs.
Nuclear reactor simulation	HPC is used to model neutron transport, heat transfer, and long-term fuel behaviour in nuclear reactors, for both safety analysis and next-generation reactor design.
Discovery of new materials	Accelerate research and development of new and more efficient materials for batteries, solar cells, and high-temperature components in power generation.

High-performance computing (HPC) is based on speed and brute force calculation, focusing on solving large and complex computational problems as quickly as possible (for example, weather modelling or fluid dynamics simulations), whilst AI focuses on simulating intelligence and learning patterns by allowing the machines that simulate human intelligence, to reason, learn, perceive, and make decisions. The differences between one and the other are revealed in the essence of their methodologies: whereas in high-performance computing a massive number of predefined deterministic algorithms are executed by parallel processing, which implies executing the instructions exactly as programmed, with AI non-deterministic algorithms are used (for example, machine learning, or deep learning, to learn from the data and make predictions or classifications). The results achieved with both are unequivocally unique: whilst high-performance computing achieves an accurate numerical result or a high-resolution simulation (for example, a weather forecast or a molecular structure), with AI a learned model is created that can predict a difficult result to calculate through other methodologies: for example, 'The price will go up', or 'The machine is about to fail'.

High-performance computing does not exclude AI, and vice versa. The parallel evolution of both has been taking place since the decades of the '60s and '90s in the 20th century. High-performance computing allowed 2D/3D seismic data and static numerical simulations of reservoirs to be run on centralised computers, assigning limited data interpretation decisions to human experts. With the arrival of advanced AI starting in 2018, these calculations have been carried out using deep learning to achieve a fast and highly accurate interpretation of vast seismic and geological data. By using digital twins, downhole data is integrated in real time with historical models, providing dynamic and adaptive production forecasts and optimizing the location of wells with far greater accuracy. If in the 20th century scheduled maintenance, manual inspections, and simple inventory/demand models were carried out manually, as of 2010 machine learning has created predictive maintenance, analysing data from pump, pipe, and turbine sensors in order to predict failures, thus minimising costly unplanned downtime. AI-based operational efficiency has managed to optimise logistics, manage refinery performance, and forecast demand more accurately, thus improving profitability and reducing waste. Today, artificial vision based on AI monitors installations in real time to detect unsafe behaviours or anomalies in equipment. Risk prediction models analyse historical data, climate and operational records to forecast high-risk conditions, making it easier to monitor emissions and optimise energy consumption to meet sustainability goals.

In recent years, we can see how the use of AI has become more widespread in the energy sector, as its ability to adapt to current challenges is superior to that of traditional high-performance computing (HPC). This is due to the Earth's subsurface being inherently uncertain and non-linear, and traditional simulations therefore requiring a high computational cost for the repeated execution need to analyse said uncertainties. This makes AI the tool which offers the ability to learn and adapt from complex, confusing, and incomplete operational data without needing an explicit physical equation, because the AI learning and prediction environment is based on

clarifying uncertainty. AI, by entering industries that collect data from the physical world, is evolving to create what is called a 'world model'.

1.4 Evolving towards an AI of world models

Whilst today's large language models (LLMs¹¹) possess great abilities to predict the next word in a sentence, they don't really understand why a glass breaks after you drop it or how a car manoeuvres at an intersection in the rain. Traditional AI is reactive: it captures an input and produces an output. A world model, however, has an internal representation of reality that allows it to simulate the future. The most frustrating failures of AI are often due to a lack of basic physics or social intuition. Developing a world model is the main way to endow AI with common sense, and the energy sector has become the largest and most transcendental testing ground that will, quite literally, usher in a radical transformation in how AI evolves and responds to the enormous challenges ahead.

In the energy sector, world models are being developed as high-fidelity digital twins of physical systems, such as the global climate, a power grid, or a fusion plant. By 2026, major players in this space will focus on the 'AI of physics', where neural networks are constrained by the actual laws of thermodynamics and electromagnetism. The competitive landscape in these types of developments has NVIDIA developing the most advanced literal world model for energy and climate. Earth-2 is its digital twin of the entire planet that uses generative AI¹² to create kilometre-scale weather and climate simulations. Utilities use Earth-2 to predict extreme weather events, such as windstorms or heatwaves, weeks in advance to protect the power grid. Partnering with Siemens, they are building 'industrial AI' models that simulate entire power plants or factories in a virtual world before laying a single brick. DeepMind is applying the principles of world models to solve the most complex physical energy control problems, such as the simulation and control of the plasma inside a tokamak-type fusion machine. This world model of a sun-like environment allows AI to test how to control the current flowing through the superconducting magnets of the fusion device to keep the plasma stable. Another of its developments, WeatherNext 2, is based on weather prediction AI models that already outperform traditional supercomputers. With regard to renewable energies, this is vital to accurately predict the amount of solar and wind energy available at any given time. In 2026, it began a collaboration with the US Department of Energy (DOE), Genesis Mission, (DOE) to use cutting-edge models (such as Gemini) in materials science, discovering new chemical compositions for batteries and carbon capture materials.

Meanwhile in Europe, the development of energy-centred world models differs from the US approach. Whilst the US landscape is heavily driven by private tech giants, the European strategy is a mix of state-backed scientific initiatives and

¹¹ Large language models.

¹² CorrDiff is the corrective diffusion model created by NVIDIA to act as a 'smart magnifying glass' on climate world models.

industrial engineering. For 2026, Europe will seek to position itself as a leader in digital twins, essentially high-fidelity global models of physical surroundings and the planet itself. By 2026, the EU is expected to have moved towards a pan-European digital twin of the power grid. This project integrates the local grid models of 27 countries into a single giant world model of the continent's energy flow. This is crucial, as Europe's energy security now depends on sharing wind power from the north and solar power from the south in real time. The EU's flagship world model project, Destination Earth (DestinE), is a large-scale, multi-year initiative by the European Commission, the European Space Agency (ESA), and the Common European Power Market Physics Model (CEPMPM)¹³ to create a digital replica of all Earth systems by simulating the atmosphere, oceans, and land with unprecedented resolution at 1-km scale, allowing European energy providers to simulate how a weather phenomenon of one occurrence in 100 years would affect North Sea offshore wind farms or solar production in Spain, thus providing the most accurate mental map of the world's future energy availability.

1.5 A secure and trustworthy AI for the 21st century

AI's versatility in solving challenges with creativity and scalability is surprising both regulators and industry standards agencies, as AI is being developed and deployed in contexts never before conceived and at remarkable scale. Stagnant situations in the past, devoid of tangible and comprehensive solutions, have been solved thanks to AI's enormous potential.

1.5.1 Developing prediction models with renewed creativity

The development of AI-based solutions is a highly creative process, as possible solutions are explored using a highly versatile technology. One prime example of its elevated creative capacities was solving the deployment of connectivity in emerging markets such as sub-Saharan Africa. This is an enormous challenge for governments in developing countries that also have to face geographies of intense complexity. AI in this context was revolutionary as a solution to obtaining a clear vision of the location of existing power lines and facilitating better decisions on where to concentrate efforts, how to design the grid, and how to obtain the necessary equipment. Until now, space agencies have provided 'eyes in the sky' to developing countries, extending the capabilities of geostatic satellites to visualise geographies with accuracy down to the centimetre. However, AI is moving with great power to supplement and optimise where satellites do not reach. To demonstrate how AI can map medium voltage (MT) infrastructure in African countries with high precision, the AI division of U.S. company Meta formed a research consortium with the World Bank's Energy Sector Management Assistance Program (ESMAP); Sweden's Royal Institute of Technology (KTH), one of Europe's leading universities in engineering; the World Resources Institute (WRI), an institute of the MacArthur Foundation in

¹³ Common European Power Market Physics Model

Washington, D.C. whose non-profit mission is to improve people's lives, protect and restore nature, and stabilise the climate; and the University of Massachusetts at Amherst. Together, they developed a new predictive model to map medium-voltage (MV) infrastructure using public data and assumed data. To develop the model, the first step was to locate electrification at the settlement level by detecting nighttime radiance through the VIIRS day-night band sensor on NASA satellites that provided infrared radiometry images. The next step was to follow the power grid through its connecting power lines. The grid estimation algorithm sought to establish connections as efficiently as possible, using known power grids as templates, but also basing its recommendations and predictions on choosing grid routes that follow roads, avoid water, and prefer shorter routes. This second set of data was what helped the model to not only correctly predict power line routes but also to improve the results obtained only with Real World Data (RWD), such as power lines that could be seen at night without the need for satellite vision. This pilot experiment successfully achieved its purpose and has become a model that can allow governments and NGOs to use it with certainty to understand where people need electricity or where to expand water pumping infrastructure to provide basic services. The results of this model were made publicly available through the World Bank's open energy data repository, which ensured that the data could be used by governments, nonprofits, and other organisations focused on improving energy access. The great power of advanced AI is its enormous scalability for use in a wide variety of scenarios, solving diverse purposes and needs with ease and creativity without barriers.

1.5.2 A new concept of infallibility in prediction

AI does not need to predict with 100% infallibility to be trustworthy. In fact, when AI models in training reach an assumed 99% infallibility, it is suspected that learning has deteriorated, often indicating 'overfitting' or that the model has memorised historical training data but performs poorly when exposed to new real world data (test accuracy or out-of-sample performance). In the energy sector, real world data plays a very important role in the reliability of the model, and that is why one of the recent arguments for the reliability of advanced AI in creating guarantees that the model can be certified or standardised will come from companies in the energy sector that begin to develop data governance strategies that include how to treat real world data (RWD).

1.5.3 The security of AI systems in an increasingly vulnerable world

Whilst the opportunities are immense, so are the challenges. The digitalisation enabled by AI also generates new vulnerabilities, making cybersecurity a primary concern. As utilities integrate AI to manage everything from smart grids to fusion plants, they simultaneously open up a new digital frontier that both state actors and cybercriminals are rushing to exploit. The energy sector is no longer just defending against human hackers: it is also defending against adversarial AI. In 2025, the average time it takes for an AI-assisted security breach to penetrate a network dropped to just

11 minutes¹⁴, compared to the days or weeks of traditional attacks. Malicious AI can map the entire topology of a power grid in seconds, identifying 'weakest link' sensors or legacy hardware that human analysts might miss. To counter this, energy companies have implemented a strategy called 'AI Guardians': autonomous security systems that battle in real time with attacking code and make tactical defence decisions at machine speed without waiting for human approval. As we move toward a decentralised energy future (with millions of solar panels, electric vehicle chargers, and home batteries), the 'attack surface' has grown exponentially. Therefore, the energy sector is beginning to combine AI with strong quantum encryption. As AI can decode current encryption methods much faster, the next step in protecting our key infrastructures such as AI-powered fission reactors and fusion plants ¹⁵ is to move towards a zero-trust architecture, where each data packet is verified by a separate AI security layer before it can circulate over the network.

It is absolutely essential that, in parallel to the development and deployment of AI in any sector, solid barriers and cybersecurity strategies are built around it that guarantee the protection of infrastructures and the sustainment of operations.

1.5 Towards sustainable, energy-efficient AI

The significant energy and water consumption of AI data centres present a profound paradox: the same technology designed to drive energy efficiency also imposes significant new pressure on the power grid. In addition, addressing ethical considerations, data privacy, and the global talent gap requires a well-structured and well-defined governance framework. The strategic imperative for energy sector leaders is to move from a fragmented, project-based approach to a holistic strategy that views AI as a critical long-term capability, integrating technology, talent, and strong governance to responsibly realise its full potential.

Despite the challenges, it is undeniable that AI will turn the energy sector into one of the most proactive industries in charting humanity's future well-being, its energy prosperity, and carving out a future that, at the same time, demonstrates that energy resources can be managed sustainably, and that the digital civilisation that governments and the public sector are building will be supported by a strategic,

¹⁴ The Network Installers, 'AI Cyber Threat Statistics: The 2025 Landscape of AI-Powered Cyberattacks,' 2 December 2025

¹⁵ Understanding the difference between fission and fusion is key to understanding the future of energy. In simple terms, they are opposite processes: one breaks atoms and the other combines them. The former is a constant, powerful energy source that does not emit CO₂, but produces radioactive waste that lasts thousands of years, and there is a risk (albeit low) of an accident if the chain reaction is not properly controlled. Nuclear fusion, on the other hand, releases much more energy than fission, about four times more per kilogram of a fuel (which is almost inexhaustible because it is taken from sea water), does not produce long-lasting radioactive waste and is intrinsically safe (if something fails, the reaction stops on its own). Its challenge is that it is extremely difficult to achieve on Earth. Projects such as ITER that recreate the conditions of the sun's core through giant magnets and ultra-powerful lasers, are opening a gap in fusion where AI is an essential element to make it commercially viable.

valuable, and responsible sector to create the economic and social progress of the 21st century.

2 The strategic context: market drivers and maturation

The adoption of AI in the energy sector is not an incipient trend but a fundamental maturation of the market driven by the convergence of powerful forces at the macro level that reinforce themselves. The industry is moving beyond a 'pilot or planning' phase geared towards implementing practical, scalable solutions and building internal capabilities. This transition is a direct response to the increasing complexity and interconnectedness of the modern energy landscape.

The use of artificial intelligence (AI) in the energy sector has evolved significantly from early rule-based systems to today's complex machine learning models. The emergence of AI in the energy sector is a transformative evolution. Initially, the industry relied on static, manual, and often reactive processes, where data was stored in silos and decisions were based on historical norms and rigid deadlines. The advent of AI introduced a new paradigm focused on real-time data analysis, predictive capabilities, and intelligent automation in response to the growing complexity of the power grid, the need to integrate variable renewable energy sources, and the pursuit of greater operational efficiency and safety. In the oil and gas sector, the need to more accurately identify potential reserves and optimise drilling routes to reduce costs and risk (e.g., 'dry wells') has allowed AI and its immense capabilities to analyse large amounts of seismic and geological data to solve this challenge. Likewise, and perhaps most relevant is the use of AI-powered digital twins (virtual replicas of assets such as power grids, pipelines, platforms or refineries) that are used for real-time operational monitoring, simulation, and optimisation. These advances in energy efficiency have similarly brought advances in materials science, as AI is accelerating the discovery and co-design of new battery materials and solar technologies that pivot from traditional 20th century paradigms.

The road map for innovation towards challenge-responsive AI can be mapped out over decades:

2.1 The early years (1970s–1990s): Expert systems

In the initial phase, AI applications were mainly based on rule-based systems or expert systems. These systems sought to encode the knowledge and decision-making processes of human operators into computer programs. Their primary applications focused on detecting and diagnosing faults in power systems, identifying anomalies, and diagnosing equipment faults based on a predefined set of rules. In the oil and gas sector, early models were used to simplify decision-making in exploration and reservoir management.

2.2 The rise of machine learning (1990s–early 2010s): Neural networks and prediction

In the mid 1990s, the use of fundamental machine learning techniques, such as artificial neural networks and support vector machines, began to increase thanks to increasing computational capacity. Historical data could be used for more accurate prediction and neural network-based forecasting to predict load and price more accurately based on electricity demand, supply, and price data, which is crucial for market operations and grid scheduling. In the oil and gas sector, machine learning models began analysing equipment sensor data to predict failures before they occurred, moving from time-based maintenance to a proactive AI-driven predictive maintenance strategy which, instead of adhering to calendar-based static schedules or waiting for equipment to fail, uses machine learning to analyse sensor data and historical performance metrics and predict when equipment is likely to fail. The benefits are substantial, including reduced unplanned downtime, longer equipment life, and lower maintenance costs.

Machine learning has also made it possible to forecast renewable energy. The intermittent nature of solar and wind presents a significant challenge to grid stability. AI provides a solution by processing vast amounts of real-time data from weather stations, satellite imagery, and historical performance metrics to produce highly accurate predictions of power generation. This improved accuracy allows grid operators to optimise energy distribution and storage, making renewable energy more reliable and accelerating its integration into the grid.

2.3 The era of smart grids and big data (2010s–present): Deep learning and optimisation

The confluence of the concept of smart grids, the proliferation of sensors (IoT), and the massive increase in data coming from smart meters and renewable sources has led to the widespread adoption of advanced AI. This made it possible to solve the management of the bidirectional flow of energy and the variability that sources such as wind and solar drove an important innovation in AI towards the management of smart grids. Likewise, deep learning models (a subfield of machine learning) significantly improved the accuracy of wind and solar production forecasts up to 36 hours in advance, which allowed for greater grid stability and greater penetration of renewables thanks to their optimal integration into the grid. AI algorithms, by managing complex grid operations in real time, including balancing supply and demand, and optimising voltage and power flow to reduce power losses, have enabled an exponential operational efficiency increase in smart grids, a point of no return that forces the sector to continue plotting this roadmap towards automated operability.

2.4 Current trends (focus on generative AI and resilience)

By exploring advanced AI, particularly large language models (LLMs), the energy sector has begun to process, summarise, and automatically ensure regulatory compliance in complex technical and regulatory documents. More relevant still is the work being done in areas of cybersecurity and resilience, where AI-based tools are essential to monitor critical infrastructures and predict and mitigate network disruptions caused by cyberattacks or extreme weather events.

This technological shift is a strategic imperative to addressing some of the most pressing global challenges, such as climate change, energy security, and the growing demand for clean and reliable energy, marking a significant step toward a more innovative and sustainable energy future.

3.1 The AI toolkit

The application of AI in the energy sector is underpinned by a diverse and increasingly sophisticated set of technologies and methodologies. The field is evolving beyond generic algorithms to specialised, integrated systems that leverage domain-specific knowledge to solve crucial problems.

3.1 Fundamental AI methodologies

3.1.1 Machine learning (ML)

ML is AI's foundational technology, which uses algorithms that learn from data to make predictions or decisions. This includes supervised learning for tasks such as forecasting energy consumption based on historical data as well as unsupervised learning to identify patterns in unlabeled data, such as market behaviour or consumer segmentation.

3.1.2 Deep learning (DL)

A subset of ML, deep learning models are used for more complex tasks that require processing large sets of data. Examples include image recognition to analyse drone images of power lines for defects and nonintrusive load monitoring (NILM)¹⁶ to disaggregate device-level energy consumption only using smart meter data¹⁷.

3.1.3 Generative AI (GenAI)

GenAI is a powerful class of models capable of creating new and original content. In the energy sector, its applications extend beyond simple text generation to include summarising extensive technical reports, enabling rapid knowledge transfer for new engineers, generating code from natural language instructions, and creating synthetic

¹⁶ Nonintrusive Load Monitoring (NILM), also known as energy disaggregation, is an advanced signal processing and machine learning technique that identifies individual appliances and their energy consumption simply by monitoring the total electricity consumption at a single point, usually the main electricity meter. In essence, NILM solves a complex inverse problem: it takes the total power signal and breaks it down into its components without the need for independent sensors in each appliance.

¹⁷ AI-Powered Demand Side Management: Reshaping when and how we use electricity, 2005

images to simulate new transmission line routes or train defect detection models¹⁸.

3.2 Technologies that facilitate and amplify AI's deployment and use

AI's effectiveness is amplified by its integration with other parallel advanced technologies:

3.2.1 Digital twins

A digital twin is a virtual representation of a physical asset, system, or process that is continuously updated with real-time sensor data. These dynamic models allow scenario simulation, predictive analysis and testing of operational changes without affecting the physical system. For example, digital twins are used to predict corrosion in steam generators, saving utilities billions in costs annually. Even as digital twins create digital representations of the real world, a powerful trend is the development of physics-based neural networks¹⁹, which integrate physical laws and equations into the AI learning process, ensuring that predictive models are not only accurate but also physically plausible, which is a fundamental requirement for complex energy infrastructures.

3.2.2 IoT and sensor networks

The proliferation of internet of things devices and sensor networks is the foundational layer for AI applications. These sensors continuously collect real-time data on everything from vibration and temperature to electrical current and voltage. This data provides the necessary fuel for AI algorithms, enabling real-time asset health monitoring, anomaly detection, and data-driven maintenance scheduling.

3.2.3 Edge computing

Whilst IoT collects data, edge computing processes it at the source (e.g., at a wind turbine or local substation) rather than sending it to a central cloud. This achieves a reduction in latency, which is essential for self-repairing networks that must respond to a failure in milliseconds. Greater bandwidth efficiency is also achieved as AI models can filter noise²⁰ locally, sending only significant anomalies to the central system. Privacy and security are ensured as sensitive energy consumption data can be processed on-site, reducing the risk of data interception during transit.

18 Generative AI in Transmission and Substations - EPRI, AI White Paper 2025

19 The neural network is forced to learn a function that not only fits the data but also satisfies the fundamental physical law in all the points tested within the computational domain, i.e., that it cannot 'invent' or 'assume' reality but must accept it as the physical data of the real world tells it to be. This is a radical change in the training of these networks which learn by themselves. The impact that real world data (RWD) will impose on AI will accelerate the development of AGI or artificial general intelligence, the super AI that thinks and is aware of what life really is and its analogue realities.

20 The process of removing irrelevant information from a data set so you can see the 'story' the data is really trying to tell. In data analysis, noise is not sound but any random variation that does not represent the actual trend.

3.2.4 5G and 6G connectivity

The transition to 5G (and future 6G networks) provides the high-speed, high-density communication infrastructure needed for 'massive IoT'. Segmenting the network allows utilities to reserve an exclusive network for critical AI control signals, thus ensuring that they are not slowed down by public internet traffic. In this sense, ultra reliable low latency communication (URLLC) benefits from AI for the synchronisation of distributed energy resources (such as thousands of household batteries) to thus balancing the network in real time.

3.2.5 Blockchain

Blockchain acts as the 'layer of trust' for AI, especially in decentralised energy markets. In peer-to-peer (P2P) trading, AI can manage the purchase and sale of surplus solar energy between neighbours, whilst blockchain provides a secure and immutable record for such transactions, ensuring that the data used to train models has not been manipulated by malicious actors or cyberattacks.

4 Transformative applications across the energy value chain

The impact of AI is not limited to isolated improvements. Rather, it is creating a comprehensive ecosystem of solutions that is redefining key business processes. By moving from reactive to proactive and from manual to automated, the energy value chain is becoming a continuous, AI-optimised cycle that offers tangible solutions on several fronts:

4.1 Transmission, distribution, and grid management

4.1.1 Smart grids

AI is central to the development of smart grids that use digital communications technology to detect and react to local changes in usage. AI algorithms analyse real-time data from smart meters and IoT devices to predict consumption patterns, dynamically balancing supply and demand to minimise energy waste and ensure consistent service delivery. This dynamic balance is essential to maintaining grid stability and preventing outages.

Measuring the exact percentage of 'smart grids' in the world is complex, as there is no single global definition of what makes a grid 'smart'. However, energy experts typically measure progress using three main indicators: smart grid completion, smart meter penetration, and digital maturity scores. As of 2026, the global picture breaks down as follows:

Global coverage and finalisation: According to recent industry studies (e.g., Juniper Research, 2025/2026), the world is still in the initial and intermediate stages of transition. It is estimated that smart grids would make up approximately 24.2% of the global grid as of 2025, projecting this to reach of 42.7% by 2030 as the oldest

infrastructure reaches the end of its useful life and is replaced by digital systems. There is, however, the '40/40' problem: in regions like Europe, about 40% of the power grid is over 40 years old, which means that a significant portion of the global grid is still powered by analogue technology designed for one-way power flow.

Smart meters penetration (The 'eyes' of the grid): Smart meters are the most visible component of a smart grid. They provide the two-way communication necessary for AI's operation. Total units in global installations exceeded 1.8 billion units by the end of 2024 and are projected to exceed three billion by 2030²¹. The world's smart grid leaders are mainly in North America, with an approximate penetration of 81%, although China has reached a penetration close to 100% in urban areas, acting as a massive data engine for AI-driven network management. Europe, in the meantime, is catching up rapidly (averaging about 72%), driven by EU mandates for decarbonisation.

4.1.2 Fault detection and self-repairing networks

Traditional methods of fault detection are often slow, mostly analogue,²² and lack predictive capabilities. AI-powered systems are revolutionising this by processing real-time data from sensors to detect anomalies and anticipate faults before they cause serious breakdowns. This is enabling the development of 'self-repairing' networks, which use AI-powered detection and intelligent control systems to autonomously detect, analyse, and respond to failures. These systems can automatically isolate faults and reconfigure power distribution, preventing nearly 45% of potential service outages and minimising power restoration times by up to 60%. This significantly improves grid resilience and reliability.

4.1.3 Outage management

AI improves outage management by using data from smart meters and sensors to determine the exact location of a fault. It can also predict restoration times based on the type of outage, location, weather conditions, and available resources, allowing utilities to provide more accurate and timely information to customers.

4.2 *Energy markets and trade*

Accurate forecasting is crucial to ensure grid stability and security of supply. AI models can be trained with historical data and incorporate a number of additional

21 Counterpoint, 'Global Smart Meter Installations Set to Surpass 3 Billion by 2030 amid Accelerating Adoption,' 11 November 2025

22 Historically, inspections of high-voltage networks have been carried out almost entirely by humans and helicopters. Recently, drones equipped with thermal vision are rapidly becoming the main tool for this work, but AI is the third-generation tool that is propelling autonomous inspections thanks to autonomous drones that are installed in substations. They take off automatically, fly a programmed circuit of kilometres and return to their base to recharge without any human touching a controller. Instead of one person looking at 10,000 photographs of power poles, artificial intelligence software 'filters' the data and automatically flags only images that show rust or damage.

data sources, such as real-time weather reports and economic indicators, to predict future consumption patterns more accurately. This capacity is especially important for managing the variability introduced by renewable energy sources.

Likewise, the volatility of modern energy markets, driven by the growing share of renewables, is a key motivator for the adoption of algorithmic trading. AI-powered platforms analyse large datasets in real time, providing predictive insights and risk assessments that enable more informed, cost-effective business decisions. These algorithms can execute trades autonomously with limited human intervention, allowing for greater flexibility and faster reactions in dynamic markets. However, this is not a complete replacement for human traders: many companies find that the most valuable approach is a symbiotic relationship where algorithms handle complex computations and data processing whilst human experts make the final strategic decisions based on the results.

4.3 Demand management and customer engagement

The energy sector, when it serves the consumer, is making great changes in terms of the services provided, its innovation, and the approach to creating individualised experiences.

Automated charging and control of smart appliances: AI is a key enabler for demand management, which aims to redefine when and how electricity is used. AI autonomously adjusts smart devices, such as thermostats, heat, ventilation, and air conditioning systems, as well as electric vehicle chargers, to shift energy use to off-peak hours. This is made possible by reinforcement learning, which allows AI to understand user preferences and balance energy cost savings with convenience. This capability turns passive consumers into active participants in grid stability.

Personalised information and engagement: AI provides a significant advancement in customer engagement by delivering personalised energy insights. Through technologies such as nonintrusive load monitoring, which disaggregates energy usage from smart meter data, AI can provide customers with detailed, device-specific consumption patterns and efficiency recommendations. This hyper-personalised approach not only promotes energy efficiency but also builds trust and encourages customers to become partners in grid stability.

Customer service and call centre support: Generative AI is revolutionising customer care by powering intelligent self-service tools and AI-assisted agents. By automating routine queries and providing call centre representatives with nuanced, real-time data, AI has been shown to reduce high billing calls and increase customer satisfaction rates.

5 Navigating the AI energy paradox: challenges, risks, and critical governance

The transformative potential of AI is a double-edged sword. Whilst it allows for unprecedented efficiency, it also introduces new and complex risks and comes with a significant environmental impact. The 'AI energy paradox' is a core challenge that requires deliberate and strategic management.

5.1 *The operational and technical landscape*

The implementation of AI in the energy sector is not without its obstacles. One of the main challenges lies in integrating advanced AI with a legacy infrastructure that was not designed for digitalisation and real-time data flows. This is compounded by the need for high-quality, standardised data, as raw data from smart grids is often incoherent, incomplete, and inconsistent. In addition, there is a recognised talent gap in the industry, with a significant shortage of professionals with technical expertise specialising in both AI and energy-specific operational technology. This lack of expertise in both domains is a critical hurdle to scalable AI adoption.

5.2 *Cybersecurity and system resilience*

The increased digitalisation and connectivity required for AI-based power grids create a rapidly expanding threat landscape. AI-based tools act as a 'force multiplier' in both directions, improving threat detection and enabling more responsive protection whilst empowering adversaries with sophisticated new attack vectors. Specific threats include false data injection and time-delay attacks, where manipulated sensor data can trick control actions and potentially cause network instability. The rise of adversarial machine learning also allows malicious actors to evade detection. Defending against these threats requires proactive, layered defence as well as a new type of workforce that understands both AI/IT and energy-specific OT.

In 2025, cybersecurity reached a new milestone in innovation with zero trust architecture, which has gone from being a theoretical concept to a regulatory requirement for critical infrastructures, particularly in the energy sector. Unlike traditional perimeter security, which acts as a wall around a castle, zero trust treats every user, device, and software component as a potential threat, even those already inside the system, and acts as a specialised defence against these 'next-generation' threats:

A. Countering AI-driven social engineering

Attackers now use generative AI to create hyper-realistic deepfakes of energy executives or 'perfect' phishing e-mails. In these situations, the zero trust defence is oblivious to the human factor. Even if an employee is tricked into

revealing their password, the system still requires multi-factor authentication and contextual verification for each action. In addition, the status check of the device is carried out. If the login comes from a device that hasn't been scanned for malware in the past hour, access is instantly denied, stopping the AI-driven breach from the get-go.

B. Prevention of 'lateral movement' with micro-segmentation

AI-powered malware is designed to spread like a virus through the network until it finds the 'brain' (the control center). The zero trust defence divides the network into thousands of isolated 'micro-segments', producing the screen effect: if a hacker infects a smart meter in a residential neighbourhood of a city, it is trapped in that tiny segment. The hacker cannot access high-voltage transmission lines or nuclear cooling systems because there is no route without explicit re-verification.

C. Defence against 'data poisoning'

Malicious AI can attempt to 'poison' the data being sent to the AI of a power grid, for example, by simulating a massive increase in energy demand to cause the system to shut down. With zero trust defence, each AI sensor and 'agent' is assigned a unique digital identity. When analysing the continuous behaviour of each sensor, if one starts sending data that seems 'synthetic' or out of the ordinary, the zero-trust policy engine marks it as 'unreliable'. The system then switches to a backup data source or safe mode until a person can verify the integrity of the data.

Feature	Impact on security	Status in the industry by 2025
Focus on identity	Does not let stolen passwords be the cause of blackouts.	Standard for all new EU and US grid projects.
Continuous monitoring	Detection of 'insider threats' or compromised AI in real-time.	Integrated with DeepMind-style AI monitors.
Assume a cybersecurity breach	The system remains functional even during an active attack.	Required by NERC CIP and NIS2 regulations.
Minimum privilege	Employees only see what they need to do their jobs.	Disruptions related to human error are reduced by approximately 40%.

Summary of benefits for power plants (2025 data)

In the field of nuclear fission, zero trust is already integrated into the design of the small modular reactors currently under development. Although they work with nuclear power, their real value lies in how they can assist with industrial decarbonisation in power grids: unlike large plants that are difficult to 'turn off and back on', modular reactors can adjust their power quickly to cover the gaps when there is no sun or wind. Since these reactors are typically designed for remote or autonomous operation, they use zero trust to ensure that remote signals are encrypted,

verified, and restricted to specific one-way data diodes, making it physically impossible for a hacker to send a shutdown order from outside an authorised control room.

5.3 *AI's environmental footprint*

The 'AI energy paradox' is a key challenge of our time. Whilst AI helps companies reduce energy consumption by up to 60% in some cases by optimising building management and smart grids, the technology itself consumes enormous amounts of energy when it comes to training AI models with trillions of parameters, as is the case in high-computing centres or data centers of companies dedicated to training large language models (LLMs). ²³Until 2022, data centres accounted for about 2% of energy-related carbon emissions, and this included data centres where AI was not trained

Since 2025, the landscape has changed dramatically for those AI companies that have burst onto a market hitherto dominated by large foundational models, mainly developed by US companies. By the end of 2025, there is already much talk about this being the year in which 'Green AI' went from being a niche academic interest to a crucial business requirement, therefore making it impossible to continue with the computational expenditure of previous years, which forecast scenarios that, in terms of energy, are impossible to assume in most countries.

At present, the industry is moving away from the 'bigger is better' philosophy and toward a design that prioritises efficiency. The latest advances and trends in reducing the computational and environmental footprint of AI by the end of 2025 have reconfigured the forecasts of many agencies. Most of all, there has been a paradigm shift in the development of foundational models on which advanced AI is based.

(A) Algorithmic 'slimming' techniques

Researchers have found that much of the energy used by large language models is wasted computing. New techniques are eliminating this waste thanks to the appearance on the market of Chinese models and their new proposals on architecture and model learning. The most revolutionary techniques in 2025 were:

DeepSeek and MoE (Mix of Experts): The Chinese language model DeepSeek, launched in mid-January 2025, presented a unique architecture that allowed it to reduce its needs for high computing, the result of the embargo on state-of-the-art chips and lithographic design tools that the US and Europe imposed on China since 2019. Instead of using all the parameters for each calculation, the model dynamically selects some 'expert' subnets to process the data input. This makes the model faster and cheaper to run, as it avoids the massive memory and power consumption of a fully dense model. This new architecture, inspired by machine learning inference principles, has enabled models to maintain exceptional performance whilst consuming

²³ International Energy Agency, 'Electricity 2024. Analysis and forecast to 2026'.

up to 90% less energy per query.

Extreme quantisation (1-bit and 2-bit): Traditionally, AI uses 16 or 32-bit numbers. By 2025, advancements in '1-bit' architectures have allowed models to run with much lower accuracy. This reduces memory use and power consumption by four to eight times, with negligible loss of accuracy.

Knowledge distillation: Large 'teacher' models are used to train 'student' models, which are 10 times smaller but retain more than 90% of their capacity. This makes them efficient enough to run on local devices rather than in massive data centres.

(B) Hardware: the transition to edge computing

Sustainability is driving a massive transition to on-device AI, which avoids the energy-intensive transfer of data to the cloud. The laptops and phones of 2025 now feature dedicated AI chips or NPUs (neural processing units), optimised for 'inference' (execute the AI) rather than 'training'. These chips are 100 to 1,000 times more energy efficient than general-purpose GPUs. The new chips inspired by the human brain (neuromorphic computing) only consume energy when they receive a peak of data. This 'event-based' processing uses a fraction of the electricity of traditional chips running on a continuous clock.

(C) Carbon-aware programming

Google and other cloud providers have deployed 'carbon-smart' platforms through techniques such as time shifting (AI training tasks that are not time sensitive are automatically scheduled for when the local power grid has a surplus of wind or solar power, and localization) or digitally 'teleporting' work loads to data centres in sunny or windy regions, maximising real-time carbon-free energy use.

(D) The energy tax of 'reasoning'

A crucial discovery for 2025 is the 'reasoning gap'. The most recent data as of December 2025 confirms that the new 'reasoning' models (which think step-by-step) can consume between 30 and 700 times more energy than the standard models, as they generate thousands of internal 'thoughts' before giving an answer. To address this, 2025 systems use 'router AI', a tiny, low-power AI that decides whether the user's question is simple (e.g., 'What's the weather like?') or complex. Simple questions are sent to tiny models, thus saving high power for really complex problems.

Technique	Energy saving potential	Status (end of 2025)
Mix of Experts (MoE)	~90% reduction	Standard on the new frontier models.
Quantisation (1-bit/2-bit)	4x–8x reduction	Being rapidly adopted for mobile AI.
On-device AI (edge).	100x–1,000x	Integrated into most new consumer electronics.
Carbon-aware programming	~30% Carbon reduction	Mandatory under many corporate ESG policies.

Chart summarising energy-saving techniques

(E) Deployment of the first 'green AI' commercial developments

Europe is currently a world leader in sustainable AI regulation (EU AI Act) and efficiency research. The most recent specific examples and data for 2025 that deserve to be cited as examples:

1. Spain: The 'prosumer' revolution and smart grids

Spain is leveraging its huge solar and wind capacity by using AI to manage decentralisation, which is inherently more sustainable than centralised fossil fuel plants.

Altano Energy (Madrid): This startup uses AI to manage an integrated clean energy platform throughout the Iberian market. Their AI models analyse consumption patterns to automatically switch customers to the cheapest, greenest electricity available in real time, reducing the need for high-carbon plants for peak hours.

The A3E-INDAL project: This groundbreaking collaboration between the University of Castilla–La Mancha and the technology centre Ainia succeeded in developing AI software that 'mimics an energy expert'. It is specifically designed to run on energy-efficient hardware in food processing factories (such as canned meat plants) to identify energy savings of up to 17% without the need for connection to a massive, energy-intensive data centre.

Endesa and Red Eléctrica: Recent data for 2025 shows that 56% of Spain's electricity currently comes from renewable energy. Spanish utilities use machine learning models (such as Random Forest and XGBoost) to predict energy prices and demand. These models are thousands of times smaller than large language models, but have improved grid stability and significantly reduced waste.

2. Mistral AI (France): The leader who prioritises efficiency

Mistral AI has become Europe's answer to Silicon Valley, but with a radical focus on 'small language models' (SLMs). According to its July 2025 transparency report, Mistral was the first company to publish an 'environmental footprint' report for its Mistral Large 2 model. The prime consequence of this action was to demonstrate that a model 10 times smaller generates impacts with a smaller order of magnitude for the same task. Mistral's strategy encourages companies to bundle AI requests and use the smallest possible model for the task (e.g., using Mistral 7B for a summary instead of GPT-4).

To understand this impact in all its dimensions, just compare Open AI Chat GPT4 and small foundational models²⁴ developed by Mistral and other companies:

²⁴ Whilst the term 'foundation model' was coined by Stanford in 2021 to describe models trained with broad data that can adapt to many tasks, the 'small' variant is a specific technical evolution from 2024–2025. A small foundation model (SFM) is a versatile AI model trained with diverse, high-quality data sets that, unlike its 'large' counterparts (LLM), is intentionally designed with significantly fewer parameters (typically less than

Metric	Large general model (e.g. GPT-4)	Specific model for small tasks (e.g., Mistral/SLM)
Energy Consumption	High (comparable to a small town)	90% lower
Water consumption for cooling	~500 ml for every 10–50 queries	Negligible
Infrastructure	Hyperscaled massive data centres	Local 'edge' / NPU devices
Latency	Superior (cloud-dependent)	Real time

Impact of the large vs. small model (2025)

5.4 Ethical Considerations and Algorithmic Bias

The deployment of AI in areas of great importance, such as energy infrastructure, raises complex ethical considerations. A key risk is algorithmic bias, as AI models trained with biased data can perpetuate such biases, resulting in unequal access to clean energy or disproportionate exposure to pollution in certain communities. This risk underscores the crucial need for transparency and accountability, ensuring that decisions made by AI systems are explainable and that a human being is responsible for them, especially in an environment in which failures can have catastrophic consequences. In addition, the collection and analysis of large amounts of data on energy consumption raises significant data privacy concerns that must be addressed through robust governance frameworks.

When regulators look at biases in AI and seek to create 'safe' AI, their definition is multifaceted and goes far beyond just preventing physical harm. It encompasses a wide range of principles designed to ensure that AI systems are developed and used in ways that protect citizens, uphold democratic values, and promote trust, seeking equity and inclusion. Therefore, the challenge at the moment is to create 'demonstrable' AI, i.e., one whose decision-making process must be, to a certain degree, understandable. This principle, often referred to as 'explainability,' requires that users and regulatory bodies be able to understand how a high-risk AI system came to a certain conclusion. The goal is to build trust and enable accountability and recourse in the event of a failure.

6 Geopolitical and regulatory frameworks: shaping the future of AI in energy

The strategic importance of AI transcends the corporate and operational spheres, reaching a geopolitical and national security dimension. The race for AI supremacy is not merely technological. It is closely tied to a nation's ability to provide the 'raw energy' and 'computer security' critical to the operation of such systems. The role of

10 billion). The goal of an SFM is to achieve performance tailored to 10 to 100 times its size in specific reasoning or specialised tasks whilst maintaining a minimal computational footprint.

the energy sector is therefore a priority, as a nation's ability to generate and supply reliable and affordable energy is now a critical component of its technological leadership in the age of AI.

6.1 The evolving regulatory landscape

Governments around the world are beginning to define the future of AI through proactive regulation. The European Union's AI Act is the world's first comprehensive law on AI, and establishes a risk-based classification system. The energy sector's status as critical infrastructure places it in the 'high risk' category, subjecting its AI systems to strict regulations, including lifecycle assessments and mandatory registration in an EU database. This framework demands transparency and accountability, and defines how AI models are developed and managed.

Where the regulator's reach ends — and perhaps this is the greatest challenge — is in dealing with agentic AI, which makes decisions without consulting the human, for example, when there is a need to act quickly at critical moments and other examples described in previous chapters. The regulatory vacuum regarding how to hold an autonomous system accountable for actions is complicated beyond generative AI and foundation models because it is a completely different operating system that does not include the human in its decision-making processes and which can use other technologies to perform its tasks. In this case, seeking responsibility already expands to third parties and this is a huge regulatory risk. In 2026 and 2027, when thousands of intelligent agents will be operational (perhaps in combination with quantum computing) existing regulations will be forced to modify some of the parameters used in creating principles of accountability and transparency of language models, because agentic AI is not a model but rather an architectural pattern or a system design, instead of a unique 'model' like GPT-4 or Claude.

The specific regulatory 'gaps' that have recently been identified and that will constitute the new framework for efficient regulation can be divided into several fields:

- The 'human-in-the-loop' fallacy: Many regulations assume that a human will review the AI result before using it. In agentic AI, the goal is to eliminate the human from the cycle to gain speed and scale. Current laws do not yet have clear rules for 'human-in-the-loop' (where only humans oversee) or 'human-out-of-the-loop' systems.
- 'Chain' liability: If an agent is created that uses an OpenAI model, a Google search tool, and a Stripe payment tool, and that agent makes an illegal purchase, the regulatory framework has to calibrate where the liability resides and how. The current focus of EU AI Act on the 'supplier' of the base model does not fully cover the 'orchestrator' who connected all those

tools.

- Sandboxing and 'blast radius': The risks of generative AI mainly concern information. Agentic AI risks are operational. Existing laws focus on data privacy and security, but do not yet mandate 'digital sandboxes' or 'spending limits' for AI agents, which are the equivalent of physical security guards on factory robots.

Faced with these challenges, regulators are beginning to change their strategy. In early 2026, we will see new discussions on:

- Dynamic documentation: Requiring agents to maintain a 'black box' flight recorder for each call and tool-related decision.
- Auditability of agents: Ensure an agent can explain why they took a specific action, not just what it generated.
- Emergency switches: Mandatory emergency stop protocols for autonomous systems.

6.2 The geopolitical race for 'computer security'

The analogy that 'computing is the new oil' highlights the deep link between a nation's energy capacity and its technological competitiveness. The immense energy demands of AI data centres mean that the nations that control access to reliable energy and supercomputing infrastructure will wield the same kind of power as those that once dominated energy supplies. This context elevates a nation's ability to modernise its grid, expand low-carbon energy sources, and improve resource efficiency from a sustainability goal to a national security imperative. Indeed, the push for 'sovereign AI' — the push by nations to develop their own AI infrastructure, models, and data within their borders — is a direct response to this, as countries seek to reduce their exposure to geopolitical risk by developing their own national AI capacity.

Unsurprisingly, by 2026, sovereign AI has become a major driver of change in the energy sector. This trend is transforming the relationship between technology and energy, moving from one of 'consumer and supplier' to a deeply integrated strategic alliance. Here's how sovereign AI is impacting the sector:

The energy 'entrance fee' for sovereignty

Nations like the UAE, Saudi Arabia, and India are discovering that sovereign AI is as much about energy policy as it is about technological policy. Unlike the global cloud (where data centres can be located anywhere with inexpensive power), Sovereign AI requires data centres to be built locally. This puts enormous pressure on national grids, which were not designed for such high-density loads. AI training also requires

'always available' energy. This is revitalising interest in nuclear power, specifically in small modular reactors, which provide constant, carbon-free power for sovereign data clusters, whilst driving a renewed interest in commercially developing fusion power.

'Smart grids' as a sovereign asset

To manage the massive energy spike caused by localised AI, countries use that same AI to manage their energy grids. Sovereign AI models are being trained based on local weather and consumption patterns to optimise the network in real time. This reduces energy waste from wind and solar farms. By controlling the AI that manages the grid, nations protect their critical energy infrastructure from external cyber interference, a key pillar of sovereignty.

Change in energy investment

There is a trend towards 'AI growth zones', geographical areas where energy infrastructure is specifically accelerated for AI. In this context, governments and local state entities no longer only buy energy, but now co-invest in high-voltage transmission lines and on-site generation (such as carbon-capture gas turbines) to ensure that their sovereign models are never disconnected. Sovereign wealth funds, such as PIF in Saudi Arabia or Mubadala in the UAE, are investing billions in 'green' energy projects specifically to boost their national AI ambitions, effectively linking the future of their oil-based economies with an AI future based on renewable energy.

Ultimately, sovereign AI is transforming the energy sector from a quiet utility to a strategic national security frontier. As countries move away from global dependence on the cloud and toward localised, high-density infrastructure, the power grid is no longer just a 'supplier' but the backbone of a nation's digital autonomy. In this new scenario, the success of a country's AI ambitions will be measured not only by the sophistication of its algorithms but by its ability to guarantee a stable, sustainable, and sovereign electricity supply, making the search for intelligence a permanent catalyst for the global energy transition.

Strategic Recommendations

The way forward for organisations involved in energy is not a simple adoption plan, but a multifaceted strategy that views AI as a foundational capability to be developed and not simply a product to be purchased. Success depends on a holistic approach that integrates technology, talent, and strong governance right from the start.

7.1 Technology and innovation strategy

Organisations should prioritise high-impact use cases that offer a clear return on investment (ROI) and scalability, such as predictive maintenance, renewable energy forecasting, and smart grid optimisation. This approach allows small-scale pilot programs to test feasibility before scaling them up. In addition, it is critical to promote

and invest in energy-efficient hardware and AI-optimised cooling solutions to address the AI energy paradox, ensuring that AI's net impact is positive.

7.2 *Organisational and talent strategy*

The significant talent gap must be addressed through a strategic workforce plan that prioritises the acquisition and development of dual domain expertise in both AI/data science and energy-specific operational technology (OT). The most successful AI deployments in the energy sector involve building a dedicated data science team and fostering a culture of collaboration with business stakeholders, demonstrating the importance of an integrated approach to technology and talent.

7.3 *Governance and risk management*

A comprehensive AI governance framework is essential to ensure regulatory compliance, ethical use, and robust risk management from development to implementation. This framework should include strict data privacy and cybersecurity protocols to protect against new AI-driven threats such as data poisoning and adversarial attacks. Organisations must also actively work to mitigate algorithmic bias and ensure transparency and accountability in all AI-driven decisions.

7.4 *Collaboration and ecosystem development*

Finally, organisations must collaborate with regulators, academia, and industry peers to shape policy and share best practices. By engaging in public-private partnerships, the energy sector can help accelerate the secure development and deployment of next-generation technologies whilst ensuring that AI serves the public interest and contributes to a more resilient and sustainable energy future for all.

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Chapter Five

Energy port infrastructures: pillars of global energy security A strategic analysis of risks and outlook

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Abstract

Port energy infrastructures have been consolidated as essential elements for global energy security. In a context where hydrocarbons, oil, gas and coal continue to account for more than 80% of global energy consumption, The discharge and redistribution of hydrocarbons become critical nodes for the functioning of the international economy.

Although traditional geopolitics has generally focused its attention on the major maritime bottlenecks (choke points) such as Panama, Malacca, Bab el-Mandeb or Gibraltar, this analysis underlines that energy ports are equally or even more strategic. Unlike maritime routes, these infrastructures often lack operational alternatives and the interruption of their operation would have an immediate impact on overall supply.

The risks they face are growing and multidimensional: terrorism, cyber attacks, regional conflicts, extreme weather events and geopolitical tensions. In a scenario of slow energy transition and persistent dependence on fossil fuels, the resilience, modernization and protection of these facilities becomes a priority.

Keywords

Port, oil, natural gas and security

IMPORTANCE OF FOSSIL FUEL PORTS FOR GLOBAL ENERGY SECURITY



WHAT ARE THESE PORTS?



MARITIME INFRASTRUCTURES SPECIALIZED IN LOADING AND UNLOADING OIL, NATURAL GAS, AND COAL.



CONNECT **PRODUCERS, REFINERIES, STORAGE FACILITIES, AND INTERNATIONAL MARKETS.**



SERVE AS **CRITICAL NODES** IN THE GLOBAL ENERGY CHAIN.

WHY THEY ARE ESSENTIAL FOR ENERGY SECURITY



ALLOW COUNTRIES TO **IMPORT OR EXPORT FUELS** ACCORDING TO THEIR DEMAND.



AVOID INTERRUPTIONS THAT WOULD AFFECT ELECTRICITY, TRANSPORTATION, AND INDUSTRY.



GUARANTEE THE CONTINUOUS FLOW OF ENERGY.

DIVERSIFY ROUTES AND SUPPLIERS



REDUCE DEPENDENCY ON A SINGLE COUNTRY OR REGION.



INCREASE RESILIENCE IN THE FACE OF GEOPOLITICAL CRISES.

SUPPORT ECONOMIC STABILITY



70% OF THE WORLD'S OIL TRADE IS TRANSPORTED BY SEA.



PORTS PROVIDE MORE **STABLE PRICES** AND **CONSTANT ACCESS TO ENERGY.**



RISKS THEY FACE

GEOPOLITICAL TENSIONS



BLOCKADES, SANCTIONS, OR CONFLICTS CAN SHUT DOWN KEY PORTS.

PHYSICAL VULNERABILITY



TERRORISM, CYBERATTACKS OR ACCIDENTS MAY DISRUPT OPERATIONS.



REQUIRE HIGH STANDARDS OF SAFETY AND MAINTENANCE.

HOW THEY STRENGTHEN ENERGY SECURITY

MODERN INFRASTRUCTURE



LNG TERMINALS, STORAGE TANKS AND SPECIALISED DOCKING FACILITIES.



CAPACITY TO RECEIVE LARGE SHIPS (VLCC, LNG CARRIERS).

INTERNATIONAL COOPERATION



AGREEMENTS BETWEEN COUNTRIES TO KEEP ROUTES OPEN.



COORDINATED EXERCISES ON MARITIME SECURITY AND PHYSICAL SECURITY IN PORTS.

CONCLUSIONS



WITHOUT FOSSIL FUEL PORTS, THE GLOBAL ENERGY SYSTEM WOULD COLLAPSE DUE TO A LACK OF SUPPLIES.



FOSSIL FUEL PORTS ARE STRATEGIC PIECES THAT SUPPORT THE GLOBAL ECONOMY.

Introduction

Consumption of crude oil barrels in 2025 was slightly over 103 million barrels per day worldwide, which approximately 60%–70% were transported by sea. As for natural gas, figures for 2025 are expected to reach 78 billion cubic metres, of which approximately 20–30% is transported by sea, and this percentage is on the rise: in 2025 alone, 96 new gas tankers were expected to join the global fleet.

According to official data gathered by CORES¹ and the CNMC², in 2024 Spain imported 64.6 tonnes of crude oil, equivalent to about 473 million barrels, amounting to practically 100% of Spanish oil consumption as the country has no significant oil production of its own nor do any international oil pipelines enter its territory. In terms of natural gas, approximately 16.8 billion cubic metres (bcm) of LNG were unloaded whilst another 9.9 bcm arrived from Algeria through the Medgaz pipeline, covering total consumption of 29 bcm, of which about 4.4 bcm were reexported. All of this makes Spain a European energy hub dependent on its port infrastructures for the entry and redistribution of fossil fuels.

Given global levels of oil and gas consumption in 2025 and forecasts for the coming years, it would seem unrealistic to think that the world's use of oil and gas will end in the short or medium term, thereby making it necessary to secure, among other things, points of loading and unloading.

Current estimates with regard to transport of oil and natural gas worldwide, in Europe, and in Spain are as follows³:

OIL	MARITIME TRANSPORT	PIPELINE	TRAIN/ROAD
Worldwide	60%–70%	20%–30%	5%–10%
Europe	70%	25%	5%
Spain	99%–100%		

NATURAL GAS	MARITIME TRANSPORT (LNG)	PIPELINE	TRAIN/ROAD
Worldwide	30%–35%	65%–70%	Marginal
Europe	30%–35%	65%–70%	
Spain	65%–70%	30%–35%	

A classic theme in hydrocarbon geopolitics has always been the importance of certain strategic locations in maritime routes known as chokepoints. These include the Panama Canal, the entrances to the Red Sea, the Strait of Gibraltar, the Strait of

¹ CORES, Corporación de Reservas Estratégicas de Productos Petrolíferos. Spain's official oil stockholding agency, which collects and publishes oil and gas statistics.

² CNMC, Comisión Nacional de los Mercados y la Competencia. Spain's official market regulator, which supervises the national gas and electricity systems.

³ <https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=615492&utm>.

EU's petroleum imports fall as LNG shipments rise in 2025

Malacca, and the Strait of Bab-el-Mandeb, which often becomes the centre of attention whenever tensions erupt involving Iran and its standing threat to block the pass with the help of Houthi rebels. A number of secondary chokepoints also exist. These are just some of the examples that regularly appear whenever a crisis or possible armed conflict threatens to plunge the world into a new energy crisis.

Other points, however, also exist that hold vital importance to ensuring worldwide hydrocarbon supply and which, though they rarely make headlines, are just as important as maritime chokepoints. These are the ports for loading and unloading of oil, natural gas, and their derivatives. These ports have an additional handicap in that they have no alternative, as opposed to what happens at times with maritime routes.

In an interconnected world where energy demand grows steadily and fossil fuel sources still account for 80% of global consumption, the ports where hydrocarbons are loaded and unloaded play a key role. These points of transit allow the movement of crude oil, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and refined derivatives between producing and consuming countries.

Despite their importance, energy ports seem condemned to a secondary role. This oversight constitutes a strategic vulnerability, especially in a context of growing threats of all kinds, physical and cyber terrorism, geopolitical tensions, extreme natural events, armed conflicts, etc.

Energy security has emerged as an essential part of world geopolitical and economic stability. Some of the world's busiest oil ports play a crucial role in global energy logistics, handling massive volumes of crude oil, natural gas and refined petroleum products.

These include ports such as the Port of Rotterdam in the Netherlands, Europe's largest and an important oil refining and distribution hub for the entire continent. Another is the Port of Houston in the United States, a key actor in the energy corridor along the US Gulf Coast and a centre for both imports and exports of crude oil and petroleum products. Elsewhere, Ras Tanura in Saudi Arabia is one of the world's largest oil export terminals whilst the Port of Singapore is a strategic transshipment hub in Asia and vital for oil trading and storage.

Something similar can be said for liquefied natural gas (LNG) infrastructures, as the world's main LNG ports are likewise crucial for global energy commerce. These ports are equipped with specialised terminals for LNG import and exports, which often require large-scale infrastructure for the liquefaction and regasification of natural gas.

Ras Laffan Industrial City in Qatar, with the world's largest LNG export terminal, handles a significant share of global LNG supply. In the United States, the Port of Sabine Pass, located in Louisiana, is one of North America's largest LNG export facilities. In Europe, the Port of Sines in Portugal is a key hub for LNG imports being a deepwater port and a strategic position on the Atlantic Ocean. The Yamal LNG plant in Russia, north of the Arctic Circle, is a vital Russian LNG extraction facility despite the harsh working conditions in this part of the world. Hosting one of India's

busiest LNG terminals, the Port of Dahej is crucial to meeting the country's growing energy demand. South Korea's Port of Incheon is an important LNG import terminal and serves one of the world's largest LNG consumers. Lastly, the Port of Yokohama in Japan plays a key role in the country's supply chain, with Japan being the world's top importer of LNG. All of these are just a few examples to be kept in mind.

1 Ignorance of the risks

When we talk about key infrastructures, many experts and even media outlets seem stuck in conversations about oil pipelines, gas pipelines, and straits. They are usually the infrastructures that grab the most headlines and dominate debates, as if they were the only guardians of our energy security. But it's an obsession and, in reality, a dangerous distraction. By focusing all our attention on these three types of infrastructure, we neglect the other strategic nodes whose vulnerabilities can have disastrous consequences.

There is no doubt that pipelines and maritime shipping routes are of vital importance. However, making them our sole point of concern is a mistake. National and global energy security does not boil down to these three things alone. It is a bias that leads to a false sense of security and control, and which prevents us from seeing the whole picture in terms of risk.

But it's not just oil and gas ports that are vital: ports in general are the backbone of global commerce. Ports are the gateway for everything that makes our daily lives possible: food, fuel, medicines, technology. And still, they are absent from public discourse, as if invisible. What would happen if a key port was paralysed due to a physical or cyberattack, or simply an accident? The answer is simple: broken supply chains, market instability, and an immediate economic impact. The invisibility of ports is not harmless but rather a vulnerability that we are choosing to ignore.

The lack of investment in physical and digital protection is another consequence of this ignorance of the risks. Whilst cyberattacks become increasingly sophisticated and physical threats become unpredictable, we continue to rely at times on obsolete systems. It's like leaving the door open and not expecting anyone to enter. There is a widening gap between our perception of security and to what extent that protection actually exists. And as for physical security, one need look no further than the drones of unknown origin overflying many European airports in 2025 to understand that we are wholly defenceless to drone attacks on port infrastructures.

Perhaps the gravest error is to assume that each country can deal with these risks on its own. The absence of international cooperation is a luxury we cannot afford. Critical infrastructures are global by their very nature, meaning that whatever happens in a European port can have repercussions in Asia and the Americas. Without alliances, shared protocols, and an earnest exchange of information, our reactions are condemned to being too little and too late.

Ignorance of the risks is not simply a lack of information. It is also a lack of interest in information and analysis that leads to a dangerously complacent attitude. Whilst

we remain fixated on pipelines and straits, we are neglecting a vital component of the we points in our system. Recognising the importance of ports, investing in security, and relying on international cooperation are not options: they are obligations. The question is not whether we should do this but how long we are going to take to react. Whilst it is true that many steps have already been taken, taking a deeper look at many ports leads one to believe that there is still much to do.

2 Bolstering port security

Securing the world's ports is a matter of global urgency. As we have said, ports are much more than mere entry and exit points for goods: they are truly the logistical heart of global commerce. Nevertheless, their security continues taking a backseat to other issues in public discourse. Amid a scenario of growing threats—from cyberattacks to physical sabotage—it has become imperative that we take tangible measures to fortify their resilience.

The first line of defence must be both digital and physical.

From the digital perspective, ports depend on IT systems to manage operations, coordinate cargo, and ensure the traceability of goods. Without regular cybersecurity audits, ports run the risk of their vulnerabilities going undetected until an attack paralyses all activity. Transparency and continuous assessment are key to anticipating threats.

No port can rely on a single IT system. System redundancy—alternative systems that can spring into action if the main systems fail—is vital in preventing collapse. In an environment in which every minute of inactivity means, among other things, millions in losses, delays, and the loss of confidence, being able to react immediately marks the difference between resilience and chaos.

In addition to digital security, physical security is just as necessary. Ports must be secured against intrusions, sabotage, and outside threats through strict access controls, advanced surveillance, and contingency plans. Physical infrastructures are just as vulnerable as their digital counterparts are require comprehensive protection.

The risks to ports transcend borders. An attack on one strategic port can have repercussions in markets across different continents. This is why international cooperation and the creation of shared protocols is so essential. Port security cannot be an isolated undertaking: it requires global coordination, exchange of information, and a joint response.

However, security does not depend solely on systems and protocols: ultimately, people are at its core. Investing in specialised training for port workers and in public awareness-raising campaigns goes a long way towards forging a culture of prevention. Well-prepared personnel know how to detect anomalies, respond quickly, and mitigate the impact of incidents.

As we've said, securing ports is not a luxury but a necessity. The proposals offered here—digital audits, system redundancy, physical security, international cooperation

and training—are not simple recommendations. They are vital elements that guarantee the secure flow of global commerce. Any neglect of this urgency would only ensure fragility in a world that demands resilience.

3 The risks of port concentration and expansion without diversification

Returning to the matter at hand, the concentration of ports around oil, oil derivatives, and natural gas has become a decidedly risky strategy. What may seem like logistical efficiency is really a strategic burden and a multiplier of risks. When too many strategic flows depend on a handful of nodes, any interruption—whether by accident, due to attack, or because of geopolitical crisis—can lead to collapse on a global scale.

Ports specialised in hydrocarbons concentrate massive volumes of crude oil and liquefied natural gas. This concentration turns these facilities into high-value targets. The effects of an incident in one key port go beyond the regional scope, paralysing entire supply chains and causing prices to skyrocket. Efficiency, thus, simply results in fragility.

Such dependence on a reduced number of ports created systemic vulnerability. We're not just talking about physical risks, such as sabotage or natural events, but also hybrid threats that can include cyberattacks capable of crashing management systems, disinformation campaigns that can destabilise markets, or geopolitical pressures t

hat weaponise infrastructures. Port concentration effectively amplifies the risk inherent to any threat.

The emergence of green hydrogen and other new fuels should be treated as an opportunity to diversify logistics nodes. However, the trends seem to indicate a repetition of the same pattern: the concentration of operations in a few specialised ports. This not only serves to lock in these vulnerabilities but also adds additional layers of risk to the most sensitive and strategic of products.

Port concentration of oil and oil derivatives, natural gas, and now green hydrogen is a strategy that, despite its apparent efficiency, is deeply dangerous. Without the diversification of logistics, every port becomes a bottleneck and a perfect target. Securing these infrastructures and expanding the network of energy nodes is not simply an option: it is the only way to keep the heart of global commerce from becoming its Achilles's heel.

The following table illustrates this point:

Dimension of risk	Concentrated ports	Diversified ports
Impact due to interruption	High	Low
Attractiveness to threats	High	Low
Operational redundancy	Limited	High
Production cost	Elevated, concentrated	Elevated, distributed
Systemic resilience	Fragile	Robust

4 Energy ports and the pitfalls of expansion

The construction of new port infrastructures for hydrocarbon commerce stands out as a strategic necessity in a world that still depends—and will continue to depend for many years—on oil and natural gas. However, the road that leads to such expansion is full of obstacles that cast doubt on the viability and, especially, the sustainability of such an enterprise.

Building a port specialised for hydrocarbons is not a minor undertaking. Budgets can well exceed \$10 billion, making each project a high financial risk. Moreover, with an energy transition underway, committing these kinds of resources to fossil fuel infrastructures seems like an investment in an uncertain future.

Port construction projects, especially those related to energy, often face opposition from local communities and environmental organisations. Their construction entails an impact on coastal ecosystems, added emissions, and pollution risks. Social opposition leads to delays and can erode a project's legitimacy, thus influencing political calculations focused more on electoral criteria than energy security.

A port, no less, is not an island and requires land, railway, and energy connections in order to function. As such, the difficulty of integrating these infrastructures in saturated areas or with geographical limitations adds extra complexity and cost. Without an efficient logistical network, a port becomes a giant with leaden feet.

Construction of an energy port can take more than a decade to complete. In a global market where demand and technology changes quickly, these far-off deadlines only add more uncertainty to projects. Something that seems indispensable today could be obsolete tomorrow. Hydrocarbon ports are also subject to geopolitical tensions and energy market volatility. Changes in government, international crises, and a sharp drop oil prices can turn a multimillion-dollar project into a financial black hole. Any lack of political or economic stability is as big an obstacle as the cement that supports a port's infrastructures.

Thus, the expansion of ports specifically designed for hydrocarbons faces a dilemma: is it worth the billions invested in infrastructures that soon could be made obsolete by the transition to clean energy? All the financial, social, logistical, political, and other obstacles are not simple technical barriers to overcome: they are warnings that the model of concentration around fossil fuels, which some believe is past its time, in truth still has many years ahead. Port expansion may indeed be a good option. Nevertheless, some believe it is better to batten down the hatches now than to risk the future on colossal investments. We trust that it will never happen, but if one day one of these ports is blown sky-high—and heaven forbid it should occur—we will have to decide how to divide the blame.

5 A little-known reality

5.1 The strategic function of energy ports

Energy ports are more than simple energy nodes where multiple systems converge: maritime transport, storage, processing, distribution, and digital monitoring. Their function is not limited to the loading and unloading of energy products, as they also include:

- Temporary storage in high-capacity tanks.
- Interconnections with refineries and regasification plants
- Land distribution via pipeline and tanker trucks.
- Digital monitoring via SCADA⁴ systems and OT⁵ networks.

The operational efficiency of these ports determines the continuity of energy supply in entire regions. Any paralysis, for any reason, could cause an unprecedented disaster that would surely create a domino effect with consequences beyond energy supply, affecting industries, homes, and essential services. Ultimately, the ensuing erosion of public confidence in the political system could lead to great instability. Then, radicals groups on one end of the spectrum or the other would likely attempt to take advantage of such instability to generate chaos.

6 The world's premier energy ports

Whilst not forgetting to keep the value of brevity in mind, we will now focus our study on the energy ports we consider to be the world's most important due to their capacity, location, and strategic importance:

⁴ SCADA (Supervisory Control and Data Acquisition) is a system that enables: real-time industrial process monitoring; monitoring of devices such as valves, engines, sensors, and PLCs (programmable logic controllers); data collection from multiple locations for dispatch to a central station; visualisation and analysis of process performance for making informed decisions.

⁵ OT (Operational Technology) is hardware and software for managing physical industrial processes such as energy, manufacturing, transport, etc.



6.1 Ras Tanura (Saudi Arabia)

Located on the eastern coast of Saudi Arabia, Ras Tanura is not just a port city but also a key component in the clockwork of global energy. Since its founding in the 1940s as a strategic enclave for oil exportation, Ras Tanura has grown into one of the world's largest and most sophisticated oil ports. Operated primarily by Saudi Aramco, it represents the logistical heart of a nation whose economy revolves around oil.

The Port of Ras Tanura was born as part of an ambitious oil infrastructure project led by Saudi Aramco. It was initially designed to be populated by foreign workers, especially from the United States, in a separate community full of Western-style services. With the passing of time, it has transformed into a crude oil export operations centre with facilities that rival those of any industrial port on the planet.

Ras Tanura handles a significant portion of the oil that Saudi Arabia exports around the world, totalling over 250 million tonnes of crude per year. Being a deepwater port and with the construction of artificial islands, it is capable of receiving the massive VLCC oil tankers⁶. In addition to crude oil, it also handles refined products from the nearby refinery, one of the world's largest.

⁶ Terminals for VLCC (Very Large Crude Carrier) ships—capable of transporting up to 320,000 tonnes of dead weight—require specialised infrastructures due to their size and draught.

Generally, over 20 metres of depth are necessary to accommodate the draught of these ships.

Mooring systems: SBM (Single Buoy Mooring) or CALM (Catenary Anchor Leg Mooring) for safe operations at sea.

Pumping capacity: High speed loading/discharge for large volumes of crude.

Land infrastructure: Pipelines connected to oil fields or refineries.

The port's infrastructure includes:

- Offshore platforms operated by Saudi Aramco and international partners such as Schlumberger and Halliburton.
- A private airport for logistical operations.
- Land connections with industrial centres such as Jubail and Dhahran.
- Industrial automation systems based on SCADA and OT networks.

The oil leaving Ras Tanura goes to supply major economies such as those of China, Japan, South Korea, various countries in Europe, and the United States. Multinational corporations such as Shell, ExxonMobil, and Total have trade agreements with Saudi Aramco, which consolidates the port as a vital node in the global energy system.

Security at Ras Tanura is top priority. In terms of physical security, the port has perimeter fencing, armed guards, biometric access controls, and regular patrols. However, it is in the digital realm where the deployment of an advanced protection architecture is evident.

SCADA systems supervise industrial processes in real time whilst OT networks connect sensors, PLCs, and actuators with control centres. This infrastructure is segmented to prevent any attack on the IT network from affecting the OT network⁷. Other security systems include industrial firewalls, intruder detection systems, artificial intelligence to analyse traffic, and server redundancy to ensure operational continuity.

Despite all the measures taken for maximum security, Ras Tanura is not immune to risks. In March 2021, an attempted drone attack on nearby Saudi Aramco facilities was reported. The attack was intercepted but revealed vulnerabilities by air. Furthermore, the malware programme Shamoon,⁸ which affected Saudi Aramco 2012, illustrated how industrial systems can be the target of sophisticated cyberattacks.

Its main weaknesses include:

- The growing interconnection between IT and OT networks.⁹
- The exposure and concentration of critical infrastructure such as offshore platforms.
- Economic dependence on oil, which turns any interruption into a national threat.

⁸ Shamoon is one of the most destructive malware programmes, known for its ability to completely erase the hard drives of infected systems. Also known as DistTrack, the virus appeared for the first time in 2012 with comebacks in 2016 and 2018

⁹ IT (Information Technology) manage business-related data and digital systems whilst OT networks (Operational Technology) monitors machines, physical processes, and industrial production.

Maintaining operational continuity is vital. Likewise, protecting industrial data, environmental management, and resilience in the face of geopolitical or health crises are essential elements. Ras Tanura must be prepared to respond to contingencies of all kinds, from sabotage to pandemics.

Ras Tanura isn't simply a port: it is a symbol of global energy infrastructure. Its strategic importance requires constant vigilance, investments in security, and technological adaptation in an increasingly interconnected and vulnerable world. It represents the balance between industrial tradition and digital modernisation; between power in logistics and strength in cybersecurity. All this without neglecting classic physical security against any kind of attack, from crude or low-tech assaults to long-range rocket or missile strikes.

Over the last 10 years, Saudi Arabia has suffered several significant attacks on its oil facilities, mostly attributed to the Iranian-backed Houthi rebels in Yemen. These attacks have revealed the vulnerabilities in Saudi energy infrastructures and had global repercussions for oil markets.

The main attacks on Saudi oil facilities:

- May 2019: a drone attack by Houthi rebels on a Saudi Aramco pipeline, forcing a temporary halt in oil pumping.
- September 2019: the Abqaiq–Khurais attack, the most serious in recent history, in which drones and missiles struck the Abqaiq refinery and the Khurais oil fields, causing production in Saudi Arabia to drop to 5.7 millions of barrels per day, nearly half its capacity.
- January 2020: a 10-drone Houthi operation attack the Shaybah oil field in the Eastern Province, affecting one of the country's most important oil reserves.
- March 2021: Houthi rebels attacked Saudi Aramco's facilities in Ras Tanura.
- March 2022: drones and missiles caused a fire at a Saudi Aramco storage plant in Jeddah, close to the Formula 1 track and shortly before the Saudi Arabian Grand Prix.

6.2 Sabine Pass (United States)

Sabine Pass is the port that has spearheaded the natural gas revolution in the United States. On the US Gulf Coast on the border between Texas and Louisiana, this port terminal has redefined the role of the United States in the global energy market. As opposed to traditional ports focused on crude oil, Sabine Pass is specialised in exporting liquefied natural gas (LNG), giving it a key position in the global energy transition. Operated by Cheniere Energy, today it is the United States' number one LNG export terminal. Boasting capacity in excess of 30 million tonnes per year, it has become a key port for supply to, among other destinations, Europe following the

Russian gas crisis.

Sabine Pass's modern history begins in 2016, when Cheniere Energy opened the first LNG export terminal in the US. This marked the start of Sabine Pass's radical transformation from a Gulf Coast backwater to the leading LNG production site in the country and one of the most important worldwide.

The terminal was designed to scale rapidly, with multiple phases of expansion that have allowed it to increase production capacity and adapt to growing international demand.

Sabine Pass is home to highly specialised infrastructure:

- Six operational liquefaction trains, capable of producing more than 30 million tonnes of LNG per year.
- Sea docks designed for large gas tankers.
- Thousands of industrial valves, including cryogenic and rapid isolation systems such as HIPPS.
- Connected by land to gas distribution networks in the US, facilitating transport from gas fields to the terminal

These infrastructures ensure the efficiency of LNG exports whilst guaranteeing high standards of safety and sustainability in operations.

Sabine Pass exports LNG to over 30 countries consolidating the position of the United States as a "theoretically" reliable supplier in uncertain times for energy. The US has reached this role due in part to the Russian gas crisis stemming from the invasion of Ukraine and the subsequent energy sanctions imposed on Russia, in addition to the sabotage of the pipelines Nord Stream 1 and 2.

The main destinations of exports include:

- Europe, especially following the energy crisis of 2022, where LNG from the US has proved essential in reducing dependence on Russian gas despite its much higher price.
- Asia, with Japan, South Korea, and China leading demand.
- South America and the Middle East, emerging markets transitioning to cleaner energy sources.

Security at Sabine Pass is divided into two complementary levels, physical security and digital security:

- Biometric access controls for personnel.
- Perimeter surveillance with sensors, thermal cameras, and armed patrols.

- Emergency protocols in the event of leaks, fires, or sabotage.
- SCADA systems for real-time monitoring of industrial processes.
- Segmented OT networks, which prevent the spread of cyberattacks from IT networks.
- Industrial firewalls, intrusion detection systems (IDS) and artificial intelligence algorithms for traffic analysis.
- Collaboration with technology companies such as Bechtel and AMPO to ensure operational integrity.

Despite its sophistication, Sabine Pass is not exempt from threats and so must face risks and vulnerabilities:

- Cyberattacks targeting SCADA systems, especially in moments of geopolitical tension.
- Dependence on cryogenic infrastructure, which requires constant and specialised maintenance.
- Exposure to extreme weather events, such as hurricanes affecting the Gulf Coast.

To date, no serious attacks have been reported, but the terminal has undergone intensive audits by the Federal Energy Regulatory Commission (FERC), resulting in continuous improvements to its security protocols.

Sabine Pass operates under the logic of resilience and efficiency. Its priorities include:

- Operational continuity, even in crisis scenarios.
- Industrial data protection, key in preventing digital sabotage.
- Environmental management, with strict controls to prevent emissions and spills.
- Technological adaptability, to integrate new solutions without compromising safety.

Sabine Pass is much more than a port terminal: it is the symbol of the new era of US energy. Its global LNG export capacity, the cutting-edge infrastructure, and focus on security make it a benchmark for 21st century energy ports. In a world in search of alternatives to oil, Sabine Pass stands out as the port of the future where innovation, sustainability, and strategy converge.

6.3 Rotterdam (Netherlands)

The Port of Rotterdam, in the Netherlands, holds not only the title of largest port in Europe in terms of total cargo volume, but also positions itself as one of the most advanced logistics nodes in the world in the handling of crude oil, natural gas, and hydrocarbon products. In fact, it is the largest energy port in Europe, with more than 300 million tonnes of energy cargo passing through terminals for crude oil, LNG, derivatives, and petrochemical terminals. Its specialised infrastructure, intermodal connectivity, and its strategic role in European energy security make it a key component of the continent's economy.

The Port of Rotterdam, one of the largest and most advanced in the world, has witnessed a radical transformation thanks to the Maasvlakte I and II expansion. These extensions have not only increased the port's operational capacity but have also marked a turning point in port automation, positioning Rotterdam as a global benchmark in smart and sustainable logistics.

Opened in 1973, Maasvlakte I was the port's first major expansion into the North Sea. This engineering work made it possible to receive ships of greater draught and improve the port infrastructure. Although it did not incorporate advanced automation, it laid the groundwork for the technological development that would come decades later.



Operational since 2015, Maasvlakte II represents the pinnacle of port innovation. This expansion was designed from the ground up to integrate automation, energy efficiency, and environmental sustainability technologies.

Rotterdam manages about 100 million tonnes of crude oil per year, although in 2024 there was a slight drop of 4.5% due to scheduled maintenance at several

refineries. The port has unloading and storage terminals directly connected to refineries such as Shell Pernis, one of the largest in Europe. In addition, it has cross-border pipelines linking Germany and Belgium, facilitating distribution of crude oil imports by land. The port extends over 42 kilometres, where we can find five refineries, more than 30 crude oil storage tanks, dozens of terminals for petrol, diesel, fuel oil, kerosene, etc., LNG terminals with a capacity of 12 million cubic metres. Furthermore, expansion has begun with green and blue hydrogen terminal projects, which would turn Amsterdam into a hydrogen hub.

The Port of Rotterdam is connected to a vast energy transport network that makes it a strategic hub for Europe through:

- The Rotterdam–Rhineland pipeline: transporting crude oil from the port to refineries in Germany, especially in the Ruhr region.
- The Transalpine Pipeline (TAL): although it does not start directly from Rotterdam, it is connected to the European network that distributes refined products to Austria and Italy.
- Refined product terminals: from Botlek and Europoort, petrol, diesel, and kerosene are distributed by road, rail, and ship.
- Gas pipeline network: connected to the Netherlands' Gasunie network, which distributes gas throughout Western Europe.
- H2Import project: slated to receive green hydrogen from countries such as Spain, Morocco, and Chile.
- The HyTransPort project: a hydrogen pipeline that will connect the port with industrial parts of the country.
- LOHC and ammonia: terminals are being developed to import hydrogen in liquid organic form or ammonia, facilitating its safe transport.
- Rail: the port has direct links with Germany, Switzerland, and Eastern Europe, allowing the transport of energy products by train.
- River transport: more than 91,000 river vessels a year transport energy products along the Rhine and other rivers.

In short, the Port of Rotterdam stores, processes, and distributes energy across the continent through an integrated network of pipelines, railways, and river routes.

Thanks to its deepwater docks, the port can receive VLCC supertankers, making it a key entry point for oil from the Middle East, Africa, and the Americas.

The Port of Rotterdam is also noted for its ability to manage a wide range of derived products, such as fuel oil, kerosene, petrol, diesel, lubricants, and petrochemicals. In 2024, the volume of these products increased by 0.8%, driven by the fuel oil trade

and the growing demand for kerosene in the aeronautical sector.

The port is home to petrochemical clusters that transform raw materials into industrial products such as plastics, fertilisers, and solvents. The terminals are equipped with specialised pumping, cooling and chemical safety systems, adapted to the characteristics of each type of load.

Although the volume of liquefied natural gas (LNG) decreased by 5.3% in 2024, we will have to wait for official 2025 figures to see a rebound in volume proportional to the increase in US LNG purchases which followed the arrival of President Trump and his tariff policy.

Rotterdam remains a key player in the reception and distribution of LNG. Its terminals are connected to European distribution networks, facilitating supply to northern and central European countries.

Following the 2022 energy crisis and the reduction in Russian gas imports, the port has played an essential role in Europe's energy diversification. Its facilities include cryogenic tanks, regasification systems, and cargo platforms for methane tankers.

Hydrocarbon management in Rotterdam is supported by an advanced safety architecture. The port employs SCADA systems and OT networks to monitor industrial processes in real time, and has implemented specific cybersecurity protocols for hazardous product terminals.

At the environmental level, Rotterdam promotes the reduction of emissions through the use of biofuels, the electrification of docks, and carbon capture projects. These initiatives are part of its strategy to become a climate-neutral port in the coming decades.

Despite its sophistication, the Port of Rotterdam faces significant challenges:

- Geopolitical volatility can affect the stability of energy supply.
- Critical infrastructures are exposed to cyber and physical risks.
- The energy transition will require adapting traditional terminals to new fuels such as green hydrogen.
- An alarming concentration of capabilities.

The Port of Rotterdam is not just a maritime transit point: it is a strategic hub for fossil energy in Europe, with advanced capabilities to handle oil, gas, and hydrocarbon derivatives. Its role in energy security, specialised infrastructure, and commitment to sustainability make it a global benchmark in energy logistics.

But there is another reality: we could call the Port of Rotterdam the largest time bomb in Europe, alarmingly exposed to attempted physical attack by drones, dirty bombs, or other means. The port is notorious for its high degree of permeability to illicit traffic all kinds. In fact, it is considered the main gateway for illicit drugs into Europe—especially cocaine—which should be cause enough for great alarm. Both Europol and the Dutch police have warned that criminal networks use the same channels to smuggle other illicit goods into Europe. Perhaps it is necessary to remember how, throughout 2025, the appearance of unidentified drones at different European airports demonstrated the serious security deficiencies of these facilities. Far from being excluded, the Port of Rotterdam must be placed at the top of this list.

At the end of 2025, the Dutch government's National Coordinator for Counterterrorism and Security (NCTV) had established the country's official terrorist threat level as 4 out of 5, meaning that the authorities believed there to be a realistic threat of a terror attack occurring anywhere in the Netherlands.

6.4 Singapore

In the heart of Southeast Asia, where the busiest shipping routes on the planet converge, we have the Port of Singapore: the world's largest marine fuel supply port. It's also a world leader in terms of efficiency and cargo volume and, as a global hub for transshipment and bunkering,¹⁰ plays a strategic role in the global trade of oil, natural gas, and hydrocarbon products. Its privileged location, cutting-edge technology, and sustainable approach to operations make it a world leader in energy logistics, with a floating LNG terminal and future hydrogen infrastructure.

Singapore is one of the world's leading bunkering hubs, supplying fuel to thousands of vessels every month. The port manages more than four million tons of conventional fuels per month and its terminals are designed to receive, store, and distribute crude oil efficiently and safely. Its capabilities allow it to function as a regional redistribution hub, supplying neighbouring countries and facilitating intercontinental trade.

It manages a wide range of refined products such as fuel oil, diesel, kerosene, lubricants, and petrochemicals, essential for the maritime and manufacturing industry in Southeast Asia.

It houses refining and processing facilities that for transforming raw materials into high value-added industrial products.

Although Singapore is not a large producer of natural gas, its port acts as a regional LNG distribution hub. Its terminals are designed to:

- Receive methane tankers with cryogenic loads.

¹⁰ Bunkering is the process of supplying fuel to ships. Bunkering is an essential part of maritime transport operations, making it possible for ships to refuel as needed during their routes.

- Store the gas in refrigerated tanks.
- Regasify and redistribute the product to Southeast Asian markets.
- It actively participates in LNG futures trading, consolidating its role as a financial and logistics hub for gas in Asia.

Hydrocarbon management in Singapore is supported by world-class technological architecture:

- SCADA systems and OT networks for real-time monitoring of industrial processes.
- Automated cranes and autonomous vehicles to minimise risk to humans.
- Cybersecurity protocols including blockchain, artificial intelligence, and network segmentation.

Singapore is much more than a point of loading and unloading: it is a global energy hub where technology, strategy and sustainability converge. Its capacity for handling oil, gas, and hydrocarbon derivatives accurately and safely makes it, according to many experts, a model of port efficiency in the 21st century.

There are three major threats facing the ports: logistical congestion, piracy in the Singapore Strait, and regional geopolitical tensions.

The issue of logistical congestion concerns the sheer number of ships that accumulate in the area due to its strategic location. External factors, such as the crisis in the Red Sea and the increase in global demand for goods, exacerbate the problem.

As regards piracy and maritime crime, the number of attacks in the Singapore Strait shot up from seven to 27 in one year, an increase of 285%. Although many are small-scale attacks, firearms were used in 14 incidents. All of these incidents put both crews and goods at risk.

In terms of geopolitical tensions, the Straits of Malacca and Singapore are critical chokepoints for global trade and energy transportation. Regional conflicts and rivalries between powers in Asia and the Middle East can affect the free movement of goods.

There is also the matter of organised crime and cyberattacks. Modern ports, including Singapore, are targets of smuggling, organised crime and cyberattacks seeking to exploit their critical role in global trade. The technological interconnection makes the port a target for attacks that could paralyse operations or manipulate logistical data.

6.5 Ningbo-Zhoushan (China)

On the east coast of China, in the province of Zhejiang, stands the Port of Ningbo-

Zhoushan, a colossal maritime infrastructure that has risen to become one of the busiest ports on the planet. Beyond its leadership in total cargo volume in the world, the port plays a strategic role in the handling of crude oil, natural gas, and hydrocarbon products, consolidating its importance in national energy security and in global trade.

The Port of Ningbo-Zhoushan handles tens of millions of tons of crude oil each year, thanks to its specialised liquid bulk terminals. These facilities are designed to receive supertankers and facilitate the storage and distribution of crude oil to refineries and industries in China's interior.

Some of its assets include:

- Deepwater docks with capacity for VLCC vessels.
- Automated tanks with pressure, temperature, and safety control systems.
- Pipelines interconnected with regional refineries and key industrial zones.

Its strategic location in the Yangtze Delta allows for seamless connectivity with the country's main logistics corridors.

In addition to crude oil, Ningbo-Zhoushan manages a wide range of refined products such as fuel oil, petrol, diesel, lubricants, and petrochemicals. The terminals are equipped with pumping and automated mixing technology, as well as chemical safety systems for hazardous loads.

The port is also home to industrial clusters dedicated to the transformation of hydrocarbons into high value-added products, such as plastics, fertilisers, and solvents. Its intermodal infrastructure—which includes railways, motorways, and waterways—allows for efficient distribution both nationally and internationally.

Although China has other hubs more specialised in LNG, Ningbo-Zhoushan also deals with liquefied natural gas, strengthening its role as an energy logistics hub. Its LNG terminals include:

- Cryogenic tanks for safe storage.
- Regasification plants for redistribution to the interior of the country.
- Connections with energy distribution grids, which strengthen national energy security.

Hydrocarbons commerce at Ningbo-Zhoushan is backed by an advanced technological architecture:

- SCADA systems and OT networks for real-time monitoring of industrial processes.
- Cybersecurity protocols to protect critical infrastructures against digital

threats.

- Environmental measures to reduce emissions, prevent spills and protect coastal ecosystems.

The port also participates in initiatives related to the New Silk Road, reinforcing its role as a strategic node in China's trade and energy expansion.

Despite its scale and sophistication, the Port of Ningbo-Zhoushan also faces significant challenges:

- Cybersecurity risks, derived from its high degree of automation.
- Logistical congestion, especially in high-demand seasons.
- Exposure to geopolitical tensions, which can affect energy trade and maritime routes.

The Port of Ningbo-Zhoushan is not just a maritime transit point—it is a global energy hub, where operational efficiency, advanced technology, and geopolitical strategy converge. Its capacity for handling oil, gas, and hydrocarbon derivatives makes it a linchpin of China's energy security.

But security risks in Ningbo-Zhoushan are high, due to the size of the port and the presence of hazardous materials in its daily operation. Recent incidents show that even a single accident can have global repercussions on logistics, the economy, and the environment. In August 2024, a powerful explosion on the vessel YM Mobility, a container ship docked in the port, generated a huge fireball and forced the evacuation of the crew and the temporary closure of several terminals that affected international supply chains. The ship was carrying hazardous materials, which magnified the risk of fire and contamination.

7 Spain as a maritime energy hub

Spain is, at times, one of Europe's primary energy logistics nodes due to its port network specialising in the loading, unloading, and storage of crude oil, refined products, and liquefied natural gas (LNG). With more than 200 million tonnes of energy goods per year moved through Spanish ports and a storage capacity of more than eight million cubic metres, Spain attempts to maintain a strategy role in the continent's energy supply.



7.1 Port of Algeciras (Cádiz)

The Port of Algeciras is an important logistics enclave for the Mediterranean and Europe. With an annual volume of more than 100 million tonnes, specialised in crude oil, refined products and bunkering operations, it has established itself as a first-rate energy and commercial node. Its infrastructure includes modern hydrocarbon terminals, pipeline connections, and rail network, as well as advanced security systems such as leak and fire detection, perimeter surveillance, and Seveso III protocols for hazardous substances.

7.2 Port of Cartagena, Murcia

The Port of Cartagena has established itself as an important energy enclave in Spain. With an annual volume of nearly 30 million tonnes, its activity focuses on the traffic of crude oil, refined products, and liquefied natural gas (LNG). LNG storage capacity reaches 600,000 m³, making it a key node for Spanish and European energy security.

Its infrastructure is directly connected to the nearby Repsol refinery and it has an active regasification plant, bolstering its strategic role in the hydrocarbon and gas supply chain. In terms of safety and security, the port is equipped with anti-pollution containment barriers, automatic extinguishing systems, and is subject to regular industrial cybersecurity audits.

However, its importance makes it an attractive target for terrorist threats and cyberattacks, which are currently the primary risks faced. The concentration of energy operations in Cartagena makes it a potential target for terrorist groups. The hydrocarbon terminals and its regasification plant are facilities whose interruption

would have an immediate impact on the energy supply.

7.3 Port of Bilbao (Basque Country)

The Port of Bilbao, located in the Basque Country, handles an annual volume of over 25 million tonnes. Its activity focuses on the traffic of crude oil, derivatives, and liquefied natural gas (LNG). Additionally, its LNG storage capacity reaches 300,000 m³, making it a strategic node in national energy security.

The port's infrastructure includes a direct connection to the Petronor refinery as well as a regasification plant, consolidating its importance in the hydrocarbon and gas supply chain. In terms of safety and security, the Port of Bilbao has continuous environmental control systems, a network of thermal sensors, and regular emergency drills, demonstrating a commitment to prevention and resilience.

7.4 Port of Huelva (Andalusia)

The Port of Huelva is an energy enclave in southern Spain. With an annual volume of more than 30 million tonnes, its activity focuses on the traffic of crude oil, refined products, and liquefied natural gas (LNG). Its the LNG storage capacity is up to 600,000 m³, consolidating its role as a strategic node in Spanish and European energy security.

The port's infrastructure is extensive and complex, with nine docks, 13 mooring points and over 110 kilometres of pipes connected to pipelines, which guarantees an uninterrupted flow of hydrocarbons and gas into the interior of the peninsula.

7.5 Port of Barcelona (Catalonia)

The Port of Barcelona is an energy and logistics hub in Spain. Its activity is focused on the traffic of liquefied natural gas (LNG) and refined products, with an LNG storage capacity of 760,000 m³, the largest in the country. This infrastructure makes it a key point for national and European energy security.

Its high-capacity regasification plant and multipurpose terminals reinforce its strategic role in the supply chain. In terms of security, the port has redundant control systems, continuous environmental monitoring and integrated contingency plans, demonstrating a commitment to prevention and resilience.

7.6 Port of Sagunto (Valencia)

The Port of Sagunto is an important energy hub on the Spanish Mediterranean coast. Its activity focuses on the traffic of liquefied natural gas (LNG), with a storage capacity of 600,000 m³, making it a critical point for national energy security.

The port's infrastructure includes a modern regasification plant and direct

connection to the national gas pipeline network, guaranteeing the continuous supply of gas to the interior of the peninsula.

7.7 Port of Ferrol (Galicia)

The Port of Ferrol is an energy enclave specialised in the traffic of liquefied natural gas (LNG). With a storage capacity of 150,000 m³,* its smaller-scale regasification plant and its specialised terminals make it an important point within Spain's energy network, although with less volume than other major ports. This is perhaps due to its difficult-to-access location in the Ferrol estuary, despite the infrastructure being designed for safe and efficient operations.

7.8 Puerto de Gijón (Asturia)

The Port of Gijón has reclaimed its role in the Spanish energy sector with the reactivation of its regasification plant. Its activity focuses on the traffic of liquefied natural gas (LNG), with a storage capacity of 300,000 m³ that makes it important node for gas distribution in northern Spain. The port's infrastructure includes direct connection to the northern distribution network, ensuring energy supply to the region and reinforcing its strategic importance.

8 Threats, strengths and weaknesses

This strategic relevance of Spanish ports in terms of hydrocarbons and their derivatives generally makes them highly attractive targets for terrorist threats and cyberattacks, which represent the most critical risks faced today. The concentration of energy traffic and the presence of critical facilities make all these ports a potential target for terrorist groups.

Any attack on a port's critical infrastructures, the explosions caused, sabotage on loading/unloading operations, coordinated attacks against ships in bunkering operations or hydrocarbon terminals, oil pipelines, gas pipelines, etc., with the resulting interruption of operations, would have an immediate impact on energy supply.

In many cases, a port's strategic location—whether close to the Strait of Gibraltar or very close to large populations—makes it a sensitive point in international conflicts and regional tensions. The impact of an attack would be disastrous, from the interruption of energy flows and economic losses in the millions to the weakening of international confidence in the port as a safe node—in addition to the risk involved for the local population, though perhaps not receiving sufficient consideration.

Strengths would include implementing Seveso III protocols¹¹ at times or SCADA

¹¹ The Seveso III Directive (officially Directive 2012/18/EU) is the European regulation that regulates the

systems, advanced detection systems and perimeter surveillance. These ports can also boast physical security systems and industrial cybersecurity audits.

Its weaknesses include critical dependence on digital systems for operational management. The digitisation of port operations, computerised logistics management, and remote control of a large part of operations opens the door to cybersecurity risks. Attacks on control systems that manage plants and terminals can manipulate them and alter critical processes. Leak sensors can be altered and automated cranes can be paralysed. There is the risk of the use of ransomware, which would lock authorities and operators out of port management systems and demand ransoms, thereby affecting operational continuity. Hybrid threats must also be considered, blending physical and digital attacks to maximise impact. And let us not forget the high concentration of energy traffic in a single node. Sometimes, a direct connection to refineries and regasification plants poses a risk. There are also simple physical attacks, using any of the procedures that terrorists currently employ.

Conclusions

As we have already discussed, global energy dependence on hydrocarbons makes up a significant percentage. Ensuring the production, transport, and distribution of these hydrocarbons is of the utmost importance if we wish to avoid serious energy and economic crises. This chapter has attempted to shed light on what we could call the ugly duckling of the story: ports for loading and unloading of hydrocarbons, which are yet another link in a fragile chain that must be safeguarded in its entirety.

The global energy port network is truly a vital part of global trade and energy. It must not only guarantee national supply but also buttress energy security across the globe. Thus, port security is paramount.

The importance of energy ports makes them a priority target for physical terrorism threats and cyberattacks. Port resilience will depend on their ability to fortify physical and digital security, diversify critical infrastructure, and establish international partnerships that ensure rapid and coordinated incident response.

In some cases, their proximity to major centres of population makes them doubly interesting targets for terrorism. The consequences of physical attacks can be devastating, not just in terms of energy but also with regard to human casualties.

Greater awareness must be raised among the relevant authorities regarding this vulnerability. The logistical advantages of large concentrations of energy installations

prevention and control of major-accident hazards involving dangerous substances, named after the 1976 chemical accident in Seveso, Italy. It aims to reduce the likelihood of explosions, fires, or toxic leaks and minimise their consequences on human health, the environment, and property. The directive classifies establishments into two tiers according to the amount of hazardous substances present, imposing obligations such as notification to the authorities, preparation of safety reports, internal and external emergency plans, and information to the population about risks and preventive measures. In Spain, it is implemented through Royal Decree 840/2015, which adapts these regulations to Spain's national legal framework and obliges chemical industries to maintain high standards of safety and transparency.

in ports is a double-edged sword, which begs consideration as this concentration increases.

Maintaining the current structure of mega-ports, done mainly for economic reasons, means assuming a very high risk that can take an incalculable toll on human lives and capital.

Generally speaking, the focal points of maritime routes, which are given so much importance, usually have alternatives. Whilst it is true that these alternatives are usually longer and therefore make products more expensive, they nevertheless exist as alternative. The same, however, cannot be said for many loading and unloading ports.

The war in Ukraine has shown us how drones have become a lethal, low-cost threat that is very difficult to counter at present. Moreover, the problem also exists beyond Ukraine, if we consider the problems caused by the mere presence of rogue drones near European air traffic. The use of these same drones, but armed, against port energy facilities is a real threat for which we must be prepared.

Joe Calnan

Abstract

Canada is a major energy producer and exporter, yet its role in the global energy system is often understated. This paper examines Canada's position in the global geopolitics of energy. In doing so, it considers the geographical and geological determinants of Canada's international energy trade and energy dependencies, alongside the country's constitutional structure, Indigenous rights, climate policy, and security partnerships. The paper finds that the obscurity of Canada's role in global energy systems stems from its close energy interdependence with the United States. Canadian energy geopolitics is therefore defined by tensions between economic gravity and political autonomy, infrastructure constraints and export diversification, and economic security and social license. These findings illuminate the formidable barriers facing Canada's current efforts to diversify its energy trade.

Keywords

United States, dependence, diversification, sovereignty, environment.

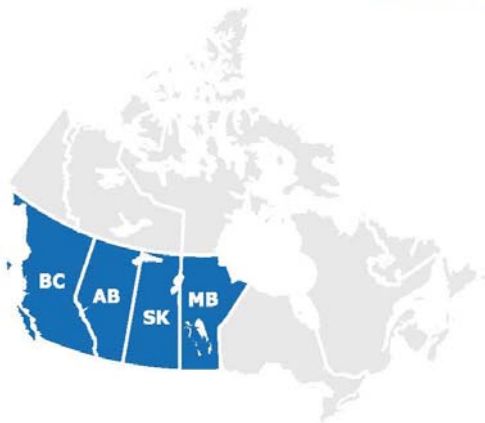
¹ Chapter originally written by its author in English

CANADA'S INTERNATIONAL CONTEXT AS AN 'ENERGY SUPERPOWER'

CANADA'S IMPORTANT MEMBERSHIPS



CANADA'S TWO HALVES



WESTERN CANADA NET ENERGY EXPORTER:

BC - BRITISH COLUMBIA AB - ALBERTA
SK - SASKATCHEWAN MB - MANITOBA

2024 PRIMARY ENERGY PRODUCTION (PJ)	2024 SECONDARY ENERGY CONSUMPTION (PJ)
22,608.6	3,996.0

EASTERN CANADA NET ENERGY IMPORTER:

ON - ONTARIO NB - NEW BRUNSWICK
QC - QUEBEC NS - NOVA SCOTIA
NL - NEWFOUNDLAND AND LABRADOR PEI - PRINCE EDWARD ISLAND

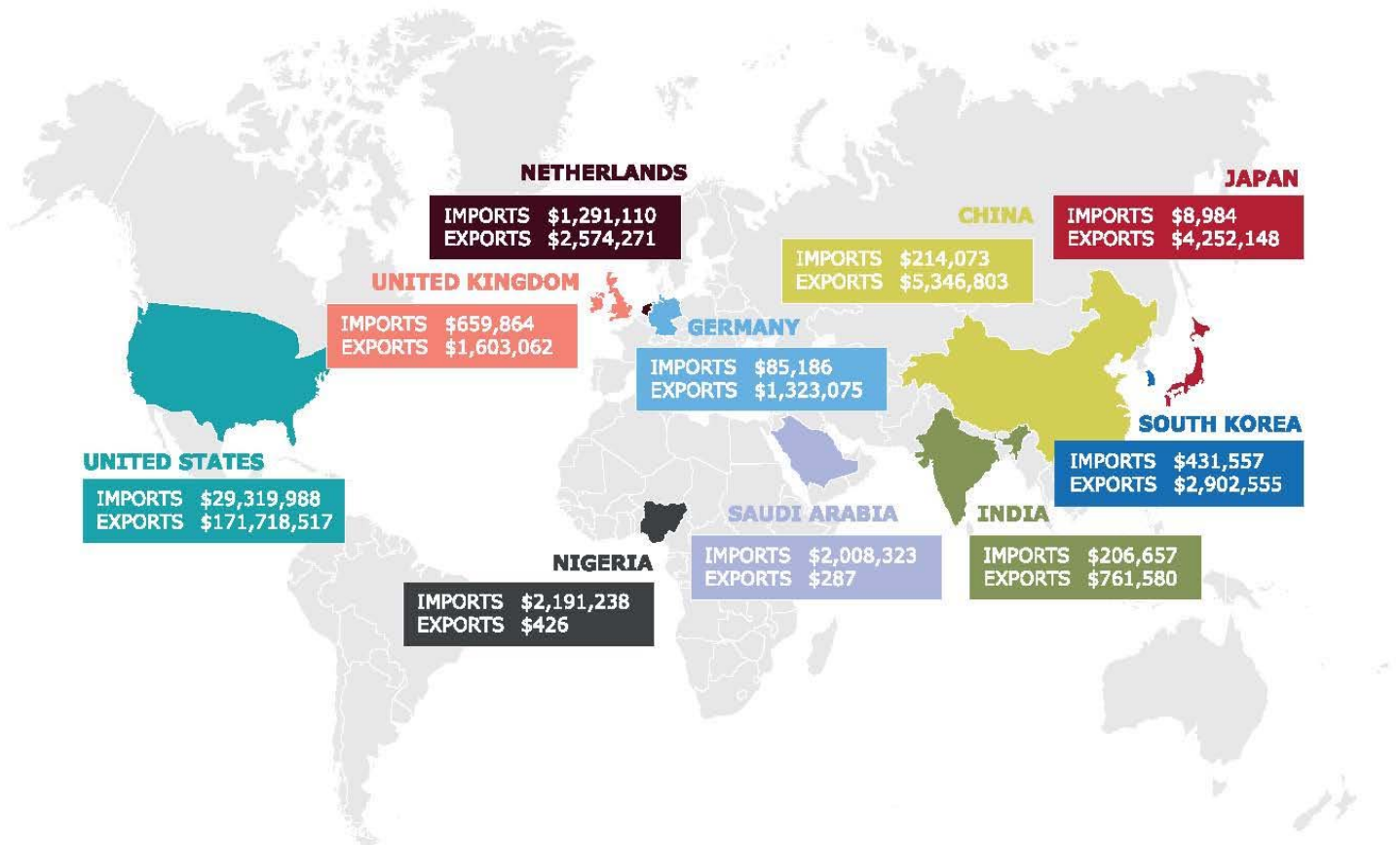
2024 PRIMARY ENERGY PRODUCTION (PJ)	2024 SECONDARY ENERGY CONSUMPTION (PJ)
1,987.7	4,345.3





Fuente: Statistics Canada. Table 25-10-0029-01. Supply and demand of primary and secondary energy in terajoules, annual. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510002901>

CANADA'S MAIN BILATERAL ENERGY TRADE PARTNERS

2024 CANADIAN ENERGY IMPORTS (\$'000 CAD) /EXPORTS (CAD \$BILLION)



CANADA AS A KEY PLAYER IN THE ARCTIC

 <p>STRATEGIC INFRASTRUCTURE ARCTIC INFRASTRUCTURE FUND - "DUAL USE" INFRASTRUCTURE FUNDING</p>	 <p>ENERGY SECURITY POTENTIAL FOR ARCTIC MAJOR PROJECTS TO HELP SUPPORT PERMANENT MILITARY PRESENCE VIA ENERGY INFRASTRUCTURE DEVELOPMENT</p>	 <p>POLAR FLEET ARCTIC FOCUS OF NAVAL DESIGN - POLAR ICEBREAKERS, ICE PACT, SUBMARINES, AND GREATER PRESENCE IN ARCTIC SHIPPING ROUTES FOR CANADIAN AND GLOBAL TRADE</p>	 <p>EARLY WARNING ARCTIC OVER-THE-HORIZON RADAR COMPONENT OF NORAD MODERNIZATION</p>
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Fuente: Statistics Canada. Table 12-10-0171-01. Canadian international merchandise trade by country and by product section, customs-based, annual (x1,000). <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1210017101>

Introduction

Canada's energy development has been shaped by geography, geology, and the country's asymmetric relationship with the United States. Proximity to the world's second-largest energy market has pulled Canadian oil and gas southward, despite anxieties about overdependence on a larger and more powerful neighbor. This energy dependence results in a dual vulnerability on energy supply and energy demand with a single trade partner. Canadian energy geopolitics is therefore defined by tension between economic gravity and political autonomy, infrastructure constraints and export diversification, and between economic security and social license.

This paper attempts to answer an important question: what is Canada's position in the global geopolitics of energy?

Geopolitics can be defined as the study of foreign relations and international policy through the lens of geography, economics, and demographics. Energy geopolitics therefore can be considered as the geographical and geological determinants of a country's international energy trade and energy dependencies. These factors are central to understanding Canada's position in the world. However, understanding Canadian energy geopolitics also requires consideration of Canada's constitutional structure, Indigenous rights, climate policy, and security partnerships. At the core of this question is Canada's unusually close economic and security integration with the United States, and how geography, economics, and demographics overdetermined the integration of their energy systems.

To engage with this question, this paper first situates Canada within the global energy system. It reviews Canadian energy production and consumption, highlighting the paradox of a country that is simultaneously a major energy exporter and dependent on imports. It then examines Canada's principal energy trade relationships, emphasizing the outsize role of the United States for exports and supply security. This section also considers how geography and geology have determined the regional concentration of Canadian energy resources and constrained the development of East-West energy infrastructure.

This paper then turns to Canada's domestic energy endowment and infrastructure. It traces the historical development of pipelines, ports, and electricity interties, showing how these assets have entrenched Canada's economic integration with the United States. It then examines the growing political, legal, and social barriers to building new energy infrastructure, including protections for Indigenous rights, Federal-Provincial jurisdictional disputes, and evolving public attitudes toward climate change.

Finally, this paper examines Canada's international position and prospects for diversification. Canada is a trans-Atlantic Western country embedded in post-war security and economic institutions with limited influence within those frameworks. This paper then explores potential avenues for energy diversification: eastward toward Europe, westward toward the Indo-Pacific, and northward into the Arctic. While each pathway faces significant obstacles, the Indo-Pacific emerges as the most credible medium-term option for diversification.

The paper concludes by assessing the Carney government's renewed ambition to position Canada as an "energy superpower." It evaluates whether accelerated energy infrastructure permitting can realistically enhance Canada's geopolitical autonomy, or whether structural dependence on the United States will continue to define Canada's energy future.

1 Framing Canada's Energy Geopolitics

Canada's position in the global geopolitics of energy can be understood as a balance among four forces:

1. The economic gravity of the United States, which draws Canadian energy into its orbit;
2. Persistent anxiety about the economic, social, and environmental impacts of new energy infrastructure;
3. Recurring political pressures to diversify export markets and reduce vulnerability;
4. Occasional security of energy supply concerns arising from overdependence on a single energy partner.

Historically, the gravitational pull of the U.S. market has dominated. Efforts to diversify trade and build alternative infrastructure have repeatedly failed in the face of geography, cost, political opposition, and regulatory complexity. As concerns about climate change and social impacts have intensified, the difficulty and expense of building major energy infrastructure have increased further, reinforcing Canada's reliance on existing North-South systems.

Whether the current period of political tension with the United States will be sufficient to overcome this inertia remains an open question.

2 Canada's Geography, Resources, and the Structure of Energy Dependence

Canadian leaders sometimes describe Canada as an energy superpower. By most production metrics, this description is justified. Canada produces more than twice the energy it consumes, placing it among the world's largest energy exporters. Yet this national surplus masks significant regional imbalances. Canada's energy system is deeply integrated with the larger American market, and in several regions, most notably Eastern Canada, security of supply depends heavily on imports.

Canada's geography is both its greatest strategic asset and its most enduring constraint. With a landmass of 8.8 million square kilometres (twice the European Union) Canada possesses extraordinary natural wealth, estimated by Statistics Canada at CAD\$1.36 trillion, of which energy resources account for approximately \$833 billion (Statistics Canada [StatsCan], 2025a). Oil, natural gas, hydroelectricity, and uranium underpin Canada's economic strength and international relevance. Yet the

geographical distribution of these resources, combined with formidable physical barriers, has profoundly shaped how Canada produces, consumes, and trades energy, reinforcing dependence on the United States while complicating domestic integration and export diversification.

Canada's oil and gas resources are concentrated in three regions: the Western Canadian Sedimentary Basin (WCSB), offshore Newfoundland and Labrador, and the Arctic. Of these, the WCSB, stretching from northeast British Columbia through Alberta, Saskatchewan, and into southwest Manitoba dominates production. Following the Leduc No. 1 discovery in 1947, pipelines rapidly spread east, south, and west in the 1950s to connect Western supply to Canadian and U.S. markets. The oil sands, known for decades but commercially developed beginning in 1967, experienced explosive growth between 2000 and 2020. While technologically impressive, offshore production in the Atlantic remains modest by comparison, and supplies primarily U.S. East Coast and European markets. Arctic oil and gas resources remain underdeveloped, constrained by high costs and lack of local social license.

Canada's electricity system reflects similar geographic concentration. Hydropower supplies more than 60 per cent of national electricity generation, making Canada the world's third-largest hydro producer (Natural Resources Canada [NRCan], 2024a; Energy Institute 2025). 90 per cent of that capacity is in Quebec, British Columbia, Manitoba, and Newfoundland and Labrador, clustered along a handful of major river systems. Provinces lacking comparable hydro resources such as Ontario, Alberta, Saskatchewan, and the remaining Atlantic provinces rely on nuclear and fossil fuel generation. Wind and solar play a growing but still secondary role, with adoption highly dependent on local weather conditions. Together, these patterns reinforce regional fragmentation rather than national energy integration.

Physical geography constrains Canada's linear energy infrastructure. The Canadian Shield, an immense expanse of exposed bedrock, effectively divides eastern Canada from western Canada along the Manitoba-Ontario border, making pipelines and transmission lines prohibitively expensive to build across it. As a result, Canada lacks a direct oil pipeline connecting Western production with Eastern demand. Instead, oil destined for Ontario and Quebec flows through the United States via Enbridge pipelines originally routed south in the 1950s (Taylor, 2019, pp. 165). Electricity trade follows a similar logic: Manitoba exports far more electricity generated by hydropower to the United States than to neighbouring Ontario, despite significant domestic demand (Manitoba Public Utilities Board, 2013). These structural realities help explain why Canada is simultaneously the largest exporter of energy to the United States and one of the largest importers of American energy, leaving Eastern Canada's energy security reliant on American cooperation.

Western export routes face their own geographic barriers. The North American Cordillera encompassing the Rockies, Coast Mountains, and interior ranges forms a steep barrier to Westward export from the WCSB. Overcoming it required extraordinary engineering feats such as the Trans Mountain oil pipeline and the Westcoast natural gas pipeline in the 1950s (Saywell, 1975, pp. 227-244). These projects, assisted by American capital and materials, connected Western Canadian

energy to Pacific markets in Vancouver and the American Northwest. In the contemporary period, the same geographic imperatives shape diversification efforts: Trans Mountain's 2024 expansion and LNG Canada's 2025 opening represent rare cases where political will and capital overcame terrain, regulatory complexity, and social opposition to access Asian demand.

Taken together, Canada's incumbent energy infrastructure reflects decades of adaptation to geography, political, and social constraints rather than deliberate national design. Pipelines overwhelmingly flow south toward U.S. markets, where demand is large, proximate, and accessible. East–west integration remains limited. Electricity grids are independent, with larger electricity transmission lines connecting Canada's provinces to American states than to fellow provinces. These patterns anchor this paper's central argument: Canadian energy geopolitics is not the product of a single strategic choice, but of a persistent balancing act between the economic pull of the United States; constrained and incremental diversification elsewhere; the need to maintain domestic energy security across fragmented regions; and enduring anxiety over the cost, feasibility, and social and environmental consequences of building national energy infrastructure.

2.1 Energy Production

In 2024, Canada produced approximately 5.1 million barrels per day of crude oil and natural gas liquids, alongside roughly 18.8 billion cubic feet per day of marketable natural gas (NRCan 2025a). Converted into energy terms, Canadian oil and gas production amounted to approximately 21.71 exajoules (EJ) of primary energy. Coal production added 1.15 EJ, primarily from British Columbia mines serving export markets in Asia. Non-fossil primary electricity, including hydro, nuclear, wind, tidal and solar generated 1.72 EJ. In total, Canadian primary energy production adds up to around 24.66 EJ (StatsCan, 2025b).

To put the scale of Canada's energy industry in context, Canada's total energy production is comparable to the combined energy consumption of Germany, France, and the United Kingdom. Canada is structurally important to global energy markets, even if that importance is unevenly translated into global influence.

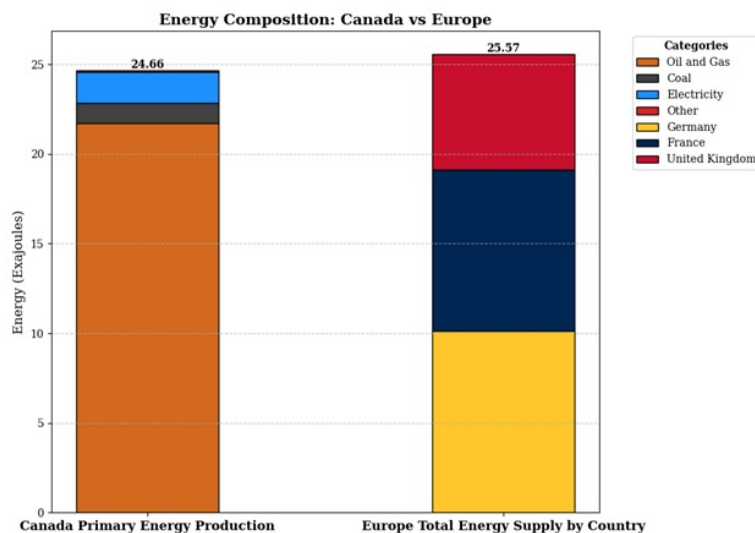


Figure 1 - Data from StatsCan, 2025b; Energy Institute, 2025

2.2 Regional Imbalances

National production figures obscure regional divides. Canada’s primary energy production is concentrated in the provinces West of the Canadian Shield, while population and consumption are more evenly distributed. Alberta alone accounts for the majority of Canadian oil and gas output, whereas Canada’s two largest provinces by population, Ontario and Quebec, fail to produce enough energy to meet their needs. As a result, Canada is one of the few net exporters whose most populous regions depend on foreign energy imports. This paradox is central to understanding Canada’s energy geopolitics.

Table 1 – Canadian Energy Production and Consumption by Region, PJ		
Region	Primary Energy Production	Secondary Energy Consumption
Canada	24,664.4	8,505.4
Canada East of Canadian Shield	1,987.7	4,345.3
Atlantic Provinces (excl. New Brunswick)	663.0	275.3
Quebec	670.7	1644.7
Ontario	654.0	2425.3
Canada West of Canadian Shield	22,608.6	3,996.0
Manitoba	199.7	285.4
Saskatchewan	1,318.3	568.1

Alberta	16,409.8	2,224.6
British Columbia	4,680.8	917.8
Yukon, Northwest Territories and Nunavut	14.8	33.3

Table 1 - Data from StatsCan, 2025b; NRCan, 2025b

2.3 Domestic Energy Consumption

Canada has one of the highest per-capita energy consumption rates in the world. At approximately 299 gigajoules per capita, this is nearly three times the European average (Energy Institute, 2025). Canada’s climate and geography explain part of this gap. Long, cold winters increase heating demand, while vast distances raise transportation energy use. Despite Canada’s vulnerabilities, it has much lower energy prices than Europe. This encourages consumption by households and provides fuel for a large base of energy-intensive industry, particularly oil and gas production, mining, and heavy manufacturing.

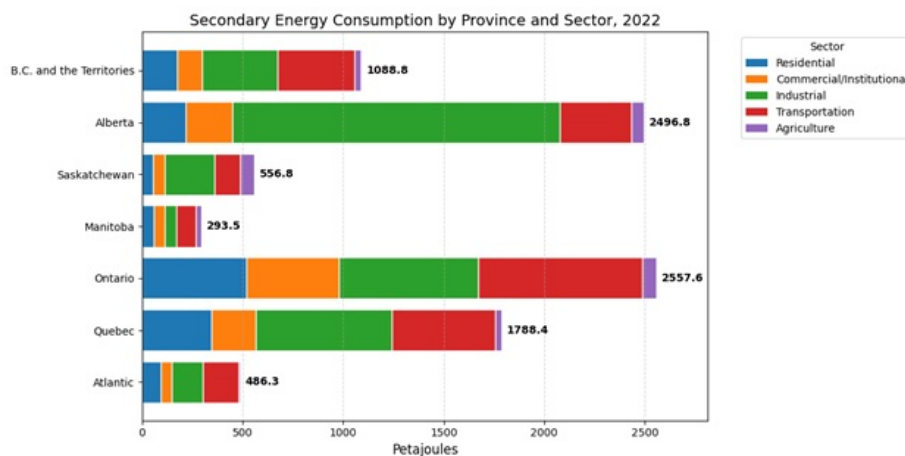


Figure 2 - Data from NRCan, 2025b

In 2024, Canada’s total energy supply (a measurement of primary energy consumption) was approximately 11.75 EJ (Energy Institute, 2025). This figure is dominated by natural gas and oil consumption. Secondary energy consumption (energy consumed in its final useful form) is lower, reflecting efficiency losses in electricity generation and fuel conversion. Industrial activity accounted for the largest share of final energy use, followed by transportation, residential, and commercial services.

OIL SANDS, ENERGY USE, AND EMISSIONS

The oil sands dominate Alberta’s energy profile and account for a disproportionate share of Canadian natural gas consumption and greenhouse gas emissions. Approximately half of oil sands production comes from in-situ facilities, which rely on steam injection to produce bitumen from underground deposits. Large volumes of natural gas are burned to generate this steam.

In 2024, oil sands operations consumed roughly 21 billion cubic metres of natural gas, comparable to the total national consumption of a mid-size European country (AER, 2025; Energy Institute, 2025). This energy intensity translates into high emissions per barrel of oil sands crude. The oil and gas sector is Canada’s largest source of greenhouse gas emissions, with oil sands operations accounting for a substantial share.

Industry-led initiatives like the Pathways Alliance aim to reduce emissions through large-scale carbon capture and storage. The question of who is responsible for paying the enormous costs associated with such a project is a key policy question.

Consumption broadly tracks population with one major exception: Alberta. Despite having less than one-third of Ontario’s population, Alberta consumes nearly as much energy. The main driver of the province’s unusually high consumption is the oil and gas sector, and especially the energy intensity of oil sands production (Alberta Energy Regulator [AER], 2025).

3 Canadian Energy Trade and Strategic Vulnerabilities

Canada’s role in global energy systems is defined by the concentration of its trade relationships with a few key partners. Canada is among the world’s largest exporters of oil and natural gas, yet its export profile is overwhelmingly oriented toward the United States. Canada also imports substantial volumes of energy from both the United States and elsewhere, creating a set of economic vulnerabilities on both security of energy supply and security of energy demand.

3.1 Energy Exports

	2024 Canadian Energy Imports	2024 Canadian Energy Exports
United States	\$29,319,988	\$171,718,517
China	\$214,073	\$5,346,803
Japan	\$8,984	\$4,252,148
Netherlands	\$1,291,110	\$2,574,271
South Korea	\$431,557	\$2,902,555

United Kingdom	\$659,864	\$1,603,062
Nigeria	\$2,191,238	\$426
Saudi Arabia	\$2,008,323	\$287
Germany	\$85,186	\$1,323,075
India	\$206,657	\$761,580

Table 2 Data from StatsCan, 2025c. Source: Data from StatsCan, 2025 c

In 2024, Canada exported more than CAD \$200 billion of energy products (NRCan, 2025a). Energy is the largest single category of Canadian goods exports, and these exports underpin a substantial share of national income, employment, and government revenue, particularly in Western Canada.

The United States dominates this picture. 88 percent of Canadian energy exports by value were sold to American customers in 2024 (StatsCan, 2025c). All forms of Canadian energy are exported Southward. Crude oil accounted for the largest share, followed by natural gas, refined petroleum products, electricity, and coal. This concentration reflects decades of infrastructure development optimized for north-south trade, as well as the scale and reliability of U.S. demand.

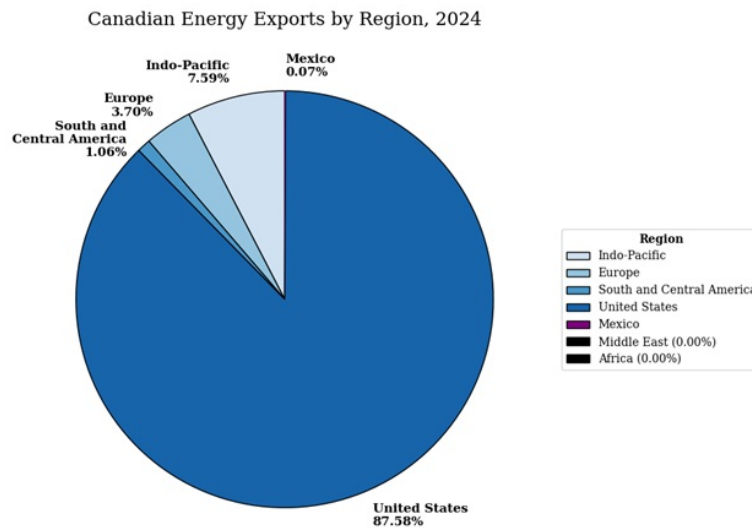


Figure 3. Data sourced from StatsCan, 2025c

Canada’s non-U.S. exports are modest by comparison. The Indo-Pacific accounted for around 7.6% of total energy exports, with China, Japan, and South Korea as the principal destinations. Indo-Pacific countries are expected to receive a larger share of Canadian energy into the future owing to the completion of the Trans Mountain Pipeline Expansion and the LNG Canada project, which has allowed more WCSB resources to reach the Pacific. Europe received only a modest share of Canadian energy

exports. Cut off from Western Canada's energy resources, exports to Europe are sourced from Canada's Atlantic offshore oil industry.

3.2 Energy Imports

Despite its status as a net energy exporter, Canada also imports large quantities of energy. In 2024, Canada imported CAD \$56.1 billion of energy from international trade partners, primarily crude oil, refined petroleum products, and natural gas (NRCan, 2025a). Unsurprisingly, the United States is once again the dominant partner. More than four-fifths of Canada's energy imports originate south of the border. These imports are critical to Eastern Canada's economy, supplying fuels and electricity to Ontario, Quebec, and the Atlantic Provinces (Statistics Canada 2025d). Crude oil and refined petroleum products from Europe, the Middle East, and West Africa supplement American supplies for some refineries and product import terminals in Quebec and New Brunswick (Statistics Canada 2025d)

Canada's dependency on energy imports is intertwined with geography and infrastructure. Eastern Canada lacks a direct pipeline route to access Western Canadian oil, and is therefore dependent on foreign imports and infrastructure which crosses U.S. territory. Another important consideration is economics. Even though Eastern Canada has a pipeline to bring in Western Canadian natural gas, the deployment of hydraulic fracturing in the Marcellus Shale in the United States just south of Ontario has resulted in a massive increase in regional natural gas production and low prices. As a result, much of Eastern Canada's traditional supplies sourced from Western Canada have been displaced by imports from the United States (Canadian Association of Petroleum Producers [CAPP], 2025).

4 Strategic Vulnerabilities

Canada's energy trade profile creates a dual vulnerability. On the supply side, Eastern Canada depends heavily on imported energy. While Western Canadian oil and gas provides a large share of Eastern Canadian energy supply, much of these supplies (particularly for oil) are moved through American-regulated pipeline systems in the Midwestern United States. On the demand side, Western Canada relies on continued access to the U.S. market to absorb the bulk of its energy exports. These separate vulnerabilities can result in disjointed Canadian policy when engaging with the United States on energy, as explored later in the paper.

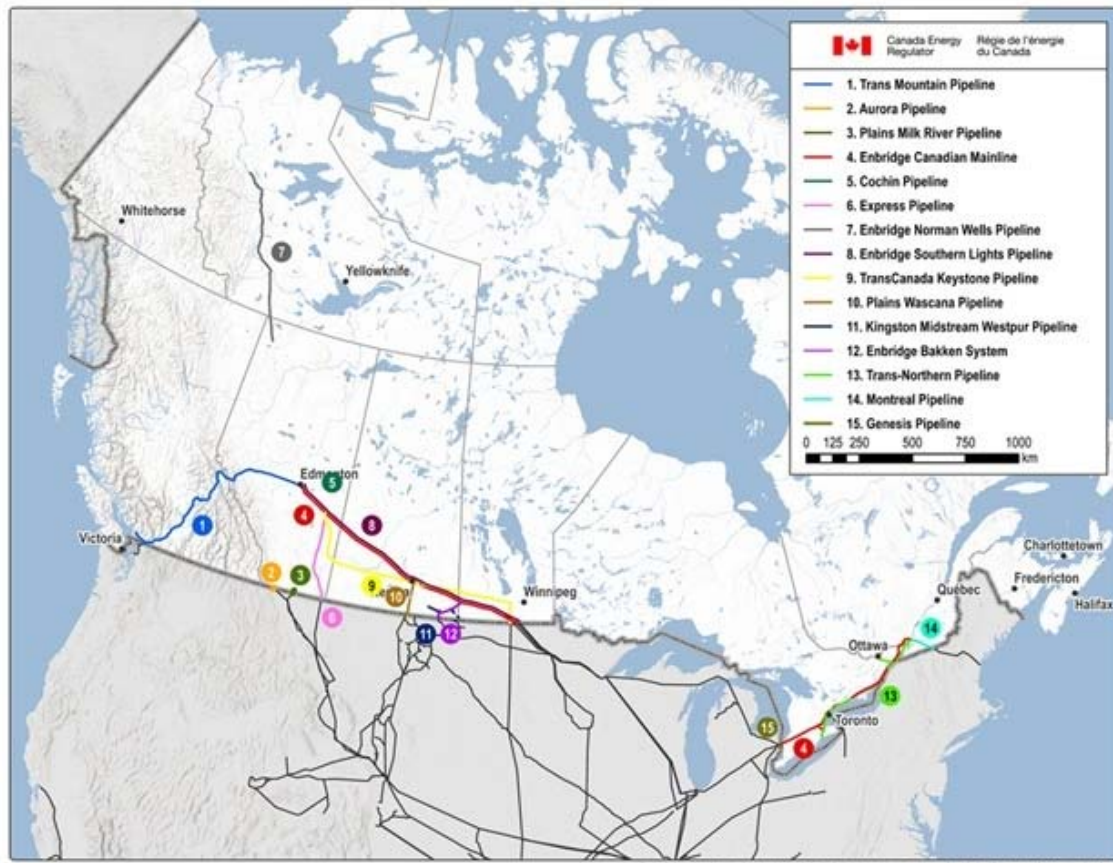


Figure 4. Map courtesy of Canada Energy Regulator [CER], 2025

A serious disruption of Canada-U.S. relations could not only threaten export revenues but also undermine the security of energy supply in Canada's most populous regions. While such a scenario remains unlikely, its consequences would be severe. These vulnerabilities are not easily resolved. Geography, sunk infrastructure costs, regulatory barriers, and political opposition all limit Canada's ability to rapidly reorient trade flows. As a result, diversification efforts tend to be incremental rather than transformational.

THE PIPELINE DEBATE, 1956

Several Canadian governments have invested substantial political and financial capital in efforts to bridge the energy infrastructure gap between Eastern and Western Canada. The most prominent example is the 1956 “Pipeline Debate” surrounding the construction of the TransCanada natural gas pipeline, championed by C.D. Howe. Charles Decateur Howe was an influential minister under the Liberal Party of Canada governments of William Lyon Mackenzie King and Louis St. Laurent, serving in their cabinets from 1935-1957. Known as the “Minister of Everything” during the Second World War, he is often described as the father of Canadian industrialization.

The project was designed to transport Alberta’s abundant natural gas eastward along an all-Canadian route north of the Great Lakes. In theory, keeping the infrastructure in Canada would limit the scope of possible American interference in the future operation of the pipeline, therefore boosting Canadian energy sovereignty. The central complication was that the companies behind the TransCanada consortium were predominantly American-owned, owing to limits on the financial and technological capacities of Canadian firms (Saywell, 1975, pp. 254).

Restricting the pipeline to an all-Canadian route proved commercially unviable, forcing both the federal government and the Government of Ontario to intervene financially. The federal government assumed responsibility for the most challenging segment of the project through a specially created Crown corporation (Saywell, 1975, pp. 251). As a result, the enormous costs of crossing the muskeg of eastern Manitoba and blasting through the Canadian Shield in western Ontario fell directly on the federal treasury.

Federal support also included a \$72 million loan to TransCanada, which the government pushed through the House of Commons ahead of a June 7, 1956 construction deadline. The aggressive use of parliamentary procedure, combined with public anger over what was widely perceived as the “surrender” of critical national infrastructure to American ownership, provoked a major political uproar. The resurgence of economic nationalism sparked by the Pipeline Debate ultimately contributed to the defeat of the Liberal government and the political downfall of C.D. Howe in 1957 (Ibbitson, 2023, pp. 162).

Despite having campaigned against the pipeline, the newly elected Progressive Conservative government under John Diefenbaker chose not to halt its construction. Diefenbaker recognized the pipeline’s importance for prairie economic development (Ibbitson, 2023, pp. 164-166). Nevertheless, the change in government marked the beginning of a renewed period of Canadian anxiety regarding American influence over Canada’s energy sector and broader economy. This unease was formally articulated later

5 Political, Legal, and Social Constraints on Energy Infrastructure

Though geography and geology establish physical limits on Canada’s energy system, law and policy define the limits of what is acceptable in Canada. Over the past two decades, the construction of major energy infrastructure in Canada has become progressively more difficult, expensive, and uncertain. This is not the result of a single constraint, but of the interaction among three distinct veto points: Indigenous rights, climate policy, and federal–provincial governance. Building new energy infrastructure requires project proponents to navigate these veto points. Successfully managing this complex landscape is commonly referred to as gaining “social license” to move forward with a project. The growing challenge of gaining this social license has resulted in difficulty building new energy infrastructure.

5.1 Indigenous Rights

The constitutional entrenchment and judicial expansion of Indigenous rights has altered the political economy of infrastructure development. Court decisions over the past several decades have established a robust duty to consult and, in some cases, accommodate Indigenous communities whose rights may be affected by proposed projects (Bankes, 2020). In practice, this has transformed Indigenous communities into decisive actors in energy geopolitics. Infrastructure projects that secure durable Indigenous support can proceed, albeit slowly. The result is not uniform opposition to energy development, but heightened uncertainty and negotiation costs.

This new reality can be seen as a correction for past mistakes. Canada's historical energy infrastructure buildout often came at the expense of Indigenous traditional lands and livelihoods. For example, the construction of the W.A.C. Bennett Dam in the 1960s flooded a huge swath of land used by the Tse'kehne people of Northeast British Columbia (Sims, 2017). The balance between preserving the traditional use of lands and building new infrastructure for economic development and security is a challenge that Canada will be negotiating for many years to come.

5.2 Climate and Public Opposition

Limiting the emissions which cause climate change has become a central principle of Canadian energy policy since the Liberal Party of Canada's return to power in 2015. Federal and provincial climate commitments, including emissions caps, carbon pricing, and regulatory standards, directly shape the viability of new infrastructure. These policies interact with public attitudes which in some regions are hostile to fossil fuel expansion. Even where projects meet formal regulatory requirements, they may fail politically if they are perceived as inconsistent with Canada's climate objectives (Calnan, 2024a). This dynamic increases project risk and lengthens timelines, reinforcing investor caution.

In recent years public attitudes toward the environment-economy tradeoff have begun to shift. In 2015, 67% of Canadians polled prioritized the environment versus 24% who prioritized economic growth. In 2025, these attitudes have switched, with 57% of Canadians prioritizing the economy versus 35% prioritizing the environment (Nanos Research, 2025).

5.3 Federalism and Regulatory Complexity

Canada's federal structure adds another layer of complexity. Energy development straddles federal and provincial jurisdiction, creating overlapping regulatory processes and frequent political disputes. Provinces control resource development, resource taxation, and interprovincial infrastructure, while the federal government regulates energy on federal lands, nuclear energy, and interprovincial and international infrastructure (Library of Parliament, 2019). Environmental regulation is a joint and often contested responsibility.

This division of authority often produces paralysis and politicization. Major projects become symbols of national identity, regional grievance, and partisan conflict. As a result, infrastructure debates increasingly extend beyond economics into questions of legitimacy, the constitutional division of powers, and national purpose.

6 Canada's International Position

Canada is firmly embedded within the Western group of nations. It has a long history of democratic governance, a market-oriented economy, and deep participation in post-Second World War multilateral institutions. Canada is a founding member of the North Atlantic Treaty Organization (NATO), the Group of Seven (G7), the Organisation for Economic Co-operation and Development (OECD), and the Five Eyes intelligence network. As an Arctic nation, Canada is also a member of the Arctic Council, which was established in Ottawa in 1996. In addition, Canada belongs to the Commonwealth of Nations, reinforcing institutional and cultural ties to the United Kingdom and other former British colonies. Canada also positions itself as an Indo-Pacific nation: it is a founding member of the Asia-Pacific Economic Cooperation (APEC) forum and a growing trade partner with economies across the region.

Canada's core security relationships are North American and transatlantic. NATO membership commits Canada to collective defence under Article 5, anchoring its security policy within the Western alliance. Canada maintains a forward military presence in Central and Eastern Europe through Operation REASSURANCE, including approximately 2,000 Canadian Armed Forces personnel deployed as part of NATO's Multinational Brigade in Latvia (Canadian Armed Forces, 2025). Canada also hosts the NATO Climate Change and Security Centre of Excellence in Montreal. Canada's membership in the Five Eyes intelligence community tightly integrates Canadian intelligence agencies, such as the Communications Security Establishment, the Privy Council Office's Intelligence Assessment Secretariat, and the Chief of Defence Intelligence with counterparts in the United States, the United Kingdom, Australia, and New Zealand. Canada and the United States are also bound through the North American Aerospace Defense Command (NORAD), an integrated aerospace warning and control system responsible for the defence of North America.

Economic and diplomatic engagement further reinforce Canada's Western alignment. Canada frequently frames its international role through its identity as a "G7 country." Importantly, Canada's inclusion in the G7 was bolstered by its huge energy reserves. The creation of the G7 was triggered by the 1970s energy crisis, and the addition of one of the Western bloc's few energy exporters made sense for the goals of the diplomatic group (Gordon, 2023). Canada's international aid is also supportive of Western multilateral institutions. Canadian development assistance is channeled through the United Nations system, the International Monetary Fund, the World Bank Group, and the World Trade Organization (Global Affairs Canada, 2025).

Following the Conservative Party's shift toward free trade under Prime Minister

Brian Mulroney in the 1980s, Canadian economic policy has consistently embraced free trade agreements. Today, Canada participates in a broad network of trade agreements, including the Comprehensive Economic and Trade Agreement with the European Union; the Comprehensive and Progressive Agreement for Trans-Pacific Partnership with Indo-Pacific economies; and, most significantly, the North American Free Trade Agreement and its successor, the Canada–United States–Mexico Agreement. Canadian energy trade and energy investment has steadily grown under the auspices of these legal frameworks, subject to commodity prices.

Cultural heritage influences Canadian foreign policy and, indirectly, energy diplomacy. Canada's institutional, legal, and linguistic ties to Europe are the foundations of alignment with Western norms. Diaspora communities and heritage stemming from Europe have shaped stances on security issues which affect energy supply chains. Canada's participation in the First and Second World Wars, for example, was linked to its identification with Great Britain as the "Mother Country." More recently, Canada's large Ukrainian diaspora is thought to have encouraged Ottawa's firm response to Russia's annexation of Crimea in 2014 (Ibbitson, 2014). At the same time, Canadian popular culture is heavily influenced by the United States. Canada's entertainment ecosystem, including television, film, music, and social media, is dominated by American firms and platforms, reinforcing cultural overlap alongside economic integration. Canada's links to Western countries indirectly influence Canada's energy geopolitics and energy diplomacy. To the extent that Canadians hope to increase energy exports, their preferred partners are European countries (Nanos, 2025). This preference has become more pressing following the Russian invasion of Ukraine and subsequent energy crisis in Europe.

Decades of benign foreign policy have contributed to Canada's reputation as a constructive and positive international actor (Bricker, 2024). Building on this perception, recent Canadian governments have pursued a values-oriented foreign policy. Under Prime Minister Justin Trudeau, this approach reached its high-water mark through Canada's "feminist foreign policy," emphasizing women's empowerment and gender equality. Climate policy was another central pillar of Canadian diplomacy during this period, creating an inherent tension between Canada's values and the economic reality of being a major exporter of oil and gas.

This values-based approach rested on a strategic environment in which Canada's security, trade, and diplomatic position were underpinned by positive relations with an American hegemon. For example, Canada's membership in the G7 is the direct result of American intervention. In 1976, U.S. President Gerald R. Ford insisted that Canada be included in the second Summit in Puerto Rico, overruling French objections (Gordon, 2023). Furthermore, Canada's integration with the American security apparatus through the Five Eyes intelligence sharing alliance and NORAD is inconceivable without a uniquely close relationship between the two countries.

In recent years, however, Canada has struggled to meet key military and security commitments. In 2023, Canada was the only NATO member that failed to meet both the alliance's target of spending two percent of GDP on defence and the benchmark that 20 percent of defence spending be allocated to equipment and research and

development (Maddison, Fraser, & Cowan, 2024). Canada has also fallen short of its peacekeeping commitments: despite a 2016 pledge to deploy up to 600 personnel to United Nations missions, as of October 2025 only 27 Canadian troops and police officers were serving in UN peacekeeping operations (United Nations Peacekeeping, 2025). In 2023, reporting by the *Washington Post* on a leaked Pentagon document revealed frustration within the Biden administration regarding Canada's military preparedness, including an allegation that Prime Minister Trudeau had privately indicated Canada would never meet the NATO spending target (Coletta, 2023). Canada's exclusion from the AUKUS submarine and advanced technology partnership among the United States, Australia, and the United Kingdom further underscored these concerns. While Canada has no immediate requirement for nuclear-powered submarines, the narrowing of technology sharing within a smaller subset of Five Eyes partners has raised questions about the risk of marginalization within Canada's preferred Western security institutions (Carvin & Juneau, 2023).

Canada remains a member and a supporter of the main post-war Western-led institutions. Despite this identification with the west, Canada's existing energy infrastructure isolates it from influencing economic outcomes in European countries. Instead, Canada's energy geopolitics are likely to draw it closer to the United States and the Indo-Pacific.

7 The Inexorable Draw of Canada–U.S. Energy Integration

Canada's energy sector, like much of its economy, is deeply interwoven with that of the United States. As outlined earlier in this paper, the United States is Canada's largest partner for both energy exports and imports. Over time, this relationship has endured periods of close cooperation, suspicion, and periodic protectionism on both sides of the border. These shifts have strongly influenced the development of Canada's energy industry and infrastructure. Across decades, Canada has repeatedly weighed longstanding fears of U.S. political domination against the prosperity made possible by access to a much larger market. U.S. President Donald Trump's rhetoric has intensified these tensions, renewing political interest in diversifying Canada's energy exports beyond the United States.

Western Canada has been an energy exporter to the United States since the completion of the Interprovincial Pipeline. In 1955, Canadian exports of "petroleum, crude and partly refined" were valued in nominal terms at \$36.3 million (Dominion Bureau of Statistics, 1956). Today, Western Canada's energy exports to the United States generate well over one hundred billion dollars in annual revenue (NRCan, 2025a). Eastern Canada, by contrast, remains reliant on oil and natural gas supplies either produced or controlled by the United States. Western Canadian crude oil and refined products are delivered to Ontario and Quebec through pipelines transiting Michigan. These supplies are augmented by imports of American crude oil and refined products. Following the shale revolution, Eastern Canada has also come to import most of its natural gas from the United States. As a result, the energy sectors of Canada and the United States are now broadly co-dependent (Johnston & Calnan 2024).

At the beginning of the oil and gas industry, the two energy systems were kept independent. After Confederation in 1867, oil and gas production in Southwest Ontario was shielded from American competition through duties and non-tariff barriers, and later through the “National Policy” tariffs introduced by the second Macdonald government in 1878 (Taylor, 2019, pp. 46). As global oil production expanded and competition intensified, Canadian producers and refiners grew increasingly reliant on these trade restrictions to protect their domestic markets.

That protection proved illusory. Under Wilfrid Laurier’s Liberal government, tariffs were dismantled, and Canada’s largest oil company Imperial Oil was acquired by the American giant Standard Oil. This outcome was inevitable. Oil from Southwest Ontario had a high sulphur content, and Standard Oil controlled the patents for the Frasch desulphurization process (Taylor, 2019, pp. 45). At the same time, Ontario’s oil resources were limited, and production began to decline sharply after 1900. Canada would remain dependent on American oil and gas supplies until the discovery of oil at Leduc, Alberta in 1947 and the pipeline boom of the 1950s, developments that were themselves driven by American capital and expertise (Kureth, 1985). In 1959, U.S. President Dwight Eisenhower gave Canadian oil favourable treatment in American import quotas, further encouraging Canadian exports to the United States (Eisenhower, 1959).

The United States had strong strategic reasons to secure Canadian oil supplies in the latter half of the 20th century. In 1956, Shell geologist M. King Hubbert predicted that U.S. crude oil production would soon peak and then decline (Hubbert, 1956). By the early 1970s, this forecast had been realized, as American production entered a prolonged downturn. At the same time, international oil companies including the American majors were losing control over Middle Eastern reserves, while newly empowered OPEC producers acted to raise crude oil prices. Against this backdrop, early investments in the Canadian oil sands began to appear increasingly attractive, promising decades of supply from a politically stable and trusted neighbour.

After 1988, Canada’s crude oil exports to the United States expanded rapidly, driven by oil sands growth and a stable bilateral relationship. Between 1990 and 2010, refineries in the U.S. Midwest invested billions of dollars to process more heavy sour crude from the oil sands (Oil Sands Magazine, 2020). Rising volumes of Canadian oil also reshaped American energy infrastructure, including the reversal of the Capline Pipeline to move Canadian crude from the Midwest to the U.S. Gulf Coast.

The post–Cold War consensus around free trade proved to be more fragile than expected. Prior to Donald Trump’s election in 2016, political opposition to globalization was gaining strength in the United States. Backlash in the U.S. against the Trans-Pacific Partnership became so intense that even Hillary Clinton disavowed the agreement during her presidential campaign. Trump’s return to office in 2025 has further expanded American opposition to foreign cooperation by openly questioning long-standing economic and security arrangements with Canada. U.S. tariffs have targeted Canadian manufactured goods, including autos, steel, and aluminum, while Trump stated in early 2025 that the United States would use “economic force” to absorb Canada as its 51st state.

To date, American tariffs have had limited direct impact on Canada's energy sector,

THE NATIONAL ENERGY PROGRAM

Canada has experienced several waves of economic nationalism in response to American influence over its energy sector. The pipeline debate of the early 1950s, discussed previously, was one such episode. Another was the National Energy Program (NEP), introduced by Pierre Trudeau's Liberal government and implemented from 1980 to 1985 in response to the oil crises of the 1970s. Among other objectives, the NEP sought to redirect discounted Western Canadian oil to Eastern refineries and to reduce the proportion of Canadian oil production controlled by American companies (Noakes, 2006). By 1973, 80 per cent of Canada's petroleum revenues were collected by foreign-owned firms, the American majors (Globerman & Shapiro, 1998).

Unlike the earlier National Policy tariffs, the National Energy Program provoked fierce opposition from Western Canada's energy industry. It remains widely viewed in the region as an effort to redistribute Western resources to the federal government and to lower energy prices for the benefit of Eastern Canadian oil consumers (Nemeth, 1997). By this point, Western Canada was firmly established as a competitive exporter to the United States and saw little value in being constrained to domestic markets. Following Pierre Trudeau's departure from office in 1984, Canadian and American governments found themselves ideologically aligned on free trade. This period of closeness produced the Canada–United States Free Trade Agreement in 1988, followed by the North American

but American policy could have larger impacts in coming years. Canadian oil and gas exports are shielded by USMCA exemptions, leaving manufacturing centres in Ontario and Quebec more exposed (Tombe, 2025). Energy nonetheless is an important part of Canada's strategic response. Early in this most recent trade dispute, there were calls to weaponize energy exports, though Canada refrained from such measures. The American intervention in Venezuela in early 2026 has raised another possible risk for Canada. If the United States is successful in diverting Venezuelan heavy crude to American refineries in the U.S. Gulf Coast, it could push Canada's crude oil exports out of that market.

Over the longer term, the pressures generated by the Trump administration have strengthened the political case for investing in infrastructure to diversify Canada's energy trade partners. However, major infrastructure and political barriers complicate Canadian efforts to diversify energy exports.

8 Canada-Europe Energy Diversification: Agreement in Principle

Energy ties between Canada and Europe are characterized by agreement in principle but modest action in practice. In 2024, Canada exported 6.6 million tonnes of crude oil and refined petroleum products to Europe, primarily to the Netherlands, the United Kingdom, and Germany. These exports originate exclusively from Canada's offshore oil industry, with crude shipments regularly departing from Newfoundland and Labrador to Europe (StatsCan 2025d). While Canada's offshore sector represents a significant technical achievement, it remains limited in scale. Newfoundland and Labrador accounts for approximately 2.3 per cent of total Canadian oil and gas production on an energy basis (Statistics Canada, 2025b).

Canadians are interested in Europe as a destination for diversifying energy trade. When asked about which export destinations Canada should prioritize, poll respondents were most likely to choose Europe (Nanos, 2025). Bolstering the views of Canadians, some major European policymakers have expressed interest in importing Canadian energy. However, building this infrastructure presents formidable economic, political, and environmental challenges, and remains a remote prospect.

Materially increasing Canada's contribution to European energy security would require infrastructure capable of moving Western Canada's vast oil and gas resources to the Atlantic coast. Historically, European governments and firms have shown less sustained interest in Canadian energy than their American counterparts. Royal Dutch Shell, for example, did not establish a Canadian subsidiary until 1911, decades after Standard Oil entered the Canadian market. As a former British colony, Canada's energy resources nonetheless attracted episodic attention from British political figures; in 1929, opposition MP Winston Churchill visited the Turner Valley natural gas fields (Finch, 2017). Even so, for much of Canada's history, British and European interest in Canadian energy focused more on developing Canadian economic self-sufficiency than on building durable transatlantic energy security ties.

The development of offshore oil production in the Jeanne d'Arc Basin off Newfoundland and Labrador marked a qualitative upgrade in Canada's energy relationship with Europe, but these exports developed slowly. Although production at the Hibernia platform began in 1997, Canada did not begin regularly exporting crude oil to the United Kingdom until November 2012. Shipments to other European countries followed in December 2013 (StatsCan, 2025d). Even then, U.S. East Coast refineries remained highly competitive customers. This is likely a result of the business plans of the companies invested in the projects. Major Canadian offshore oil platforms such as Hibernia have been led primarily by American firms including Exxon, Chevron, and Murphy Oil, with European companies such as Equinor playing secondary roles.

In principle, greater energy cooperation between Canada and Europe serves the interests of both sides. Europe's energy crisis following Russia's invasion of Ukraine has severely undermined economic security across the continent. A range of European policymakers of different ideological stripes, including European Parliament President Roberta Metsola, former German Chancellor Olaf Scholz, and Polish President Andrzej Duda have publicly supported increased imports of Canadian energy. Canada and European partners have launched multiple cooperative initiatives, including the EU–Canada High-Level Energy Dialogue, the Canada–Germany Energy Partnership, the Canada–Italy Bilateral Energy Dialogue, and several other bilateral and multilateral frameworks.

To date, these initiatives have delivered limited tangible results for European energy security or Canadian export diversification. Canada's existing pipeline network is optimized for exports to the United States and for domestic supply in Eastern Canada. Redirecting Western Canadian energy to Atlantic ports would require major new infrastructure investments. Such projects would also require the cooperation of

Quebec, which has previously blocked energy export initiatives such as the Énergie Saguenay LNG project (Calnan, 2024). Without regional buy-in, large-scale export infrastructure remains unlikely. The potential for declining European demand for natural gas further weakens the commercial case for new pipelines or LNG terminals. Proposals such as exporting LNG from Hudson Bay have attracted attention, but face their own substantial technical and political barriers.

Hydrogen represents a possible, though uncertain, exception. In 2022, Canada and Germany signed an “Agreement to Enhance German Energy Security with Clean Canadian Hydrogen”. Although Chancellor Scholz initially sought Canadian LNG, the resulting declaration emphasized Canada’s hopes to become involved in Europe’s nascent hydrogen economy. Significant uncertainties remain for the viability and timing of Canadian hydrogen exports to Europe. In Europe, insufficient policy support has slowed the development of a low-carbon hydrogen market, while analysts question whether hydrogen shipping can ever be economically viable given the energy losses involved (Liebreich, 2022).

9 Indo-Pacific Energy Diversification: Tangible Results and Political Pitfalls

Canada’s growing role in the energy security of the Indo-Pacific reflects the same core tensions that define its broader energy geopolitics: the economic attraction of large external markets, political efforts to diversify exports away from the United States, the constraints imposed by domestic infrastructure and regulation, and persistent anxieties about sovereignty, security, and foreign influence. The Indo-Pacific offers Canada its greatest long-term growth opportunity outside North America, but it is also a region where geopolitical risk is acute.

9.1 China and the Limits of Strategic Diversification

China has an inescapable gravity in Canada’s Indo-Pacific energy calculus. As a disruptive economic superpower, China presents both enormous commercial opportunity and significant political risk. Rapid industrialization and urbanization created a vast appetite for Canadian natural resources, including energy, even as China’s growing economic presence raised concerns in Canada about political influence and the difficulty of balancing relations with both Beijing and Washington.

In 2005, Prime Minister Paul Martin signed a cooperation agreement with the People’s Republic of China promoting bilateral collaboration in oil and gas, nuclear energy, energy efficiency, and clean energy. At the time, China was experiencing a decade of double-digit economic growth alongside the fastest expansion of energy demand in world history. Between 2000 and 2010, Chinese energy consumption rose from 40 exajoules to 100 exajoules, surpassing both Europe and North America as an energy consumer.

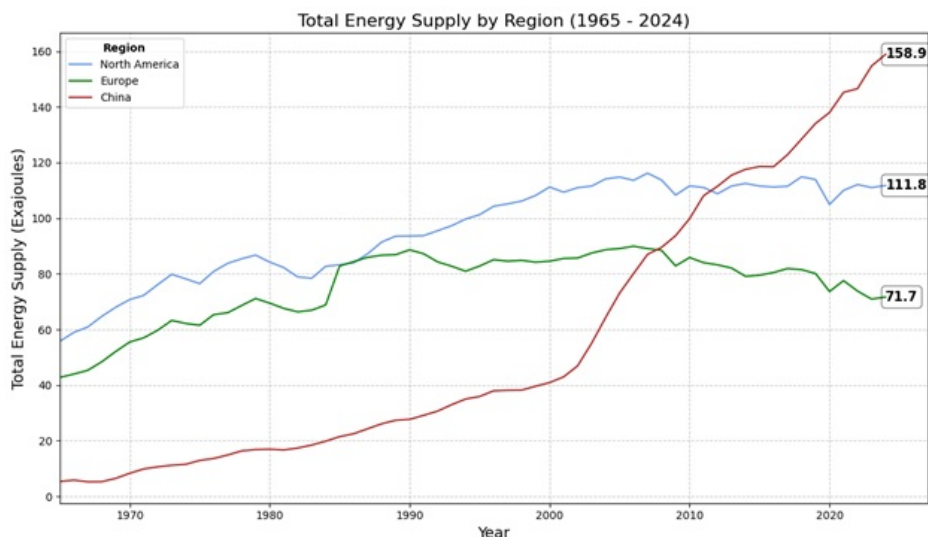


Figure 5. Data from Energy Institute, 2025

Sustaining this growth required large-scale energy imports. In 2001, China announced its “going out” strategy, encouraging state-owned enterprises to invest abroad. This explicitly included the exploitation of foreign resources in partnership with local firms (Rongji, 2001). The 2005 cooperation agreement was soon followed by substantial Chinese investment in Canada’s energy sector, particularly the oil sands, whose scale and technological sophistication were highly attractive for Chinese energy firms. That same year, CNOOC acquired a 16.7 per cent stake in MEG Energy. In 2010, Sinopec purchased a 9 per cent share of the Syncrude project, and in 2012 CNOOC fully acquired Nexen for \$15 billion. PetroChina also holds interests in several oil sands projects, including MacKay River and Dover. Beyond hydrocarbons, China imports significant volumes of Canadian metallurgical coal from southeastern British Columbia and operates two CANDU nuclear reactors near Hangzhou.

These developments generated unease within Canada. CNOOC’s purchase of Nexen was particularly controversial, partially because of Canada’s close alliance with the United States. While Canadian authorities were reviewing the purchase, Canada’s spy agency CSIS warned that takeovers by Chinese firms may threaten national security (Steger & Alini, 2012). At the time, the United States was reviewing the possible security risks posed by China’s telecommunications champion Huawei, and warned Canada about the risks of economic integration with the Asian superpower. Following the Nexen takeover, the Harper government introduced new rules under the Investment Canada Act to limit the ability of state-owned enterprises to acquire controlling stakes in oil sands companies (Burton, 2012). Rising U.S.–China tensions, especially over Huawei, placed Ottawa in an increasingly uncomfortable position. This culminated in the 2018 arrest of Huawei executive Meng Wanzhou at the request of U.S. authorities and China’s retaliatory detention of two Canadian citizens.

The relationship has since proven difficult to repair. In 2024, a public inquiry found that China had interfered in two recent Canadian elections. Later that year, Canada joined the United States in imposing 100 per cent tariffs on Chinese-made electric vehicles, triggering an ongoing trade dispute. While diplomatic relations have partially stabilized, these developments have sharply constrained the political space for

deeper energy cooperation with China.

9.2 Pacific Infrastructure and Asian Markets

Despite significant Chinese investment in Canadian production, until recently Canadian energy infrastructure did not support export to the Indo-Pacific. At first, China attempted to coordinate building this infrastructure. In 2005, PetroChina signed a cooperation agreement with Enbridge to explore a pipeline to British Columbia's northwest coast, later known as the Northern Gateway project. The proposal faced intense regulatory, environmental, and political opposition and was cancelled by the Trudeau government in 2016. Canada's longstanding moratorium on oil tanker traffic along the northern British Columbia coast, eventually formalized by the Oil Tanker Moratorium Act in 2019, effectively closed deepwater ports such as Kitimat and Prince Rupert to crude oil export (Chong & Sweeney, 2017).

Following the cancellation of Northern Gateway, the Trans Mountain Expansion became the sole viable route for exporting Canadian crude to the Indo-Pacific. After years of delays and cost overruns, exports from the Westridge Marine Terminal finally began in May 2024. One of its first cargoes headed to China (StatsCan, 2025d). Since then, China has consistently ranked as the second-largest importer of Canadian crude oil. However, prospects for further expansion are uncertain. After decades of rapid growth, Chinese oil demand appears to be plateauing as electric vehicles displace gasoline and diesel consumption.

China also plays a role in Canada's natural gas sector. CNOOC, PetroChina, and Sinopec hold upstream natural gas assets in British Columbia and Alberta. PetroChina also is a key partner in LNG Canada, which began exporting liquefied natural gas to Asia in June 2025. Between May and October 2025, China received four LNG cargoes from the project (CER, 2026).

9.3 Beyond China: Indo-Pacific Partners and Incremental Diversification

Even excluding China, the Indo-Pacific accounts for the majority of Canada's non-U.S. energy trade. Canada is a member of the Comprehensive and Progressive Agreement for Trans-Pacific Partnership and has sought deeper economic ties with the region's growing economies. Japan and South Korea, both democratic allies identified in Canada's Indo-Pacific Strategy as security partners, have long-standing energy relationships with Canada. ASEAN countries, particularly Malaysia, also play a growing role, though volumes remain modest.

Japan's integration into Canada's energy sector dates back decades. Mitsui & Co.'s Canadian subsidiary was established in 1956, with interests spanning oil, gas, and coal. By 1977, coal was Canada's single largest export to Japan, valued at \$520 million annually (Government of Canada, 1977). In 2024, Canadian energy exports to Japan totaled \$4.2 billion. LNG Canada is expected to deepen this relationship: Mitsubishi Corporation holds a 15 per cent stake in the project, and Japan imported five LNG cargoes between May and October 2025 (CER, 2026).

South Korea has similarly expanded its footprint. The state-owned Korea National Oil Corporation entered Canada's energy sector in 2009 through the acquisition of Harvest Energy, gaining exposure to oil sands and natural gas assets. KOGAS holds a stake in LNG Canada and imported nine cargoes during the project's first six months (CER, 2026). South Korea is also the largest foreign operator of CANDU nuclear reactors, having commissioned four units at the Wolsong plant in 1983, and remains a major importer of Canadian metallurgical coal.

ASEAN countries (with the notable exception of Singapore) currently import little Canadian energy. Limited refining capacity for heavy crude and abundant regional energy resources have constrained demand, though rising consumption and declining production could alter this balance (Calnan, 2025). Malaysia's state-owned PETRONAS has positioned itself accordingly, becoming a major investor in Canadian upstream natural gas and the second-largest equity holder in LNG Canada after Shell. Southeast Asia may also emerge as an important market for Canadian nuclear technology exports.

India represents the most significant long-term growth opportunity, though Canada's relations with the South Asian giant are nearly as fraught as those with China. With enormous economic and industrial growth expected in the coming decades, India's energy demand is expected to rise sharply through to the middle of the 21st century (International Energy Agency [IEA], 2021). Yet Canada–India energy cooperation, particularly in nuclear technology, remains constrained by historical and political tensions. These include India's use of a Canadian-supplied reactor to help it develop nuclear weapons in the 1960s. More recently, deteriorating bilateral relations are linked to the Khalistan separatist movement and the killing of separatist leader and Canadian citizen Hardeep Singh Nijjar, allegedly by Indian agents.

10 Canadian Energy in the Arctic

Energy development in the Canadian Arctic is shaped by extreme infrastructure costs, limited local markets, and the federal government's long-standing objective of economically developing and securing its vast northern territory. Canada's three northern territories Yukon, the Northwest Territories, and Nunavut together cover an area comparable to the European Union, yet have fewer than 140,000 residents in total (StatsCan, 2025e) This sparse population severely constrains the commercial viability of large-scale energy infrastructure. Most regions of the far North lack refineries, pipelines, power plants, or transmission lines, resulting in a fragmented and energy-insecure system.

At the same time, sustained presence in the Arctic is essential to reinforcing Canadian sovereignty. Canada's 2024 defence policy, *Our North, Strong and Free*, places particular emphasis on “defending the Arctic and North and its approaches against new and emerging threats through credible deterrence” (Government of Canada, 2024, pp. 11). In such a remote and sparsely populated region, monitoring activity and enforcing Canadian law is both difficult and costly. The most visible manifestation of this challenge is Canada's claim that the Northwest Passage

constitutes internal waters, a position contested by the United States, the United Kingdom, and most other maritime powers. Notably, Russia passively supports Canada's claim in forums such as the Arctic Council, since it parallels Russia's assertion of control over its own Northern Sea Route (Lalonde, 2022).

The central challenge for Canada is therefore to maintain effective Arctic sovereignty without imposing unsustainable fiscal burdens on the federal government. The Canadian Armed Forces' Arctic presence is widely regarded as understaffed, while existing infrastructure continues to deteriorate after decades of underinvestment (Department of National Defence, 2024). One strategy for reducing the cost of revitalization is the development of dual-use infrastructure: projects that serve both civilian and strategic purposes. Identifying viable non-military uses, however, remains difficult. Energy development has repeatedly been proposed as one such avenue, offering the possibility of supporting sovereignty objectives while improving local economic conditions.

Energy security considerations provide a compelling domestic rationale for Arctic infrastructure investment. Many northern communities rely almost entirely on diesel fuel for electricity and heating. This dependence creates persistent vulnerabilities: diesel deliveries are constrained by seasonal shipping windows, supply disruptions during winter months are common, and operating costs are extremely high. Local governments lack the tax base to maintain this infrastructure, leaving communities dependent on federal subsidies and emergency support. Reducing diesel reliance would improve reliability, lower emissions, and enhance community resilience, but alternative systems face steep logistical and financial barriers.

Several proposals have emerged to address these challenges. The Kivalliq Hydro-Fibre Link would connect Nunavut communities to Manitoba's hydroelectric grid via a 1,200-kilometre transmission line, providing both electricity and broadband connectivity. Another option is the deployment of small modular reactors (SMRs). Canada's SMR Action Plan explicitly considers Northern and remote communities as potential early adopters, where SMRs could displace diesel generation (Canadian Small Modular Reactor Roadmap Steering Committee, 2018). While both approaches promise improved energy security and reduced emissions, they would require massive upfront investment and sustained federal funding, raising questions about long-term affordability and political feasibility.

From a geopolitical perspective, Arctic energy development occupies a distinct place within Canada's broader energy strategy. Unlike Europe or the Indo-Pacific, the Arctic does not offer opportunities for export diversification or accessing foreign markets. Instead, it reflects the inward-facing side of Canadian energy geopolitics: shoring up domestic energy security, reinforcing territorial sovereignty, and managing the social and environmental consequences of infrastructure in sensitive regions. Any Arctic energy strategy must therefore reconcile national strategic objectives with Indigenous rights, environmental protection, and fiscal constraint.

One exception to this rule is the possible development of an energy export terminal through Hudson's Bay. This speculative project could potentially meet both local

energy needs and serve as a launching point for export diversification. It could also serve as dual-use infrastructure for a Canadian military presence. The most advanced proposal is the NeeStaNan LNG export terminal proposed by Fox Lake Cree Nation, which would see Western Canadian natural gas exported from Port Nelson in northern Manitoba. Much like the other major Arctic energy projects, this project is at an early stage. Questions linger about its economic viability. Hudson's Bay is only free of ice for a portion of the year, and maintaining year-round deliveries of LNG may require specialized tankers and expensive heavy icebreaker escorts. This adds an additional major cost hurdle to an already expensive project.

11 Canada as an “Energy Superpower”

The re-election of Donald Trump and the election of Prime Minister Mark Carney may mark a turning point in Canada's energy geopolitics. Shortly after the American election, President-elect Trump pledged to impose sweeping 25 per cent tariffs on all goods imported from Canada and Mexico. He went further, arguing that Canada's reliance on the United States for security and trade justified its absorption as America's “51st state.” While inflammatory, Trump's rhetoric underscored a persistent reality: Canada's position in global security, trade, and diplomacy remains deeply shaped by its relationship with the dominant postwar superpower.

THE MACKENZIE VALLEY PIPELINE

The Mackenzie Valley Pipeline remains the clearest historical example of both the ambition and the limitations of using energy infrastructure to “open” the Canadian Arctic. Major onshore and offshore oil and gas discoveries in the Beaufort–Mackenzie region of the Northwest Territories during the 1960s sparked federal interest in linking northern resources to southern markets. Because large-scale infrastructure in the northern territories falls under federal jurisdiction, Prime Minister Pierre Trudeau’s Liberal government actively supported proposals for a natural gas pipeline running south along the Mackenzie River Valley.

From the outset, the pipeline was conceived as more than an energy project. In 1972, the federal government released planning guidelines outlining an expansive vision in which the pipeline would anchor a broader development “corridor” through the Mackenzie Valley. Proposed accompanying infrastructure included “a highway, a railroad, electric power transmission lines, telecommunication facilities, etc.” (Department of Indian Affairs and Northern Development., 1972) Like later Arctic strategies, this vision treated energy infrastructure as dual-use: a means of stimulating economic development, improving energy security, and reinforcing Canadian sovereignty in a remote and sparsely populated region.

Trudeau explicitly framed the Mackenzie Valley Pipeline as a nation-building project comparable to the Canadian Pacific Railway. In 1973, he argued that “It is expensive, but so was the Canadian Pacific Railway a century ago. Is it too big a project for Canada? Only in the view of those who have lost faith in what Canada is all about” (Munzur, 2021). As with contemporary Arctic infrastructure debates, projects meant for northern development are considered on their strategic and political objectives rather than commercial returns.

In practice, however, the project proved politically and legally unsustainable. The 1972 federal election reduced the Liberals to a minority government reliant on New Democratic Party support, weakening Ottawa’s ability to push the project forward. At the same time, Indigenous organizations and environmental groups mobilized significant opposition to the pipeline. Reflecting growing concern about the social and environmental consequences of Arctic energy development, the federal government appointed former NDP politician and British Columbia Supreme Court Justice Thomas Berger in 1974 to lead an inquiry into the

Trump’s remarks provoked a sharp backlash in Canada and helped propel Carney’s Liberals to victory. Yet the underlying vulnerability remains. As earlier sections have shown, Canada’s energy systems exemplify the extent of North American economic integration. Electricity, oil, and natural gas flow through a dense, cross-border infrastructure network shaped more by geography than by political boundaries. No other pair of countries has developed such extensive energy co-dependence. As the smaller partner, Canada bears greater risk: the United States can diversify its trade and security relationships far more easily than Canada can. Compounding this imbalance, Canada faces weak productivity growth, with underinvestment in machinery and equipment contributing to stagnant per-capita GDP growth and declining relative living standards.

It is in response to these structural challenges that the Carney government has revived the Harper-era ambition of “realizing our full potential as an energy superpower” (Prime Minister of Canada, 2025). In this context, the phrase signals less a desire for coercive leverage than an effort to reduce vulnerability through scale, reliability, and diversification. Central to this strategy is the rapid approval and

construction of energy infrastructure to expand export options beyond the United States while maintaining Canada’s role as a dependable supplier to its primary market.

In June 2025, Parliament passed the *Building Canada Act*, a powerful new statute allowing the federal government to designate certain developments as “Projects of National Interest” (PoNIs). Projects added to Schedule 1 of the Act are effectively pre-authorized and exempted from key provisions of the *Impact Assessment Act* (Building Canada Act, 2025). The government may also exempt PoNIs from laws and regulations listed in Schedule 2, many of which have already been added. This framework represents a significant recalibration of federal authority over infrastructure approval. To execute on this approach, the Carney government established the Major Projects Office (MPO), tasked with accelerating approval timelines and advising on PoNI designation. Of the thirteen projects currently under MPO review, seven involve energy infrastructure, including major transmission lines, LNG Canada Phase 2, the Ksi Lisims LNG project, and a small modular reactor project in Ontario (Major Project Office, 2026).

Federal–provincial coordination is also central to the “energy superpower” vision. A Memorandum of Understanding between Ottawa and Alberta commits both governments to expanding oil and gas production and exports. As written, the MoU also commits the two governments to reducing emissions from heavy oil production to “best-in-class” levels by 2050 through an escalating industrial carbon tax (Government of Canada & Government of Alberta, 2025). The MoU envisions construction of the large-scale Pathways carbon capture and storage project alongside a new pipeline capable of transporting at least one million barrels per day of Alberta oil sands crude to Asian markets.

While the feasibility of Pathways and a new export pipeline are contested, other elements of the MoU have more immediate regulatory implications. The MoU eliminates the proposed Oil and Gas Emissions Cap and halts implementation of the Clean Electricity Regulations in Alberta, reversing course on two flagship Trudeau-era policies that had generated significant resistance within the energy sector. The agreement also anticipates further expansion of the Trans Mountain pipeline, potentially increasing total capacity to 1.25 million barrels per day.

11.1 Challenges for the Energy Superpower Vision

Despite its appeal, the real implications of being an “energy superpower” remain ambiguous. Traditionally, the term describes states that wield energy exports as geopolitical leverage, such as Saudi Arabia’s protection under the U.S. security umbrella, Russia’s coercive gas diplomacy, or Qatar’s outsized global influence. As a free-market economy which supports rules-based dealings with other nations, Canada is poorly suited to take on such a role. Attempting to emulate these countries would undermine Canada’s credibility as a stable supplier. A more realistic strategy is for Canada to continue acting as a trusted energy security partner to the United States while incrementally expanding relationships with Europe and the Indo-Pacific.

Tensions also remain between expanded oil and gas exports and Canada's climate commitments. Many of Prime Minister Carney's early actions roll back elements of Trudeau-era climate policy, leaning on industrial carbon pricing as the federal government's central mitigation tool. However, this single tool is increasingly expected to accomplish multiple policy goals. Canada's *Climate Competitiveness Strategy*, released alongside Budget 2025, frames carbon pricing as both an emissions-reduction mechanism and a means of improving export competitiveness (Finance Canada, 2025, pp. 104). The strategy argues that lower-emissions oil and gas will retain value in a decarbonizing world, and so the incentives need to be put in place now to rapidly decarbonize. However, it leaves unresolved a fundamental question: if global decarbonization falters, will it be in Canada's national interest to tax its main export industry, thereby reducing its competitiveness against other nations?

The competitiveness challenge is also relevant for the staying power of the recently reinvigorated Canadian economic nationalism. While expanding export routes to Asia and Europe could strengthen Canada's negotiating position with the United States, private firms must be judicious with their capital spending. They may not be convinced that taking on the risk of building expensive energy diversification projects is a worthwhile investment for their shareholders. For example, TransCanada Pipeline is now a continental energy firm named TC Energy which often prefers investing in the U.S. over Canada (TC Energy, 2025). For many investors, infrastructure serving U.S. demand remains more profitable than politically uncertain projects aimed at distant markets. Moreover, the Trump administration's economic nationalism could further attract capital away from Canada, as firms seek alignment with American policy priorities. There are also serious questions about whether current or future U.S. Administrations will tolerate Canada diversifying in the wrong direction by becoming one of China's foremost energy security partners.

Canada's energy geography builds a stubborn logic into its energy geopolitics. Canada possesses vast resources, and the United States offers unmatched scale of demand. This natural partnership has underpinned Canada's prosperity for decades. Yet the reorientation of American foreign policy under Trump, embodied in a sphere of influence-based approach to the Western Hemisphere, may force Canada into uncomfortable choices. The country may have to weigh the material benefits of deeper integration within an explicit American sphere of influence against the economic and security risks of actively pursuing greater autonomy. In this sense, the "energy superpower" debate does not resolve Canada's energy geopolitics, but restates its central dilemma.

Conclusion

Rising trends of economic nationalism around the globe and the resulting threats to multilateral institutions pose major challenges for Canada. This problem is especially heightened as the United States turns away from its traditional role as the guarantor of an admittedly imperfect rules-based international order. The Trump Administration's "51st State" rhetoric is especially unhelpful for maintaining a positive

and trusted bilateral relationship. While a serious disruption in relations between Canada and the United States remains unlikely, the consequences for Canada could be particularly severe where it comes to energy vulnerability.

Like any energy system, Canadian energy is the result of geographical and geological conditions. What makes Canada's energy industry different is its proximity to massive American energy demand. Canada is vulnerable in two distinct ways: it is reliant on the United States as a market for Western Canadian energy supply, and it is also reliant on the United States for its security of energy supply. Canada is also heavily integrated with the American-led security apparatus through NATO, NORAD, and the Five Eyes intelligence community. Canadian energy geopolitics is therefore defined by tension between economic gravity and political autonomy, infrastructure constraints, and export diversification, and between economic security and social license.

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