A Synergistic Future: Integrating Nuclear Fusion with Renewable Energy Systems for Global Energy Transition

David Gilles

Independent Researcher

david@davidgillesresearch.publicvm.com | ORCID: 0009-0006-5123-7384

June 28, 2025

Author Note

This manuscript was edited and revised with the assistance of Google Gemini 2.5 Pro, an AI language model developed by Google.

Correspondence concerning this article should be addressed to David Gilles.

Email: dgilles426@gmail.com Phone: +1 (818) 565-9735

Abstract

The global energy transition, driven by the climate crisis, is increasingly dominated by variable renewable energy (VRE) sources, whose inherent intermittency presents a critical challenge to grid stability and necessitates the integration of firm, dispatchable, carbon-free power to ensure a reliable energy supply. This paper critically evaluates the potential role of nuclear fusion, not as a standalone baseload generator, but as a synergistic component within a VRE-dominated energy system, arguing that its viability is contingent upon a clear-eyed assessment of its benefits as a flexible energy hub against significant, newly quantified challenges in waste management, resource sustainability, and economic competitiveness. Through a systematic review and synthesis of recent literature spanning engineering, life-cycle assessment (LCA), materials science, and socio-economic analysis, we find that fusion demonstrates significant potential to provide firm power and high-quality process heat for integrated applications such as green hydrogen production, thereby enabling the decarbonization of hard-to-abate sectors. However, this potential is tempered by three critical findings: current reactor designs are projected to produce substantial volumes of Intermediate-Level Waste (ILW) requiring long-term geological disposal; global scalability may be limited by resource constraints, including competition for lithium with the battery industry and reliance on limited supplies of beryllium and helium; and fusion's projected high Levelized Cost of Energy (LCOE) is unlikely to be competitive with VREs for bulk electricity generation. We conclude that fusion's most plausible role is as a flexible partner to renewables, but its development requires a strategic pivot towards designing for load-following and hybrid applications, developing advanced materials to minimize long-lived waste, and engaging in transparent, life-cycle-informed assessments to ensure its path is aligned with the principles of a truly sustainable and equitable global energy future.

Keywords: nuclear fusion, energy transition, life-cycle assessment (LCA), integrated energy systems, sustainable energy

A Synergistic Future: Integrating Nuclear Fusion with Renewable Energy Systems for Global Energy Transition

The accelerating impacts of the climate crisis represent the most formidable environmental and engineering challenge of the 21st century. The scientific consensus, articulated through bodies like the Intergovernmental Panel on Climate Change (IPCC), establishes an unambiguous mandate: to limit global warming to 1.5°C above pre-industrial levels, a rapid, deep, and near-total decarbonization of the global energy system is not merely an option, but an imperative. This monumental task requires a fundamental re-engineering of the world's primary infrastructure, shifting away from the combustion of fossil fuels that has powered industrial society for over a century towards a new energy paradigm founded on principles of sustainability, scalability, and equity.

The primary vector for this global energy transition has been the remarkable and rapid deployment of variable renewable energy (VRE) sources, principally solar photovoltaics (PV) and wind power. Driven by precipitous cost reductions and supportive policy frameworks, VREs are no longer a niche alternative but the dominant form of new energy capacity being installed globally. This success has fundamentally altered the long-term outlook for decarbonization, demonstrating a viable pathway for generating vast quantities of carbon-free electricity. However, the intrinsic nature of these technologies—their variability dependent on weather and diurnal cycles—presents a profound systems-level engineering challenge. High penetration of VREs introduces significant intermittency into the electrical grid, creating challenges for grid stability, reliability, and the economic viability of all generating assets. Without firm, dispatchable power sources to balance supply and demand, societies risk either grid instability or the significant economic and environmental loss associated with the curtailment of clean energy during periods of peak production.

This inherent challenge of a VRE-dominated grid creates a clear and compelling need for complementary technologies that can provide firm, carbon-free, and dispatchable power. For decades, nuclear fusion has been heralded as the ultimate solution to humanity's energy needs. The promise of fusion is rooted in its fundamental physics: harnessing the power of stellar processes to generate immense energy from abundant terrestrial fuels—deuterium from seawater and lithium for tritium breeding—without producing greenhouse gases, long-lived radioactive waste, or the risk of a core meltdown. Decades of international research, from the pioneering work on magnetic and inertial confinement to the construction of massive experimental facilities like the International Thermonuclear Experimental Reactor (ITER), have advanced our understanding of plasma physics to the point where demonstrating net energy gain is now a question of engineering rather than fundamental science.

Yet, the very context in which fusion was conceived has been transformed. The traditional vision of fusion power plants as direct, one-for-one replacements for large, baseload fossil fuel or fission plants is becoming increasingly anachronistic. The future energy grid will not be a simple system requiring constant, monolithic power blocks, but a complex, dynamic, and highly integrated network. The most significant value in this new grid will lie not in raw baseload capacity, but in flexibility: the ability to rapidly ramp power up and down to follow load, complement the fluctuating output of VREs, and ensure the system remains stable and economically efficient. Consequently, the value proposition of nuclear fusion must be critically re-evaluated. Its success will no longer be measured solely by its ability to generate power, but by its capacity to synergize with the new energy landscape.

This re-evaluation opens a more sophisticated and compelling potential role for fusion: as a flexible, integrated energy hub. The paradigm is shifting from viewing nuclear plants merely as electricity generators to seeing them as the core of Nuclear-Renewable Hybrid Energy Systems (N-R HES). In this model, a fusion reactor's immense thermal and electrical output can be dynamically dispatched to multiple applications beyond the electrical grid. This vision leverages fusion's unique ability to produce constant, high-quality heat, a capability that distinguishes it from VREs. This thermal energy can be used to power high-temperature steam electrolysis (HTSE), the most efficient known method for producing carbon-free "green" hydrogen.

This hydrogen vector is critical, as it provides a pathway to decarbonize the "hard-to-abate" sectors—such as heavy industry, shipping, and long-haul transport—where direct electrification is impractical. Furthermore, the co-generation of process heat can directly support industrial activities like chemical synthesis and manufacturing, while excess electrical power can be directed towards other vital services like large-scale water desalination. This integrated approach not only maximizes the economic return on a high-capital asset but also positions fusion as a key enabler of a circular, sector-coupled economy, providing a firm, reliable backbone that enhances the value and penetration of VREs.

However, as fusion transitions from a theoretical physics concept to a tangible engineering project, its promise must be tempered with a rigorous, systems-level assessment of its full life-cycle sustainability. A technology's environmental footprint is not limited to its operational emissions. The Life-Cycle Assessment (LCA) framework compels us to consider the "embodied" energy and emissions associated with the entire supply chain, from raw material extraction and manufacturing to construction and decommissioning. Initial LCA studies indicate that while fusion, like other nuclear technologies, has a very low life-cycle carbon footprint, its upstream impacts are non-trivial and must be transparently accounted for.

This critical lens must also be applied to one of fusion's most proclaimed advantages: its waste profile. While fusion does not produce high-level waste in the form of spent nuclear fuel, recent materials science research indicates that the intense neutron bombardment inherent to the D-T fuel cycle will activate the reactor's structural components. This process is now understood to produce significant quantities of Intermediate-Level Waste (ILW), which, under current international regulatory frameworks, requires long-term deep geological disposal, similar to waste from fission reactors. This finding fundamentally challenges a core part of the historical narrative and places fusion's waste stream in a much more direct comparison with that of advanced Generation-IV fission technologies.

Finally, the viability of fusion must be assessed against the dual pragmatic tests of scalability and global equity. The immense technological complexity of fusion power plants translates to high capital costs and significant resource requirements. The global-scale deployment needed to make a meaningful impact on climate change would require secure supply chains for strategic materials, including not only lithium for the fuel cycle but also beryllium as a neutron multiplier and helium as a coolant, all of which face their own constraints. The projected Levelized Cost of Energy (LCOE) for first-of-a-kind fusion plants is expected to be substantially higher than that of established VREs, raising significant questions about its market competitiveness. This economic reality leads to a crucial question of equity: can a technologically intensive, high-capital energy source like fusion be a globally equitable solution? Or does it risk becoming an energy source accessible only to the wealthiest nations, potentially widening the gap in the global energy transition and failing to address the needs of the Global South where energy demand is growing most rapidly?

This paper will therefore conduct a critical, multi-faceted evaluation of the role of nuclear fusion in the impending global energy transition. It will argue that fusion's most viable and valuable future is not as a standalone baseload power source, but as a flexible, integrated partner to renewables. However, this potential is contingent upon the fusion community confronting and overcoming significant, newly-clarified challenges in life-cycle sustainability, radioactive waste management, resource scalability, and economic competitiveness. The paper is structured in two parts. Part I will explore the strategic and synergistic potential of fusion, examining its role as a firm power source and an integrated energy hub, including its applications in micro-grids and the hydrogen economy. Part II will provide a critical assessment of fusion’s practical viability, analyzing its full life-cycle environmental footprint, its complex waste profile, its resource and scalability constraints, and the overarching challenges of economic viability and equitable global deployment. Through this balanced analysis, we aim to provide a realistic and nuanced roadmap for the future development and potential integration of fusion energy into a sustainable and just global energy system.

Part I: The Strategic and Synergistic Potential of Fusion Energy

2. Fusion as a Source of Firm, Carbon-Free Power

The scientific and engineering rationale for the continued pursuit of thermonuclear fusion is anchored in its potential to provide a source of energy that is simultaneously high-density, carbon-free, and reliant upon a virtually inexhaustible fuel cycle. While the technological pathway to commercialization remains arduous, a comprehensive evaluation of fusion's role in a future energy system must begin with an analysis of this fundamental value proposition. This section will first deconstruct the core attributes of fusion power, then examine the primary scientific approaches being developed to achieve net energy gain, and finally, reposition fusion’s strategic function within the modern context of a VRE-dominated electrical grid where flexibility and firmness are paramount.

2.1 The Fundamental Value Proposition

The primary driver for fusion research is its potential to address the trilemma of energy security, environmental sustainability, and scalability. As Ongena et al. (2016, p. 398) state, “Our modern society requires environmentally friendly solutions for energy production... Nuclear fusion is an important option for a clean and safe solution for our long-term energy needs.” The most accessible fusion reaction for terrestrial application is the one between the hydrogen isotopes deuterium (D) and tritium (T). The intrinsic appeal of this D-T fuel cycle lies in the global abundance of its primary feedstocks. As described by Ongena et al. (2016, p. 399), “the fuels for DT fusion reactions are deuterium, which is plentiful, as 1/6,000th of all water on Earth contains this atom, and lithium, widely available in rocks and oceans,” from which tritium is bred within the reactor itself.

This fuel cycle translates to an extraordinary power density and fuel efficiency, orders of magnitude beyond chemical combustion and substantially greater than nuclear fission. The minute mass-to-energy conversion rate of the fusion process means that minuscule quantities of fuel can release vast amounts of energy. This efficiency is starkly illustrated by the fact that “about 15 g of DT fuel suffices to produce all the electrical energy needed by one EU citizen for 80 years” (Ongena et al., 2016, p. 399). This characteristic fundamentally alters the material handling, transportation, and geopolitical constraints associated with the fuel supply chain. Furthermore, the operational process is inherently carbon-free. The primary product of the D-T reaction is an energetic alpha particle (a helium nucleus) and a neutron. Once the alpha particle has transferred its energy to the plasma, it forms a benign byproduct, as “The fusion product is He, a non-radioactive, chemically inert substance, not contributing to climate change” (Ongena et al., 2016, p. 408). This operational cleanliness is the central pillar of fusion’s environmental case, positioning it as a direct long-term alternative to fossil fuel combustion.

2.2 Pathways to Net Energy Gain: Magnetic and Inertial Confinement

Harnessing fusion energy requires creating and containing a plasma at temperatures exceeding 150 million °C. The scientific community has predominantly advanced two distinct but complementary approaches to overcome this challenge: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).

Magnetic confinement, the more mature of the two approaches, leverages the principle that charged particles are constrained by magnetic fields. As Ongena et al. (2016, p. 399) explain, “A charged particle in a strong magnetic field is bound to the magnetic field lines as a result of the Lorentz force... it follows a helical (corkscrew) path around a field line. This is called ‘magnetic confinement’.” The primary MCF configuration is the tokamak, a toroidal device that uses powerful magnets and a strong induced plasma current to confine the hot fuel.

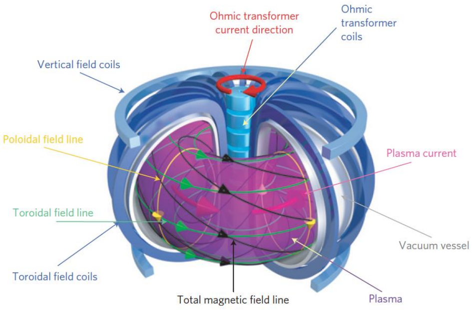


Figure 1. A schematic diagram of a modern tokamak, illustrating the primary magnetic field systems. The toroidal field coils generate the main confining field, while the central ohmic transformer induces a current in the plasma. This plasma current, in turn, generates a poloidal magnetic field. The superposition of these fields creates the helical magnetic surfaces that confine the plasma particles. (Adapted from Ongena et al., 2016).

Decades of research have yielded substantial progress, to the point that, “Since the early 1990s, up to 16 MW of fusion power has been released in pulses of a few seconds, corresponding to a power multiplication close to break-even” (Ongena et al., 2016, p. 398). This scientific advancement has culminated in the global construction of ITER, a device designed to produce 500 MW of fusion power and demonstrate a tenfold power amplification, thereby validating the scientific feasibility of sustained fusion burn. A prominent alternative is the stellarator, which “relies on currents external to the plasma to create the helical magnetic configuration” (Ongena et al., 2016, p. 400). While technologically more complex, devices like Japan’s Large Helical Device (LHD), which “started operation in March 1998” (Ongena et al., 2016, p. 400), offer the potential for inherently steady-state operation, a key advantage over the naturally pulsed tokamak.

Inertial confinement represents a fundamentally different approach, what Hora (2004, p. 439) terms the “well-known alternative of inertial confinement fusion using laser or particle beams.” Instead of continuous magnetic containment, ICF seeks to achieve fusion conditions through immense compression. The concept was enabled by “the discovery of the laser that this can be used for producing extremely high energy densities within very short times in very small volumes as needed for controlled ignition of nuclear fusion reactions" (Hora, 2004, p. 441). In a typical ICF scheme, high-power lasers or particle beams rapidly ablate the outer surface of a small fuel pellet, creating an implosive force that compresses and heats the core to the point of ignition. While both MCF and ICF face distinct and significant physics and engineering challenges (Walsh et al., 2019), they represent credible, well-established scientific pathways toward achieving net energy gain.

2.3 The Modern Role: Load-Following and Firm Capacity

The contemporary energy system, increasingly characterized by high VRE penetration, forces a re-evaluation of fusion's strategic role. The classic model of baseload power is being supplanted by a system that prioritizes flexibility and firmness to manage intermittency. Indeed, as renewable generation often exceeds demand, it can drive electricity prices to be "very low or even negative, meaning that plants must either curtail output or sell electricity at a loss" (Bragg-Sitton et al., 2020, p. 2). In this environment, the primary value of a firm generator is its ability to provide dispatchable power that can stabilize the grid and complement variable sources. As Nicholas et al. (2021, p. 4) note, "Within a grid with large fractions of intermittent renewables, dispatchable energy sources that can match demand will lower overall system costs."

Fusion is therefore increasingly positioned not as a standalone source, but as a technology that is both a "primary source and by complementing and enabling other clean energy sources" (Bragg-Sitton et al., 2020, p. 1). However, achieving this flexibility is a significant technical challenge. While a fusion plasma can, in principle, be modulated, this is "complicated by knock-on effects associated with reduced plasma power output" and creates a "tension between load-following directly with the plasma power output and control of the plasma" (Nicholas et al., 2021, p. 4). Safely navigating the multi-dimensional parameter space of a burning plasma while dynamically altering its output requires a level of control that far exceeds the demands of steady-state operation. The engineering complexity is substantial, as “real-time control systems must ‘pilot’ them through a multidimensional parameter space, avoiding regions dangerous to the plasma confinement” (Nicholas et al., 2021, p. 4). Therefore, while the potential for fusion to provide firm, flexible power is clear, its practical implementation remains a key research and development challenge. Ultimately, fusion's success in a future, VRE-dominated market may hinge on its ability to solve this intermittency problem. Its contribution will be most significant in a scenario where it “can help mitigate renewables’ intermittency problems” (Nicholas et al., 2021, p. 8), thereby solidifying its role as a critical enabler of a deeply decarbonized and reliable energy system.

3. The Integrated Energy Hub: Fusion's Role Beyond Electricity

The strategic re-evaluation of nuclear fusion's role is predicated on a fundamental paradigm shift occurring across the global energy sector: the move away from centralized, siloed electricity generation towards highly coupled, multi-input, multi-output Integrated Energy Systems (IES). Within this new framework, the value of a high-capital asset like a fusion power plant is no longer measured solely by the kilowatt-hours it delivers to the grid, but by its ability to dynamically allocate thermal and electrical energy to a portfolio of services, thereby maximizing its capacity factor, economic return, and overall contribution to deep decarbonization. This section will explore this paradigm shift, detail the conceptual frameworks for system integration, and examine the specific non-electric applications—namely hydrogen production, industrial process heat, and water desalination—that constitute the core of fusion's potential role as a flexible energy hub.

3.1 The Paradigm Shift to Integrated Energy Systems (IES)

The primary driver for the development of IES is the economic and operational pressure placed on firm power generators by the high penetration of VREs. As noted by Bragg-Sitton et al. (2020, p. 3), the resulting electricity price volatility has led "several US nuclear plants... to evaluate the technical and economic feasibility of redirecting excess energy (electrical or thermal) to the production of other commodities or to energy storage systems." This move from a singular focus on electricity to a diversified output model defines the core of the IES concept. Such systems are envisioned to "incorporate multiple energy resources and generation technologies to support multiple energy users, directly leveraging thermal energy or electricity," with sophisticated control schemes designed to "dynamically apportioning thermal and/or electrical energy to provide responsive generation to the power grid while maximizing energy efficiency/utilization" (Bragg-Sitton et al., 2020, p. 3).

This vision necessitates a departure from the traditional view of the grid, where dispatchable generators simply compensate for the "shortcomings of RESs" (Gabbar et al., 2020, Energies, p. 1). Instead, it proposes a symbiotic relationship.

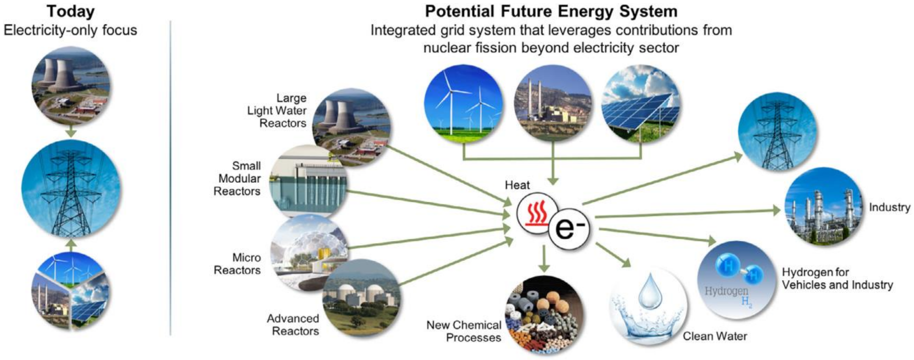


Figure 2. A conceptual model illustrating the transition from a traditional electricity-only focus to a potential future Integrated Energy System. A central nuclear heat source (e.g., a fusion reactor) provides thermal and electrical energy that can be dynamically dispatched to the grid or to co-located industrial processes to produce non-electric commodities like hydrogen and clean water. (Adapted from Bragg-Sitton et al., 2020).

Initiatives like the U.S. Department of Energy's program on IES were established specifically to "evaluate potential options for the coordinated use of nuclear and renewable energy generators to meet energy demands across the electricity, industrial, and transportation sectors" (Bragg-Sitton et al., 2020, p. 1). In this context, a fusion plant would function as a firm, reliable backbone, generating constant heat and power that can either be sent to the grid or diverted to industrial off-takers, effectively creating a persistent, high-value demand sink for its own energy output. This ability to redirect energy provides a critical economic buffer, allowing the plant to maintain high-capacity operation even when grid electricity prices are low or negative, while simultaneously enabling the deeper penetration of VREs by providing essential grid-stabilizing services.

3.2 Case Studies and Coupling Methods

The translation of the IES concept into practice requires the development of robust frameworks for coupling the nuclear heat source with various renewable inputs and industrial processes. The complexity of this integration can vary significantly, ranging from simple electrical connections to deeply intertwined thermal and chemical systems. Gabbar et al. (2020, Energy Reports, p. 189) have proposed a useful taxonomy for these architectures, outlining three distinct methods: "Direct Coupling, Single Resource and Multiple products-based Coupling, and Multiple Resources and Multiple products-based Coupling." Direct coupling represents the simplest form, where multiple generators feed into a common electrical bus. However, the more advanced models are where the synergistic potential is greatest.

In a "Single Resource and Multiple Products-based Coupling" model, the fusion reactor is the primary energy source. Its output is dynamically partitioned; for instance, "The recovered waste thermal energy from the nuclear reactor... is utilized to serve thermal demand and different thermal applications. For instance, a part of electricity and waste heat can be utilized in the seawater desalination plant and hydrogen production plant" (Gabbar et al., 2020, Energy Reports, p. 192). This model requires the integration of sophisticated energy conversion technologies to manage the flow between different energy vectors. For example, a "Heat-to-Electricity (H2E) unit is included in this hybridization to convert excess heat energy to electricity, depending on the need of electric demand" (Gabbar et al., 2020, Energy Reports, p. 192). This allows thermal energy not immediately required for an industrial process to be converted back into a valuable grid service. Such a system architecture transforms the fusion plant from a passive generator into a dynamic and responsive component of the larger energy ecosystem, capable of optimizing its output based on real-time economic and grid signals.

3.3 Applications: Hydrogen, Process Heat, and Desalination

The ultimate value of a fusion-centered IES lies in the portfolio of high-value, non-electric commodities it can produce. These applications leverage the unique capability of a fusion plant to provide a continuous and reliable supply of both electricity and high-quality heat. The most prominent among these are the production of hydrogen, the supply of industrial process heat, and the desalination of water. Bragg-Sitton et al. (2020, p. 2) broadly define this as the "production of additional, nonelectric commodities (eg, potable water, hydrogen, and liquid fuels) via excess thermal and electrical energy from the nuclear system."

Hydrogen, in particular, is seen as a cornerstone application. It is an essential chemical feedstock and a clean energy carrier that can decarbonize sectors where direct electrification is difficult. An IES centered around fusion is uniquely positioned for its production, as hydrogen can be "employed in multiple off-take industries (eg, steel manufacturing, fertilizer production, biomass upgrading, chemical production...)" making it "particularly attractive as an intermediate commodity whose end use may vary based on the regional resources and needs" (Bragg-Sitton et al., 2020, p. 5). Fusion's ability to provide high-temperature heat is critical, as "High-temperature steam electrolysis (HTSE) utilizes heat and electricity to split water into hydrogen and oxygen, where the additional heat reduces the amount of work needed" (Bragg-Sitton et al., 2020, p. 6). This makes it a more efficient process than electrolysis powered solely by electricity from VREs.

Beyond hydrogen, the direct supply of process heat to industrial facilities is a major application. "The manufacturing industry currently uses about 25 exajoules (EJ) of delivered energy," with a significant portion derived from "fossil-fired combustion as a source of either direct heating... or indirect heating" (Bragg-Sitton et al., 2020, p. 4). By co-locating a fusion plant with industrial parks, this fossil-fuel-based heat demand could be met with a carbon-free source, representing a significant vector for industrial decarbonization. Finally, in an increasingly water-stressed world, desalination represents another vital service. "Desalination via RO [reverse osmosis]... can be driven via excess electricity during times of high renewable generation or low demand" (Bragg-Sitton et al., 2020, p. 5).

The economic case for these applications is compelling. By diversifying its revenue streams, the fusion plant is less susceptible to electricity market volatility. The ability to "co-generat[e] hydrogen" or "simultaneously co-generating load-following electricity could improve the economics of load-following" (Nicholas et al., 2021, p. 4). This transforms the operational calculus of the plant, enabling it to maintain high availability and profitability while providing a suite of products and services essential for a deeply decarbonized, resilient, and sustainable global energy system.

4. Technology Pathways for Deployment: From Large-Scale to Micro-Grids

The strategic potential of nuclear fusion, as established in the preceding sections, can only be realized through concrete technology deployment pathways. The choice of these pathways is not merely a technical decision but a strategic one with profound implications for the structure of future energy grids, economic viability, and the potential for globally equitable access. Historically, fusion development has been predicated on a centralized, large-scale model. However, the evolution of the global energy system and an increasing focus on energy democracy and resilience have given rise to new, more flexible deployment concepts. This section will first examine the conventional large-scale roadmap for fusion deployment, then explore emerging small-scale and micro-hybrid models, and finally assess the potential for these divergent pathways to contribute to global energy security and a just energy transition.

4.1 The Conventional Roadmap: Large-Scale, Grid-Stabilizing Plants

The established international strategy for fusion energy development follows a linear, progressive scaling model, beginning with large-scale experimental devices and culminating in gigawattclass power stations. This "conventional roadmap" is best exemplified by the global effort centered on the International Thermonuclear Experimental Reactor (ITER). The “main objective of ITER is to demonstrate the feasibility of a burning fusion plasma,” and “although not yet a power plant, the size and complexity of ITER are indeed challenging” (Ongena et al., 2016, p. 407). ITER is designed as a scientific proof-of-concept, a necessary precursor to a demonstration power plant (DEMO) that will be the first to connect to the electrical grid.

The engineering and design logic of this pathway is based on scaling up proven tokamak physics to a size sufficient for net power production. As Ongena et al. (2016, p. 408) note, "Present designs [for DEMO] foresee a major radius R_0 in the range 7–9 m (the major radius of ITER is 6.2 m), which should be sufficient to provide the high Q." The DEMO concept, which forms the basis for most governmental fusion programs, envisions large, centralized plants that leverage economies of scale to produce power competitively, with “designs similar to the EU-DEMO1 design (Federici et al., 2002)" serving as the dominant template (Nicholas et al., 2021, p. 2). The strategic function of these large-scale plants is clear: to provide a firm, carbon-free source of bulk power. In a future energy system dominated by intermittency, such a plant “could serve as a carbon-free large-scale backup electricity system to cover dark and windstill periods in a system dominated by intermittent energy from wind and the Sun” (Ongena et al., 2016, p. 408). This pathway positions fusion as a direct successor to the large, centralized fossil fuel and fission plants of the 20th century, providing essential grid-stabilizing services at a national or continental scale.

4.2 Emerging Concepts: Small-Scale and Micro-Hybrid Systems

In parallel to the conventional roadmap, a disruptive trend is emerging, driven by a recognition that flexibility and distributed generation are becoming increasingly valuable. This has led to a focus on smaller, more adaptable nuclear systems. The guiding principle is that future "nuclear plant designs are beginning to come in smaller packages that can provide dispatchable, clean energy in distributed energy systems that are even more complementary to today's evolving grid" (Bragg-Sitton et al., 2020, p. 4). This conceptual shift mirrors developments in the advanced fission sector, particularly the interest in Small Modular Reactors (SMRs).

For fusion, this has catalyzed interest in concepts like the Micro Modular Reactor (MMR), which is defined as a "small-scale reactor, characterized by a power rating in between 1 MWe to 20 MWe" (Energies 2020, 13, 1642, p. 9). The advantages of such a system lie in its "small size, affordability, security, reliability, and innovativeness" (Energies 2020, 13, 1642, p. 9), enabling factory fabrication and more rapid deployment compared to gigawatt-scale projects. This modularity opens up new possibilities for integration, leading to the concept of the Nuclear-Renewable Micro Hybrid Energy System (N-R MHES). An N-R MHES is defined as a system where the "modular-scale coupling method" allows a small fusion reactor to be integrated with local renewable resources, with "immense applications in remote community service, transportation electrification, distant oil and gas mining facilities, and remote chemical industries" (Energies 2020, 13, 1642, p. 4).

These systems are explicitly designed for off-grid or microgrid applications. As Gabbar et al. (2020, IEEE Access, p. 9) note, there are "three types of hybridization techniques of N-R MHES for off-grid applications... proposed in this paper." Such a system represents a "unique model of power supply for remote areas" (Abdussami, Adham, and Gabbar, 2020, p. 190), providing a self-contained, resilient energy solution where a large, centralized grid is either unavailable or impractical.

4.3 Energy Security, Democracy, and Equitable Deployment

The choice between large-scale and small-scale deployment pathways carries significant geopolitical and socioeconomic weight. The conventional, centralized model implicitly reinforces existing energy paradigms. In many developing nations, "Energy planning... has typically followed a top-bottom approach," where "decision-making takes place inside governmental institutions" (Vanegas Cantarero, 2020, p. 5). The deployment of large, capital-intensive fusion plants could perpetuate this model, potentially reinforcing the influence of state-level actors and international corporations in a dynamic that some critics have likened to a "'new scramble' for the continent's... wealth" (Vanegas Cantarero, 2020, p. 5).

In contrast, the distributed, modular nature of N-R MHES offers a pathway more aligned with the principles of energy democracy. This concept entails "a reclaim of social and public control over the energy sector, and a restructure of the energy sector... to better support democratic processes, social justice and inclusion" (Vanegas Cantarero, 2020, p. 8). Smaller, community-scaled systems could, in theory, provide local control over energy resources. However, this is not a simple solution, as demonstrated by the fact that even "community renewable energy faces challenges such as... lack of local technical and operational knowledge, and lacking or conflicting regulatory framework" (Vanegas Cantarero, 2020, p. 7). The technological leap to operating a micro-fusion plant would be orders of magnitude greater.

Nonetheless, the potential for a more equitable global energy distribution is a powerful motivator for both pathways. For large-scale fusion, its reliance on globally abundant fuel could "help to reduce energy dependencies in the world, an important factor contributing to a more peaceful world" (Ongena et al., 2016, p. 408). For small-scale systems, the key advantage is their ability to serve complex, remote loads that cannot be met by renewables alone. As Abdussami, Adham, and Gabbar (2020, p. 205) argue, while a "RESs-based microgrid is capable of handling small-scale residential load," many "industries and commercial platforms... are located in remote areas where electricity and thermal demand are significantly high... Therefore, N-R MHES could be the most profitable and reliable hybrid energy system in this respect." By providing a complete energy solution for remote industrial or community needs, these small-scale systems could become a critical tool for sustainable development, offering a pathway to leapfrog fossil-fuel-dependent infrastructure and foster genuine energy independence.

5. The Hydrogen Economy Link: A Critical Application for Fusion

The potential for nuclear fusion to serve as an integrated energy hub, as established in the previous section, finds its most compelling and strategically significant application in the production of clean hydrogen. The transition to a "hydrogen economy" is increasingly recognized as a critical pathway for deep decarbonization, particularly for sectors where direct electrification is technologically or economically prohibitive. A fusion reactor, with its unique ability to provide a continuous, carbon-free source of both high-quality heat and electricity, is theoretically well-positioned to become a cornerstone of future hydrogen production. This section provides a life-cycle analysis of various hydrogen supply chains, evaluates the specific advantages fusion offers for efficient hydrogen generation, and assesses fusion's role in decarbonizing hard-to-abate sectors via the hydrogen vector.

5.1 Life-Cycle Analysis of Hydrogen Supply Chains

A comprehensive assessment of hydrogen's environmental credentials requires a rigorous life-cycle analysis (LCA) that accounts for all upstream and downstream emissions and energy consumption. As Ren et al. (2020, p. 3) establish, it is necessary to model the "life-cycle energy consumption and GHG emissions of hydrogen supply chains" to make a valid comparison between different production pathways. The results of such analyses reveal a stark differentiation based on the primary energy source.

The most common and currently cheapest method of producing hydrogen is through steam methane reforming (SMR) of natural gas (NG). However, this pathway carries a significant carbon footprint. Ren et al. (2020, p. 12) find that "NG-based hydrogen has slightly lower GHG emissions... than electricity but about twice that of fossil fuels." Likewise, hydrogen produced from coal gasification has even higher emissions. In contrast, hydrogen produced using electricity from carbon-free sources presents a much cleaner profile. The analysis by Ren et al. (2020, p. 12) concludes that "Hydrogen production from hydropower/nuclear power... and by-product hydrogen... have the same or slightly lower GHG emissions as fossil fuels." This highlights a critical fact: the environmental benefit of hydrogen as an energy carrier is entirely dependent on its production method. Using hydrogen produced from unabated fossil fuels offers no climate advantage over the direct combustion of those fuels.

Furthermore, the physical properties of hydrogen introduce significant energy penalties in its supply chain. Due to its low density, hydrogen must be highly compressed or cryogenically liquefied for storage and transport, processes which are themselves energy-intensive. The analysis by Ren et al. (2020, p. 19) underscores that "The primary-energy consumption and GHG emission in the hydrogen transportation and storage stage are high and cannot be ignored." For gaseous hydrogen, transport via "a pipeline has high costs with low energy consumption" (Ren et al., 2020, p. 13), making it suitable only for dedicated industrial corridors. This places the energy burden on compression and storage, which must be factored into the overall life-cycle cost and efficiency of any hydrogen-based energy system.

5.2 Fusion's Potential for Efficient Hydrogen Production

It is within this context of production efficiency that nuclear fusion offers a distinct advantage. While hydrogen can be produced via electrolysis using electricity from any source, including VREs, the efficiency of this process can be significantly enhanced with the addition of high-quality heat. As Bragg-Sitton et al. (2020, p. 6) explain, "High-temperature steam electrolysis (HTSE) utilizes heat and electricity to split water into hydrogen and oxygen, where the additional heat reduces the amount of work needed." This thermodynamic advantage means that for the same electrical input, a greater volume of hydrogen can be produced, lowering the effective cost and improving the overall energy return on investment.

A fusion reactor is an ideal energy source for HTSE. While current-generation light-water fission reactors operate at temperatures too low for direct coupling, Bragg-Sitton et al. (2020, p. 6) note that they "can be used by employing temperature boosting techniques, such as resistive heating or chemical heat pumps," although this introduces efficiency losses. Advanced nuclear concepts, however, are designed for much higher outlet temperatures. The high-temperature gas-cooled reactor (HTGR), an advanced fission design, is a direct analogue for the potential of future fusion plants. The "[HTGE-SOFC] high-temperature electrolysis system comprising a high-temperature gas-cooled reactor and solid oxide fuel cell" (Ren et al., 2020, p. 3) demonstrates a fully integrated system where nuclear heat directly drives the electrolysis process. Future fusion power plants, particularly those utilizing advanced coolants like helium or molten salts, are expected to operate at similar or higher temperatures, making them perfectly suited for direct, high-efficiency coupling with HTSE plants. This direct provision of clean, high-temperature heat is a unique capability that VREs cannot offer, positioning fusion as a potentially superior technology for bulk hydrogen production.

5.3 Decarbonizing "Hard-to-Abate" Sectors

The strategic importance of clean hydrogen lies in its ability to serve as a versatile energy vector for decarbonizing sectors of the economy that are resistant to direct electrification. The "transport sector accounts for about 21% of global energy consumption, among which the share of oil is 94%" and is responsible for "almost a quarter of the world's total" direct CO_2 emissions from fuel combustion (Ren et al., 2020, p. 1). While battery electric vehicles are a viable solution for light-duty transport, heavy-duty applications such as shipping, aviation, and long-haul trucking require a more energy-dense carrier, a role for which hydrogen is well-suited.

Beyond transport, hydrogen is an essential feedstock for heavy industry. As Bragg-Sitton et al. (2020, p. 5) outline, "Hydrogen can be employed in multiple off-take industries (eg, steel manufacturing, fertilizer production, biomass upgrading, chemical production...)." In many of these applications, such as the production of ammonia for fertilizer or the use of hydrogen as a reducing agent in green steel manufacturing, hydrogen is a chemical necessity. Providing a carbon-free source of hydrogen for these industries is therefore a direct and indispensable pathway to their decarbonization. A fusion-powered

IES can thus anchor an entire industrial ecosystem, providing the foundational commodity for a sustainable manufacturing and transportation sector.

While the co-generation of hydrogen decreases the net electrical output of a fusion plant, it enhances its overall economic viability and systemic value. The ability to switch between electricity production for the grid and hydrogen production for industrial or transport markets provides crucial revenue diversification. This flexibility is economically rational, and as Nicholas et al. (2021, p. 4) suggest, "co-generating hydrogen... would decrease overall energy efficiency," but this is a trade-off that "could also be taken with renewables or fission to allow for long term energy storage." The hydrogen produced can act as a form of long-duration energy storage, a critical need in a 100% renewable system that batteries cannot easily fulfill. By producing hydrogen, a fusion plant not only decarbonizes hard-to-abate sectors but also provides the means to ensure energy security across seasonal timescales, solidifying its role as a critical enabler of a fully decarbonized, reliable, and integrated energy future.

Part II: A Critical Assessment of Fusion's Viability and Footprint

6. Life-Cycle Sustainability: Beyond Operational Emissions

A robust evaluation of nuclear fusion's role in a sustainable energy future necessitates an analytical framework that extends beyond the narrow metric of operational emissions. While fusion power plants, like their fission and renewable counterparts, produce no direct greenhouse gases (GHGs) during operation, a comprehensive environmental assessment requires a holistic, life-cycle perspective. Concerns have been raised that a singular focus on operational carbon dioxide may obscure significant upstream environmental burdens, potentially leading to incomplete or misleading conclusions about a technology's overall sustainability. As Junne et al. (2021) note, there are concerns that upstream impacts "may affect the emissions reduction potential of low-carbon technologies and that other environmental stressors may be overlooked." This section, therefore, employs the methodology of Life-Cycle Assessment (LCA) to provide a more complete accounting of fusion's environmental footprint. It first outlines the LCA framework, then quantifies the "embodied" GHG emissions associated with fusion in comparison to other low-carbon technologies, and finally analyzes the critical issue of burden-shifting, whereby optimizing for one environmental metric can lead to adverse side-effects in others.

6.1 A Holistic Environmental Assessment using LCA Methodology

Life-Cycle Assessment (LCA) is a systems-level analytical tool designed to "quantify the potential impacts of technologies and processes across a comprehensive set of environmental categories, covering entire life cycle chains, associated emissions, and ecologically relevant extractions from the environment" (Junne et al., 2021, p. 1). This methodology is essential for evaluating energy technologies, as conventional energy system models often neglect crucial upstream impacts. As Pehl et al. (2017, p. 939) point out, while direct emissions are often modeled, "other indirect emissions, in particular those related to energy required for the construction of power plants and the production and transportation of fuels and other inputs... are not considered in the optimization." This omission is significant because the manufacturing of energy infrastructure—be it a wind turbine, a solar panel, or a fusion reactor—is an energy- and material-intensive process that carries its own environmental footprint.

To analyze the complex trade-offs inherent in designing a low-carbon power system, this paper utilizes the outputs of multi-objective optimization models that integrate LCA indicators. This approach allows for the calculation of a "pareto front that allows us to assess the trade-offs between system costs and life cycle greenhouse gas (GHG) emissions of future power systems" (Junne et al., 2021, p. 1). By mapping this frontier, one can quantify the economic cost of reducing total life-cycle GHG emissions and identify the technology mixes that achieve different levels of environmental performance, thereby providing a robust basis for policy and technology choices.

6.2 Quantifying "Embodied" Greenhouse Gas Emissions

When viewed through an LCA lens, all low-carbon technologies exhibit a non-zero GHG footprint. The key differentiators are the magnitude of these emissions and the life-cycle stage in which they occur. LCA studies projecting the performance of technologies in a future, decarbonized energy system provide valuable insights.

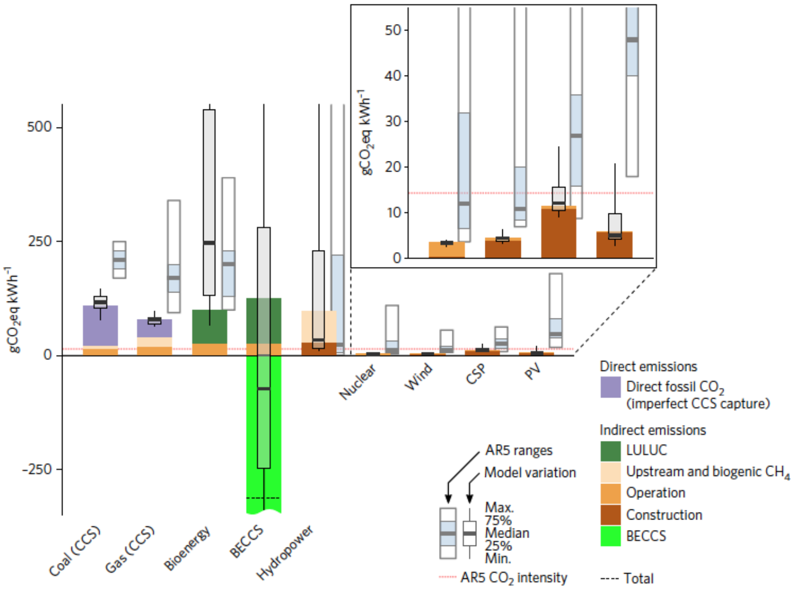


Figure 3. Specific direct and indirect life-cycle greenhouse gas (GHG) emissions for various power generation technologies, projected for a 2°C-consistent mitigation scenario in 2050. The bars show the global average, with breakdowns for construction, operation, LULUC, upstream CH_4, and residual direct CO_2. Nuclear power is shown to have a life-cycle GHG footprint comparable to wind and solar, and significantly lower than fossil fuels with CCS or bioenergy. (Adapted from Pehl et al., 2017).

For a 2050 scenario, Pehl et al. (2017, p. 939) project life-cycle emissions for nuclear power (the closest proxy for fusion in comprehensive LCA literature) to be in the range of "3.5–12 $gCO_2eq\ kWh^{-1}$," a figure comparable to wind and solar power and significantly lower than fossil fuels with carbon capture, which are estimated at "78–110 $gCO_2eq\ kWh^{-1}$."

In a cost-optimized, highly renewable European power system, the carbon footprint of the electricity mix is projected to be around "67 g CO_2eq/kWh." However, in a system optimized for the lowest possible life-cycle GHG emissions, this footprint decreases dramatically to "12 g CO_2eq/kWh" (Junne et al., 2021, p. 11). This dramatic reduction highlights a critical structural shift in the source of emissions. As systems become more ambitious in their decarbonization goals, the environmental impact moves progressively upstream. Junne et al. (2021, p. 11) find that "whereas direct CO_2 emissions account for 23% of the total life cycle GHG emissions in the cost optimum, their share drops to 0% in the solution with least life cycle GHG emissions. At this point, all GHG emissions are caused by background processes."

This finding is of profound importance for fusion. It implies that as the grid becomes cleaner, the embodied emissions from manufacturing and construction become the dominant, and eventually sole, source of the technology's carbon footprint. The relative environmental performance of fusion will therefore depend critically on the energy and material intensity of its construction compared to other technologies. On this front, the data are favorable. An analysis of Embodied Energy Use (EEU) by Pehl et al. (2017, p. 940) finds that "fossil fuels (coal and gas), bioenergy and hydropower have significantly higher EEU than nuclear, wind and solar power." This suggests that the energy investment required to build a fusion plant is competitive with, and likely lower than, that for many other energy sources, bolstering its case as a sustainable long-term option from a GHG perspective.

6.3 Secondary Environmental Impacts and Burden Shifting

A singular focus on minimizing GHG emissions can obscure trade-offs with other environmental indicators, a phenomenon known as burden-shifting. A multi-objective optimization that includes a wide range of LCA impact categories reveals that while "the majority of indicators show co-benefits with reduced life cycle GHG emissions," a few critical impacts increase. The analysis by Junne et al. (2021, p.

13) is unequivocal: "Only three impact categories increase with the reduction of life cycle GHG emissions... The increase in nuclear power is responsible for adverse side-effects."

The deployment of nuclear power (and by extension, fusion) as a tool to drive down system-wide GHG emissions creates specific, quantifiable pressures on other environmental systems. The "strongest adverse side-effect on human health... results from exposure to ionizing radiation caused by nuclear energy, which increases with its use (up to a factor of ~34 compared to the cost-optimal solution)" (Junne et al., 2021, p. 14). Furthermore, as life-cycle GHGs are reduced by deploying more nuclear capacity, "fossils and water depletion become dominated by nuclear power. For nuclear power, cooling water has a high impact on water depletion" (Junne et al., 2021, p. 14). This is a critical finding, as it highlights that the very technology deployed to solve the climate problem exacerbates other key sustainability challenges, namely radioactive risk, fossil resource depletion (through the uranium fuel cycle), and water stress.

This creates a complex decision matrix for policymakers. For instance, a comparison of VRE-dominated systems reveals that "wind-dominated systems have half as much life cycle GHG emissions as PV-based systems," and that "PV-based systems have a higher environmental impact on indicators that affect human health and ecosystems than wind-dominated systems" (Junne et al., 2021, p. 14). A choice to heavily rely on solar PV to avoid the land-use or aesthetic impacts of wind would therefore come with a penalty in terms of both GHG emissions and other ecosystem health indicators. The inclusion of fusion into this mix adds another layer of complexity. The key conclusion from this holistic assessment is that "the reduction of life cycle GHG emissions largely increases ionizing radiation, water consumption and depletion of fossils (particularly uranium) due to the expansion of nuclear power" (Junne et al., 2021, p. 16). There is no single technology that optimizes for all environmental outcomes. The development and deployment of fusion must therefore be understood not as a perfect solution, but as a strategic choice with a unique and significant set of environmental trade-offs that are fundamentally different from those associated with VREs.

7. The “Clean” Waste Problem: Deconstructing Fusion’s Waste Profile

A central and long-standing tenet in the advocacy for nuclear fusion has been its putatively superior environmental profile with respect to radioactive waste when compared to nuclear fission. This argument has been foundational to its public and political support, promising an energy source that circumvents the contentious issue of long-term, high-level nuclear waste disposal. Indeed, as Nicholas et al. (2021, p. 4) observe, "One of the commonly stated advantages of fusion over fission is the misconception that it will not produce 'long-lived' radioactive waste." However, recent, more detailed analyses based on realistic engineering designs and advanced materials science are challenging this historical narrative. A critical deconstruction of fusion's actual waste profile reveals a more complex reality, necessitating a direct and nuanced comparison with advanced fission technologies. This section will trace the origins of the "low-activation" design goal, present the modern evidence indicating that fusion will produce significant quantities of Intermediate-Level Waste (ILW), and compare the resulting waste management challenges with those of advanced fission reactors.

7.1 The Historical Claim and the Low-Activation Criterion

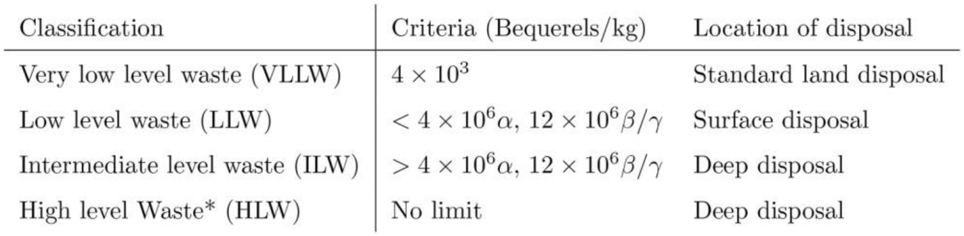
The initial promise of a cleaner waste stream from fusion energy is not unfounded; it is rooted in the fundamental physics of the D-T reaction. Unlike fission, which produces a wide spectrum of highly radioactive fission products and transuranic elements, the primary product of D-T fusion is inert helium. The radioactivity associated with fusion arises not from the fuel or its direct products, but from the secondary activation of the surrounding reactor materials by high-energy (14.1 MeV) neutrons. Recognizing this, "in the 1980s the fusion materials community discussed methods to reduce the volume of long-lived radioactive waste generated by neutron activation" (Nicholas et al., 2021, p. 4).

This effort culminated in a core design philosophy centered on materials selection. The strategy "was implemented by introducing a 'low-activation' or 'reduced-activation' material criterion," which was formally defined as ensuring that "The materials selection for fusion energy's nuclear waste production, after an initial ~100 years removal from the reactor, can be disposed of in low-level waste repositories" (Nicholas et al., 2021, p. 4). This criterion established a clear engineering target: to develop structural materials that would decay to background radiation levels on a timescale of a century, thereby avoiding the need for deep geological disposal associated with high-level waste. "For this purpose," Nicholas et al. (2021, p. 4) explain, "reduced-activation (or low-activation) structural steels were designed, and neutronics modelling concluded these steels would meet the low-activation criterion and hence only be classified as low-level waste (LLW)." This conclusion, based on decades of materials research, formed the scientific basis for the claim that fusion would not produce long-lived waste.

7.2 Modern Evidence: Intermediate-Level Waste from Structural Materials

The optimism of the low-activation criterion has been tempered by recent, more sophisticated analyses that use detailed, engineering-grade models of future fusion power plants like DEMO. These studies focus on the performance of specific, developed-for-purpose materials under realistic operational conditions. The leading candidate for the primary structural material in European DEMO designs is a specific type of ferritic/martensitic steel. As noted by Nicholas et al. (2021, p. 4), "EUROFER97 reduced-activation steel is the leading fusion structural material... and has been chosen as the neutron-facing structural material in the EU-DEMO1 reactor design."

While EUROFER97 was explicitly designed to meet the low-activation goal, the latest neutronics calculations, which incorporate more detailed physics and more realistic impurity levels, project a different outcome. The central, critical finding is that "the EUROFER97 steel... will always exceed the reduced-activation criterion, and hence be classed as intermediate-level waste (ILW)" (Nicholas et al., 2021, p. 4). This reclassification from Low-Level Waste (LLW) to Intermediate-Level Waste (ILW) is not a minor semantic point; it has profound regulatory and practical consequences.



Classification	Criteria (Bequerels/kg)	Location of disposal
Very low level waste (VLLW)	4×10^3	Standard land disposal
Low level waste (LLW)	$< 4 \times 10^6 \alpha$, $12 \times 10^6 \beta/\gamma$	Surface disposal
Intermediate level waste (ILW)	$> 4 \times 10^6 \alpha$, $12 \times 10^6 \beta/\gamma$	Deep disposal
High level Waste* (HLW)	No limit	Deep disposal

Table 1. Radioactive waste classification according to the UK Nuclear Decommissioning Authority. The distinction between Low-Level Waste (LLW) and Intermediate-Level Waste (ILW) is determined by activity concentration thresholds for alpha and beta/gamma-emitting radionuclides. Waste exceeding these thresholds falls into the ILW category, which requires deep geological disposal. (Source: Nicholas et al., 2021, adapted from the UK Nuclear Decommissioning Authority, 2017).

"Under current UK nuclear law," for example, "ILW requires geological disposal. Therefore, the latest research indicates that fusion plants could produce nuclear waste which requires long-term subsurface disposal, similar to fission plants" (Nicholas et al., 2021, p. 4).

The volume of this waste is substantial. A commercial fusion power plant is a massive industrial facility, and the components subjected to the highest neutron flux—the first wall, breeder blanket, and divertor—comprise a significant mass of steel. "Recent EU-Demo designs require 1300–1500 metric tons of steel that will be strongly irradiated and thus become ILW" (Nicholas et al., 2021, p. 4). The root cause of this activation is the unavoidable presence of trace elements and impurities within the steel alloys, which transmute under neutron bombardment into long-lived radioisotopes. As the analysis makes clear, "It is hard to avoid this: the elements responsible are either required for mechanical properties or are present as natural ore impurities in the tens of parts-per-million concentrations, the reduction of which might not be technically or economically feasible" (Nicholas et al., 2021, p. 4).

7.3 Comparison with Advanced Fission and Broader Implications

This revised understanding of fusion's waste stream necessitates a recalibration of its advantages relative to advanced fission reactors. While it remains true that fusion will not produce spent nuclear fuel or the extremely long-lived actinide isotopes that characterize high-level fission waste, the distinction becomes less stark. The fact that fusion will produce large volumes of ILW requiring deep geological disposal fundamentally "weakens one of the main arguments for fusion over fission" (Nicholas et al., 2021, p. 4).

The comparison with specific advanced fission designs is even more striking. When comparing the ILW produced per unit of steel in the reactor, Nicholas et al. (2021, p. 4) find that "more intermediate-level waste (ILW) may be produced by fusion than by fission: the European Sodium-Cooled fission Fast Reactor (SCFR) design has a lower percentage of ILW per total reactor steel mass compared to the EU-DEMO1 design." This suggests that, on a ton-for-ton basis, the waste produced by some advanced fission concepts may be less problematic than that from currently envisioned fusion plants.

This places the fusion community at a crossroads. One path forward is to lobby for a new regulatory framework specific to fusion waste. One could argue that "inert steel poses a lower risk of biosphere penetration than waste from fission," and therefore a separate, "internationally consistent categorisation for fusion structural waste" should be created (Nicholas et al., 2021, p. 5). However, it is "unclear how easy this would be," and success is far from guaranteed. The alternative is to "relax the LLW criterion altogether and accept that fusion will generate ILW" (Nicholas et al., 2021, p. 5). This would represent a significant shift in public messaging but would align the technology's promotion with the latest scientific evidence. Ultimately, the "clean waste" argument for fusion is no longer absolute but relative, and its true advantage lies not in the complete absence of long-lived waste, but in the absence of high-level, heat-generating waste and the actinide products associated with nuclear proliferation concerns.

8. Resource Constraints and Scalability Challenges

The transition from scientific demonstration to global-scale industrial deployment introduces a new set of constraints that are determined not by plasma physics, but by material science and geology. While the promise of fusion is often articulated in terms of its inexhaustible fuel, a critical analysis of the full material inventory required for the construction and operation of a large fleet of fusion power plants reveals significant potential bottlenecks. The scalability of fusion energy, therefore, depends not only on its technological readiness and economic competitiveness but also on the secure and sustainable supply of several key strategic materials. As Nicholas et al. (2021, p. 6) aptly state, "Whilst it is true that fusion has access to an abundant source of deuterium and lithium fuel, it remains uncertain whether other reactor-relevant resources could become severe limiting factors." This section examines these constraints, focusing first on the primary fuel cycle, particularly the competition for lithium, and second on the strategic non-fuel materials—notably beryllium and helium—that are essential for current reactor designs.

8.1 Fuel Cycle Constraints: Lithium and Tritium Breeding

The D-T fuel cycle, while offering immense energy density, is predicated on the ability to breed tritium from lithium. Deuterium is readily and abundantly available in seawater, but lithium, the feedstock for tritium, is a terrestrial resource with a finite global reserve base. Current assessments of these reserves are generally optimistic for fusion's long-term prospects. An updated analysis suggests that "current accessible resources of terrestrial lithium could provide 2800 years of fusion power" (Nicholas et al., 2021, p. 6), an ample supply for many centuries of operation. Furthermore, should terrestrial reserves prove insufficient, "Access to lithium in seawater would increase potential reserves for fusion and energy storage by several orders of magnitude" (Nicholas et al., 2021, p. 6). From a purely resource-availability perspective, the fuel for fusion energy appears secure for the foreseeable future.

However, this long-term view obscures a more immediate and pressing challenge: near-term competition for lithium resources from other rapidly growing low-carbon technologies. The most significant competitor is the battery industry, where lithium is a critical and unsubstitutable component for electric vehicles (EVs) and grid-scale energy storage. This creates a direct conflict, as "the increase in competition with other industries, notably batteries for energy storage and electric vehicles (EVs), could consume these reserves much faster—potentially within decades" (Nicholas et al., 2021, p. 6). This timing is critical. Given that the EV industry is already undergoing massive expansion, it is forecast to place significant strain on lithium supply chains well "before fusion is commercialised" (Nicholas et al., 2021, p. 6).

This creates a complex techno-economic dynamic. While the use of lithium in fusion reactors and batteries is chemically distinct—fusion requires the specific isotope ^{6}Li, while batteries can use natural lithium—it is unlikely that two separate supply chains will develop. It has been proposed that "an economy could be established whereby enriched ^{6}Li is used solely by fusion reactors and 'depleted' ^{7}Li used by the energy storage industry" (Nicholas et al., 2021, p. 6). However, the economic and logistical feasibility of such a segregated market is questionable, especially given the established and powerful market forces of the battery industry. The more likely scenario is direct competition for a single, fungible lithium supply, which will inevitably drive up costs and could create significant bottlenecks for the initial deployment of a fusion fleet. While the ultimate backstop of extracting lithium from seawater exists, the "economic and environmental costs of processing the necessary quantities of seawater must be considered" (Nicholas et al., 2021, p. 6) and are expected to be substantially higher than for terrestrial mining.

8.2 Strategic Material Constraints: Beryllium and Helium

Beyond the fuel cycle, the scalability of current fusion reactor designs is constrained by the availability of two other critical materials: beryllium and helium.

Beryllium plays an essential role as a neutron multiplier in many proposed breeder blanket designs. The high-energy neutrons produced by the D-T reaction must interact with lithium to breed tritium, but a single neutron-lithium interaction is often insufficient to produce a replacement triton and account for system losses. Beryllium is one of the few light elements that, when struck by a high-energy neutron, can emit two lower-energy neutrons, thereby multiplying the neutron population and ensuring a tritium breeding ratio greater than one. The problem is that beryllium is a rare and toxic element. As Nicholas et al. (2021, p. 6) report, "As of 2018, the estimated identified world beryllium supply was 100, 000 metric tons... If a beryllium-based breeder blanket is selected for a DEMO reactor, a maximum of 200–300 reactors could be constructed." This presents a hard ceiling on the global scalability of any fusion design reliant on beryllium. The challenge is compounded by the fact that "The beryllium cannot be fully recycled because it is transmuted during neutron multiplication" (Nicholas et al., 2021, p. 6). Substitution is also difficult, as "the choices for neutron multipliers are fundamentally limited by nuclear physics, which leaves one of the only other options as lead" (Nicholas et al., 2021, p. 6), a material that introduces its own set of significant engineering and safety challenges (e.g., corrosion, high density).

Helium presents a different but equally critical constraint. Current designs for large-scale, magnetically-confined fusion reactors rely on powerful superconducting magnets to contain the plasma. These magnets must be cooled to cryogenic temperatures, a task for which liquid helium is the only practical coolant. This creates a significant demand on a resource that is already facing a critical global shortage. Ongena et al. (2016, p. 408) note that "He as a coolant is relatively scarce," and while more could be made available "with additional investments in the gas industry," the supply is fundamentally finite. Analysis by Nicholas et al. (2021, p. 6) quantifies the scale of the problem: "The total helium inventory contained in the number of fusion DEMO reactors needed to supply 30% of global energy demand is around 2% of the global helium resource, and helium has an exponential reserve index of around 100 years." Critically, fusion power plants would be net consumers of helium. Even when "accounting for the helium directly produced by the D-T fusion reaction, fusion as a non-sustainable consumer of helium would exacerbate an already critical supply situation" (Nicholas et al., 2021, p. 6). While energetically costly extraction from the atmosphere is possible and would only "lower Fusion's EROI by around 1%" (Nicholas et al., 2021, p. 6), it does not solve the underlying scarcity issue. The most viable long-term solution may be technological: the development of "high-T_c superconductor materials would be advantageous... enabling the use of coolants other than He, for example, liquid nitrogen" (Ongena et al., 2016, p. 408). Without such a breakthrough, helium availability could pose a significant constraint on the large-scale deployment of superconducting magnetic fusion reactors.

9. Economic Viability and Equitable Access

Beyond the significant scientific and material challenges, the ultimate deployment of nuclear fusion will be determined by its economic viability and its capacity to contribute to a just and equitable global energy transition. While fusion promises long-term energy security, its high-capital, technologically intensive nature presents formidable economic hurdles, especially in a market increasingly defined by the falling costs of variable renewables. A comprehensive assessment must therefore analyze not only the projected cost of fusion power but also its cost-effectiveness as a tool for climate mitigation and the profound challenge of ensuring its benefits can be accessed globally, particularly by developing nations. This section assesses the Levelized Cost of Energy (LCOE) for fusion, evaluates its comparative cost-efficiency for CO_2 abatement, and examines the socio-economic barriers to its equitable global deployment.

9.1 Assessing the Levelized Cost of Energy (LCOE) for Fusion

The economic viability of any power generation technology is most commonly benchmarked by its Levelized Cost of Energy (LCOE), a metric that amortizes the total life-cycle costs of a plant over its total energy output. For fusion, which is intrinsically a high-capital, low-fuel-cost technology, the LCOE is dominated by the initial construction and financing costs. Projections for first-of-a-kind commercial fusion plants, based on detailed engineering designs like the EU-DEMO concept, suggest a high LCOE. For example, a comprehensive model by Entler et al. (2018) found "a levelized cost of energy (LCOE) of 175$/MWh with a direct capital cost (with contingency) of $7.4 billion" (Nicholas et al., 2021, p. 3).

This high cost is a direct consequence of the immense technological complexity. As Nicholas et al. (2021, p. 3) observe from the real-world costs of analogous large-scale nuclear projects, "Given that ITER and Hinkley Point C are both projected to cost over $20 billion each, we assume a cost over 100$/MWh is more realistic" The LCOE is highly sensitive to these upfront capital expenditures. Further modeling indicates that "Fusion's LCOE is sensitive to the initial capital cost," with a plant costing $6.2 billion yielding "a LCOE of 121$/MWh," while a less expensive, $3.9 billion plant could theoretically achieve “a LCOE of 83$/MWh" (Nicholas et al., 2021, p. 3).

When placed in the context of the modern energy market, these figures present a stark economic challenge. The costs for mature renewable technologies have fallen precipitously and are projected to continue their decline. As Nicholas et al. (2021, p. 3) summarize from Lazard's authoritative analysis, "currently the LCOE of large solar PV is between 40 and 46$/MWh, [and] onshore wind between 29 and 56$/MWh.” The implication of this market reality is unavoidable: "Therefore we assume both utility-scale solar and onshore wind to be significantly cheaper than fusion by the time fusion becomes commercially viable, and possibly indefinitely" (Nicholas et al., 2021, p. 3). On a pure LCOE basis, fusion will likely be unable to compete with VREs for bulk energy generation. Its economic case, therefore, cannot rest on being the cheapest source of electricity, but must be built upon the value it provides as a firm, dispatchable, and integrated energy source.

9.2 Cost-Effectiveness for CO2 Mitigation

While fusion's LCOE may be high, its value as a climate mitigation tool can be assessed through a different lens: its cost-effectiveness in displacing CO_2 emissions. Here, the comparison is not just with VREs, but with other firm, low-carbon sources like nuclear fission. Because of their high capacity factors and reliability, nuclear technologies can provide a large, constant stream of carbon-free power, which can be highly efficient for decarbonization.

Studies comparing the cost-efficiency of nuclear fission and renewables for climate mitigation have found that nuclear power can be a more economically efficient tool. Kim et al. (2020, p. 1) conclude that "nuclear power generation is more cost-efficient than is renewable energy generation in mitigating CO_2 emissions, even with the external costs of accidents and health impact risks." The underlying reason for this is that a smaller investment in nuclear capacity is required to achieve the same amount of emissions reduction.

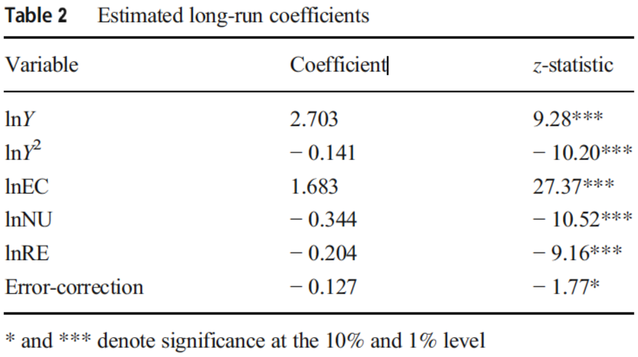


Table 2 Estimated long-run coefficients

Variable	Coefficient	*z*-statistic
$\ln Y$	2.703	9.28***
$\ln Y^2$	− 0.141	− 10.20***
lnEC	1.683	27.37***
lnNU	− 0.344	− 10.52***
lnRE	− 0.204	− 9.16***
Error-correction	− 0.127	− 1.77*

* and *** denote significance at the 10% and 1% level

Table 2. Estimated long-run coefficients from a panel cointegration analysis of the impact of energy consumption and generation on CO_2 emissions in 16 major nuclear-generating countries. A negative coefficient indicates that an increase in the variable reduces CO_2 emissions. (Source: Kim et al., 2020).

The analysis shows that "to reduce CO_2 emissions by 1%, nuclear power and renewable energy generation should be increased by 2.907% and 4.902%, respectively" (Kim et al., 2020, p. 1). This translates into a direct cost advantage: the total cost to mitigate 1% of CO_2 emissions was calculated to be "$1.70 billion for the nuclear power and $3.97 billion for renewable energy" (Kim et al., 2020, p. 1).

These findings suggest that the most cost-effective strategy for deep decarbonization is not a choice between technologies, but a synergistic combination. As Saidi & Omri (2020, p. 1) argue, "the best option to reduce CO_2 emissions is to aim for a mix of nuclear and renewable energy. No need to choose. On the contrary: the two sources of energy are complementary." Although these studies focus on fission, the conclusions are directly applicable to fusion. Given its similar operational profile (high-capacity, dispatchable), fusion would likely exhibit a similar, or even superior, cost-effectiveness for CO_2 mitigation, providing a strong economic argument for its development from a climate policy perspective, even if its direct LCOE remains high.

9.3 The Challenge of Equitable Global Deployment

The final and perhaps most profound challenge concerns the equitable global deployment of fusion energy. The transition to a clean energy future is not merely a technological or economic exercise; it is a global development project that must address deep-seated inequalities. For developing nations, the energy transition is inextricably linked to "expectations of economic development, social inclusion, and environmental sustainability" (Vanegas Cantarero, 2020, p. 1). The deployment of any new energy technology in the Global South must be assessed against these multifaceted goals.

Fusion, as a high-capital, technologically sophisticated energy source, presents significant barriers to entry. The "economic, socio-cultural, and institutional constraints" that already limit the "large-scale deployment of renewable energy technologies" (Vanegas Cantarero, 2020, p. 1) would be magnified for fusion. The immense upfront investment and advanced technical expertise required could place it out of reach for many developing nations, risking a future where the most advanced clean energy technologies are concentrated in wealthy countries. This could exacerbate global energy inequality and hinder the achievement of global climate targets, as the "generation capacity is not yet enough to reduce total CO_2 emissions" in the developed world alone (Kim et al., 2020, p. 5), necessitating global deployment.

An energy transition that relies solely on technologies that are only accessible to a fraction of the world's population would be a "big burden to world economy" and would fail the test of equity (Kim et al., 2020, p. 6). Therefore, if fusion is to play a meaningful role in the global energy transition, international frameworks for technology transfer, financial assistance, and capacity building will be essential. The development of smaller, more modular fusion concepts, as discussed in Section 4, may offer a more plausible pathway for equitable access than gigawatt-scale plants. Ultimately, the fusion community must engage proactively with the principles of a just transition, ensuring that the development of this technology considers not only its technical merits but also its potential to contribute to a more sustainable and equitable world for all.

Conclusion and Research Outlook

This paper has conducted a critical evaluation of the potential role of nuclear fusion technology within the context of a global energy transition dominated by variable renewable energy. The analysis demonstrates that while the foundational promise of fusion as a dense, carbon-free energy source remains valid, the strategic and environmental landscape in which it must compete has been fundamentally altered. The synthesis of recent findings from plasma physics, systems engineering, materials science, and life-cycle assessment forces a recalibration of fusion's value proposition and illuminates a more nuanced, albeit challenging, path to its eventual deployment.

The most salient finding of this work is that fusion's most plausible and valuable role is not as a simple baseload replacement for 20th-century power plants, but as a flexible, firm, and fully integrated partner in a renewables-heavy energy system. The proliferation of low-cost VREs means that the greatest value for a firm power source now lies in its ability to provide dispatchable power and ancillary services that stabilize the grid and enable deeper VRE penetration. Furthermore, by functioning as an integrated energy hub, a fusion plant can dynamically allocate its immense thermal and electrical output to produce high-value, non-electric commodities such as clean hydrogen, industrial process heat, and desalinated water. This sector-coupling model enhances the economic case for a high-capital asset and positions fusion as a critical enabler for decarbonizing the hard-to-abate sectors of the economy, a task for which direct electrification is ill-suited.

However, this strategic potential is contingent upon overcoming a series of formidable and newly clarified hurdles. The path to viability requires confronting three critical challenges that have, until recently, been understated in the broader discourse. First, the problem of radioactive waste, long considered a solved issue, has re-emerged. Detailed neutronics analyses now show that current designs, even with reduced-activation steels, will produce significant volumes of Intermediate-Level Waste that require deep geological disposal, placing fusion's waste stream in a much closer comparison with advanced fission than previously acknowledged. Second, the global scalability of fusion is constrained by the finite supply of several strategic materials. The impending competition for lithium with the battery industry, and the reliance of current designs on limited resources like beryllium and helium, pose significant, unresolved bottlenecks to the deployment of a large, global fleet of fusion reactors. Third, the economic competitiveness of fusion remains a profound challenge. The high projected LCOE will make it difficult to compete with VREs on a cost-per-kilowatt-hour basis, meaning its economic case must be built on the systemic value of its firmness and flexibility, a value that is not always captured in current energy markets.

These findings compel a strategic reorientation of fusion research and development. To remain relevant and viable in a rapidly evolving energy landscape, the global fusion program must proactively address these challenges. Therefore, this paper proposes the following key research directions:

1. **A primary design focus on flexibility and integration.** The historical pursuit of steady-state, baseload operation should be augmented, if not superseded, by a focus on designing for load-following and dynamic power modulation. Research must prioritize the development of robust plasma control schemes and reactor technologies that can operate efficiently and safely across a wide range of power levels and can seamlessly integrate with industrial co-generation processes like high-temperature electrolysis.
2. **A concerted materials science effort to minimize long-term waste.** The fusion materials program must move beyond the now-questionable goal of achieving purely Low-Level Waste. A more pragmatic and critical objective is the development of advanced structural materials that are explicitly designed to minimize the production of the most problematic, long-lived isotopes. This includes research into novel alloys that reduce reliance on elements like nitrogen and molybdenum, and a full-systems evaluation of non-steel structural materials and alternative breeder blanket concepts.
3. **Transparent and proactive engagement with holistic sustainability assessments.** The fusion community must fully embrace the frameworks of Life-Cycle Assessment and techno-economic analysis. The development of future fusion concepts should be guided from the outset by a comprehensive understanding of their full environmental footprint, resource requirements, and socio-economic implications. This includes transparently assessing the challenges of equitable deployment in a global context and ensuring that the development of fusion technology is aligned with the broader principles of a truly sustainable and just global energy future.

In conclusion, nuclear fusion is not a panacea, but it remains a technology of immense promise. By shifting its focus from a standalone solution to that of an integrated, flexible partner to renewables, and by honestly confronting the profound engineering and sustainability challenges ahead, the fusion community can ensure that this long-term endeavor remains a vital and credible component of humanity's effort to mitigate the climate crisis.

Outlook and Broader Implications

Ultimately, the most profound role for fusion may not be to solve the energy problems of the 21st century, but to enable the ambitions of the 22nd and beyond. While this paper has focused on integrating fusion into a terrestrial energy system, its unique physics—unmatched power density and low fuel mass requirements—make it an ideal power source for high-impulse space propulsion. A viable fusion rocket would fundamentally alter humanity's relationship with the solar system, enabling rapid transit between planets and opening up the possibility of in-space resource utilization and manufacturing. Therefore, even as the challenges of terrestrial deployment are being addressed, the research and development in fusion science should also be viewed as a long-term investment in the foundational technology for an interplanetary civilization. The materials, physics, and control systems being developed for a power plant on Earth are the very same that could one day power a vessel to Mars, recasting fusion not just as a solution to a global crisis, but as the engine for humanity's next great expansion.

References

[1] A. Gabbar, H., Abdussami, M. R., & Adham, Md. I. (2020). Techno-economic evaluation of interconnected nuclear-renewable micro hybrid energy systems with combined heat and power. Energies, 13(7), 1642. https://doi.org/10.3390/en13071642

[2] Abdussami, M. R., Adham, M. I., & Gabbar, H. A. (2020). Modeling and performance analysis of nuclear-renewable micro hybrid energy system based on different coupling methods. Energy Reports, 6, 189–206. https://doi.org/10.1016/j.egyr.2020.08.043

[3] Bragg-Sitton, S. M., Boardman, R., Rabiti, C., & O'Brien, J. (2020). Reimagining future energy systems: Overview of the US program to maximize energy utilization via integrated nuclear-renewable energy systems. International Journal of Energy Research, 44(10), 8156–8169. https://doi.org/10.1002/er.5207

[4] Gabbar, H. A., Abdussami, M. R., & Adham, Md. I. (2020). Optimal planning of nuclear-renewable micro-hybrid energy system by particle swarm optimization. IEEE Access, 8, 181049–181073. https://doi.org/10.1109/ACCESS.2020.3027524

[5] Hora, H. (2004). Developments in inertial fusion energy and beam fusion at magnetic confinement. Laser and Particle Beams, 22(4), 439–449. https://doi.org/10.1017/S0263034604223242

[6] Junne, T., Cao, K.-K., Miskiw, K. K., Hottenroth, H., & Naegler, T. (2021). Considering life cycle greenhouse gas emissions in power system expansion planning for europe and north africa using multi-objective optimization. Energies, 14(5), 1301. https://doi.org/10.3390/en14051301

[7] Kim, H. S. (2021). Comparison of cost efficiencies of nuclear power and renewable energy generation in mitigating CO2 emissions. Environmental Science and Pollution Research, 28(1), 789–795. https://doi.org/10.1007/s11356-020-10537-1

[8] Nicholas, T. E. G., Davis, T. P., Federici, F., Leland, J., Patel, B. S., Vincent, C., & Ward, S. H. (2021). Re-examining the role of nuclear fusion in a renewables-based energy mix. Energy Policy, 149, 112043. https://doi.org/10.1016/j.enpol.2020.112043

[9] Ongena, J., Koch, R., Wolf, R., & Zohm, H. (2016). Magnetic-confinement fusion. Nature Physics, 12(5), 398–410. https://doi.org/10.1038/nphys3745

[10] Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E. G., & Luderer, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nature Energy, 2(12), 939–945. https://doi.org/10.1038/s41560-017-0032-9

[11] Ren, L., Zhou, S., & Ou, X. (2020). Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. Energy, 209, 118482. https://doi.org/10.1016/j.energy.2020.118482

[12] Saidi, K., & Omri, A. (2020). Reducing CO2 emissions in OECD countries: Do renewable and nuclear energy matter? Progress in Nuclear Energy, 126, 103425. https://doi.org/10.1016/j.pnucene.2020.103425

[13] Vanegas Cantarero, M. M. (2020). Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. Energy Research & Social Science, 70, 101716. https://doi.org/10.1016/j.erss.2020.101716

[14] Walsh, C. A., McGlinchey, K., Tong, J. K., Appelbe, B. D., Crilly, A., Zhang, M. F., & Chittenden, J. P. (2019). Perturbation modifications by pre-magnetisation of inertial confinement fusion implosions. Physics of Plasmas, 26(2), 022701. https://doi.org/10.1063/1.5085498

Tables

Table 1

Radioactive waste classification according to the UK Nuclear Decommissioning Authority.

Classification	Criteria (Bequerels/kg)	Location of disposal
Very low level waste (VLLW)	4×10^3	Standard land disposal
Low level waste (LLW)	$< 4 \times 10^6\ \alpha$, $12 \times 10^6\ \beta/\gamma$	Surface disposal
Intermediate level waste (ILW)	$> 4 \times 10^6\ \alpha$, $12 \times 10^6\ \beta/\gamma$	Deep disposal
High level Waste (HLW)	No limit	Deep disposal

Note: Data adapted from Nicholas et al. (2021), originally sourced from the UK Nuclear Decommissioning Authority (2017). The table presents the regulatory thresholds used in the United Kingdom to classify radioactive waste. The distinction between waste categories is based on the activity concentration (in Becquerels per kilogram) of alpha (α) and beta/gamma (β/γ) emitting radionuclides. These thresholds are critical for determining the required disposal pathway, with Intermediate-Level Waste (ILW) necessitating deep geological disposal.

Table 2

Estimated long-run coefficients

Variable	Coefficient	z-statistic
lnY (Income)	2.703	9.28***
$\ln Y^2$ (Income Squared)	-0.141	-10.20***
lnEC (Energy Consumption)	1.683	27.37***
lnNU (Nuclear Consumption)	-0.344	-10.52***
lnRE (Renewable Consumption)	-0.204	-9.16***
Error-correction	-0.127	-1.77*

Note: Source: Kim et al. (2020). The table shows the estimated long-run coefficients from a panel cointegration analysis modeling the determinants of CO_2 emissions in 16 major nuclear-generating countries. Variables are presented as natural logarithms (ln). Y represents real GDP per capita; EC represents energy consumption per capita; NU represents per capita electricity generated from nuclear sources; and RE represents per capita electricity generated from renewable sources.

*p < .10. ***p < .01.

Figures

Figure 1.

Schematic diagram of a modern tokamak, illustrating the primary magnetic field systems. The toroidal field coils (blue) generate the main toroidal confining field. The central solenoid, or ohmic transformer (center), induces a powerful current in the plasma (red arrows), which both heats the plasma and generates a secondary, poloidal magnetic field (yellow lines). The superposition of these two fields creates the helical magnetic surfaces (black line) that confine the plasma particles and prevent them from touching the reactor walls.

Source: Adapted from Ongena et al. (2016).

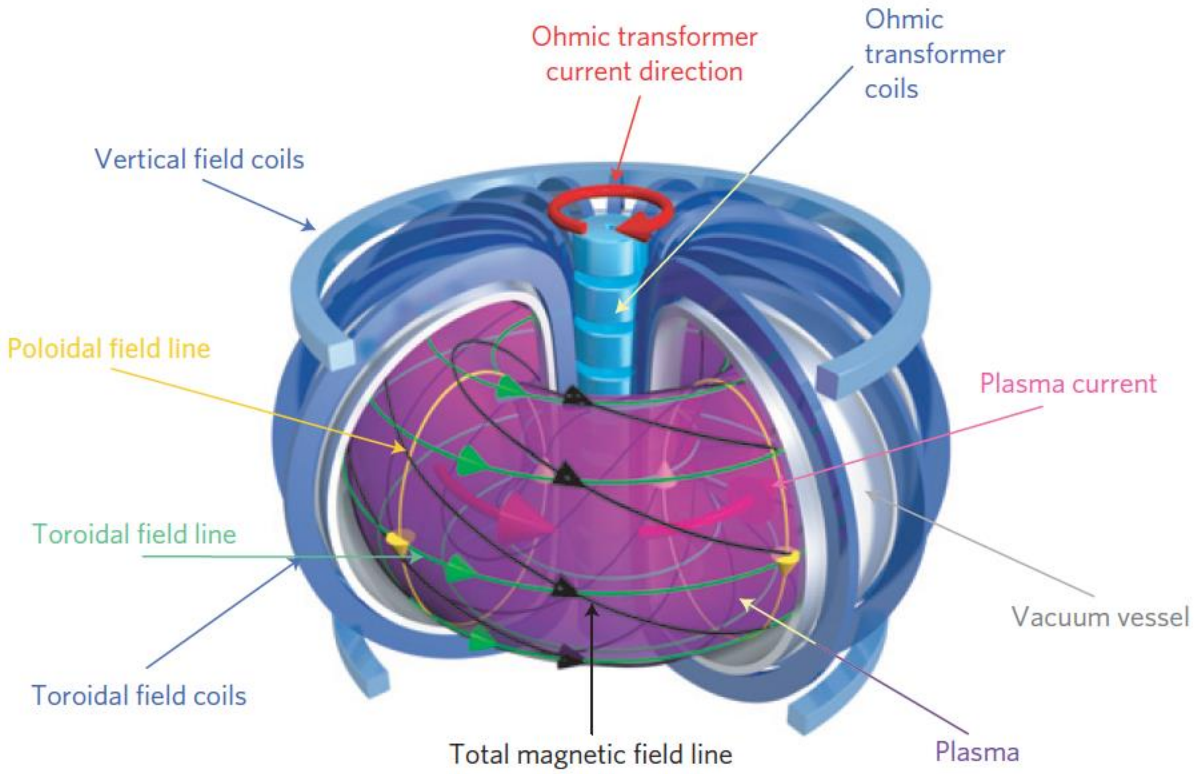


Figure 2.

A conceptual model illustrating the transition from a traditional electricity-only system (left) to a potential future Integrated Energy System (right). A central nuclear heat source (e.g., a fusion reactor), complemented by variable renewable sources, provides thermal (heat) and electrical (e^-) energy to a dynamic hub. This hub can dispatch energy to the electricity grid or to co-located industrial processes to produce non-electric commodities such as hydrogen (for transport and industry) and clean water. This integrated model is designed to maximize asset utilization and enable the decarbonization of multiple economic sectors.

Source: Adapted from Bragg-Sitton et al. (2020).

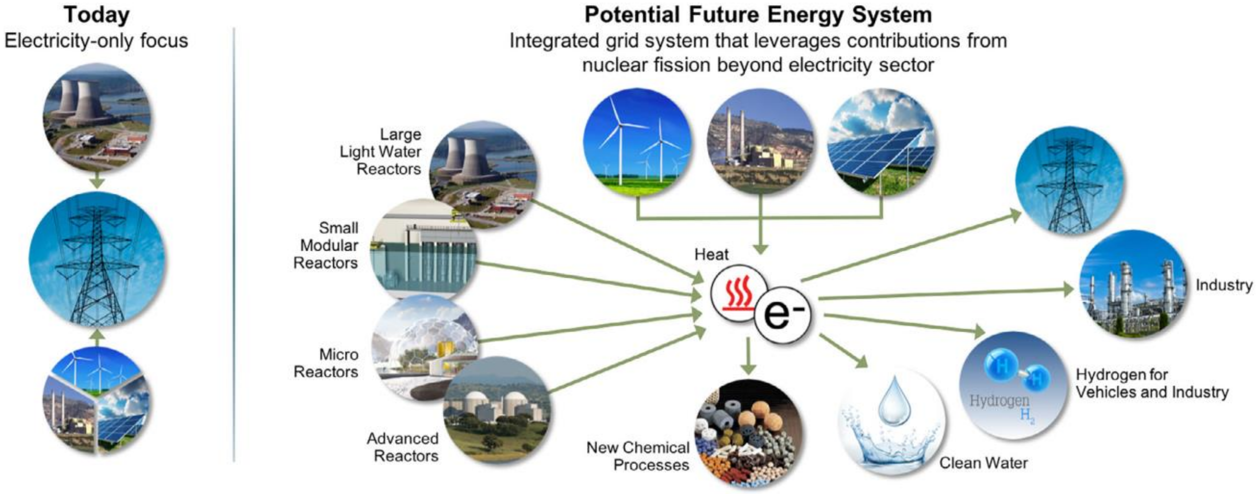


Figure 3.

Specific direct and indirect life-cycle greenhouse gas (GHG) emissions for various power generation technologies. The data are projected for a 2°C-consistent global mitigation scenario in 2050, and emissions are measured in grams of CO_2 equivalent per kilowatt-hour (gCO_2eq/kWh). Each bar represents the global average, with colored segments showing the breakdown of emissions by life-cycle stage, including construction, operation (residual/imperfect capture), upstream and biogenic CH_4, and Land Use, Land-Use Change, and Forestry (LULUC). Nuclear power is shown to have a life-cycle GHG footprint comparable to wind and solar, and significantly lower than fossil fuels with carbon capture (CCS) or bioenergy.

Source: Adapted from Pehl et al. (2017).