Industrifonden

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Investing in Fusion for a Fossil-Free Grid

Report Two Focusing on Novel Fuels in Our Deep Tech X Energy Series

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About Industrifonden

Founded in 1979, Industrifonden has a proven legacy of backing emerging science and ground-breaking technologies so that they can transform into the industries of tomorrow. We manage more than SEK 5 billion in an evergreen fund, and invest in early-stage companies, from seed to series A, and sometimes earlier. Our areas of expertise are Deep Tech, Life Science and Transformative Tech, and we currently have 50+ Nordic companies in our portfolio.

Industrifonden has been a long-standing and active investor in clean tech and energy, with companies such as Kisab, Enginzyme, Peafowl Plasmonics and ZeroPoint in its portfolio.

About the Authors

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Deep Tech Investment Manager

Mala Valroy is an Investment Manager within the deep tech practice at Industrifonden. She has built a solid foundation in multiple technologies as a scientist and held senior leadership roles in Fortune 500 companies scaling innovations in emerging markets. As a founder, operator, and board member she has worked with and advised early-stage startups in several verticals. Mala holds a Master of Science in General Management from the Stockholm School of Economics, as well as Master of Science in Biochemistry from Dartmouth College.

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Patrik Sobocki leads the deep tech practice at Industrifonden with a specific interest in science-based technology in biology/healthcare and climate. Training in finance and PhD in data sciences turned serial entrepreneur. Over the past 10 years his focus has been on M&A in tech companies at growth stage in Europe and with Industrifonden for six years. Patrik is on the board of six start-ups - amongst other Enginzyme with a disruptive cell-free synbioplatform in biomanufacturing.

Executive Summary

This investment thesis is the second in a suite of six reports under our Deep Tech x Energy theme and focuses on investment opportunities within nuclear fusion. The Deeptech x Energy reports include deep dives and an analysis of the latest trends in:

- Investing Ahead of the Decarbonization Curve
- Scaling up the production of novel fuels (This report)
- Innovative technologies to make renewable energy mainstream
- Looking beyond lithium for energy storage & supply
- Disrupting industrial processes & digitalization
- Accelerating carbon capture discovery & deployment

In this Report

- **Market analysis**: We analysed the competitive & regulatory landscape and assessed the role of fusion in a 2050 decarbonized energy mix
- **Private investments**: We highlight key deals to identify fund profiles that fit private investments in fusion and the role of public funding
- **The case for venture capital**: We interviewed VCs and strategic investors to identify the scale-up and exit opportunities
- **Placing our bet**: Our case for Novatron fusion

Introduction

There are 36 privately funded fusion startups at the time of writing this report, compared to just one in 2001. The value of private investments in fusion has tripled in the past twenty years and is estimated to be over $4.4 billion today (1). A successful investment in fusion could return the fund, but the technical risks and a long financing pathway must be factored into the decision process. As an evergreen fund, we are uniquely positioned to invest in early-stage science and engineering-based innovations, such as fusion.

What is fusion?

Fusion is the energy produced by two atomic nuclei combine to produce a heavier atomic element, releasing massive amounts of energy in the process. Stars like our sun fuse over 500 million tonnes of hydrogen every second and produce almost 600 million tonnes of Helium (2). Here on Earth, scientists first achieved fusion in 1958 (3) and almost seventy years later, the Lawrence Livermore National Laboratory in the US has been able to produce more energy from fusion than they spent (4).

The fuel for fusion is a combination of the hydrogen isotopes deuterium and tritium. Deuterium, or heavy water, can be harvested from the atmosphere or sea. Tritium is radioactive and artificially generated from lithium. When deuterium and tritium, or two deuterium atoms are fused, helium, and neutrons are produced with an enormous amount of energy released as a by-product. Aside from the abundant carbon-free energy these neutrons become interesting as we discuss both risks and spinout opportunities.

A fundamental aspect of fusion is that it depends on three “levers”:

- the confinement of plasma,
- the density of the plasma and
- the ionic temperature

The combination of these is called a triple product. With high plasma confinement and density, fusion can occur at lower temperatures like it does in space – but that still means 150 million °C. Fusion reactors are evaluated using the Lawson Criterion, which calculates the energy output from fusion vs the energy needed, also referred to as the Q factor. Using this, we can see what triple points are relevant for “reactor conditions” and what ratios of energy output are needed to reach energy break even or commercial grade fusion.

Fusion is an essential component of a fully decarbonized energy grid

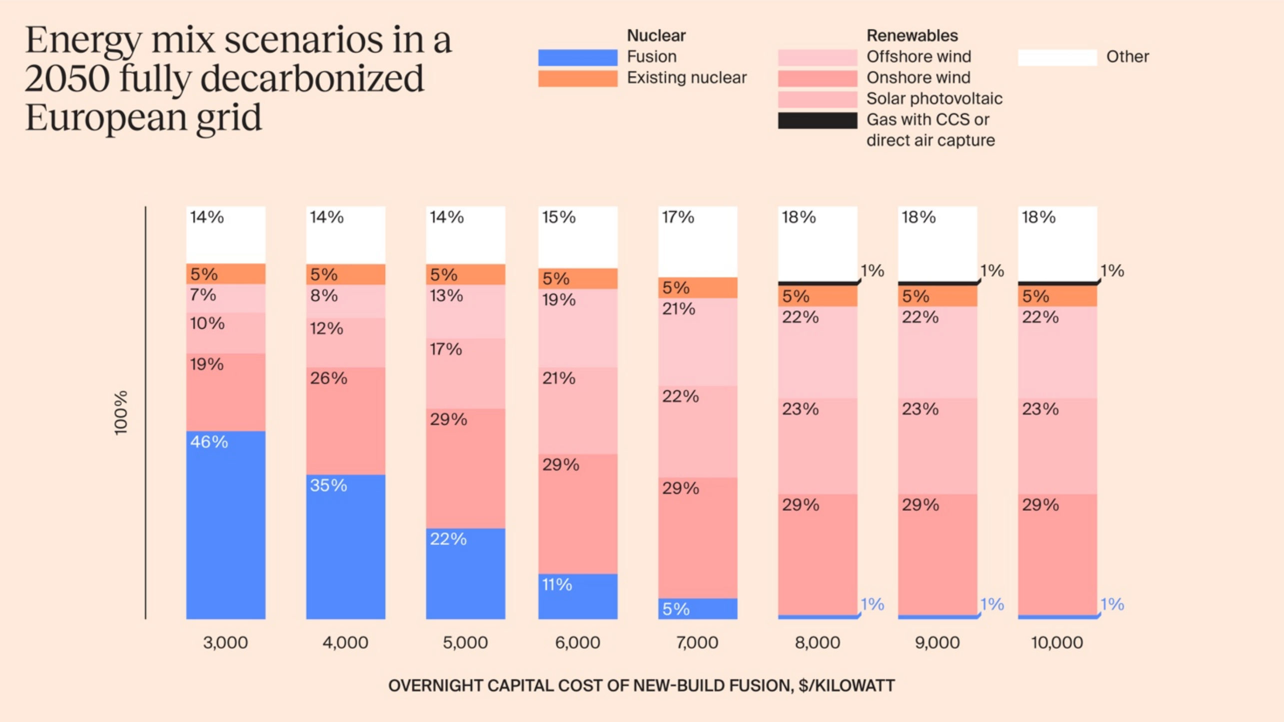
We foresee a future that is mostly powered through renewable energy, with fusion and novel fuels supplementing the grid as the baseload. Looking at a range of simulated cost scenarios, fusion could contribute to almost 50% of a fully decarbonized European grid by 2050 (1). Both the finite supply of fossil fuels and the climate-related demands from the Paris Agreement dictate that a future energy grid must be powered by alternative sources. Estimates vary widely and project that renewables could be as low as 27% (5) to as high as 85% (6) of the energy mix by 2050. There seems to be agreement, however, that there will still be a need for alternative energy sources to fill the gap. These novel fuels must outperform fossil fuels from an energy density perspective, which put nuclear and hydrogen on the map.

Hydrogen is a strong contender but is extremely combustible and therefore requires a complicated logistics chain where it is transported as ammonia or in other forms. As we mentioned in Report One, hydrogen also has extremely high global warming potential (GWP) if released into the atmosphere and it escapes easily during transport even when confined to pipes and tanks. Nuclear fission has its own well known environmental and safety concerns, while running the reactors as well as concerns regarding the disposal of continually radioactive waste.

Fusion by comparison has far lower environmental and safety risks, according to the experts we have interviewed. Reactors can run on heavy water alone, but even if they use tritium the radiation can be blocked by a centimeter of air or a few millimeters of aluminium. There is no continuously radioactive waste to dispose of and the material that is made radioactive by the neutron beams can be contained by the material choices around fusion reactors. Fusion holds the promise of producing nearly 4 million times as much energy than burning coal, oil, or gas and 4 times more energy than fission (at equal mass) (7)

While we have made considerable strides in fusion research, full-scale power to the grid from commercial fusion reactors could still be 20-30 years away. ITER is the world's largest publicly funded fusion project to prepare for commercial fusion, and is funded by the EU, Japan, Russia, China, India, Korea, and the US. It aims to produce 10x more energy than it consumes and distribute the knowledge to other nations to build their own commercial fusion reactor. China is already building its ITER equivalent, called CFETR with the aim to achieve commercial fusion by 2030. The UK has put forward a concrete strategy to become the global exporter of fusion technology (8) in the coming decades and the US has announced that the Department of Energy will launch an agency-wide initiative to accelerate partnerships with the private sector (9). Finally, research shows that the scientific progress, advances in material sciences and reactor design improvements being made could also significantly lower the levelized cost of energy (LCOE) of fusion to match cost-levels of renewables in the future (10).

Based on these collective facts, we believe that fusion will be an essential complement to renewables in a future fully decarbonized energy grid.


Energy mix scenarios in a 2050 fully decarbonized European grid

*Source: McKinsey "Will fusion help decarbonize the power system?"

The timing is ripe for private investments in fusion

There is a unique opportunity due to the synergies between the steady scientific progress of publicly funded research and the explosive pace with which privately funded companies are innovating and experimenting with alternative approaches. The timing is ripe for private investments since advancements in technological developments have brough fusion research and reactor designs out from the laboratory into the engineering phase.

Demonstration of scientific feasibility

The energy output from fusion vs. the energy consumed is expressed as what is known as a Q factor. Over the decades, the Q factor of fusion reactors has improved over 1000x and recently the Lawrence Livermore National College demonstrated net positive energy from fusion (Q= 1.54). Publicly funded reactor experiments such as ITER are targeting to produce 10 times more energy than they consume by 2035 (Q=10). Using the Lawson criterion, this milestone is near-ignition, and there is a small increment needed to achieve steady state fusion and power to the grid can begin. Several private fusion companies are targeting earlier timelines, and they are well-past the prototype stage. Relative newcomers such as Helion Energy are aggressively ramping up commercial commitments, such as the recently announced deal to supply

Microsoft with Fusion energy by 2028. Veterans such as Commonwealth fusion are also building commercial fusion reactors, such as SPARC.

Strategic investors will likely drive technology consolidation

Mature fusion companies such as TAE have raised almost $1.2 bUSD to date from institutional investors, sovereign wealth funds and high net wealth individuals (11). Both TAE and General Fusion has received investments from the likes of Cenovus Energy and Chevron Technology Ventures, indicating that traditional oil and gas giants have started strategically investing in the sector to future-proof their portfolio. Players such as Google have also invested in fusion, presumably to hedge their ever-increasing need for energy to power data centers and advanced computing. In the long run, we foresee these strategic players driving market consolidation.

Strategic investor	Target company	First investment
Cenovus Energy	General Fusion	2011 (Series B)
Eni	Commonwealth fusion	2019 (Series A)
Equinor	Commonwealth fusion	2020 (Series A2)
Chevron Technology Ventures	Zap Energy	2020 (Series A1)
	TAE Technologies	2022 (Series G)
Google Alphabet	TAE Technologies	2022 (Series G)
Toyota Energy	Avalanche	2023 (Series A)
Honda	NT-Tao	2023 (Series A)
Mitsubishi	Kyoto Fusioneering	2023 (Series C)

Enabling technologies & scalable innovations

Several enabling technologies have matured in the last two decades which reduce engineering complexities and the costs of a fusion power plant as well as increase the efficiency of the reactors.

- *High temperature superconducting (HTS) magnets*: Until the early 1980s, no superconductivity was observed above the temperature of 23 Kelvin (-250 °C), which made them unusable for magnetic plasma confinement (12). Through advances in material sciences, HTS magnets have been created which can handle fusion grade temperatures and allow smaller modern reactors to produce as much energy as their larger but older peers (13).
- *Advanced computing*: Exascale computing and algorithms are needed for modelling the complex physics of reactor grade plasmas, assisting with detailed

engineering design work, understanding the properties of materials under extreme conditions or in processing the large quantities of data produced by reactor experiments (14).

- *3D printing*: Additive manufacturing can significantly reduce the costs of a fusion power plant, quickly print several iterations of components and generate fast resolution to complex engineering problems.

Regulatory landscape in favor

Interviews with regulatory experts inform us that fusion is less likely to require complex legislation, since it has few environmental and safety concerns than fission. Existing laws and regulations for fission can also be adapted for fusion. The United Kingdom has an explicitly stated fusion strategy and regulates it similarly to particle accelerators or medical isotopes (12). The United States recently followed suite and announced that fusion will be regulated under article 30 of the Code of Federal Regulations, unlike fission which falls under Article 50 (13) (14). This means that costs for regulatory efforts needed to secure approval have gone down from billions of dollars to tens of millions for a fusion power plant. Consequential to this new announcement, the timeframe for such permits would then also take around a year instead of 10 years (15).

Fusion is a highly lucrative venture opportunity - but only for a limited few

While private investments have certainly scaled, not every venture capitalist is suited to invest in the space. Investors must be able to take a high risk and can work with time frames that go beyond the traditional 10-year fund structure. They must have sufficient dry powder for follow on investments in large rounds with high valuations. Finally, the area is highly technical, and investors must have access to experts who can help them navigate early-stage solutions in order to find a true opportunity. Two key factors that indicate that fusion can deliver venture scale are:

Technology readiness

The timing for commercial fusion has been an ever-moving target, with delays in publicly funded efforts such as ITER and private companies who have been building for almost two decades. The step changes in Q factors mapped below are logarithmic, and the distance to ignition (Q>10) now that we have gone past breakeven (Q=1) is smaller than when fusion was first proved in 1958 (Q= ~10^{-4}). Thus, the field is well suited for early-stage investments.

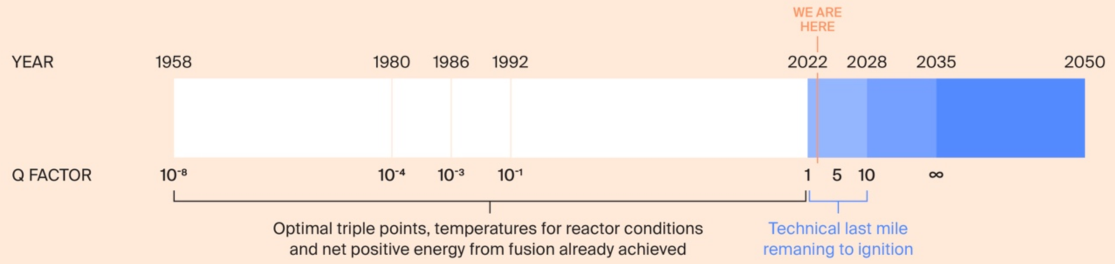
Scaling readiness

Aside from the regulatory momentum from key markets, analysis shows that future fusion reactors could deliver energy at price points that match renewables (10). Engineering advancements in the growing number of private efforts are reducing the capex costs for materials and subcomponents, introducing more scalability to the fusion sector. This indicates an emerging potential for commercial scale.

The Last Mile for Fusion

Timeline of fusion energy
output & Milestones

$$Q = \frac{\text{Energy output from fusion}}{\text{Energy consumed to create fusion}}$$



Q=1
Energy Breakeven
Plasma is stable. Fusion energy gain factor. Net energy positive example from Lawrence Livermore National Laboratory achieved Q=1.54

Q=5
Engineering Breakeven
Plasma stays stable long enough to become self heating. Energy extracted from the reactor can be partially fed back to heating the reactor itself.

Q=10
Ignition Tipping Point
ITER, funded by the EU, US, UK, China, Japan, South Korea, India and Russia, aims to test plasma in 2025 and full fusion by 2035.

Q ∞
Ignition
Plasma temperatures high enough for self-sustaining fusion.

Commercial Breakeven
The economic value of electricity leftover after recirculation can pay for the reactor. Full integration as grid base load estimated to be in 2050.

Industrifonden's view

The promising momentum from strategic investors, enabling technologies and regulatory tailwind strengthens the prospect that a commercial fusion reactor that begins to supply limited power to the grid can be built by 2030. We believe that in the coming decade, there will be a cross-pollination across the various fusion approaches currently under development. Given the activity from strategic investors, we believe they will play a key role in driving this consolidation through M&A within the same time frame. Our best guess is that Oil & Gas companies will be first movers in this regard and will lead this consolidation for magnetic confinement reactors. For the inertial confinement and orthogonal approaches, M&A activity from mobility companies and data giants will lead the technology consolidation. Based on interviews with scientific experts and founders of private fusion companies, we foresee a future scenario where multiple fusion alternatives will exist, even in a post-consolidated market.

We therefore believe the best-case scenario for a fusion investment is a technology-based exit.

Additionally, we have identified several fallback exit opportunities that can still generate significant returns:

- Sale of secondaries: transaction activity in the space shows financing rounds go well into Series E and beyond with investments from private equity, strategic investors, and late-stage VCs
- Spin outs: Magnets and neutron beams from fusion can be applied to other sectors such as medical scanning in healthcare
- Minority IPO: As companies scale, the infrastructure buildout can be separated from the core technology

Novatron contributes with a key technology

Our interest in the sector led us to the Swedish fusion technology company Novatron in which we recently made an initial investment. There are a few key reasons we believe that Novatron represents a unique early-stage opportunity within fusion.

All magnetic confinement reactors are designed to tackle the problem of plasma stability and density. The ideal magnetic field for this should be concave and get stronger as particle move outward to contain the plasma effectively. Tokomaks and stellarators have attempted to tackle this by designing highly specialized magnets in toroidal and helical forms, respectively. Novatron has chosen a different and potentially superior approach.

Unique magnetic field design

Novatron has developed a proprietary design of the magnetic field specifically constructed to minimize plasma leakage. Novatron's concave magnetic fields could be able to achieve significantly higher ionic temperatures than tokamaks. This makes it a highly relevant model for future ignition, to trigger self-sustaining fusion and bring fusion energy to the grid.

No scientific black box

Novatron has focused on redesigning the magnetic field concept instead of building new magnets and is based on research from 70 year on magnetic mirror reactors. The simulation data has been vetted by veteran plasma physicists from Lawrence Livermore National College, MIT, and Yale. The advisory Board has academic members from the University of Wisconsin, home to the currently in-use Wisconsin HTS Axisymmetric Mirror machine. The results will be published in peer reviewed and public journals, lending credibility and validating the core technology.

Commercially scalable and less costly design

Due to the reactors design, Novatron anticipates that it will be able to produce almost twice the energy output than a tokamak type ARC reactor. Experts say that it will require less fuel and the lack of customized magnets imply that overall costs will also likely be much lower with this reactor design. It does not need to be shut down for cleaning meaning that it can produce energy for longer uninterrupted periods.

Another unique aspect is the reactor may be able to have direct conversion to electricity. Existing reactors have an intermediary step, to transfer fusion energy to thermal energy before it can be converted to electricity. This implies that the engineering breakeven for Novatron's patent-pending design will be achieved at a lower cost than other fusion reactors.

Competitive advantage in a consolidating market

Finally, in the future we foresee a cross pollination of technologies. We may eventually need to choose between different types of tokomaks or stellarators, but there are synergistic possibilities between the various categories of reactor types. Magnetic mirror reactors can complement tokamak type reactors, as exemplified in the collaboration between the Wisconsin HTS Axisymmetric Mirror (WHAM) and the MIT spinout, Commonwealth Fusion. Novatron's design is unique and could be combined with other axisymmetric magnetic mirrors in tandem or with tokomaks if the technology consolidations were to manifest.

Magnetic Confinement Fusion (MCF)
Z-pinch, tokomaks (toroidal magnets), stellarators (helical magnets) and Magnetic Mirror Machines (Open magnetic field) & field reversed

Inertial Confinement Fusion (ICF)
Laser Induced fusion, projectile magneto inertia

Orthogonal approaches
Fusion using non-neutronic fuels, novel deviations of traditional MCF & ICF reactors or revival of discontinued concepts

Glossary of terms

Plasma: A fourth, superheated state of matter where electrons are ripped out of atoms to form an ionic gas (first three states are solid, liquid, and gas)

Q factor: Energy produced vs. energy needed for fusion. A Q factor of 10 means 10x more energy is produced than required to generate fusion

Magnetic Confinement Fusion (MCF): Reactors that contain the plasma using magnetic fields: Z-pinch, tokomaks (toroidal magnets), stellarators (helical magnets) and Magnetic Mirror Machines (Open magnetic field) & field reversed

Inertial Confinement Fusion (ICF): Hydrogen fuels are physically compressed and heated to very high temperatures using lasers. Essentially the same technology as the hydrogen bomb – but completely safe. E.g., Laser Induced fusion, projectile magneto inertia

Orthogonal approaches: Fusion using non-neutronic fuels, novel deviations of traditional MCF & ICF reactors or revival of discontinued concepts

Breakeven: When energy needed for fusion is equal to that which is produced. *Scientific breakeven* to achieve fusion is Q=1. In addition, energy is required to run the reactor, *so engineering breakeven* is Q= 5-8 for most reactors. To provide commercial power to the grid, the amounts of electricity must be so large that the revenues from supply costs.

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