PHOTONICS21

Tematys
Exploration of photonics markets

Photonics for the energy production market

Focus on fusion energy

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Contents

1. Context and introduction

Every second, the sun emits its energy as photons – the smallest possible particles of electromagnetic radiation. With the exception of nuclear power, these light particles are the foundation for nearly all the energy used on Earth, following various physical and chemical transformations. Atmospheric temperature variations, along with the Earth's rotation, generate wind. Sunlight heats water, causing evaporation, which forms clouds that eventually produce rain, feeding rivers and streams. Plants capture solar energy through photosynthesis, while coal and oil are derived from fossilised biomass. Animal energy comes from biomass digested as food, and biofuels and biogas originate from a chemical transformation of biomass.

For centuries, energy came from animal and human muscles, wind, water mills, and fire. Each source had a specific purpose: muscles for agriculture, transport and crafts, wind for transport, wind and water for mills and fire for heating, lighting, cooking and crafting. Then, carbonised energies of coal and oil, along with engines, greatly increased our capacities. Later, electricity was exploited based on fossil fuel production and, where possible, hydropower before the deployment of nuclear plants.

With climate change taking centre stage at the COP28 convention in December 2023, the urgent need to replace fossil fuels with cleaner energy sources has become more apparent than ever. The cleanest energies available today are produced as electricity. This document describes how photonics are a major asset in producing electricity that does not pollute the atmosphere. It also details how photonics is a supporter and an enabler to all energy sectors, either to maintain facilities, to help reduce emissions, or to monitor climate change and its impact.

The second part of this document focuses on fusion power, an environmentally friendly energy source regarded as the ultimate solution for generating large-scale electricity and replacing nuclear fission. Unlike fission, fusion does not rely on finite fuel sources or combustibles and produces no long-lived radioactive waste. This report details how photonics serves as a key enabler for the various nuclear fusion approaches under research today.

2. Photonics as a major asset for a cleaner energy mix

Photovoltaics. Photovoltaics is the most evident contribution of photonics to a more sustainable energy production. Photovoltaic electricity is not only produced in farms, on the roof of buildings or as shade in parking lots. It has become very common in individual houses. However, solar cells also help to power equipment that cannot be connected to the grid: consumer devices like watches, highway emergency call boxes, and satellites, which have “wings” made of solar panels that unfold during orbit.

Figure 1: More and more parking lots are equipped with solar panels which produce electricity but also provide shade to cars. Source: aapsky on iStock.

Thermo-solar. Photovoltaics is not the only way to use the sun as an energy source. In many countries, rooves on buildings are equipped with thermo-solar water heaters. It is a simple and cheap way to pre-heat tap water before it enters the regular water heater, reducing the energy needed to bring it to a comfortable setpoint. The same effect is also used but at a much larger scale in large solar-thermal plants where mirrors concentrate the sunlight to heat a water target at a very high temperature, which activates a generator.

Photonics as an enabler of a decarbonised energy mix. Nuclear plants, wind turbines, hydroelectric dams, photovoltaic farms, and the grid are large infrastructures that need maintenance, monitoring, or just operation. Photonic-based instruments are critical tools for an optimised operation. Thermographic cameras detect defects in electrical cables without having to climb on very high pylons. LIDARs measure the wind profile and significantly increase the productivity of wind turbines. Optical fibre sensors help monitor the integrity of large hydroelectric dams.

Out at sea, advanced cameras embedded in satellites can detect illegal cleaning of oil tankers or monitor large methane emissions from gas pipelines.

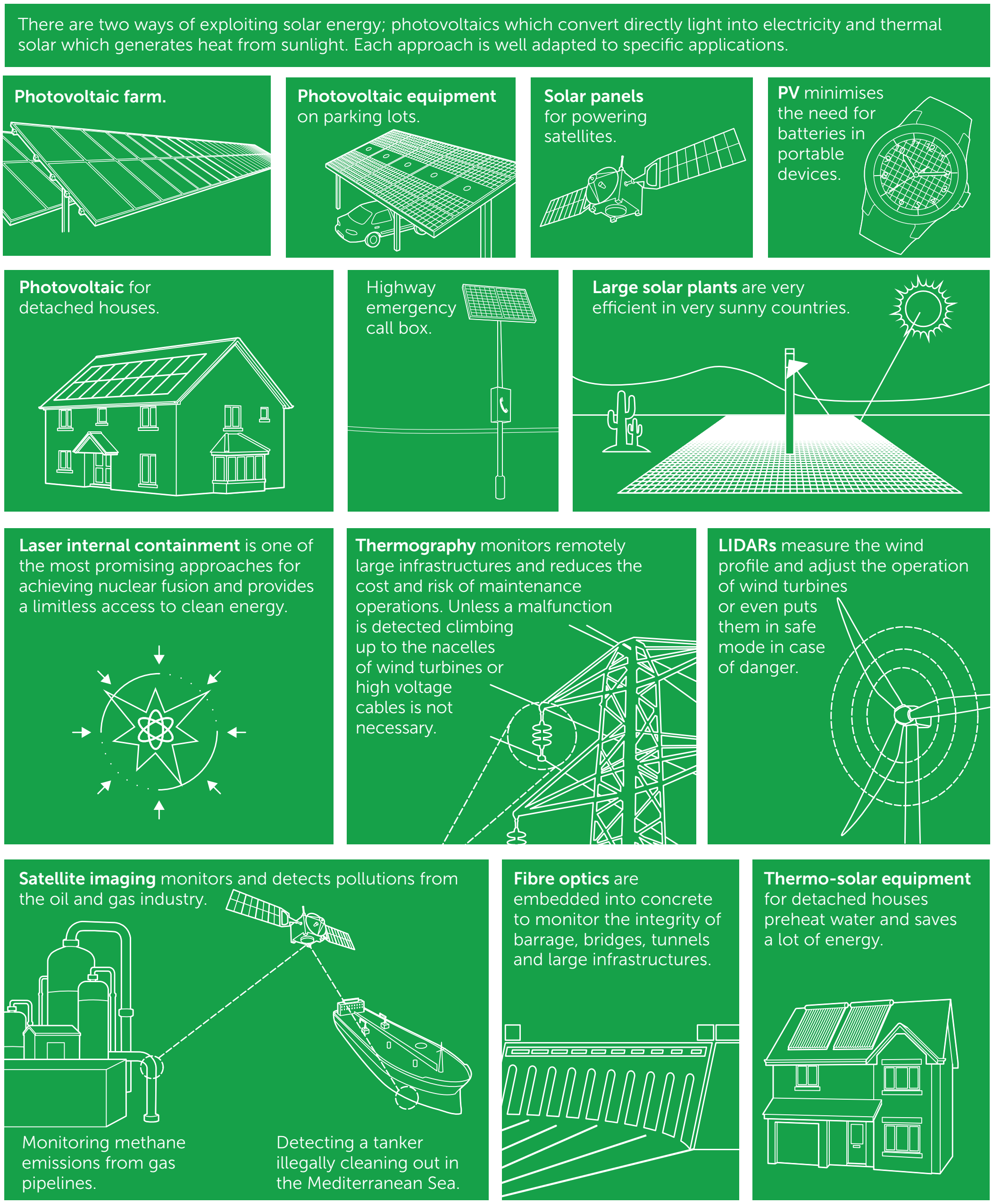


Figure 2: Two ways of exploiting solar energy. Source: Tematys/ Photonics21, 2023.

Photovoltaics is the most evident contribution of photonics to a more sustainable energy production. However, photonics are also widely used for the surveillance of all other energy equipment. In the long term, high-powered lasers will eventually make the dream of nuclear fusion come true.

3. Photonics as an enabler of nuclear fusion

3.1 To achieve nuclear fusion and exploit the energy it produces is an extreme industrial challenge

Nuclear fusion is a reaction where two or more atomic nuclei, typically deuterium and tritium (isotopes of hydrogen), combine to form one or more different nuclei along with subatomic particles such as neutrons or protons. For fusion to occur, the nuclei must be brought close together. However, their electrical charges cause them to repel each other. Overcoming this repulsion requires an immense amount of energy at extremely high temperatures. When fusion finally happens, it releases an even greater amount of energy, which can be harnessed to generate electricity.

In the sun, nuclear fusion occurs between hydrogen atoms at temperatures around 15 million degrees Celsius. On Earth, the temperatures required for fusion of other nuclei can be much higher, reaching several hundred million degrees Celsius, far exceeding the conditions inside a star. Consequently, the fuel becomes too hot to be contained in a physical vessel and must be suspended using methods such as magnetic, electric, or electromagnetic confinement.

This is why, harnessing fusion energy to generate electricity presents several extraordinary challenges. Among many, four major challenges stand out:

- While the highly energetic neutrons are the target product of the fusion reaction and yield the most energy of the reaction, they also wear down and weaken all surrounding materials.
- Most fusion approaches aim at combining deuterium and tritium, which requires a temperature of 100 million degrees Celsius. This temperature is extreme but the fusion of other combustibles requires even higher temperatures up to the billion Celsius[1]. Unfortunately, if deuterium is abundant, tritium is rare on Earth and must be produced by bombarding lithium with the neutrons produced by nuclear fusion.
- Another challenge is the extraction of heat in order to produce electricity. The fusion energy is produced out of a few milligrams of combustible, i.e. a tiny volume. Efficiently extracting the produced heat and transferring it to turbines is a significant industrial challenge. While some fusion reactor designs facilitate this process, others require the development of specific solutions.
- The fourth challenge is scalability and industrialisation. All current designs, including ITER, the largest one, are demonstrations. Once a concept's feasibility is proven, it will be necessary to demonstrate how the idea can be scaled up and, even more challenging, to prove that the plants can run for decades. One does not need to be an engineer to understand that operating at multimillion-degree temperatures poses significant material and engineering problems that have yet to be resolved.

[1] https://en.wikipedia.org/wiki/Nuclear_fusion

In conclusion, fusion energy offers great perspectives in the long term, but there is still a long way to go. In this human endeavour, Photonics plays a critical role at three levels.

1. Every concept needs high-precision or sometimes extremely high-precision manufacturing processes. Industrial lasers and photonic-based advanced control systems are critical solutions in very high-precision manufacturing.
2. It is not possible to manipulate multimillion-degree hot combustibles which produce huge streams of particles without very advanced contactless sensors and metrology systems. Photonic-based instruments are, by essence, well suited for such a hard environment.
3. Some approaches, especially the inertial laser concept, directly use lasers as a core means to confine and compress the combustible to such pressure and temperature to induce fusion.

The contribution of photonics to nuclear fusion is detailed in this chapter.

3.2 The different approaches to fusion

There are more than a dozen different nuclear fusion reactor concepts (table 1). The objective of this report is not to describe all of them in detail. The reader is invited to refer to the reference sources[2,3,4,5]. The most studied concepts are tokamaks, stellarators and inertial. The inertial concept is more detailed in the present report as it relies on lasers and has already shown promising results in 2023[6].

Method (source:)	Confinement approach	Photonics as a core component for operation	Photonics as metrology, sensing and control enabling technology
Tokamaks	Magnetic	No	Yes
Stellarators/Heliotrons	Magnetic	No	Yes
Inertial/Laser	Inertial	Yes	Yes

Table 1: List of nuclear fusion concepts under study and development.
Source: Tematys/Photonics21, 2023 – Data: IAEA.

[2] World survey of fusion devices 2022 / International Atomic Energy Agency. ISBN 978–92–0–143122–6
[3] https://www.iaea.org/topics/fusion
[4] https://www.iter.org/news
[5] https://www.fusionindustryassociation.org/
[6] https://www.nature.com/articles/d41586-023-03923-5

Table 1 (continued): List of nuclear fusion concepts under study and development. Source: Tematys/Photonics21, 2023 – Data: IAEA.

Method (source:)	Confinement approach	Photonics as a core component for operation	Photonics as metrology, sensing and control enabling technology
Alternative device concepts			
Reversed Field Pinch	Magnetic	No	Yes
Simple Magnetized Torus	Magnetic	No	Yes
Spheromak	Magnetic	No	Yes
Field Reversed Configuration	Magnetic	No	Yes
Levitated Dipole	Magnetic	No	Yes
Magnetic Mirror Machine	Magnetic	No	Yes
Dense Plasma Focus	Magnetic	No	Yes
Pinch	Magnetic	No	Yes
Spherical Tokamak	Magnetic	No	Yes
Magnetised Target Fusion	Magneto-inertial	No	Yes
Inertial Electrostatic Fusion	Electrostatic	No	Yes

Because of the urgent need for decarbonised energy sources, research on fusion has been boosted in recent years. While a majority of initiatives are publicly funded – and by far mostly concern tokamaks – a significant number of start-ups were launched recently, thanks to capital funds, often backed by billionaires concerned by climate change. Over 130 experimental, public and private fusion devices are operating, under construction or are being planned. Furthermore, a few organisations are considering designs for demonstration fusion power plants.[7]

3.3 Inertial confinement, lasers as the fusion engine

The principle of inertial confinement fusion (ICF) involves shooting synchronised extremely short and powerful laser pulses all around a solid mixture of deuterium (D) and tritium (T) in order to compress it as fast as possible. As the pressure of the medium rises, so does its density and temperature, enabling the conditions required for fusion to be reached. In this way, the ICF method mimics in a small way what a star naturally achieves through its stationary gravitational collapse.

[7] Jennifer Hiller, "Tech Billionaires Bet on Fusion as Holy Grail for Business", The Wall street Journal, April 2023, https://www.wsj.com/articles/tech-billionaires-bet-on-fusion-as-holy-grail-for-business-9a48a2ac

But this approach is complex to develop and, above all, to master. The first challenge involves the methods used to compress the D-T fuel pellet. While the laser energy required to converge on the target may seem reasonable (a few megajoules), compression times are very short (a few tens of nanoseconds). The powers to be mobilised are, therefore, colossal, on the order of several hundred terawatts (TW), and require dedicated facilities. Such facilities already exist at the experimental stage, such as the Laser Megajoule at the CEA (Commissariat à l'énergie atomique et aux énergies alternatives) in France or the National Ignition Facility based at Livermore in the USA.

The second challenge of the inertial pathway lies in achieving the perfect convergence of several hundred laser beams on the target so as to ensure the most uniform compression all around the mixture and avoid instabilities that would reduce the energy confinement qualities. Indeed, a "direct attack" on the target by the beams is ultimately unable to ensure this good uniformity of compression. A so-called "indirect attack" strategy soon proved far more efficient. To achieve this, the D-T target is itself enclosed in a specially shaped gold cavity. The beams are then used to "heat" this cavity, which begins to emit X-rays, which are then absorbed by the D-T target. Isotropy is controlled by the geometry of the cavity.

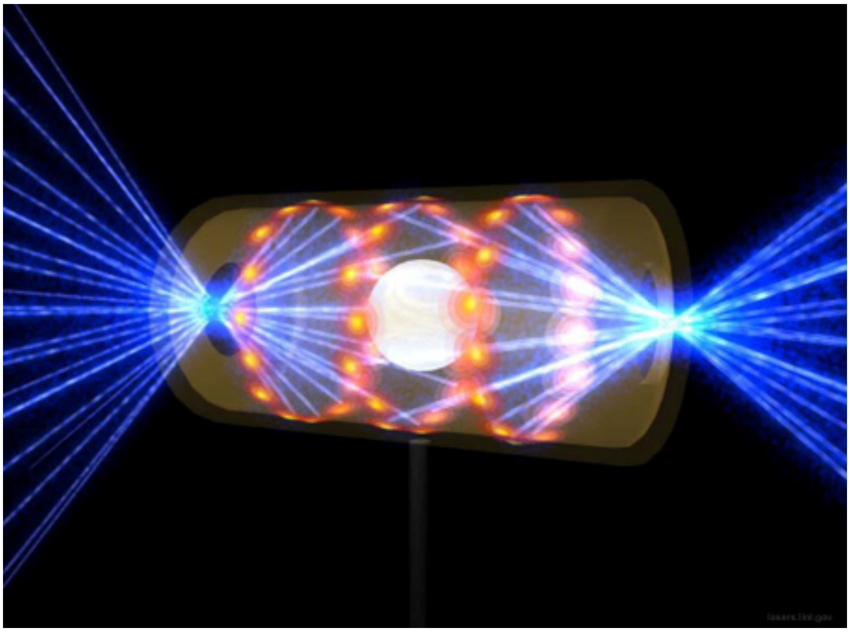
The National Ignition Facility recently reported (August 2021) a significant breakthrough in demonstrating the scientific feasibility of this approach. Indeed, an energy of 1.3 MJ was produced by a 1.7MJ laser pulse for about a tenth of a microsecond. This record seems to have been made possible not only by the reliability and quality of the laser pulse but also by a series of target optimisations (shape, positioning, etc.) that brought the experiment closer to its objective.

The inertial route, while enabling fusion reactions to take place during the implosion of a D-T target, does not yet allow us to envisage the rapid production of energy using this process. To be technologically, industrially and commercially viable, several industrial challenges are still unsolved: how to collect the power released by the implosion, how to repeat this implosion several dozen times per second to produce usable energy, and how to ensure a favourable energy balance by comparing all the energy mobilised to provoke the implosions and the energy produced in the form of electricity.

In conclusion, the IFC approach relies entirely on advanced photonics: advanced and very high-quality optical mirrors and components, crystals, amplifiers, and metrology instruments to control, synchronise and focus the laser beams.

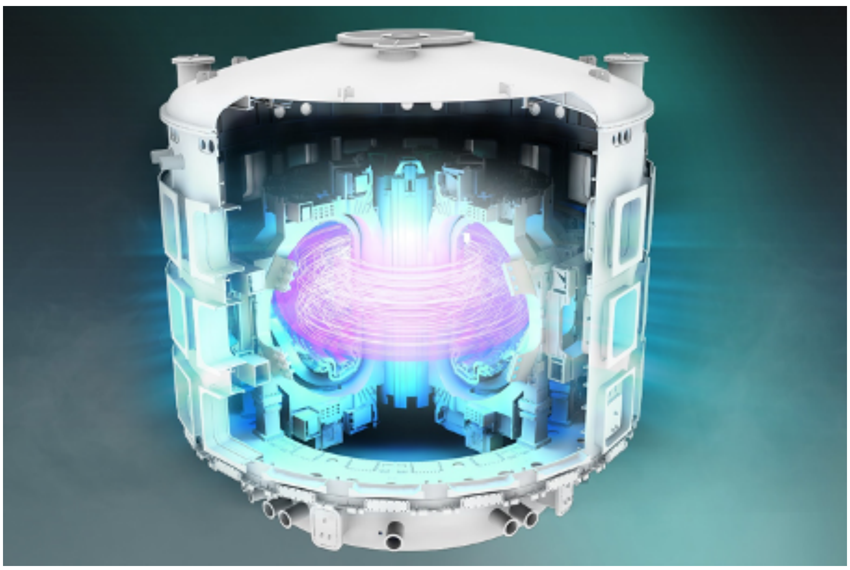
Developing and building the Laser Megajoule in France enabled the generation of a full photonic ecosystem near Bordeaux and generated 3,000 jobs. Today, the companies of this cluster create a business which goes far beyond the photonic technologies developed and acquired for building the Megajoule facility.

Figure 3: Inertial confinement fusion: artist's rendering of a target pellet inside a capsule with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur.
Source: Courtesy of Lawrence Livermore National Laboratory.



3.4 Magnetic confinement main concepts: Tokamak and Stellarators

Figure 4: ITER will be the world's largest tokamak, with a plasma volume of 840 m^3.
Source: ITER, 08 Juin 2023.



In magnetic confinement fusion, hundreds of cubic metres of deuterium-tritium plasma are confined by a magnetic field and heated to fusion temperature. The confinement is achieved in toroidal (doughnut-like) or annular chambers surrounded by huge magnetic coils, which produce extremely intense magnetic fields capable of inducing the levitation of the plasma ring and preventing it from touching the wall of the chamber.
The main concepts of magnetic confinement are tokamaks and stellarators. Both types of reactor have their advantages: tokamaks are better at keeping plasmas at high temperatures, while stellarators are better at keeping them stable.

In a tokamak, the field is created by a series of coils evenly spaced around the torus-shaped reactor, and the poloidal field is created by a system of horizontal coils outside the toroidal magnet structure. A strong electric current is induced in the plasma using a central solenoid, and this induced current also contributes to the poloidal field.

Unlike tokamaks, stellarators do not require a toroidal current to be induced in the plasma. In a stellarator, the helical lines of force are produced by a series of coils, which have to be helical in shape. Producing coils of complex and very precise shapes is a great challenge, which means that more tokamaks are being developed today. However, photonics could change the game in the near future (see 3.5).

So far, some tokamaks have succeeded in triggering fusion reactions for a short time. The record is seventeen minutes and thirty-six seconds, but none of them has achieved a net power gain greater than 1, i.e., producing more energy than that required to heat and confine plasma.

Whatever the fusion approach, and even when the confinement is magnetic or electrostatic, no complex infrastructure like fusion reactors can work without photonics as a critical enabler. Metal or ceramic parts are cut, drilled, surfaced, and welded with lasers. They can even be directly produced by laser-based additive manufacturing. The quality control of each part needs advanced imaging and metrology equipment; the millimetric precision assembly of the parts of the tokamak ITER, weighting 200 tons, is enabled by laser instruments; all robotics rely on cameras or LIDARs; the control and metrology of operations uses advanced photonic instruments.

The following section illustrates how photonics is crucial for manufacturing the complex shapes of a stellarator design, which would be impossible to produce without lasers.

3.5 Industrial lasers to build fusion set-ups, an example of Renaissance Fusion

Renaissance Fusion (RF) is a start-up based in Grenoble, France, that aims to develop a stellarator fusion reaction. In 2023, RF has raised a total of €16.4 million from venture funds.

A common challenge for designing stellarators is building coils of complex shapes with high precision.

The innovation of RF combines a disruptive design but also a disruptive strategy for manufacturing the coils. Rather than making coils with wrapped wires, RF plans to deposit a layer of high-temperature superconductors on cylinders and, after, use lasers to very precisely engrave complex 2D patterns, which will create the required shapes for the magnetic confinement[8]. This approach is a huge manufacturing simplification and allows a much higher design precision thanks to the flexibility enabled by lasers.

When all cylinders are made, they are assembled to make the doughnut.

RF's concept simplifies heat extraction and tritium production by using liquid metal flowing around the cylinders.

[8] https://renfusion.eu/

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