

Section Six: Nuclear Energy

Is nuclear energy “green”?

It depends on what you mean by *green*.

Why many experts group it with low-carbon /clean energy?

- Very low life-cycle greenhouse-gas emissions (mining → construction → operation → decommissioning). The Intergovernmental Panel on Climate Change (IPCC) reports a median **12 g CO₂/kWh** for nuclear on a life-cycle basis—similar to wind and far below fossil fuels.
- Reliable (“firm”) power: runs day and night, helping balance weather-dependent renewables. The UK government describes nuclear as “reliable, low carbon... proven at scale” in the UK.

Typical life-cycle emissions estimates reported by the IPCC:

- Nuclear: ~ **12 g CO₂/kWh**
- Wind: ~ **11 g CO₂/kWh**
- Solar: ~ **40 g CO₂/kWh**
- Coal: **800–1000 g CO₂/kWh**

Why some people don’t call it green?

- Radioactive waste needs secure management for long timescales (engineering + governance challenge).
- Accident risk is low-probability but high-consequence, shaping public concern and regulation.
- Upfront impacts: uranium mining, heavy construction materials, and water use (site-dependent).

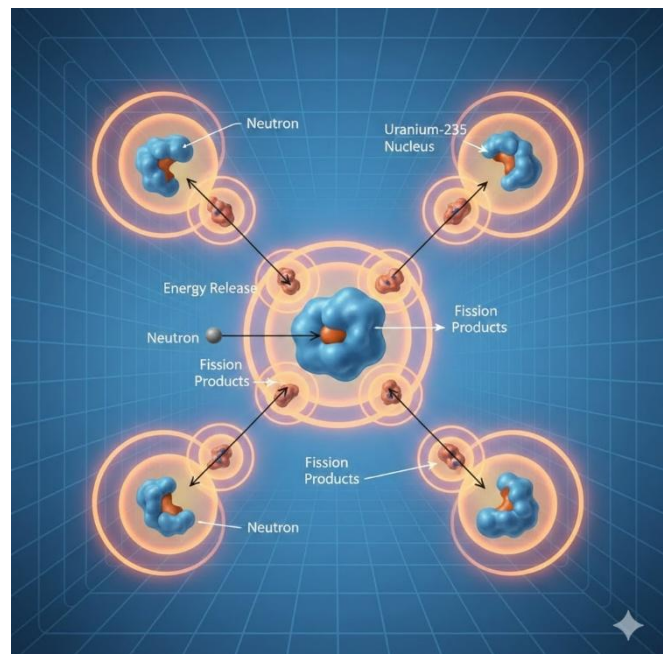
A fair summary: Nuclear is widely treated as low-carbon/clean electricity, but whether it’s “green” often hinges on how you weigh waste, accident risk, and local environmental impacts versus climate benefits.

What is nuclear energy?

Nuclear energy is energy stored in atomic nuclei. In today’s power plants, we use fission: splitting heavy atoms (usually uranium) to release heat.

Core idea:

A nuclear fission chain reaction is a self-sustaining process where the splitting of one heavy nucleus releases particles that go on to split further nuclei. This process is the powerhouse behind both nuclear reactors and atomic weapons, depending on how fast it’s allowed to happen.



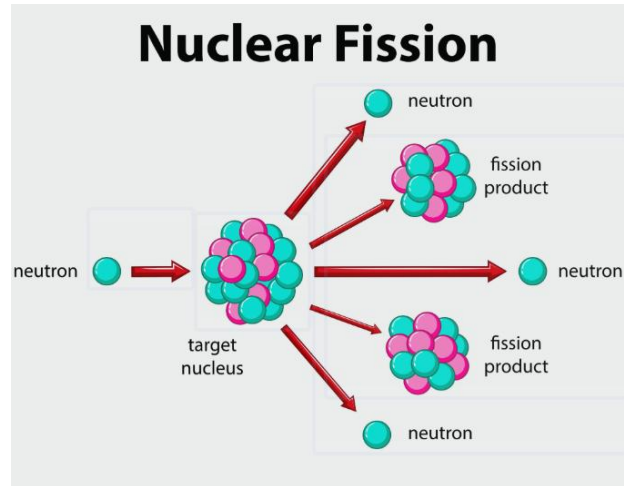
Here is the step-by-step breakdown of how a nuclear fission chain reaction unfolds:

1. Neutron Bombardment

The process begins when a "bullet"—usually a low-energy neutron—is fired at a heavy, unstable nucleus. The most common fuel used is Uranium because it is fissile, meaning it easily undergoes fission when hit by a neutron.

2. Absorption and Instability

The Uranium-235 nucleus absorbs the incoming neutron, briefly becoming Uranium-236. This extra neutron makes the nucleus extremely unstable—think of it like a water droplet that has grown too large to hold its shape.



235

3. The Split (Fission)

Almost instantly, the unstable nucleus oscillates and splits into two smaller nuclei, known as fission fragments (such as Barium and Krypton).

4. Energy and Neutron Release

As the nucleus splits, two critical things happen simultaneously:

- **Energy Release:** A massive amount of kinetic energy and gamma radiation is released. This energy comes from a tiny amount of mass being converted into energy, described by Einstein's famous equation: $E = mc^2$
- **Secondary Neutrons:** The split ejects 2 to 3 "spare" neutrons at high speeds.

5. The Chain Reaction

This is where the "chain" part comes in. Those 2 or 3 newly released neutrons fly out and strike neighbouring Uranium-235 nuclei. If those nuclei also split, they each release more neutrons, leading to an exponential increase in fissions.

In a nuclear reactor, the goal is to keep the chain reaction **critical** — meaning exactly one neutron from each fission event goes on to trigger another. If too many neutrons fly around, the reactor gets too hot; too few, and the power dies out.

Control rods are the "brakes" of the nuclear engine. Here is how they manage the physics:

1. Neutron "Sponges"

Control rods are made of materials that are excellent at absorbing neutrons without fissioning themselves. Common materials include Boron, Silver, Indium, or Cadmium. When a neutron hits a boron atom in a control rod, it is simply swallowed up, ending that particular branch of the chain reaction.

2. Physical Manipulation

The rods are physically moved in and out of the reactor core (the area containing the uranium fuel):

- **Withdrawing the rods:** When the rods are pulled out, fewer neutrons are absorbed by the boron and more are available to hit uranium atoms. This increases the rate of fission and power output.
- **Inserting the rods:** When the rods are pushed deeper into the core, they soak up neutrons like a sponge. This decreases the number of fissions, slowing down the reaction.

3. The "SCRAM" (Emergency Shutdown)

In the event of an anomaly or an emergency, the reactor undergoes a SCRAM. This is a rapid, automatic insertion of all control rods into the core. Gravity or high-pressure hydraulics slam the rods home, absorbing so many neutrons that the chain reaction is smothered almost instantly.

Beyond control rods, reactors also use moderators (like water or graphite) to slow neutrons down so they are easier to catch.

It seems counterintuitive, right? You'd think a faster neutron would smash into a nucleus with more "punch," like a bullet. But in the world of subatomic physics, it's actually the opposite.

To split a Uranium-235 nucleus, the neutron doesn't just need to hit it; it needs to be captured by it.

The "Goalie" Analogy

Imagine a soccer goalie trying to catch a ball.

- **Fast Neutrons:** If the ball is shot at 100 mph, it's likely to bounce off the goalie's hands or fly past before they can react. This is a "fast" neutron—it has too much kinetic energy to be easily absorbed by the nucleus.
- **Slow Neutrons:** If the ball is rolled gently toward the goalie, they can easily grab it and hold on. These are called Thermal Neutrons. Because they are moving slower, they spend more time near the nucleus, giving the strong nuclear force a better "grip" to pull them in.

The Role of the Moderator

Since neutrons are born "fast" during fission (traveling at about 10% the speed of light), we need a way to slow them down so they can keep the chain reaction going. This is the job of the moderator.

The moderator is a substance—usually **water**, **heavy water**, or **graphite**—that surrounds the fuel rods. Here is what happens:

1. A fast neutron is ejected from a fissioning atom.
2. It crashes into the nuclei of the moderator (like a billiard ball hitting another ball).
3. With every collision, the neutron transfers some of its kinetic energy to the moderator atoms.
4. After a few bounces, the neutron slows down to "thermal" speeds (matching the temperature of its surroundings).
5. Now "slow," it is much more likely to be captured by the next Uranium-235 nucleus it encounters.

Why this Matters for Safety?

This relationship between speed and absorption is a built-in safety feature for many reactors (like Light Water Reactors).

If a reactor gets too hot, the water (moderator) turns to steam or expands. Since steam is less dense than liquid water, there are fewer atoms for the neutrons to hit. The neutrons stay "fast," they fail to be captured by the Uranium, and the chain reaction naturally slows down. This is known as a negative void coefficient.

Most of the world uses water-cooled reactors (including the UK's operating fleet).

- **Fuel:** ceramic uranium pellets stacked in fuel rods.
- **Moderator** (in many designs): slows neutrons to sustain the chain reaction.
- **Control rods:** absorb neutrons to control power (like a "brake").
- **Coolant:** carries heat away from the core.
- **Containment:** thick steel/concrete barriers for safety.

What is nuclear energy used for?

Main uses

- **Electricity** (grid supply; high capacity factor/steady output).
- **Heat for industry** (in some countries): high-temperature steam for processes.
- **District heating** (less common, but feasible).
- **Hydrogen production** (emerging): using nuclear electricity and/or heat.

Cost: what drives it (and typical ranges)

Nuclear economics are dominated by upfront capital cost and financing.

What makes it expensive

- Large, complex builds (lots of concrete/steel, specialized labour)
- Long schedules → interest during construction
- Strict safety/regulatory requirements (important, but adds time/cost)
- First-of-a-kind builds tend to overrun more than repeat builds

Time to build

For large conventional plants, a common planning reality is 7 to 15 years from early development to operation (site licensing, design approvals, financing, construction, commissioning). Delays happen often, especially on first builds.

UK example: Hinkley Point C began construction years ago and has been reported as delayed to around 2030.

Types of nuclear power (and what “micro-nuclear” means)

A) Reactor types you’ll see in textbooks

- **PWR (Pressurized Water Reactor):** most common globally; high-pressure water removes heat and produces steam via a steam generator.
- **BWR (Boiling Water Reactor):** water boils in the reactor vessel to make steam directly.
- **PHWR/CANDU:** heavy-water moderated; can use different fuel options.
- **Gas-cooled reactors** (historic UK specialty): the UK’s **AGR** fleet uses gas cooling and graphite moderation.

B) “Advanced” and “modular” reactors (newer directions)

- **SMR (Small Modular Reactor):** smaller (often ~50–300+ MW electric), factory-built modules aiming for faster, cheaper, repeatable builds.
- **AMR (Advanced Modular Reactor):** “advanced” coolants/fuels (e.g., high-temperature gas, molten salt, sodium) targeting higher temperatures and new industrial uses.
- **MMR / microreactor (“micro-nuclear”):** *very small* reactors (often single-digit MW to tens of MW electric), designed for remote sites, military bases, islands, mines, or as local resilient power.

The UK’s “Advanced Nuclear Framework” explicitly discusses SMRs, AMRs and Micro Modular Reactors (MMRs) as categories for civil energy use.

Why microreactors are interesting

- Can serve off-grid or weak-grid locations
- Potentially faster deployment (if designs are licensed and supply chains mature)
- Could provide combined heat + power locally

Big caveat: Microreactors are promising, but most are still **pre-deployment**; licensing, fuel supply (often HALEU for some designs), security, and economics at small scale are the hard parts.

How many nuclear plants are in the UK?

As of early 2026, the UK has five operating nuclear power station sites with nine operational reactors (8 AGR + 1 PWR), totalling about 5.9 GW.

Operating sites (commonly listed)

- **Sizewell B** (PWR) – Suffolk
- **Torness** (AGR) – Scotland
- **Heysham 1** (AGR) – England
- **Heysham 2** (AGR) – England
- **Hartlepool** (AGR) – England

Note: The UK nuclear regulator (ONR) also tracks reactors that have **ceased generating** and are in defuelling/decommissioning stages.