iMAGINE – 7,500 YEARS OF SUSTAINABLE ENERGY FROM NUCLEAR WASTE

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Let's create sustainability through technology development to unlock new energy resources, thereby bolstering national energy security and supporting the UK's transition to net-zero.

Creating a limitless, zero waste, clean and uninterrupted supply of energy for the world – this sounds like a utopian vision for all humanity. But as energy security becomes an increasingly important issue for the UK in the face of turbulent geopolitical events and challenging net-zero carbon targets come into sharper focus, is there a way to turn this dream into reality?

Most of us would think that even if such an ideal technology could ever be invented, it certainly would not be economically viable and must involve a '*high-risk, high-reward*' development process. Imagine, if this dream was not as far-fetched as it seems – developmental risks were low due to existing experience but rewards still as high; the technology was financially feasible; and, most importantly, public concerns were addressed by making people an important stakeholder during the development life-cycle. Maybe all we need to create such a breakthrough energy technology is to embrace a new vision for the future by moving away from limited, linear thinking and adopting transformational strategies for the entire system from *cradle-to-grave*.

iMAGINE – A NEW APPROACH TO ENERGY

At the University of Liverpool, we are taking on this challenge by developing iMAGINE [1], a novel and holistic nuclear system designed to generate vast amounts of energy while solving the current nuclear waste problem. iMAGINE will allow us to harvest almost 100 times more energy from mined uranium as compared to current commercial nuclear reactor technologies and dramatically reduce the amount of nuclear waste. It is an integrated nuclear system based on a chloride molten salt reactor where fuel exists as a molten mixture of chlorides of uranium (UCl_3 + UCl_4) and sodium ($NaCl$ or common salt). Being in a liquid state means the fuel also acts as the coolant, addressing most safety issues of present reactors. iMAGINE's design also allows the fuel to be accessible, enabling an integrated fuel cycle instead of the currently complex, time consuming and segregated one.

Our research shows that iMAGINE can operate on *spent nuclear fuel* (SNF; see Figure 2) from existing reactors [2,3] without the need for prior separation of uranium and plutonium from other material in SNF, a process known as *reprocessing*. Extracting energy from the 7,000 metric tonnes of legacy spent nuclear fuel [4] with iMAGINE can deliver low-carbon electricity for around 250 years for the UK at current consumption levels! Moreover, it can also use currently stored *tailings* – a by-product of the uranium enrichment process used during fuel production for current reactors – as fuel. By using the approximately 200,000 metric tonnes [4] of uranium locked in tailings, iMAGINE could provide electricity for 7,500 years – worth more than £1,000 trillion [(a)] at today's market value!

iMAGINE, thus transforms the

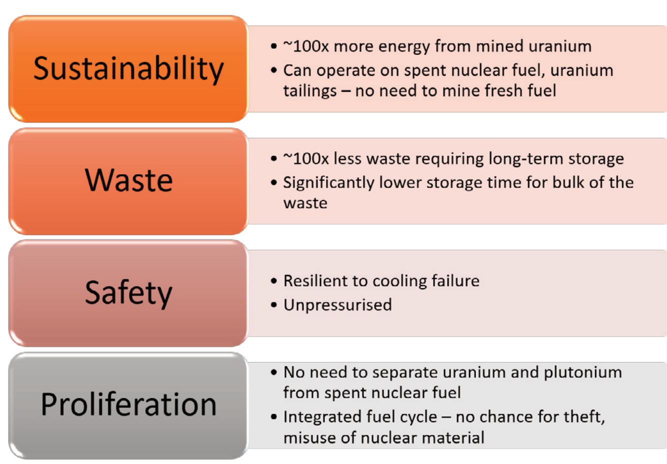

Figure 1 – Benefits of iMAGINE

existing nuclear waste burden in the UK into a precious asset – a virtually inexhaustible energy resource. Importantly, this source of energy is already stored in the UK making us independent of electricity related fuel imports and global energy security issues. This innovative system also addresses important public concerns around nuclear waste disposal by reducing the amount of waste requiring long-term storage by almost 100 times in comparison to current commercial reactor technologies, and decreasing the storage time to only a few hundred years for bulk of the waste.

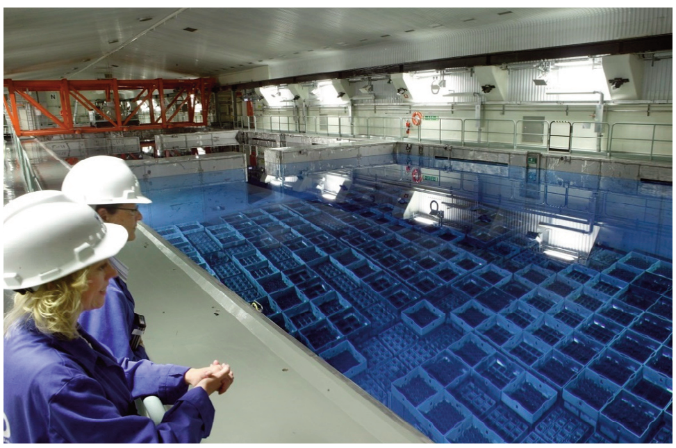

Figure 2 – Interim storage of spent nuclear fuel (Source: SKB[7])

CURRENT NUCLEAR ENERGY SYSTEMS

Nuclear energy has undoubted potential to contribute towards our national decarbonisation goals, with the UK committing to "delivering new and advanced nuclear power" under the Government's Ten Point Plan for a Green Industrial Revolution[8] published in 2020. This commitment was reiterated in 2022 with the Government setting a goal to deliver up to 24GW of nuclear power (25% of our projected electricity demand) by 2050[9].

However, the currently existing commercial nuclear reactors typically harvest less than 1% of the energy contained within mined uranium. The rest is discarded as waste, either in the form of spent nuclear fuel or tailings. Think of it like buying an electric car with a huge battery capacity only to realise that just 1% of its capacity could be used before the battery needs to be replaced or recharged. Nuclear engineers have known about the energy waiting to be extracted out of the mined uranium since the initial days of reactor technology in 1950s.

The *closed nuclear fuel cycle* was proposed as the solution to extract more energy from uranium. It involves reprocessing SNF (as is done at Sellafield), using the separated uranium and plutonium as fuel in fast reactors (as is done at Dounreay), and repeating this process multiple times. Think of this as having to recharge your electric car battery, but after using only a small fraction of its total capacity, and repeating this process many times over. Fast reactor technology – which uses high-energy or *fast neutrons* for fission and can convert left-over materials into new fuel – has been pursued by various countries but high costs and complexity prevented its successful commercialisation. Besides this, the need for separation of uranium and plutonium raises concerns about their potential misuse to produce weapons.

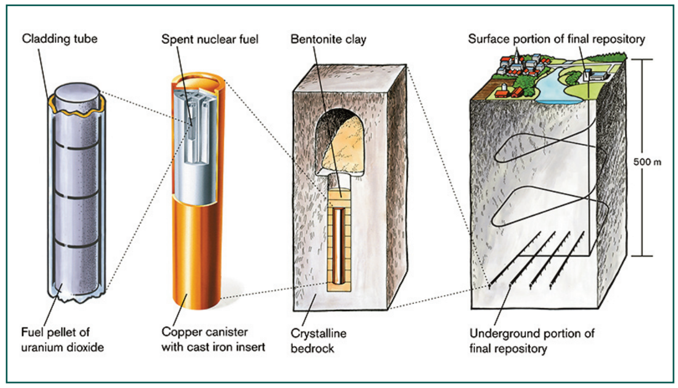

Figure 3 - Spent nuclear fuel disposal (Source: SKB[10])

Due to the limited commercial success of closing the fuel cycle, spent (or already burnt) nuclear fuel is currently destined for *deep geological disposal*[11] (Figure 3) in most countries, including the UK. This involves isolating the waste for more than 100,000 years in underground vaults hundreds of metres below the earth's surface. This is required as some of the constituents of nuclear waste, mostly uranium, heavier elements, and some fission products, have a very long *half-life* – the time taken for the radioactivity of a material to reduce by half. One of the main drivers of public concern around this method is how reliably and accurately scientists can predict safe storage so far into the future and ensure that no radioactive material leaks out.

TURNING NUCLEAR WASTE INTO ENERGY FOR THE UK

Our aim for iMAGINE is to support the UK's demand for decarbonisation using sustainable, low-waste, affordable, low-carbon 24/7 energy with resource security by developing a demand-driven technology, rather than creating technology-driven demand. iMAGINE also addresses public concerns around nuclear weapons proliferation by avoiding the need for separation of uranium and plutonium, thus eliminating all possibilities of their potential misuse for producing weapons. Moreover, recycling existing waste material as fuel means there is no need to mine new uranium. iMAGINE is also safer than current reactors as the molten salt acts as both fuel and coolant making the system inherently resilient against cooling failures. High boiling point of the salt means there is no need to operate the system at high pressure, thereby ruling out accident scenarios which dominate the safety designs of current nuclear reactors.

iMAGINE focusses on holistic thinking by considering all stages – mining of uranium ore, energy production, final disposal of waste, and most importantly, the public. However, like other nuclear reactor technologies, this novel and innovative system also has a long maturity horizon from conceptualisation to commercialisation. Therefore, a long-term development plan (Figure 4) is essential for its success which must be supported by sustained and concerted efforts. After all, efforts during COVID-19 proved the value of targeted research! Such long-term coordinated efforts can only be assured through the creation of a robust research infrastructure at the national-level in the UK.

Indeed, this long-term effort will have technical, financial, political, and societal risks. However, these can be mitigated and minimised effectively

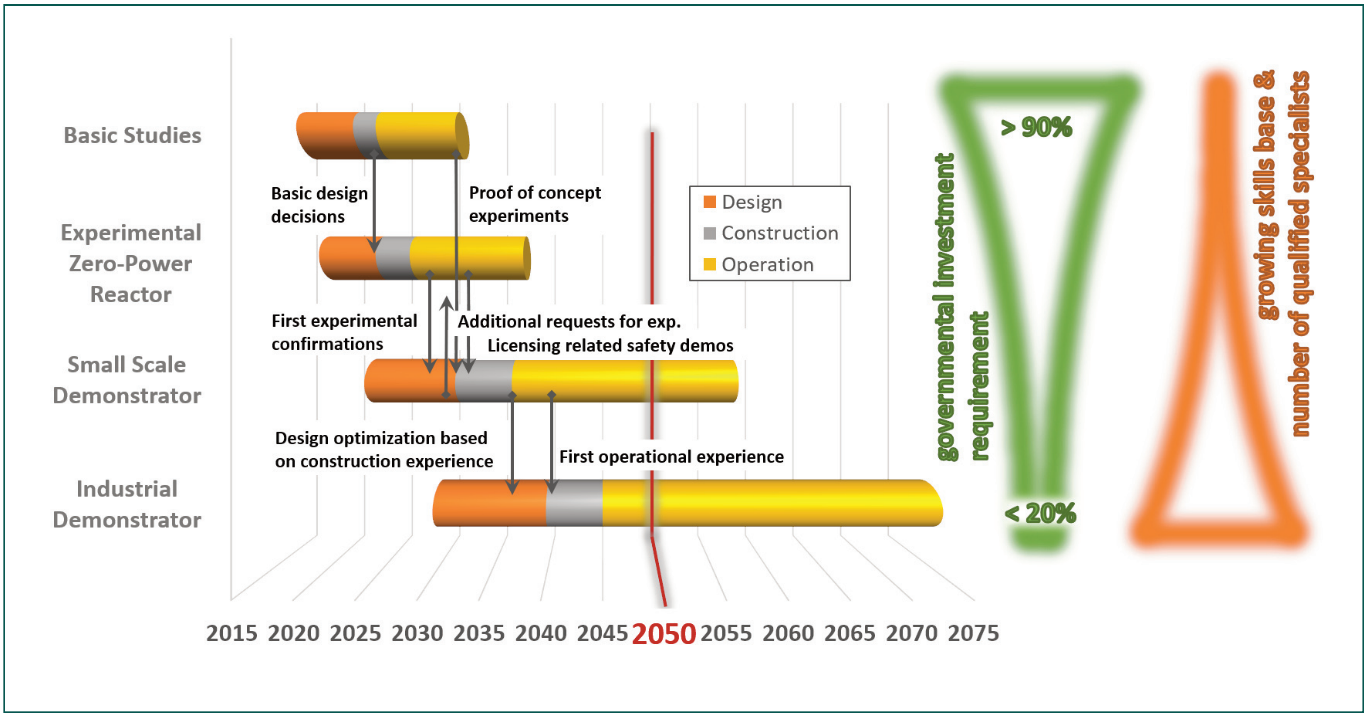

Figure 4 – Development plan for iMAGINE

through our proposed stepwise development plan.[1] Swift progress can be achieved through planning the appropriate steps to ensure quick feedback. Our approach enables capacity building – industrial, regulatory and human capital – alongside technology development (see graphic on the right of Figure 4). Not only has the adoption of such a stepwise paradigm delivered success in the past, such as during the early stages of nuclear energy technologies in the 1950s,[12] similar plans have been adopted by other countries for the development of innovative reactor technologies[13].

It is important to embed active risk mitigation at every step of the development process with effective risk communication in order to transparently convey the pros and cons of a new technology to the public. Moreover, there is a strong need for social justice and democratisation of the technology development process, especially for all things nuclear. This is being done through early engagement with the public to understand people's perception, expectations and demands. After all, addressing the public's needs is the key to creation of a successful demand-driven technology.

iMAGINE's technology might not be currently ready, but let's dare to imagine this breakthrough opportunity of the 21st century. iMAGINE has the potential to make the UK a scientific, technological and energy superpower, cementing our position at the forefront of the global sustainable energy and climate change challenge. However, to be successful in the future, we must take the first steps today.

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(a) Current annual electricity consumption in the UK is worth £143 billions
Average electricity price UK[5] = 52p per kWh; Total annual electricity consumption UK (2022)[6] = 275.24 TWh = 275.24 billion kWh