U.K. Nuclear Innovation and Research Office: Experience of Flexible Nuclear and the Road to Net Zero

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In 2019, the United Kingdom was the first major economy to legislate for net zero GHG emissions by 2050. Net zero refers to achieving a balance between the amount of GHG emissions produced and the amount removed from the atmosphere. There are two contributing actions that work in tandem to achieve net zero: Reducing existing emissions and actively removing GHGs. In short, the pathway to 2050 will require total decarbonization of the U.K. energy system, and any remaining emissions must be compensated for with carbon removal activities, such as direct air capture and changes to land use and lifestyles. This has provided the impetus to consider how low carbon technologies could be deployed to deliver on changing energy usage profiles and an overall scale up in demand. The U.K. Committee on Climate Change (CCC) has shown the scale of the challenge in Figure 1.

The four highest-emitting sectors are transportation, energy supply (generating electricity from burning fuels such as coal, oil, and natural gas), business (commercial use of electricity), and residential (heating homes). Together, these account for around 84% of emissions in 2018 (BEIS 2020).

The United Kingdom's overall energy usage is around 1,700 TWh (BEIS 2019b), and, by 2050, this is anticipated to increase by around 40%–50%, with electricity demand doubling from 300 TWh today (Stark et al. 2019a), Currently, 53% of the U.K. electricity supply is low carbon, with 21% from VRE, 20% from nuclear, and 10% from bioenergy and hydropower (BEIS 2019b). This energy mix has generally not required nuclear to operate flexibly; however, recently, in a period of very low demand, one of the U.K. nuclear power stations was reduced in power output to support balancing of the electricity grid.

This document encompasses one section of a larger report, titled Flexible Nuclear Energy for Clean Energy Systems. The full report can be found at https://www.nrel.gov/docs/fy20osti/77088.pdf. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.

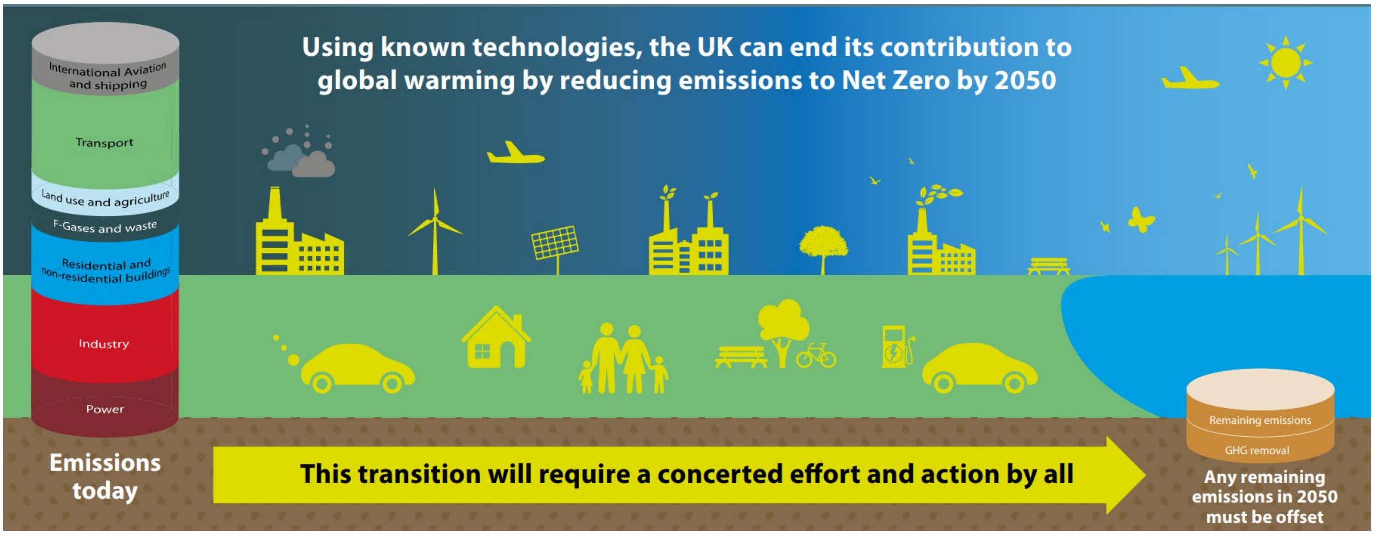

Figure 1. CCC report key message

Source: CCC.

Figure 2 highlights anticipated decarbonization pathways from nuclear energy to a range of sectors; many of these are distributed or mobile carbon emitters that are challenging to decarbonize. Recent modeling outputs on the U.K. energy system indicate nuclear energy applied for these purposes is advantageous toward achieving the lowest-cost net zero energy system. In doing so, this may also provide synergies with the need for a more flexible supply of electricity and other energy vectors (hydrogen and heat) in commercially attractive ways. Whole-system decarbonization therefore provides an opportunity for nuclear energy to work with established technologies in new ways.

The United Kingdom has a long history of civil nuclear research, development, operations, and decommissioning, having commercially operated a fleet of Generation II Magnox reactors, Generation III advanced gas reactors and a Generation III PWR. Deployment of these reactor fleets in the United Kingdom have resulted in experience of civil nuclear, including an element of flexible operation, dating back to the first commercial civil nuclear reactor fleet in the 1950s.

Alongside base load generation, the United Kingdom has historically used the output of civil nuclear reactors for:

- Complementary siting of industrial facilities reliant on a secure source of electricity
- Energy storage systems, such as pumped storage, located nearby to nuclear power stations
- District heating for an industrial site collocated with a nuclear power station.

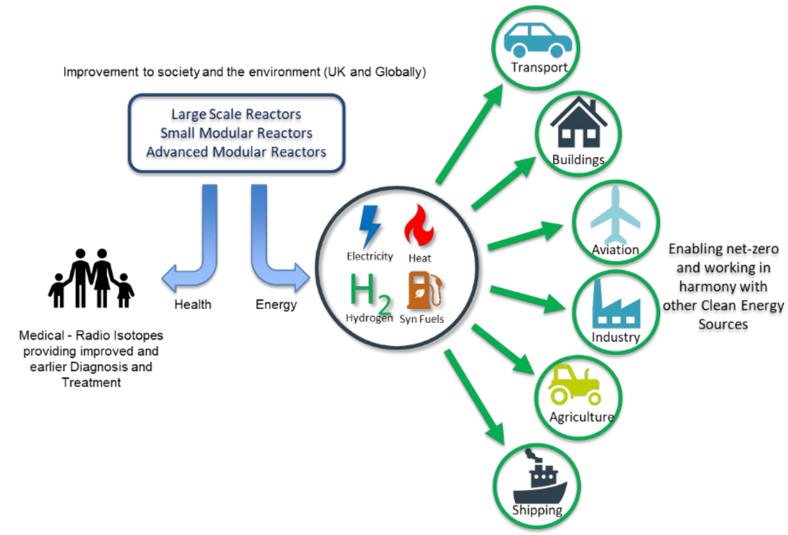

Figure 2. The flexible potential of civil nuclear

Source: U.K. BEIS.

1.1 Flexible Nuclear in the United Kingdom

Civil nuclear power generation in the United Kingdom goes back to 1956 when HRH Queen Elizabeth II opened the new power station at Calder Hall in Cumbria, the world's first commercial civil nuclear power station. This marked the start of civil nuclear generation in the United Kingdom that, to date, has seen the deployment of three different reactor types: the Magnox fleet of 26 reactors across 11 sites (now retired), the advanced gas reactor fleet of 14 reactors across 7 sites, and the single PWR at Sizewell B.

The operating statistics for these technology types have been exceptional, and nuclear continues to be one of the largest contributors to clean electricity production in the United Kingdom. Through the latter half of the last century, the United Kingdom's nuclear generating capacity steadily increased (see Figure 3) peaking at 12.7GWe in 1994, which at the time was around 17% of total installed capacity (Roberts and Clark 2018).

For the most part, the United Kingdom's nuclear power stations have operated at full power, providing base load electricity and during the 1950's and 1960's synergies between energy supply from nuclear, storage and usage were exploited to maximize the output of the U.K. nuclear fleet. This chapter explores some of the approaches taken.

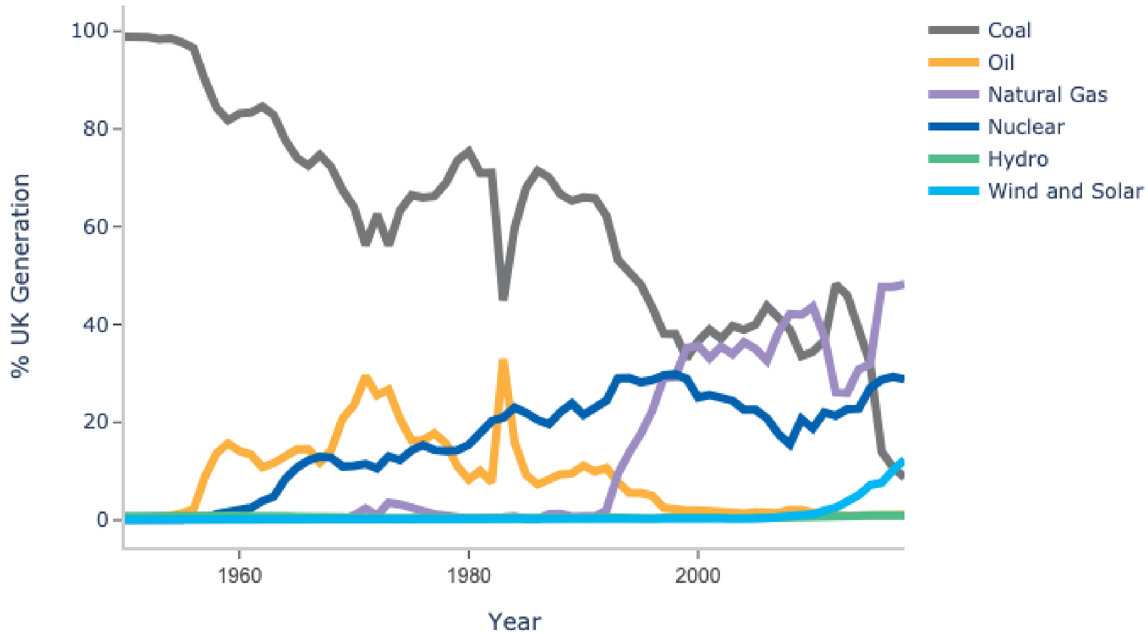

Figure 3. U.K. electrical output by fuel source

Source: (BEIS 2019c)

1.1.1 Major Energy User Local to Nuclear Plant

The Wylfa nuclear power station was the last of the U.K. Magnox stations. Its two reactors operated between 1971 and 2015 and delivered a combined output of 980 MWe. The plant was built on the island of Anglesey, located in far northwest Wales, remote from significant urban or industrial development. To stimulate growth of the island economy and provide local jobs, an aluminum smelting plant was constructed concurrently within 15 miles of the power station to capitalize on the new, local and reliable energy resource. During operation, the aluminum plant drew 255 MWe of power from the Wylfa plant over a dedicated high-capacity electric cable. Anglesey Aluminum operated successfully from 1971 to 2009, employing 540 workers and adding to the direct local economic benefits of the Wylfa site.

The challenge for the Anglesey Aluminum plant was that once the Wylfa plant was scheduled for closure, the contract for power provision could not be renegotiated, and with no alternative realistic source of local electricity, the aluminum works closed in 2009.

1.1.2 Energy Storage Systems

The United Kingdom has two pumped water energy storage plants, both in North Wales: Ffestiniog and Dinorwig. Both plants are within reach of the two now-decommissioned nuclear stations; Wylfa and Trawsfynnyd. Articles from the period refer to the strategic intent to exploit the synergies between pumped storage and the local nuclear power stations (Lovins 1973). The energy storage plants started operating in 1963 and 1982, respectively, and they remain operational today (Electric Mountain n.d.).

Pumped water energy storage systems utilize excess power to the grid during periods of low demand (assumed to be at night) to pump water to a raised reservoir. Water is then released at periods of high electricity demand (during the evening for example) using gravity to reverse the pumps to become turbines. At Ffestiniog, the capacity is 360 MW via two sets of pump/turbines and 1.7 GW via six pumps/turbines at Dinorwig, the latter having an operational duration of 5 hours from a full top reservoir.

1.1.3 District Heating

The use of civil nuclear power to drive local district heating dates to the operation of the very first civil nuclear reactor at Calder Hall. For over 40 years, the Calder Hall reactors on the Sellafield site provided steam to meet the site demands for industrial process heat and space heating over a local heat network.

The use of the reactors for industrial heat applications was integral to the design of Calder Hall, which operated until the decommissioning of the reactors in 2003. In 1998, a 168 MWe replacement gas plant was constructed on the periphery of the site to meet the continuing demand for energy. This outlines the value and scale of the reactor's contribution to supporting the site with electrical and heat energy cogeneration.

1.2 Historical Lessons

The lessons to be drawn from previous activities to leverage synergies between nuclear and non-nuclear technologies focus on strategic planning of energy assets to balance local and national energy systems and the regional considerations to enable local benefits. The pumped storage assets of Ffestiniog and Dinorwig both remain significant national assets, albeit now focused on energy storage more generally, including for balancing of the U.K. VRE supply.

The operational success of Anglesey Aluminum partnered with the Wylfa power station and the long-term supply of district and process heat to the Sellafield site from the Calder Hall reactors demonstrate that parallel thinking to maximize local energy provision can be successful and support heavy industry, enduring local jobs and wider economic benefits. However, long-term security of supply issues need to be considered, as does siting and regulation. This is relevant to the current thinking in the United Kingdom on the decarbonization of industrial clusters.

The U.K. government has undertaken studies into the most energy-dense industrial regions, or clusters (BEIS 2019a), which showed that the demands of these areas are substantial in terms of electricity and industrial heat. Significant benefits can be achieved through local and regional strategy planning of energy supply and industrial energy usage. Through understanding the lessons from the United Kingdom's previous experience (as noted in Chapter 1.1), there is an opportunity for industrial clusters to leverage nuclear energy for decarbonization at a regional level. SMRs (both Generation III and Generation IV high temperature) may also present opportunities for more flexible siting to support these regional decarbonization efforts.

1.3 Modeling our Future Net Zero Energy System

Today, governments have the challenge of enabling our future energy needs to be met via the most cost-effective route. There are numerous predictive tools to support related decision-making, all of which use different inputs and derive their solutions dependent on an array of selection criteria including economic, technical (including technology maturity), and social/political criteria. They are also based on the limitations in thinking and data availability.

Since the United Kingdom legislated for Net Zero GHG emissions by 2050, the range of potential future energy scenarios being modeled has taken on a new focus. This chapter describes some of the outcomes relevant to flexibility.

1.3.1 The CCC Report

The CCC report (Stark et al. 2019b) uses the Energy System Modeling Environment software, amongst other tools (Stark et al. 2019a), to predict a number of scenarios for the United Kingdom's future energy system requirements in 2050 and the potential routes to deliver net zero. The Energy System Modeling Environment model is a cost optimization model that takes into consideration emission intensity, resource availability, technology development rates, and system capacity and flexibility. For CCC work, the inputs are set specifically by the CCC members and their advisors

A number of energy system scenarios are modeled based on a wide range of low-carbon technologies, lifestyle changes, and land use shifts. Prior to 2019, the United Kingdom was targeting 80% reduction in emissions by 2050, from 1990 baseline levels. Analysis showed that there would be relatively high confidence of achieving this target with reasonable changes to the energy system. However, to deliver on a 100% emissions reduction target (net zero), a broad range of speculative measures and technologies (or assumptions about foreseeable technologies) need to be introduced. An example of a speculative assumption would be that very high (i.e., 99%) capture rates from carbon capture and storage technology can be delivered.

The report outlines a need to double U.K. electricity generation between 2019 and 2050, primarily due to electrification of transport and heating. It projects that this equates to a fourfold increase in low-carbon electricity, with an equal requirement for of 30–60 GWe flexible and base load generation. This is in addition to the extensive building of renewable power infrastructure. The CCC outlines the importance of flexibility highlighting how the commercial case for future energy generating assets can be supported by the project, either in its own right or by partnering with flexible energy conversion systems.

1.3.2 Energy Systems Catapult

The Energy Systems Catapult has analyzed the potential future pathways to realizing a net zero energy system. The most recent work, (McKinnon, Milne, and Thirkill 2020), centers on two main deployment scenarios: (1) Clockwork, a centralized approach where national-level decision-making drives the development of the energy systems; and (2) Patchwork, a decentralized approach where local and regional decision-making results in variability of approach across the nation.

Given a set of input parameters, the model finds the least-cost energy mix in 2050 and generates the potential energy system assets that would be required. An output is provided in 5-year intervals to provide the user with an indication of what could be low-regret decisions on technology investment and deployment in the near, medium, and longer term.

Nuclear is modeled as several discrete technologies, that is, large-scale nuclear and SMRs (both Generation III and Generation IV in the form of HTGR). The economic, siting, and technical attributes of these different asset types are all considered including cogeneration and flexibility. At the time of writing, the Energy System Modeling Environment model was subject to further updates to include the explicit production of hydrogen from high-temperature heat.

Figure 4 and Figure 5 provide the predicted energy mix in 2050 based on each of the scenarios, with the Clockwork scenario showing a higher level of nuclear deployment due to national programs that deliver reduced costs through project delivery learning. Under the Patchwork scenario, the higher proportion of energy provided from VRE places a very high demand on interseasonal and intraday storage, with hydrogen turbines providing peak electricity demands. The hydrogen supply is mainly from electrolysis using both curtailed and dedicated renewable supply.

The Energy Systems Catapult findings place a high value on flexibility and underline the potential of nuclear to meet a range of different energy needs, especially district heating and electricity. As part of a sensitivity study on nuclear deployment, HTGRs partnered with thermo-chemical hydrogen production appear cost-competitive generating hydrogen up to around one-third of the predicted 2050 demand, or 50–100 TWh (McKinnon, Milne, and Thirkill 2020).

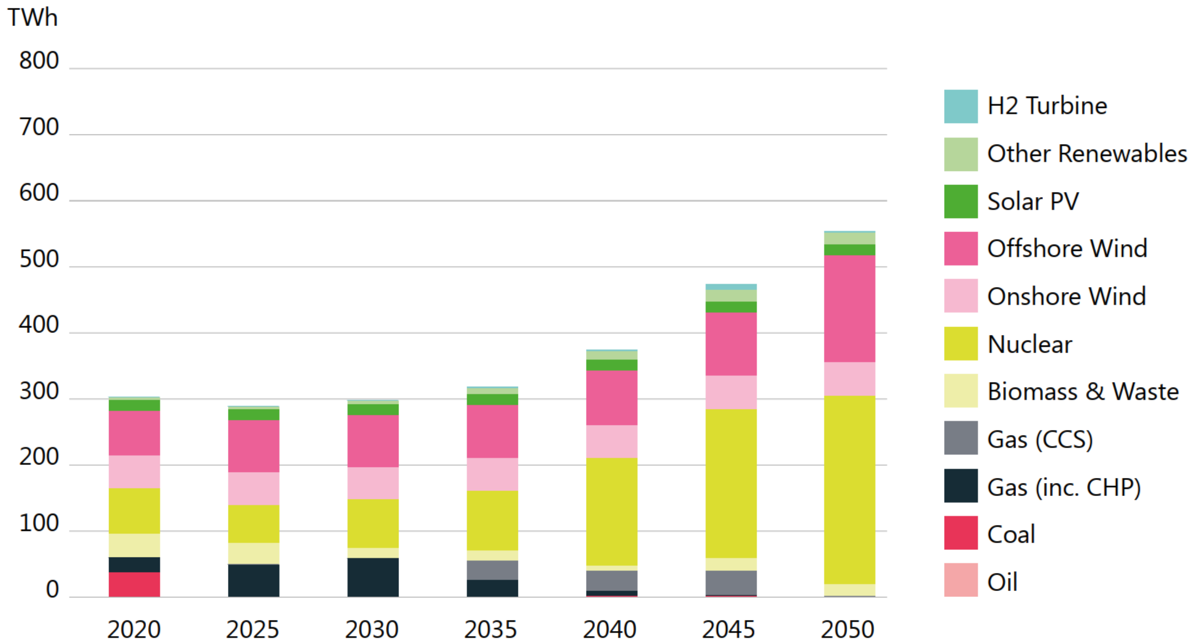

Figure 4. Energy Systems Catapult Clockwork prediction of least-cost electricity generating mix in 2050

Source: Energy Systems Catapult.

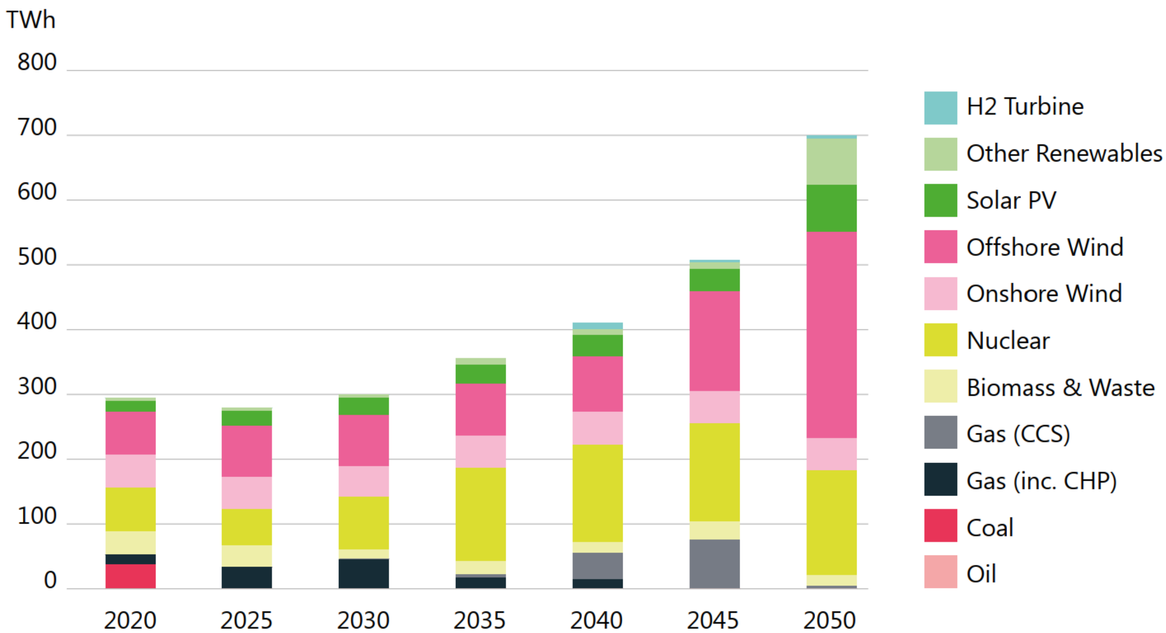

Figure 5. Energy Systems Catapult Patchwork prediction of least-cost electricity generating mix in 2050

Source: Energy Systems Catapult.

1.4 The Future of Nuclear in the United Kingdom

Work in the United Kingdom on achieving net zero has shown the importance of system thinking and the optionality provided by flexible supply and management of energy. Delivering flexibility has synergies with a future hydrogen economy through cogeneration and larger energy storage systems.

These systems could be driven by civil nuclear reactors alongside a range of other low-carbon energy sources with the role of nuclear as part of a flexible hydrogen economy becoming much more widely explored. This has been the subject of recent modeling efforts on the U.K. energy system, and the U.K. National Nuclear Laboratory is currently leading a broad scope of work to develop the United Kingdom's knowledge base on the techno-economics of hydrogen from nuclear energy.

In particular, electricity and in the future high-temperature heat from nuclear power stations could be suitable for partnering with a range of hydrogen production technologies. There are similarities with the pumped storage systems deployed in the United Kingdom, historically, as hydrogen is proposed as a chemical energy storage medium to support interseasonal and intraday balancing of electricity supply and demand. In planning the future energy system there is learning to be taken from approaches taken in the past.

Cooperation between energy supply technologies and local and national energy demands require collaboration between technology providers and regional groups, operating under market frameworks set at a government level. This not only drives the need for cost-competitive solutions but also highlights the importance of flexibility of plant output to maximize revenues through several product lines, for example electricity, hydrogen, and heat markets.

The picture for flexibility and its role in energy supply, storage, and hydrogen production in the United Kingdom is currently emerging and the precise technologies and deployment models that will comprise a future decarbonized energy system is uncertain. Commercial drivers will determine, for example, whether reactors will be deployed to deliver a single product from a dedicated system, or many; however, flexibility of energy supply from the project and the versatility of reactor technologies and the associated energy conversion systems will be crucial.

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