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The unfolding low-carbon transition in the UK electricity system

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The paper explores three periods in the UK electricity consumption–production system since World War II. The first two involved the development of an increasingly centralized, integrated system that provided electricity to meet growing post-war demand. It saw two major changes in governance, first to nationalization, then to privatization and liberalization. The third period started at the turn of the Century, driven by increasing evidence of the impact of fossil fuels on the Earth's climate. The paper focuses on the drivers of change, within the UK and externally, and how they affected governance, technology deployment, and industry structure. It draws on the multi-level perspective and the concepts of governance and technological branching points to inform the analysis of each period. It shows that there is a considerable distance to travel toward a truly sustainable electricity system.

branching points | electricity | fossil fuels | governance | nuclear

The UK electricity system has undergone fundamental changes since the Second World War (WWII). An increasingly centralized and integrated consumption–production system was developed to meet growing demand. This included expanding coverage and developing civilian nuclear power and oil firing to complement the scale-up of coal-fired generation. While many developments took place under public ownership, institutional reforms, including privatization and the introduction of competition, dominated the 1990s. This governance change led to a shift between fossil fuels—from coal- to gas-fired generation—that started to address the negative impacts on natural systems, such as high sulfur dioxide emissions from coal.

The transition to a more sustainable electricity system began in 2000, driven by increasing evidence of the impact of fossil fuels on the Earth's climate. Successive governments have strengthened incentives for lower-carbon electricity generation, phasing out coal-fired generation, and (with mixed results) improving the efficiency of energy consumption. This transition remains work-in-progress. Fossil fuels still play a significant role in the form of natural gas. There are also concerns about the environmental impacts of some renewable technologies (especially large-scale biomass), about whether the UK will reach its net-zero target for greenhouse gas emissions, and about the impact of price rises on fuel poverty and health.

This paper addresses the UK electricity system since WWII because historical, longitudinal studies help elucidate the long-term, path-dependent nature of energy transition processes. It considers the internal and external drivers of change, and how they affected governance, technology deployment and industry structure. It explores how various actors have started to address the negative impacts on natural systems. We draw on the multi-level perspective (MLP) and an analysis of "branching points." The paper shows there is much distance to travel toward a truly sustainable electricity system. Clark and Harley (1) highlight governance arrangements as one of six capacities necessary to support transitions to sustainability. This paper's focus on changes in governance leads to insights relevant to the sustainability science literature.

Section 1 outlines the literature on transitions to more low-carbon electricity systems and explains the paper's conceptual framework. Sections 2 to 4 discuss the evolution of the UK electricity system in three phases: the growth of a newly nationalized system from WWII to the late 1980s; radical privatization and regulatory reforms in the 1990s, leading to a switch from coal to gas and incremental sustainability improvements; and the legislative and regulatory changes that promoted an accelerating transition to a decarbonized electricity system since 2000. Section 5 concludes.

1. A Framework for Understanding Electricity Transitions

The MLP developed from early studies (2, 3), in which transitions were seen as driven by alignments of trajectories and processes within and between three analytical levels. Thus, niche innovation(s), such as a different new electricity-generating or electricity-using technology or practice, might gain momentum and be adopted by a hitherto stable energy consumption–production system (also called a regime) whose inertia was disturbed by internal tensions and/or by external landscape pressures (like demographic or ideological shifts or shocks like wars, economic crises, nuclear accidents, and pandemics). Researchers studied past transitions in energy, water, transport, and agriculture and explored prospective transitions. For example,

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Table 1. Branching points in three periods

Period starting date	Governance branching point	Realized technological branching points	Attempted technological branching points
1945	Nationalization	Nuclear power	Coal to oil
1979	Privatization and liberalization	Coal to natural gas; some energy efficiency	Coal to nuclear power and renewables
2000	Sustainability and GHG emissions reduction	Coal and gas to renewables; some energy efficiency	Carbon capture & storage, nuclear and more extensive energy efficiency

Rosenbloom and Meadowcroft (4) examined the evolution of the Ontario electricity regime to explore the potential for decarbonization, focusing on the political factors involved. Geels et al. (5) reformulated and applied a typology of pathways to a comparative MLP analysis of German and UK low-carbon transitions in electricity generation, while Geels and Turnheim (6) analyzed transitions in UK electricity, heat, and mobility systems.

As well as the MLP, we use the concept of branching points to examine critical moments in UK electricity system transitions. Foxon et al. (7) and Arapostathis et al. (8) developed this notion to investigate UK energy transition pathways. Here, a pathway forms via the accumulation of decisions that build momentum in a particular direction: "…actors make choices that depend on the magnitude and timing of pressures and the openness and capability of regime actors to respond to them. Thus, we define branching points as 'key decision points at which choices made by actors, in response to internal or external stresses or triggers, determine whether and in what ways the pathway is followed'" (7 p. 146). A branching point signals the start of a dynamic process that may eventually change a pathway, reinforce it, or leave it largely unchanged. Because pathways and branching points are emergent properties, actors may not consciously choose to pursue a particular branch or pathway, but to address specific challenges. For past branching points: "…for the actors involved the process of governing the transitions was continuous, contested and uncertain—it is only with hindsight that we can identify particular decisions as branching points…" (8, p. 41). Branching points "… are not junctions in networks of paths set out (by technology or fate) to be followed, or not…" (9 p. 151). Rather, a branching point is a window of opportunity whose resolution can "… orientate system configurations along new or existing trajectories … reconfiguring the envelope of future options as some possibilities are opened up and others are closed down" (10 pp. 23–24).

Here we extend the concept of branching points by distinguishing between two types. Governance branching points reflect underlying "governance logics" (11) and concern choices about system governance, including ownership, industry structure (e.g., monopolistic, oligopolistic or competitive) and key objectives. Technological branching points concern choices about the technology mixes that generate, supply, use or save electricity. They include branching points that are, to varying degrees, realized over a given period, and those that are attempted—but not realized at significant scale. The two branching point types are related: governance changes often influence technological choices, while a technological branching point's fate may affect later governance decisions. Table 1 summarizes the main BPs for each period analyzed. We selected these periods because each involves at least one major governance branching point.

2. The First Period, 1945 to 1979: System Development under New Public Ownership*

At the 1939 outbreak of WWII, nearly three-quarters of urban dwellings, only half of rural dwellings and less than a third of farms were connected to electricity supplies (12 p. 58). The UK economy was largely based on home-produced coal: It was the feedstock for electricity generation, town gas production, and rail transport, and provided most of the heat for industry, commerce, and homes. The post-war electricity system anticipated rapid growth, to support economic recovery, modernization, and rising electricity demand.

The socialist Labour Party's 1945 election win brought a landscape governance change, with plans to nationalize energy and other key industries. The Electricity Act 1947 led to the transfer of 200 generation and supply companies and 369 local authority-owned electricity assets, with the Central Electricity Board (a public corporation responsible for the national grid and major power purchases) and nearly 300 coal-fired power stations owned and operated by these organizations, to a new public corporation, the British Electricity Authority (BEA). Within the BEA, a Central Authority became responsible for the power stations, the national grid and 14 Electricity Area Boards. The Boards, their members appointed by the Minister, managed distribution and sales to 11 million consumers (13 p. 7). The nationalization was a key governance branching point, shifting the industry to state-led ownership and governance, from a pre-war hybrid market/state configuration.

The industry was required to break even, in contrast with the profit- and revenue-seeking objectives of the pre-war companies and municipalities. The Electricity Act embodied two aspirations: to spread the benefits of cheap electricity widely, and to act with genuine independence from government. Nevertheless, Hannah (13 pp. 11–12) shows that the supposed division between "general policy" as a matter for the Minister and "detailed execution" as a matter for the industry would often prove meaningless.

The BEA initially faced capacity and output crises. Post-war capacity investments were challenged by material shortages, severe weather interrupted coal supplies, and winter power

*This section draws on Hannah (12).

cuts continued into the early 1950s. By the late 1940s, household demand had almost tripled its pre-war level, stimulated by a national housing drive. Prices in real terms were half those of 10 y before (13 p. 295) and had fallen relative to those of gas and coal. However, they failed to cover the rising costs of investing to meet demand. Although economists advocated prices sufficient to cover the long-run costs of supplying extra units of electricity, more sophisticated investment and pricing approaches were not implemented until 1961. The industry then had to do more than break even (13 p. 36; 14).

In 1953, in a significant technology branching point, the Conservative government told the BEA that Calder Hall would be the first nuclear power station. The Atomic Energy Authority, a powerful actor with the ear of government, oversaw the scaling up of this British "Magnox" reactor design over the next 15 y, as ten more stations opened. Commissioned in 1956, Calder Hall reflected an optimism that nuclear power would eventually be cheaper than coal-fired power, such that no more coal stations would be built after 1965. However, nuclear did not eventually dominate generation to the extent that its proponents envisaged (Box 1).

By 1955, in another technology branching point, the BEA began adopting oil-firing. In the early 1960s, however, the National Coal Board exerted sufficient political pressure to ensure the dropping of plans for more oil-fired stations. Nevertheless, stimulated by relatively low 1960s oil prices, oil's fuel input share climbed to 29% by 1972. But the oil price shocks of the 1970s started a downward trend. By 1995, oil's share was below 5%. Despite its earlier penetration, oil's adoption ultimately proved an unrealized technological branching point.

In 1958, the government restructured the industry, in pursuit of greater efficiency and industry decentralization, giving the Area Boards more autonomy. The new Central Electricity Generating Board (CEGB) became responsible for generation, grid transmission, and wholesaling. The Area Boards, as before, focused on distribution and retailing. The new Electricity Council's membership included the Area Board chairmen and three CEGB representatives. Its duties involved raising capital for the Boards, labor relations, and advising the Minister. In its first year, the CEGB and its contractors were constructing the higher-voltage "supergrid" and 40 power stations, including three Magnox stations.

While the post-war industry had first ordered small (30 and 60 megawatt) generating units, by the later 1950s the CEGB ordered progressively larger units, some of which had design and manufacturing faults. By 1963, the CEGB ordered 30 500 megawatt units for new 2 gigawatt power stations. They took more than 5 y to commission, amid concerns about manufacturing quality delivered by British engineering firms. By the 1970s the CEGB would fare better with 660 megawatt units. As tighter planning and environmental controls distanced them from urban load centers, the new stations were sited mainly in rural areas, requiring grid expansion.

While industrial electricity demand grew, domestic sales grew faster. Appliances were cheaper and more available, many made by war-created light engineering firms. Incomes were rising and demand for labor-saving devices grew as more married women entered the labor force. Appliance sales boomed, boosted by hire-purchase financing. Between 1946 and 1966 the proportion of customers in England and Wales owning black and white televisions grew from less than 1 to 91%, cookers with ovens from 17 to 37%, refrigerators from 2 to 47% and washing machines from 2 to 60% (15 p. 84). The Clean Air Act 1956, partly a reaction to the twelve thousand deaths after the 1952 Great London Smog, led to the designation of numerous urban areas as smoke control zones, where domestic coal fires became illegal without costly smokeless coal. By the early 1960s, more than 3 million electric fires were sold annually.

In the 1960s, the industry clung to its centralized, large-scale fossil fuel philosophy, despite some experiments with smaller-scale renewable technologies, including wind. In 1962, for example, it ordered 700 megawatts of small gas turbine plants based on aircraft engines, for emergency backup and peak-lopping (13, p. 251). While this remained a niche technology, more efficient combined cycle gas turbines (CCGTs) rapidly penetrated in the 1990s.

Box 1. Nuclear electricity in the UK

Opened in 1956, Calder Hall's main purpose was to produce weapons-grade plutonium. Nuclear electricity's proponents sought "atoms for peace," amid visions of abundant, cheap energy. In 1955, the government announced plans to build ten stations, uprated to nineteen after the 1956 Suez crisis. However, a 1957 fire at the Windscale nuclear plant led to costly safety modifications to the Magnox designs. Between 1956 and 1971 ten Magnox stations were built to different designs by five competing industrial consortia. Planned to operate for two decades, most ran for four. Experiments on Magnox successors began in the late 1950s, with the AGR being chosen. Although hailed as a breakthrough, the seven AGRs opened by 1988 experienced construction delays and other problems, failing to achieve anticipated cost reductions (16).

By the 1970s, load forecasts suggested little need for more stations, but in 1979, during the second oil price shock, Margaret Thatcher's government announced a ten-station program of US-designed pressurized water reactors (PWRs). A mammoth, disputatious public inquiry eventually found in favor of the first PWR at Sizewell B. Commissioned in 1995, it was the only PWR built from the program, because of the high costs revealed by electricity privatization, falling fossil fuel prices, and weaker coal-mining unions (17, p. 29). UK nuclear generation peaked at 27% of electricity in 1997. By 2021, the share fell to around 13%. Despite renewed commitments under more recent governments, only one further nuclear plant is under construction at Hinkley C. This European PWR has experienced delays and cost over-runs. While nuclear has held almost magical allure for several governments, it remains unclear whether concerns over climate change and energy security might lead to a new, more fully realized nuclear branching point.

The advanced gas-cooled reactor (AGR), another home-grown nuclear design, became the chosen successor to the Magnox technology: seven AGRs opened between 1976 and 1988 (Box 1).

The 1970s brought landscape pressures, stemming from the mid-1960s discoveries of North Sea oil and gas and two international oil price shocks. Serious competition in the heat market arose from the gas industry's renewed competitiveness, catalyzed by its mid-1960s switch from coal and oil feedstocks to cheaper natural gas. Oil stayed relatively costly until after 1985.

In summary, the post-war nationalization was a governance branching point that shifted the coal-based system onto a pathway of large-scale, monopolistic expansion. Between 1948 and 1978, capacity rose fivefold (13 to 70 gigawatts), output grew nearly sixfold, and consumers almost doubled. Large power stations were now built away from cities, with taller chimneys for wider pollutant dispersion. Whereas, in 1948, coal supplied 99% of fuel input, by 1978, the shares were: coal, 66%; oil, 18%; nuclear, 14%; and natural gas, hydro and other fuels at 2%. Nevertheless, coal still dominated supply. Attempted technology BPs in oil and nuclear resulted in shares that surged but later declined. Thus, oil reached a 29% maximum share in fuel input in 1972 (but would fall below 5% by 1996). Nuclear power, a new niche technology, expanded more slowly than oil, reaching its maximum share in 1997.

3. The Second Period, 1979 to 2000[†]: Neoliberalism, Privatization, Competition, and the Dash for Gas

In 1979, the Conservative party regained power, led by Margaret Thatcher. She and several ministers were proponents of a radical shift to less state intervention, market-based solutions, and individual choice (18). This change to neoliberal market-based governance with liberalization (competition) at its heart, led to a major governance branching point and further technology branching points.

In 1982, the energy Minister, Nigel Lawson, questioned the prevailing "natural monopoly" arguments for state ownership of vertically integrated energy industries. The government's role, he said, was not to plan energy but set a framework to ensure that the market would operate with minimal distortion, and energy be produced competitively and efficiently. The Energy Act 1983 opened the industry to private suppliers. In 1992 the government would demote the Department of Energy to a sub-ministry and ceased publishing energy forecasts.

After its 1983 re-election, the government pursued its ambition to break the power of the National Union of Mineworkers (NUM), appointing new leaders of the CEGB and the National Coal Board judged more likely to resist union demands. The NUM's 1984 to 1985 strike ended after much bitterness and hardship. The CEGB had maintained electricity supplies by drawing on its oil-fired power stations and stock-piling coal beforehand. The coal industry's clouded future now depended on the electricity market, having lost the town gas production market and most other sales.

[†]This and subsequent sections draw on (18).

After the 1987 Conservative election victory, the government began electricity privatization, a major governance branching point. Although economists argued that a competitive model required generating capacity to be split into five or six companies, for pragmatic political reasons this did not happen. A 1988 White Paper, Privatising Electricity, proposed dividing generation between a duopoly of two companies, National Power and PowerGen, with the former's portfolio big enough to include the nuclear stations and the latter big enough to compete with it. By July 1989, liabilities for nuclear fuel reprocessing and decommissioning costs had become clear. City financiers baulked at investing in a company saddled with them. Committed to its timescale, the government kept nuclear stations in state ownership.

Privatization created National Power and PowerGen, a new National Grid company, owned by the Regional Electricity Companies, successors to the Area Boards, and two integrated companies in Scotland. Electricity was now traded in a wholesale power market. This radical process of restructuring created the conditions for a major technological branching point through the "dash for gas" (Box 2).

Box 2. Innovation in fossil fuel electricity generation: The dash for gas

The rapid growth of gas-fired power in the 1990s was a by-product of the governance shift due to privatization and liberalization. During the 1980s, manufacturers had developed gas-fired CCGT technology to a "utility scale" (19). During the privatization process the government wanted to ensure competition for the incumbent generators National Power and PowerGen, and to reduce the role of coal. It encouraged the electricity distribution companies, the Regional Electricity Companies (formerly Area Boards), to invest in generation plant. The UK thus became a test bed for this new generation of gas-fired plants in the "dash for gas." The shift to private sector aims, time horizons and risk preferences made the CCGTs especially attractive: they had lower capital costs, smaller efficient scales, shorter construction times and better environmental performance than coal or oil.

The government lifted the restrictions on using gas for electricity production to facilitate this process. Controversially, the regulator allowed the Regional Electricity Companies to include the costs of contracts with CCGT developers in their regulated price caps, and to pass them through to customers (18, pp. 166–173). The proliferating investment plans by the Regional Electricity Companies and other independents provoked the incumbents to invest, since (as one CEO stated), they "didn't want to be left with a fleet of second-hand taxis." By the late 1990s, gas-fired power generated 40% of UK electricity. Coal's displacement led to unplanned reductions in air pollutant emissions and transboundary acid deposition in Europe, leading to a former environment Minister's 1997 declaration that the UK was no longer the "Dirty Man of Europe."

Box 3. Energy efficiency policy

A significant focus on energy efficiency started after the 1970s oil shocks. This involved several programmes by the new Department of Energy (20). They focused on funding energy efficiency improvements of homes and industries, and public information campaigns. The 1980s Conservative administrations' focus on market solutions emphasised the role of energy prices in driving energy efficiency. Privatization and liberalization in the 1990s led to new developments. The electricity regulator implemented new obligations on electricity suppliers that ran from 1994 to 1998.

Energy efficiency improved significantly in the 2000s and 2010s from both further European Union (EU) legislation on appliance standards and labelling, and more effective UK policies. Energy supplier obligations were tightened through an Energy Efficiency Commitment policy (2002 to 2012) (Ibid.), complemented by increased funding for households that spent over 10% of their income on energy. 2010 saw a potentially significant branching point when the new Coalition government announced a "Green Deal" energy efficiency policy. This "pay as you save" policy (Ibid.) offered loans for energy efficiency measures. The policy failed (21), financing measures in only 14,000 homes during its first 3 y (2013 to 2015).

Policy then reverted to a more limited focus on low income and vulnerable households. This remained until the COVID-19 pandemic, when the government announced a new Green Homes Grant in 2020. This also failed, allocating only 20% of its budget (22). A 2017 study found that cost effective investments to 2035 could save about a quarter of UK household energy use (23). Energy efficiency remains a significant unrealized technology branching point.

The failure to establish a more competitive structure meant a significant role for regulation. The regulator was charged with promoting competition and protecting short-term consumer interests through price-cap regulation. However, the 1989 Electricity Act did not include serious duties relating to environmental protection or long-run energy security.

In 1988, after 5 y of resistance, the UK reluctantly accepted the targets of the European Commission's Large Combustion Plant Directive (LCPD), introduced in response to the impacts of national and trans-boundary environmental damage. Costly reductions of sulfur and nitrogen oxide emissions (SO_2 and NOx) from coal-fired power plants would be needed. Also in 1988, Margaret Thatcher addressed the Royal Society about the threat of climate change. By 1990 a White Paper, This Common Inheritance, recognized it as a global challenge and endorsed the use of economic instruments to address pollution. In 1993, the government issued a White Paper, The Prospects for Coal, acknowledging that burning fossil fuels in power stations was a major source of harmful emissions whose regulation would eventually constrain UK coal use.

State-owned Nuclear Electric also faced financial challenges. The Electricity Act 1989 had authorized the Fossil Fuel Levy, effectively a "nuclear tax" to fund reprocessing and waste management. To make this work, the Regional Electricity Companies faced a Non-Fossil Fuel Obligation requiring them to buy a proportion of their power from non-fossil sources. Most of this Obligation was met by purchasing nuclear electricity, with the rest from renewable electricity (a condition of European approval of the policy). By May 1995, a government review found no evidence that new nuclear stations would be needed to abate emissions or strengthen energy security, also concluding that they were not commercially attractive. In 1996 the newer reactors and some of their liabilities were privatized as British Energy.

The electricity privatization process included the phased introduction of retail competition. After 7 y, in 1998, domestic and small consumers could now choose their supplier. Prices had started falling in the mid-1980s. Debates persisted over the extent to which liberalization contributed to this decline. After a regulatory investigation into National Power and PowerGen's market power, in 1994 they agreed to divest 6 gigawatts of plant. The prices at which they could bid into the Pool were also capped. After much neglect of energy efficiency, from 1994, the regulator implemented energy efficiency standards of performance for electricity suppliers (Box 3).

Tony Blair's Labour government was elected in May 1997. While keeping the market-based approach to governance, its first term focused on making liberalization work "better," especially for social and environmental objectives. It imposed a windfall tax on the utilities, after concerns about market power, evidence of their large profits, and a media campaign against "Fat Cat" directors' earnings. The tax raised £5.2bn, with the proceeds funding a program to alleviate youth unemployment.

By 1997, 13 gigawatts of CCGT capacity operated. No longer a niche innovation, its generation share had grown to 27%, mostly at the expense of coal and the hard-hit mining communities. Successive governments had not tried to secure a "just transition" for these communities in a long-declining industry. By 1995, UK SO_2 and CO_2 emissions had fallen significantly, making it much easier to achieve the European LCPD targets. In 1997, the UK had also accepted a target for reducing greenhouse gas (GHG) emissions after signing the Kyoto Protocol. The EU agreed an overall 8% target reduction in GHG emissions by 2008 to 2012, relative to a 1990 baseline, assigning the UK a 12.5% reduction as its share. The government started to shift taxation from "goods" like labor to "bads" like pollution, introducing the Climate Change Levy on businesses in April 2001, offset by cutting National Insurance contributions (a form of income tax). Some of the proceeds were used to establish the Carbon Trust, founded to help businesses cut emissions. Incremental regulatory reforms followed in 2000, with new social and environmental guidance to the regulator.

The switch to market-oriented governance in this period led to a major technology branching point for the electricity system. After privatization, a niche technology, the CCGT, further weakened coal's dominance. Although the 1989 Electricity Act paid no attention to sustainability, Conservative and then Labour governments gradually did, faced with international landscape concerns about sustainability and airborne pollutant emissions.

4. The Third Period: The Unfinished Transition to a Decarbonized System

4.1 Energy Policy Moves Up the Political Agenda 2000 to 2008. This period includes two related branching points that span governance and technology choice. Governance reforms were implemented to ensure that sustainability and carbon emissions reduction received much more attention in energy policies. This led to a decisive shift in technology priorities in favor of renewable sources of electricity such as wind, solar and biomass. At the start of this period, 75% of UK electricity was still from fossil fuels, with most of the remainder generated by nuclear power (Fig. 1). Despite 10 y of policy support, renewables occupied a small-scale niche, their contribution rising slightly from 2 to 3% between 1990 and 2000 (23). Energy efficiency policies had made some progress, including new levies on energy bills to pay for the programs utilities delivered (Box 3).

Landscape pressures on the system began to build at the turn of the century due to the strengthening evidence about climate change. In 2000, a Royal Commission on Environmental Pollution report called for the UK's first long-term GHG emissions reduction target: a 60% cut from 1990 levels by 2050. In 2001, Prime Minister Blair set up a wide-ranging energy policy review, beginning a brief period of more inclusive public and stakeholder engagement (25). The review led to a major governance branching point that included the adoption of this long-term target, and a primary emphasis on renewable energy and energy efficiency. A 2003 Energy White Paper confirmed these priorities.

The political momentum behind long-term GHG reductions continued. Other landscape pressures strengthened the shift towards a greater role for government. The "ownership" of climate change action now included the powerful finance ministry (HM Treasury). The Chancellor Gordon Brown commissioned Nicholas Stern to review the economics of climate change and make policy recommendations. His report (26) made a strong case for rapid emission reductions, to avoid greater costs from future impacts.

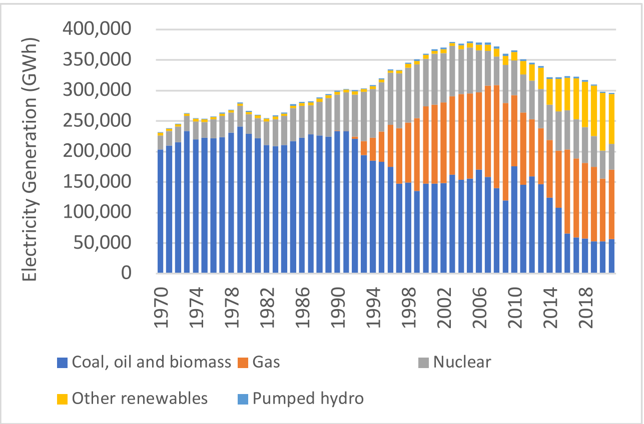

Fig. 1. UK Electricity Supplied by Source, 1970 to 2021 (24).

By the mid-2000s, the UK became a net energy importer because of declining oil and gas production. International fossil fuel prices rose after around two decades at relatively low levels (27). These landscape pressures led to a 2007 Energy White Paper (28). A significant change, proposed by the government chief scientific adviser and some incumbent utilities, was a renewed commitment to nuclear power. As Blair said when announcing the 2005 policy review: "The issue back on the agenda with a vengeance is energy policy... Energy prices have risen. Energy supply is under threat. Climate change is producing a sense of urgency" (29).

These pressures combined with shifts in party politics to reinforce the salience of sustainability. After 8 y in opposition, in 2005 the Conservative Party elected a new leader, David Cameron. He had a modernizing agenda, including stronger emphasis on environmental protection. This led to a positive dynamic of competition between the Conservatives and the Labour Party over which had the "greenest" policies (30). Environmental Non-Governmental Organizations had already proposed much more ambitious annual GHG emissions cuts. Building on this, Cameron declared support for new climate change legislation with legally binding emissions reductions.

4.2 Increased Momentum for Sustainability, 2008 to 2010. This political competition led to the 2008 Climate Change Act, opposed by only three Members of Parliament (30). It had not been a foregone conclusion that the government would respond to political pressure in this way. The Act, which reinforced the governance branching point in favor of environmental sustainability, also led to technological branching points. It included a more ambitious, legally binding commitment to long-term emissions reductions: an 80% reduction from 1990 levels by 2050. It also established a series of statutory 5-y carbon budgets. A new independent statutory body, the Committee on Climate Change, would advise government on future budgets and targets and monitor implementation. The government created a new ministry, the Department of Energy and Climate Change.

Because of the Act, electricity sector sustainability became even more important, because emissions reductions in that sector could help to decarbonize the wider economy via more electrification. A comprehensive plan to reduce emissions by 2020 (31) proposed increasing the renewable electricity share to 30% by 2020, to demonstrate technologies to capture and store carbon emissions from coal-fired power stations and to support new nuclear power. It also included more ambition on energy efficiency and a plan to install "smart meters" in all homes by 2020.

By 2010, renewables generated 7% of UK electricity. More effective support policies were the main driver, coupled with falling costs of some technologies. The decision to provide different levels of subsidy for each technology from 2009 had a crucial impact. This was a key technological branching point which led to a significant role for offshore wind in electricity decarbonization (Box 4). This momentum was reinforced by the EU Renewable Energy Directive, signed by the Prime Minister in 2009. It committed the UK to sourcing 15% of its overall energy mix from renewables by 2020.

Box 4. Offshore wind

Until 2021, the UK had the world's largest deployment of offshore wind capacity. This technology has played a major role in the rapid growth of renewable electricity production since 2010. Offshore wind expansion in the UK and elsewhere has driven dramatic cost declines. Success was not initially certain. The decision to support offshore wind was an important technological branching point that reinforced the transition to a low-carbon electricity system. Offshore wind was first demonstrated in northeast England in 2001 (33), followed by government support for further scale-up through capital grants, site licensing and research. In 2009, reformed subsidy levels included a higher offshore wind subsidy.

However, offshore wind costs remained high. In 2011, a government Renewable Energy Roadmap included a target for them to fall to £100/megawatt hour (from around £140/megawatt hour) by 2020 (34). In practice, however, costs fell much more quickly than expected. The Coalition government's Electricity Market Reform (EMR) package included a new approach to subsidizing renewables. The big change came with a 2015 move to auctions. By the third auction round in 2019, costs had fallen by around two-thirds to £40–42/megawatt hour (35 Appendix 1). Capacity doubled during this period, and annual generation increased threefold. By end-2021, 12.5 gigawatts of offshore wind capacity had been installed, with more planned or under construction. This technology now generates around 10% of UK electricity. In 2022, government ambitions rose to a new target of 50 gigawatts of capacity by 2030 (36).

The government also prioritized support for other renewable energy niches—particularly small-scale "micro-generation" at household and community level. This was to enable citizens and communities to contribute to emissions reduction—and bring climate action closer to their everyday lives. In the 2006 Microgeneration Strategy, the energy minister said: "In many respects microgeneration epitomizes today's society. It is high tech and can be tailored to individual taste. It provides freedom and independence to the user" (32). This strategy was followed by proposals for feed-in tariffs in 2009.

4.3 A Managed Market for Electricity, 2010 to 2015. The 2008 financial crisis changed the political and economic landscape, one of the reasons why the Labour Party was defeated in 2010 after 13 y in office. It was succeeded by a Coalition government led by the Conservative Party with the Liberal Democrats as minority partners, with mixed consequences for climate change action and sustainability. Whilst the previous decade's focus on emissions reduction continued, the Coalition disagreed over how to achieve it. The government pursued a policy of "austerity" and significant public spending cuts.

New nuclear plans mooted in the mid-2000s became more specific. The French utility Electricité de France (EdF) had announced plans for two new large-scale nuclear plants at Hinkley and Sizewell. Financial support for the first of these was agreed in 2013, via a 35-y contract at a fixed price of £92.50 per megawatt hour for the electricity generated. The additional costs will be met from consumers' energy bills. Hinkley C is under construction at the time of writing, at significantly higher costs than planned. Originally due for completion in 2017, it is likely to enter service a decade later.

Despite the progress with electricity decarbonization, there was widespread concern that policy incentives were insufficient. Following an initiative by the energy regulator ("Project Discovery"), the government developed proposals for EMR in November 2012 (37). It argued that these reforms were required to ensure £110bn of investment in low-carbon electricity infrastructure by 2020. They included four main elements:

- Long-term contracts with new, low-carbon generation plants. These had a minimum term of 15 y, and provided price certainty to investors;
- Additional incentives to ensure sufficient investment in flexible and peaking generating plant to meet demand. While this "capacity mechanism" could also support demand-side flexibility and storage, the main aim was to ensure investment in new CCGTs;
- A carbon price floor to compensate for the low and uncertain carbon prices from the EU emissions trading scheme; and
- An emissions performance standard designed to prevent investment in new, unabated coal-fired generation.

At around this time, the government reformed energy efficiency policies (Box 3). It argued that these reforms would deliver a big impact through retrofitting 14 million homes. In practice, however, this branching point ended in failure (20). It led to significantly less action to reduce household energy demand than the policies it replaced.

EMR signaled a more coordinated approach to electricity investment and governance. Whilst some observers argued that these reforms were mainly intended to make nuclear power (38) and gas generation more attractive, renewable energy was the main beneficiary. To date only one long-term contract has been agreed for new nuclear (Hinkley C, see above). The Coalition government also shared its predecessor's support for small-scale renewables investment, introducing a generous feed-in tariff in 2010.

However, the next few years saw battles between ministers responsible for energy and climate change (Liberal Democrats) and HM Treasury (led by a Conservative minister). The first round of renewable energy contracts proposed under EMR were viewed with considerable scepticism (39). One casualty was a plan to support two demonstrations of carbon capture and storage (CCS) technologies on existing fossil fuel power plants. The Treasury cancelled funding of £1bn at short notice, forcing developers to abandon projects. Another was a series of cuts to feed-in tariff rates to take account of the falling costs of solar PV technology, some instituted at short notice.

Attempts to promote investment in CCS technologies by successive UK governments were partly due to the strength of the fossil fuel lobby (40). The UK still has a significant oil and gas sector despite declining production. Gas-fired electricity generation continued to play a significant role throughout the 2000s and 2010s. After several iterations of plans for CCS demonstrations, none have delivered full-scale plants. By contrast, some other countries have established demonstrators—though international progress has been slow (41).

4.4 An Unfinished Transition, 2015–. In 2015, the Conservatives won a narrow election majority. The new energy and climate minister spoke of "a new direction for energy policy" (42) and announced a plan to phase-out coal-fired power by 2025. However, she said that the government would also be "tough on subsidies," and that power from gas, nuclear and offshore wind were the priorities. 2016 saw an effective moratorium on onshore wind and large-scale solar (35 Appendix 1) because of local opposition to siting in areas represented by the Conservative party.

Both the 2015 Paris Agreement and the 2016 "Brexit" vote to leave the EU were landscape events with important policy impacts in the late 2010s and early 2020s. Because of the Paris Agreement and the 2018 Intergovernmental Panel on Climate Change Special Report on 1.5°, the UK strengthened its long-term climate change target. In 2019, accepting Committee on Climate Change advice, the government legislated for a net-zero emissions target by 2050 (43).

The 2016 Brexit decision catalyzed political turmoil. The new government reinforced its predecessor's increasing emphasis on linking climate change action to economic and industrial development. 2017's new Industrial Strategy's four grand challenges included "maximizing the advantages for UK industry from the global shift to clean growth" (44).

The large-scale investment in renewables increased through the 2010s, driven by contract auction rounds (Box 4). Nevertheless, the breakthrough of renewables had some negative sustainability implications. Environmental Non-Governmental Organizations have questioned the carbon and biodiversity impacts of subsidized large-scale investments in biomass generation (e.g., ref. 45).

By contrast, efforts to harness the significant energy in the waves and tides surrounding the UK failed to deliver. Research and development programs have tried to grow this niche by supporting a range of devices. None have yet become commercially attractive. Plans for large-scale tidal power installations were revived in the mid-2000s, later supported by an independent review. However, the Treasury decided that such investments would be too expensive.

By 2020, the electricity system's low-carbon transition was well underway. UK electricity's carbon intensity had fallen dramatically, from 535 g/kWh in 2008, to less than 200 g/kWh in 2021. Renewable electricity generation exceeded fossil fuel generation for the first time in that year (24). However, gas is likely to generate a significant share of electricity well into the 2020s. This leaves the UK vulnerable to the impact of global fossil fuel price shocks such as the shock that began in the second half of 2021. Recovery from the Covid-19 pandemic, and Russia's invasion of Ukraine, pushed gas prices to record levels and increased oil prices sharply in 2021 to 2022.

This transition has also increased the UK's electricity system's complexity. The rapid increase in variable renewables has presented new operational challenges for the company managing the national grid (see also Lockwood, 46). This has led to more investment in electricity system flexibility. The capacity of interconnectors between the UK and other countries has almost doubled in the last 5 y (47). Electricity storage has also scaled up rapidly, though total capacity remains small in 2022. This system complexity is likely to increase due to new sources of electricity demand—particularly from the increasing adoption of electric vehicles and (in the medium term) the potential shift of heating from oil and gas to electricity.

5. Conclusions and Implications

This section draws conclusions, reflects on current challenges, and briefly situates them in relation to the sustainability science literature synthesized in Clark and Harley (1). Informed by the MLP and using the concept of branching points, this paper has explored three very different periods in the UK electricity consumption–production system, and the implications for sustainability.

All three periods involved major governance branching points that led to radical changes: nationalization after the Second WW; privatization and liberalization in the 1990s; and a series of legislative and regulatory reforms since 2000 designed to reduce GHG emissions. During the latter period, stronger evidence on climate change, political competition and public pressure led to the 2008 Climate Change Act—and a new institutional architecture to monitor progress. All three periods also included additional technological BPs. This paper has highlighted those that led to significant shifts towards low-carbon generating technologies (nuclear power, CCGTs and offshore wind) and to changes in emphasis on energy efficiency.

During the first period, government and industry paid relatively little attention to the environmental and resource aspects of sustainability. Indeed, there was some resistance to cutting impacts on natural systems. It took until the late 1980s, in the second period, before the UK agreed to concerted action to reduce sulfur and nitrogen emissions from coal-fired plants (soon serendipitously aided by the post-privatization "dash for gas"). The 1990s saw growing acceptance of the need to address climate change.

Whilst the third period's transition to zero-carbon is incomplete, it has already involved deliberate action by government, industry and civil society to improve sustainability. Increasing awareness of climate change fundamentally altered the system's development pathway, including substantial reorientation of incumbent electricity utilities. This involved radically changing their investment strategies, technology portfolios and structures (48). Carbon emissions from UK power stations fell dramatically from 159 million tonnes of CO_2 (equivalent) in 2000 to 50 million tonnes in 2020 (49). Further reductions can help decarbonize other sectors, e.g., through shifting domestic heating (currently dominated by gas) to electricity, and faster adoption of electric vehicles. Heating will be hard to electrify since it will involve persuading millions of households to make significant changes. Stimulating the uptake of new technologies and forms of energy services will require reflexive, deliberative governance of a type infrequently seen in the UK electricity system.

Recent decarbonization progress does not mean, however, that the electricity sector now has minimal impacts on natural systems. Significant fossil fuel use remains via natural gas generation, and some way to go before GHG emissions approach zero. Furthermore, some low-carbon options are controversial because of unresolved or uncertain sustainability implications. Examples include large-scale biomass combustion (which could have a significant carbon footprint and impacts on biodiversity), and nuclear power (where the industry lacks clear plans for long-term waste management and decommissioning).

Each of the three periods saw episodes of deliberate government intervention—whether to nationalize, integrate and scale up the sector after WWII, to privatize the sector in the late 1980s due to perceived inefficiencies and vested interests, or to push the sector to decarbonize in the early 21st Century. Although some governments tried to distance themselves from directly managing the electricity system, they never fully succeeded. This was partly due to the political importance of secure and affordable electricity for the economy. It was also because of the influence of lobbies that promoted or defended their favored technologies, fuels, and policies. Consistent with Clark and Harley (1), neither of the polar governance opposites, nationalization or privatization, proved a panacea for governing the electricity system and its sustainability. Nevertheless, governments will continue to play a crucial role in the attainment of a zero-carbon electricity system.

The case of the UK electricity system also demonstrates the role of governance "rescaling" in the transition to sustainability (1 p. 363). After entering the EU, the UK exerted significant pressure on other member states to liberalize their energy sectors and become more ambitious on climate change. Conversely, EU directives, ranging from atmospheric pollution to energy efficiency labeling and renewable energy targets, significantly influenced the UK system's direction. It is now uncertain whether the UK's Brexit decision will lead to greater or less progress toward sustainability.

At the other end of the scale, the electricity industry and government have paid little attention to more decentralized technologies and strategies. In the nationalized era, the emphasis was on economies of scale and integration. Privatization, liberalization, and the subsequent prominence of climate change action have led to incremental changes. For example, the Scottish Government has a distinctive set of energy policies, and a different net-zero target year. There have also been small programs to support community energy and the widespread adoption of solar PV in homes. However, the broader national centralization of decision-making continues to limit the power of local and devolved governments to shape electricity systems.

Landscape and regime pressures from outside the sector such as the Covid-19 pandemic and the aftermath of Brexit have changed UK politics again. Moreover, the 2021 to 2022 natural gas and oil price rises and the inflationary impacts of the Ukraine war have raised the salience of energy security and affordability, highlighting the vulnerability of many, especially poorer households in badly insulated homes. The history of the UK electricity system illustrates the potential of landscape pressures, niche technologies and political change to disrupt its governance and development. These disruptions can be unpredictable, nonlinear and contentious, as transition theories suggest. At the time of writing, some political actors are arguing for a more market-led approach to decarbonization or downgrading the importance of climate action altogether. While the latter argument is only being made by a minority within the governing party, these pressures mean that complete decarbonization of the electricity sector by 2035 (the current official target) and further progress toward sustainability cannot be taken for granted.

Data, Materials, and Software Availability. All study data are included in the main text or are available from the cited sources.

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