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Innovation Priorities for UK Bioenergy: Technological Expectations within Path Dependence

Les Levidow, Theo Papaioannou and Alexander Borda-Rodriguez

UK bioenergy innovation pathways have been locked into current energy infrastructure through technological expectations, especially the reciprocal requirements of state bodies and industry. Over the past decade UK policy has given bioenergy an increasingly important role for decarbonising the energy system; technoscientific innovation has been expected to expand the range of biomass that can be sustainably converted to energy. Needing industry investment to fulfil its policy aims, the UK government has faced requirements to provide long-term support measures. Innovation priorities have been shaped by policy arrangements closely involving industry with state bodies. Their expectations for future benefits have mobilised resources for bioenergy innovation mainly as input-substitutes within current energy infrastructural patterns; novel path creation lies within a path dependence. Although technical progress has encountered difficulties and long delays, expectations for economic and environmental benefits have built support, while conflating national benefits with private-sector interests. Through such expectations, innovation priorities wishfully enact some desired futures from among those which had been advocated in policy documents.

Keywords: Technological expectations, path dependence, energy infrastructure

Introduction

Over the past decade, United Kingdom (UK) policy has given renewable energy an increasingly important role. Environmental aims include: reducing greenhouse gas (GHG) emissions, moving to a low-carbon economy and better managing waste (DECC, 2009a, 2009b; HMG, 2010). Through these measures, Britain must 'make the necessary transition to low carbon – right

for climate change, energy security and jobs' (DECC, 2009b: v).

This transition is stimulated by mandatory targets. Under the Renewable Energy Directive (EC, 2009), EU member states must obtain 10% of their transport fuel from renewable sources; biofuels have been expected to provide most. The UK must also obtain 15% of all its energy from renewable sources by 2020; it seeks to fulfill at least half that target through bioenergy – a great expansion

from only 2% in 2011 (HMG, 2011b: 3, citing AEA, 2010). The UK has more ambitious longer-term targets: the Climate Change Act 2008 mandates GHG reductions of at least 34% by 2020 and 80% by 2050.

Renewable energy encompasses diverse environmental sources such as solar, wind and wave. By contrast, bioenergy depends on traditional processes for converting biomass, especially from food and wood sources which have been criticised as environmentally unsustainable (Biofuelwatch, 2012). To increase bioenergy production, excessive increases in biomass imports 'could have counterproductive sustainability impacts in the absence of compensating technology developments or identification of additional resources', according to an expert study (Thornley et al., 2009: 5623). To compensate for (or avoid) those sustainability problems, technology innovators have sought to expand the range of non-food biomass that can be converted to energy. Multiple innovation pathways have competed for public-sector funds, while also anticipating that biomass sources may become more expensive and/ or controversial.

The UK government likewise emphasises the need for technoscientific innovation to ensure expansion of 'sustainable bioenergy' for its policy aims (e.g. HMG, 2011a: 70). Mutual requirements arise: the state needs industry R&D investment, which in turn needs state incentives and long-term commitments, which in turn need explicit justifications in future benefits. These reciprocal dynamics involve several state bodies, including non-departmental organisations and funding sources as well as Ministries.

This paper provides an empirically-based understanding of how bioenergy innovation priorities are shaped by technological expectations, especially the

reciprocal requirements of state bodies and industry. The main question to be discussed is: How do expectations for future technology mobilise resources for some innovation trajectories rather than others? This question is accompanied by subsidiary questions about UK state bodies: How do they promote beneficent expectations for future technoscientific advance as means to fulfil policy goals, especially a low-carbon future? How do they establish incentives for industry investment in bioenergy innovation? How they favour some innovation pathways rather than others?

Those questions will be answered by linking two analytical concepts – technological expectations and path dependence. Previous case studies on technological expectations have analysed promise-requirement cycles, especially how promises turn into requirements for innovators. Our case study highlights requirements on state bodies and thus reciprocal dynamics with industry.

The paper is structured as follows: The first section discusses the two analytical concepts – technological expectations and path dependence – as a basis to deepen the above questions. The second section presents the research methods. The third explains how the UK's technological expectations for bioenergy innovation turn into state requirements for industry incentives, how these are officially justified within the overall 'low-carbon' policy, and how new institutional arrangements structure state-industry reciprocal dynamics. Further illustrating those dynamics, the fourth section shows how UK bioenergy innovation priorities complement high-carbon infrastructural patterns, thus extending a path dependence. The final section summarises answers to the main questions on innovation priorities.

Analytical Perspectives

As mentioned above, this paper links two analytical frameworks – technological expectations and path dependence – as dual aspects of bioenergy policy. The former can help to identify actors' different accounts of future benefits, especially as strategies to mobilise resources for specific pathways; the latter can illuminate lock-in from past infrastructure.

Technological expectations have been theorised as 'real-time representations of future technological situations and capabilities' (Borup et al., 2006: 288). Rather than simply predict future realities, expectations guide technological and economic activities, provide legitimisation and structure to them, and so ultimately direct investment towards specific innovation pathways. They not only define roles and duties but also prepare actors for opportunities and risks. .

Expectations play a central role in mobilizing resources, 'for example in national policy through regulation and research patronage' (Borup et al., 2006: 286). Technological expectations can help to convince funders and other practitioners to support a development (Geels & Smit, 2000: 882; van Lente, 1993: 185). Related terms such as technological 'promises' and 'visions' emphasize their enacting, performative character: 'expectations are wishful enactments of a desired future' (Borup et al., 2006: 286), i.e. actions meant to realise such a future.

Technology innovators may exaggerate their promises for several aims – in order to attract attention from financial sponsors, to stimulate agenda-setting processes (both technical and political) and to build 'protected spaces', e.g. protecting an innovation from market competition (Geels & Smit, 2000: 882). Given the pressure on innovators to exaggerate expectations, 'the

frequent disappointments to which they lead are accompanied by serious costs in terms of reputations, misallocated resources and investment' (Borup et al., 2006: 290).

Technological expectations can turn into requirements for the actors who formulate them. Promises may attract resources and protection but also return as obligations through 'promise-requirement cycles.' A techno-optimistic claim or a promise may become a required action – e.g. a technical specification to be fulfilled and/or political support to be provided (van Lente 2000; van Lente & Rip, 1998). State support may become a greater requirement in contexts where policy goals depend on the fulfilment of technological expectations; such a requirement, which has received little attention in the academic literature, will be the focus here.

While envisaging great change, technological expectations may complement current patterns. Industrial interests may seek 'large-scale investment in improvement options that only fit into the existing system and which, as a result, stimulate a "lock-in" situation' (Kemp & Rotmans, 2005: 49). Lock-in can result from path dependence, whereby previous trajectories constrain later ones, though this is conceptualised in different ways. According to some frameworks, self-reinforcing mechanisms prevail over actors – unless an exogenous shock gives them new opportunities. According to another framework, actors can gain collective agency as an emergent attribute of their interactions. Through alternative visions of the future, they can mobilise resources towards path creation (Garud et al., 2010: 768).

Energy systems have been analysed as path dependence and creation. In the 20th century they were largely locked-in to hydrocarbon sources (Unruh, 2000). 'Energy systems, not just individual

technologies, are largely characterized by path dependence' (Lovio et al., 2011: 277). Given the problems of hydrocarbon fuels, however, 'the path dependence forces of the old, dominant fossil-fuel technologies are turning into forces of destabilization,' thus opening up path creation (Lovio et al., 2011: 283). A key driver for energy innovation has been environmental policy, which in turn responds to public demands. Yet energy users cannot easily compare environmental effects of various sources invisibly supplying a central grid (Lovio et al., 2011: 283).

The search for secure, low-carbon energy can highlight societal choices and open up extra ones. Renewable energy has often been designed according to the 'bigger is better' view, assuming that this will be cheaper per unit energy production and GHG-reduction. By the 1990s this assumption was being contradicted by some renewable electricity technologies such as solar and wind. They were lowering their costs faster than large-scale systems, especially through modular systems (Diesendorf, 1996; Neij, 1997). In some forms, renewable energy has better compatibility with decentralised, distributed energy generation (Rohracher, 2008: 145-146). In response to social movements, energy decentralisation has been linked with renewable energy sources by some governments, especially in Scandinavia (van der Vleuten & Raven, 2006). UK bioenergy innovation encompasses diverse potential ways to link technoscientific advance with societal visions, e.g. dominant centralised infrastructure or decentralisation (Levidow et al., 2013).

When creating new pathways, however, large incumbent firms tend to accommodate pressures for GHG savings in ways protecting their previous investment. These are 'large sunk costs in roads and supporting infrastructures and even larger costs in the community structure'; alternatives would

require huge fixed costs (Lovio et al., 2011: 292). Consequently:

Incumbent technologies enjoy huge advantages including pre-established infrastructure, relative ease in obtaining finance and insurance, developed networks of suppliers, familiarity to customers, embedded technical standards and training routines, and a tight 'fit' with existing regulatory approaches (Meadowcroft, 2009: 329).

For better recouping investment, then, it pays to hit the market first - in other words, 'to build a low-carbon lock-in' (Lovio et al., 2011: 280). Thus a new lock-in may happen by design through the collective agency of dominant actors protecting past infrastructural investment.

Alongside sunk costs are sunk practices, invisibly structured by infrastructure. This is more profound than an external context: 'Infrastructure is sunk into and inside of other structures, social arrangements and technologies' (Star, 1999: 381). Together they 'structure nature as resource, fuel or "raw material" which must be shaped and processed by technological means to satisfy human ends' (Edwards, 2003: 189). In this regard, the term 'energy' often conflates specific fuel sources with entire systems, whose security and efficiency depend on infrastructural choices. By contrast to dominant infrastructures, for example, micro-generation encourages a systems approach to optimize entire local systems (Patterson, 2006).

Flexibility has been attributed to technologies per se, yet their design limits flexibility through wider infrastructural choices. When devising ways out of a high-carbon lock-in, e.g. through Carbon Capture and Storage (CCS), the main issue is flexibility of the overall energy system vis à vis path dependence and creation (Markusson,

2012: 392). Biomass-fuelled CCS has been widely expected to provide carbon-negative emissions, but such benefits depend upon numerous optimistic assumptions – about biomass production, biomass combustion, carbon capture, etc. (Smolker & Ernsting, 2012). Bionergy CCS has been promoted as a flexible technology, adaptable to various contexts and aims, yet it readily complements present infrastructure. As ‘fruits of technical fixes,’ CCS can contribute to policy aims for GHG savings in the short term, while avoiding the need for systemic innovation (Kemp and Rotmans, 2005: 48). CCS reinforces infrastructural dependence on fossil fuels: ‘It is mainly applied to make coal-fired power plants more acceptable and thus acts as an instrument for reinforced fossil fuel lock-in’ (Vergragt et al., 2011: 290). Although bioenergy-CCS is meant to offer greater GHG savings, in practice

Adding CCS does not substantially change the interrelatedness of the fossil fuel regime. It remains tightly linked with the centralized grid for power distribution and it thus weakens the viability of distributed energy sources, which are favoured by many renewable energy options (Vergragt et al., 2011: 284).

As extra impetus for path dependence, since the 1990s EU-wide policies have been liberalising the energy supply. Such changes have weakened government ownership or control over the sector (Faij, 2006). As an extreme case, the UK electricity system was bought up by foreign-owned multinational companies (Meek, 2012). Consequently, the newly privatised industries favoured less capital-intensive improvements because they were forced to recoup investment over shorter time periods than their nationalised predecessors (Shackley & Green, 2007).

Energy innovation depends upon co-financing by large-scale industry,

whose investment has been largely path-dependent, especially in the UK. For example, since the 1980s the UK government has advocated combined heat & power (CHP) for more efficiently using fuel, but this pathway attracted little investment by either public or private sectors (Russell, 1993). Energy-sector liberalisation was expected to expand opportunities for more diverse systems, yet the new electricity market created more obstacles for CHP. Consequently, the scant adoption has come mainly from some large industrial plants for their own use (Russell, 2010). Domestic micro-CHP has gained modest adoption but will remain a small niche market without coordinated support measures (Hudson et al., 2011). CHP depends on new infrastructural investment for district heating, especially from local authorities, but their capacities have been undermined by governmental centralisation since the 1990s and even further by budget constraints since 2010.

Decentralisation options such as renewable-energy micro-generation highlight design choices for linking infrastructure with users’ knowledge. Renewable energy can provide simply an input-substitute for a conventional system which separates personal behaviour from energy consumption; such design illustrates a socio-technical ‘lock-in.’ Alternatively, micro-generation can be designed for a cultural-behavioural shift towards users’ control and responsibility, linked with knowledge of renewable energy sources; this linkage offers greater opportunities to reduce energy usage and GHG emissions. Relevant technologies include biomass-fuelled boilers and micro-CHP (Bergman & Eyre, 2011; also POST, 2012). To go beyond the dominant infrastructure, decentralisation ‘implies breaking up the large energy companies and reducing dependence on the national grid for electricity supplies,’ especially through popular

engagement building an alternative power base (Scrase & Smith, 2009: 723).

Research Methods

This paper arises from a study focusing on technological expectations of numerous state bodies, as briefly described here. A decade ago bioenergy was being promoted mainly by two government bodies – the Dept of Trade & Industry (DTI) and Dept of the Environment, Farming and Rural Affairs (DEFRA). In 2009 bioenergy policy was transferred to the new Department of Energy and Climate Change (DECC), which acquired some former staff of both the other ministries. Meanwhile the DTI was renamed the Dept for Business and Industry (BIS). The Dept for Transport (DfT) sets mandatory quotas for biofuels.

Public-sector funds for novel bioenergy technology have several sources. ‘Strategic research’ has been funded mainly through Research Councils – in particular, the Biotechnology and Biological Sciences Research Council (BBSRC), and the Engineering and Physical Sciences Research Council (EPSRC). The latter has co-funded the Energy Technologies Institute (ETI), self-described as ‘a UK-based private company formed from global industries and the UK Government’. Near-market innovation has been funded mainly through government departments, e.g. via specific project grants or subsidy for renewable energy.

The study underpinning this paper used two main methods of data gathering: documents and interviews. Together these methods identified technological expectations within policy processes, as follows.

Documents: the study analysed more than thirty documents from several bodies – especially government departments, Research Councils, research institutes, Parliamentary hearings, industry and

NGOs. As listed in the References section, sources include: government departments (e.g. DEFRA, DTI, DECC), expert reports that they have cited and generally funded (e.g. AEA, NNFCC, E4tech, ERP, LCICG), research councils (e.g. BBSRC/BSBEC, EPSRC with ETI), other state bodies (EAC, RFA, CCC, etc.) whose views elicit government responses, and industry organisations (e.g., REA). Analysis focused on expectations for economic benefits and environmental sustainability, as dual rationales to mobilise investment in specific innovation pathways. Initial results led to a more systematic search of documents over the past decade, in order to identify discursive patterns – among relevant bodies and over time.

Interviews: The document analysis provided a stronger basis for interview questions, which investigated in depth the process of selecting priorities for bioenergy R&D. Face-to-face interviews have been carried out with 20 individuals from the same bodies which originated the policy documents (listed above and in the References section).

The project held two seminars (on 13.10.11 and 20.11.12), presenting preliminary results to key actors and gathering complementary data. Discussions there also provided confirmatory comments and extra material for further investigation.

Expectations within/as Reciprocal Dynamics

The UK state and industry have promoted technological expectations that bioenergy innovation will help to fulfil targets for GHG savings, among other societal benefits.

These promises have been turned into requirements for industry to demonstrate technical progress, as well as for state bodies to make long-term commitments for support measures, especially as incentives for industry investment. Within those

reciprocal dynamics, tensions have arisen among different policy aims, energy futures, innovation pathways, their uncertain feasibility and expected benefits. Those tensions have been contained through technological expectations for bioenergy innovation in general, while ostensibly keeping open future options for state support and commercial development.

Tensions among policy aims

For many years, UK bioenergy policy has implied that technological pathways are constrained or even chosen by external forces, thereby leaving priorities ambiguous. Although various measures are meant to 'deliver' government targets, policy language attributes responsibility to external forces such as innovation, technologies, commercial development and/or the market (e.g. DECC, 2009a: 53; DECC, 2011: 43; DEFRA, 2007a: 35; HMG, 2011a: 5). Along similar lines, 'The government does not pick winners; industry is better at it,' say senior civil servants (DECC participant, bioenergy workshop, 13.10.11; also interview, DECC, 14.08.12). Industry likewise requests incentives which do 'not pick winners,' e.g. for the biofuels sector (submissions in EAC, 2008b). For developing specific technologies, however, private-sector investors request a long-term, stable policy commitment.

That request has been somewhat accommodated. According to the 2012 *UK Bioenergy Strategy*, support measures should follow four general principles – e.g. to make a cost-effective contribution to UK carbon emission objectives, to target bioenergy at uses which will have no alternative low-carbon source, and to maximise the overall benefits and minimise costs (quantifiable and non-quantifiable) across the economy. It must use 'sustainably-sourced biomass' to ensure a contribution to GHG savings. Flexible innovation trajectories should

accommodate uncertainties about environmentally sustainable biomass supplies and future technological development (DECC et al., 2012a: 6-7).

In relation to those principles, the strategy document elaborates the concept 'risk.' This is given several meanings: expected benefits may not materialise; some bioenergy pathways may not be truly renewable, low carbon, environmentally sustainable, cost-effective for GHG reductions, etc. (DECC et al., 2012a: 6). 'Low risk' means that a gradual, step-wise development can indicate future feasibility at modest cost (interview, DECC, 14.08.12). As a related risk, a long-term commitment may lock out future alternatives later seen as preferable (DECC et al., 2012a: 57). A pathway may become locked in, e.g. through investment decisions and several thousand jobs, so that government may face political difficulties in shifting its support to a different pathway later; such lock-in may already be happening with conventional biofuels (interview, DEFRA, 22.05.12).

Based on those criteria, the strategy document identifies medium-term 'low-risk bioenergy pathways.' These include the following: some conventional biofuels; CHP processes efficiently utilising recoverable wastes; sustainable biomass for decarbonising power generation which currently uses coal as a feedstock (DECC et al., 2012a: 40; also 8-9). The latter justifies subsidy for co-firing biomass in coal-fired electricity plants, on the assumption that they will be phased out anyway by the late 2020s – rather than support new dedicated biomass plants (DECC et al., 2012a: 45).

Yet either pathway reinforces electricity-only generation, while losing links to CHP which could use the waste heat. Moreover, biomass input-substitution can lower SO₂ emissions below more stringent future limits for coal plants, thus helping to extend the lifespan of this high-carbon energy source

(Sloss, 2010). Thus the policy subsidises a cheap way to increase 'renewable energy' per se, rather than prioritise GHG savings. 'Although we look at 2050, the main focus is getting to the 2020 targets cost effectively' (interview, DECC, 14.08.12).

Biomass co-firing exemplifies a general pattern: biomass input-substitution has favoured large-scale supply chains, centralisation and agri-industrial biomass supply for whatever processes can maximise renewable energy by the 2020 target. Towards its fulfilment, some R&D attempts to overcome problems of current technology 'We send researchers to existing plants where certain technologies are not working, to find out why - before thinking about how to redesign the world' (interview, SuperGen Bioenergy programme, 18.09.12).

Alongside environmental aims, bioenergy policy also seeks national economic benefit of two main kinds - lowering national costs of GHG savings, and creating or capturing economic wealth. The latter can mean profit, jobs, licence patents, royalties, etc. - according to the Technology Strategy Board, which is governed mainly by industry representatives (interview, TSB, 15.06.12). Such benefits can be achieved in various ways, e.g. via technology-licensing revenue through a plant being built somewhere else in the world, or revenue from constructing a plant in the UK, according to a government consultant (interview, E4tech, 19.06.12). By targeting strong areas of national expertise, 'the UK could potentially capture 5-10% of the global market within select niches of bioenergy', e.g. by exporting intellectual property for new energy crops and advanced biofuels, according to a state-industry expert group (LCICG, 2012: 5-6). Such expectations for future economic benefit have influenced priorities for bioenergy innovation.

Bioenergy innovation as input-substitute

Corresponding to the above technological expectations, UK strategy envisages bioenergy mainly as an input-substitute within current large-scale centralised infrastructures for producing, delivering and using energy. Bioenergy resources are promoted for their flexibility, cost and 'suitability to existing infrastructure' (LCICG, 2012: 9). According to a policy assumption, economy of scale generally helps to optimise cost-effective GHG savings through bioenergy. Moreover, this avoids potential problems. As one policymaker stated: 'You just feed the energy into the power grid and there's no issue with the end user' (interview, DECC, 14.08.12).

Such policy assumptions coincide with priorities of multinational companies dominating the energy industry. Input-substitution likewise has been promoted by the Renewable Energy Association (REA), representing various energy trajectories. It advocates a key role for power stations using biomass from feedstock produced sustainably, as well as for road transport to use biofuels, which 'need to peak in 2030 and remain a significant element until 2045' (REA, 2011a). Pyrolysis oils can substitute for diesel, likewise biomass for oil in producing plastics, likewise digestate for chemical fertiliser, etc. (REA, 2011b). To incentivise substitution of fossil fuels, the REA lobbies for supportive government policies - R&D funds as well as operational subsidies.

From the standpoint of technology investors, high or uncertain costs may be incurred before clarifying technical feasibility, thus needing a long-term commitment to explore the potential. For Research Council grants, a de-risking strategy gives industry a significant influence at low cost. According to a bioenergy research manager of a research council:

We take a lot of risk out of the early fundamental research that most industry does not want to do.... We de-risk their fundamental research. And if they'd like to give us some guidance as to where that research could go, there are various ways. For instance, if they take a 10% stake in a project, then a proposal will automatically get lifted up the priority scale (BBSRC interview, 05.04.11).

Scientists' R&D proposals advocate specific technological pathways as means to fulfil various policy aims and to anticipate economic gains attracting private-sector sponsors. Their financial contribution has been an advantage or even a condition for a grant proposal to gain a Research Council grant. Co-funding has come from international companies in the biotech, enzyme, sugar and energy sectors (Eggar, 2012). Such industrial interests frame priorities for technoscientific expertise and advance. According to a research manager:

If you don't provide technologies that industry will adopt, then it's pointless having done the R&D to develop them... The future expectation for a technology has to sit within an existing landscape. You have to be able to make your new technology fit in (interview, Supergen, 18.09.12).

As related expectations, industry co-funding requires the public sector to maintain commercial confidentiality, even within the same institute, especially to protect intellectual property. These arrangements favour research agendas expecting proprietary knowledge, e.g. via company secrecy or patents (interview, BSBE, 04.08.11). This effort is meant to make UK science and industry more globally competitive. In practice, however, UK public-sector researchers compete against

each other to obtain industry finance from potentially anywhere in the world.

A key aim is to overcome the 'valley of death' which has generally kept UK research distant from commercial application, especially in bioenergy (LCICG, 2012: 27). To overcome this obstacle in near-commercial scale-up, the Energy Technologies Institute brings together several companies which thereby share the high costs and financial risks. ETI de-risks technology by identifying long-term technological needs. Set up as a club, ETI pools company funds in order to reduce financial exposure of any one company, while providing half of the overall funds from government (interview, ETI, 08.06.12). Priorities are implicitly steered through co-funding between public and private sectors, in parallel with consultation processes, e.g. through the Technology Strategy Board.

Innovation priorities anticipate bioenergy input-substitutes as invisible, so that GHG savings will not depend on consumer knowledge or behaviour. 'Bioenergy sources will not be noticed by energy consumers,' thus avoiding potential problems: 'People in the UK don't want to buy heat from CHP; they hate such projects locally' (DECC participant in our workshop, 13.10.11). If householders are invited to install biomass boilers, for example, then GHG savings depend on behavioural change; such responsibility may elicit complaints or recalcitrance. Moreover, if consumers know that a proportion of their grid-energy comes from renewable energy, then some feel entitled to increase GHG emissions in their travel behaviour. To avoid such problems, therefore, substituting renewable energy ideally 'should not require active behavioural changes from people or trigger undesirable behavioural changes' (interview, DECC, 14.08.12).

As a different future vision, UK policy and R&D strategy have also advocated

decentralisation through renewable energy, especially micro-generation, micro-CHP, etc. Local renewable sources and visibility can help give more responsibility to consumers (e.g. DTI, 2007: 12; UKERC, 2009: 3). For example, biowaste-CHP could help to decentralise production, while also enhancing use of waste-heat, thus saving GHG emissions (DECC, 2009a: 115). But such pathways have gained little from government support measures; 'lack of local heat networks' is identified as an obstacle - but not as a priority (LCICG, 2012: 16). Thus a putatively desirable future remains marginal within industry co-funding arrangements and their specific expectations for economic benefits.

Path-dependent Innovation Priorities

Amongst many potential pathways, UK bioenergy innovation priorities have generally complemented the past infrastructural investment in high-carbon production-consumption patterns, thus reinforcing a path dependence. Despite technical difficulties and long delays in those innovation pathways, expectations for economic benefits have helped to mobilise resources, while conflating national benefits with private-sector interests. Such expectations have been elaborated through state-industry institutional arrangements, as this section will show.

As a long-standing feature of UK policy documents, Carbon Capture and Storage (CCS) has been under development mainly for gas and coal-fired plants, with potential adaptation to bioenergy such as co-firing. As a strong policy imperative for biomass CCS, the 2050 targets for GHG savings would be otherwise much more costly to achieve. Thus 'the availability of CCS is key in the longer term' through linkages with other bioenergy technologies. But their costs and availability remain highly uncertain,

'especially for unproven technologies in later periods, e.g. biohydrogen for transport' (DECC et al., 2012b: 8-9, 56). Given the uncertain feasibility of bioenergy-CCS itself, 'the most appropriate energy use will vary according to the availability of carbon capture and storage' (DECC et al., 2012a: 9).

Thus expectations for bioenergy-CCS frame uncertainties about future bioenergy capacities and needs. As 'the key bioenergy hedging options against these inherent long-term uncertainties,' the UK strategy identifies three technologies - biosynthetic gas, hydrogen and advanced biofuels (DECC et al., 2012a: 38). Flexibility is attributed to such technologies per se: 'The development of flexible bioenergy technologies which can contribute to the decarbonisation of different sectors is a way of mitigating against the inherent uncertainties' (DECC et al., 2012a: 42).

For the three 'hedging options' and CCS, sub-sections below analyse how each innovation pathway has been promoted through technological expectations, with varying support and relationships to the dominant energy infrastructure. Each section presents empirical material in roughly chronological order to analyse shifts in 'real-time representations of future technological situations' (Borup et al., 2006: 288).

Biohydrogen fuel cells

For at least the past decade, the UK government has advocated the redesign of vehicles for multiple fuel sources, towards 'building competitive advantage for the UK's automotive industries as well as providing cleaner and better transport' (DTI, 2003: 63). UK policy has envisaged decarbonisation of transport through electric cars, especially using hydrogen fuel cells (DfT, 2002, 2009). These have been foreseen as flexible for storing various energy sources and supplying diverse energy uses.

According to a consultancy report for the DTI (E4tech et al., 2004: 227), UK regional capacities for hydrogen development could provide a competitive advantage in efforts 'to provide marketable products and services' (E4tech et al., 2004: 91). As national economic benefits, moreover, 'Hydrogen has the potential to create innovation-led growth and employment, to attract inward investment, and to generate export opportunities both for hydrogen and for related technologies' (E4tech et al., 2004: 144). In addition to saving GHG emissions, hydrogen fuel 'could also help to improve air quality, through zero or very low emissions of pollutants... at the point of use' (E4tech et al., 2004: 143). Those economic and environmental benefits could be enhanced through biomass gasification to biohydrogen fuel (E4tech et al., 2004: 288).

But a major obstacle would be the necessary infrastructural investment. As a transitional phase, hybrid petrol-hydrogen vehicles could offer significant GHG savings but 'do not appear to be favoured by the auto and fuel industries as a result of infrastructure needs' (E4tech et al., 2004: 64). As the report acknowledged, past investment in current petrol-vehicle infrastructure would be an obstacle. When economists reiterated a biohydrogen option, 'biomass gasification to hydrogen,' they likewise mentioned possible difficulties in 'refuelling infrastructure' for hydrogen fuel in general (Ekins and Hughes, 2010: 3).

Echoing benefits in the E4tech report, biomass could be turned into synthetic liquid fuel, according to comments in a stakeholder workshop organised by the EPSRC's UKSHEC programme. Their scenarios also linked biomass with small-scale energy localisation:

Hydrogen is produced both centrally and locally, using a variety of technologies, with a significant proportion from

distributed renewables (such as wind turbines and building-integrated PV) and biomass... (Eames & McDowall, 2005: 9).

The workshop outlined various scenarios where 'futures are also distinguished by the degree of centralisation or decentralisation of the hydrogen generation and distribution infrastructure' (Eames & McDowall, 2005: 3).

A hydrogen pathway has been often reiterated during the past decade. According to *The UK Low Carbon Transition Plan*, 'In the long term, reductions in emissions will require a radical transformation in the way vehicles are built and powered – whether hybrid, electric vehicles, biofuels or hydrogen fuel cell technology' (DECC, 2009b: 140). Government reports have anticipated 'electric and plug-in hybrid cars becoming increasingly common' from 2012 onwards. 'While electrically powered vehicles will increase demand for power, through smart management of our networks we can minimise the need for new power stations...' (DfT-BERR, 2009: 3).

The statutory Committee on Climate Change likewise envisaged a longer-term innovation pathway where transport is fully decarbonised by 2050, largely based on electric vehicles, i.e. battery and possibly hydrogen (CCC, 2011a: 151). Its *Bioenergy Review* recommended government action for ensuring alternatives to liquid fuels, especially for road transport, given the future prospect of greater competition for sustainable biomass (CCC, 2011b: 11). In particular: 'While the future use of hydrogen is uncertain, it potentially offers an important route for decarbonising heavy-duty vehicles (e.g. buses and heavy goods vehicles) where battery electric vehicles are unsuitable' (CCC, 2011b: 62, 66).

Biomass inputs would be even more desirable: 'Hydrogen production. The

production of a zero-carbon energy carrier from biomass with CCS offers negative emissions benefits similar to those for electricity generation,' further argued the Committee (CCC, 2011b: 62). To go beyond the internal combustion engine, transport fuel 'could be biohydrogen if you made it from renewable electricity or if you generated it from waste' (interview, CCC member, 17.11.11). As many stakeholders have argued, transport will need to be decarbonised 'through a combination of biofuels and other renewable energy (such as hydrogen and electricity), vehicle efficiency and reducing the need to travel' (respondents as summarised in DfT, 2011: 64).

The *UK Bioenergy Strategy* included hydrogen among three 'hedging options' for future uncertainties (DECC et al., 2012a: 36, 41). It also emphasises difficulties for biohydrogen as a relatively more uncertain option regarding feasibility and cost:

The most complex bioenergy pathway could involve one or more bioresources feeding into a conversion technology to produce a biomass carrier which is then used as an input to further conversion process to produce the final product, e.g. the steps to produce biohydrogen.... The relative costs and availability of the technologies are subject to significant uncertainty, especially for unproven technologies in later periods, e.g. biohydrogen for transport (DECC et al., 2012b: 49, 56).

Indeed, its commercialisation faces numerous technical obstacles – e.g. cleaning biogas for fuel cells, which themselves need advances in compression, lower ratios energy input-output, substitutes for rare earth-metals, etc. (HMG, 2011b: 53).

Although other innovation pathways such as advanced biofuels also face technical

obstacles, extra ones arise for hydrogen fuel cells. Several components of the supply chain need to be integrated – the focus of a recent initiative (TSB, 2012). Moreover, they need new dedicated infrastructure, thus potentially disrupting the incumbent one and incurring much greater capital costs. Partly for such reasons, this pathway has remained marginal within R&D priorities.

Advanced biofuels

Biofuel promoters have emphasised at least three future benefits, which serve as expectations for mobilising policy support for R&D funds. First, the oil and vehicle industries seek to recoup their past infrastructural investments; such interests are accommodated by R&D priorities for future biofuels. According to the Director of a Research Council, for example, 'Sustainable biofuel... is one of the few alternative transport fuels that we could roll out quickly using current infrastructure' (BBSRC news, 2009). Expert advisors recommend R&D support for future 'drop-in' biofuels which can directly substitute for petrol (ERP, 2011: 9; also AEA, 2011: 8). Second, future biofuels will provide opportunities for UK competitive advantage in marketing its technoscientific skills and in licensing technology. Third, given EU targets for renewable energy in transport fuel, all member states must greatly expand biofuel use – preferably advanced biofuels by the 2020 deadline.

Biomass conversion to liquid fuel is the least cost-effective way to save GHG emissions, as acknowledged by government. Nevertheless policy need not reflect that hierarchy because 'it does not take into account the relative importance of biomass fuel sources in delivering climate change goals and targets,' especially the EU target for renewable energy in transport fuel (DEFRA, 2007: 7). The policy pleaded a lack of alternatives to fulfill the 2020 target, while

also displacing sustainability problems onto future technological solutions:

It is likely that by 2020 second-generation biofuel technologies will be in place. This should make the production of biofuels from land much more efficient, with a reduced area needed to produce a given volume of biofuels... (DEFRA, 2007: 22).

In 2008 the government proposed a 5% target for biofuels by 2010, partly as an incentive for industry to develop second-generation biofuels. In response Parliament's Environmental Audit Committee advocated a moratorium on biofuel targets, while also counterposing other measures to reduce GHG emissions from transport, e.g. a shift towards electric vehicles and/or public transport (EAC, 2008a). The Committee also warned about a technological lock-in of current biofuels: 'support for first generation biofuels might not have the desired effect', i.e. generating viable second-generation biofuels (EAC, 2008c: 4). The Renewable Fuel Agency likewise criticised EU targets for transport fuels yet also anticipated sustainability improvements from second-generation biofuels, which would help to alleviate the 'food versus fuel' conflict (RFA, 2008: 41). In response the government maintained its support for rising targets as a necessary transitional stage towards future biofuels (EAC, 2008b: 11).

This priority resonated with the aim to export valuable knowledge. In its *Renewable Energy Strategy*, DECC emphasised export opportunities, especially for technological innovation in biofuels: UK producers 'will have the opportunity to compete in a global market if they can meet the European mandatory standards' (DECC, 2009a: 111). From approximately 2009 onwards the government greatly expanded R&D expenditure for bioenergy, especially for

2nd-generation biofuels, also known as advanced biofuels. In the controversy over UK biofuel targets, including concern about locking in conventional biofuels, beneficent expectations for next-generation biofuels played a performative role (Berti & Levidow, forthcoming).

UK Research Councils have elaborated those expectations for future benefits. For second-generation biofuels, expectations involve specific models of environmental sustainability and economic advantage – somewhat overlapping: Technoscientific innovation will expand the availability of renewable resources and will more efficiently convert them into second-generation biofuels, while also reducing GHG emissions by replacing fossil fuels. Renewable resources will be renewed on a much larger scale in a sustainable way – e.g. by cultivating plants on 'marginal land', needing fewer external inputs, converting non-edible biomass, etc.

As regards economic benefits, conversion processes are needed to produce drop-in biofuels, i.e. as exact substitutes for fossil fuels within current infrastructure (interview, DECC, 01.04.11; interview, BBSRC, 05.04.11; ERP, 2011: 6). For example, 'Liquid fuel has a remit through to 2050 because people will still want to drive their own individual transport' (interview, ETI, 08.06.12). Moreover, some sectors need energy-intensive fuel: for aircraft and long haul road freight, there are not so many alternatives currently in prospect for major reduction in GHG emissions' (ERP, 2011: 6); this clearly implies long-term dependence on liquid fuel, regardless of biohydrogen or electric vehicles.

Earlier technological expectations have encountered difficulties and delays. As a high-profile rationale for R&D expenditure on second-generation biofuels, these are essential for fulfilling the 2020 target (DEFRA, 2007: 22 as above). By 2009,

however, such future fuels were being envisaged for some time after 2020 (DECC, 2009a: 53). To fulfil the UK's 10% renewable contribution to transport fuel by 2020, none will come from advanced biofuels, as the government reported to the EU (HMG, 2010: 14).

Doubts have been raised about long-term sustainability, even of advanced biofuels. According to advice from a statutory committee, road transport should not be a long-term priority for biofuels:

Given limits to the global supply of sustainable bioenergy, it is important that this is used in an optimal fashion. In general, this implies use in applications where there are currently no feasible low-carbon alternatives to hydrocarbon input.

Therefore biofuels for road transport should be only a short-term step, argued the report (CCC, 2011b: 10). Even whenever second-generation biofuels materialise, moreover, they may not overcome feedstock shortages; indeed, they could result in competition between sectors for feedstock, according to an expert report for DECC (AEA, 2011: viii).

Despite those doubts and practical difficulties, UK government R&D priorities still favour advanced biofuels as oil substitutes within current transport infrastructure, aiming to make it more environmentally sustainable. Similar expectations continue to justify priorities for 'drop-in fuels,' thus reinforcing the internal combustion engine.

Gasification

Gasification uses high temperatures to convert biomass into syngas, which can be further converted into various energy forms. From a long history, especially in converting coal to liquid fuel, gasification has recently attracted greater interest as a more efficient flexible means to convert various

feedstocks, e.g. carbon-based waste such as paper, petroleum-based wastes like plastics, and organic materials such as food scraps (DECC et al., 2012b: 81). Such conversion could offer environmental advantages over waste incineration, as regards waste disposal and energy yield. Despite its importance, gasification has been an erratic priority over the past decade. Gasification has undergone technoscientific development abroad, but little in the UK (E4tech/NNFCC, 2009: 51-52).

In the late 1990s state support was directed at new technologies, especially gasification and pyrolysis, with expectations for short-term commercial scale-up. In particular the ARBRE (Arable Biomass Renewable Energy) demonstration project was an integrated gasification-combined cycle system to generate electricity from dedicated energy crops. It had two funding sources with contradictory aims: A 15-year contract from the Dept of Trade & Industry (DTI), under the Non-Fossil Fuel Obligation (NFFO), was intended to support reliable, ready technologies. In parallel, EC funds aimed to support experimental technologies. (Piterou et al., 2008: 2050). Such scale-up efforts were premature:

The targeting of more advanced or novel technologies was even a greater failure as the most advanced technologies have failed to materialise. This focus on novel technologies has come at the expense of support to more mature technologies which would have helped the biomass energy sector to grow and expand (van der Horst, 2005: 712).

In those ways, high expectations mobilised resources but resulted in a multiple failure - gaining little technical progress, undermining the credibility of large-scale gasification and damaging the government's reputation. By default, energy

supply companies had to import other conversion technologies which were ready for commercial use – the reverse of the original aim. Consequently, the government has been criticised for ‘picking losers.’

More recently, future expectations for gasification have been raised by government and expert reports. What role for UK investment and expertise? According to a 2009 expert report, gasification will be developed first abroad. So a key aim is to develop UK technoscientific skills which have broader relevance: ‘The gasification and pyrolysis pilots would provide general project development related skills that might be applicable to biomass to liquids, and bring to bear UK strengths in engineering and petro-chemicals’ (E4tech/NNFCC, 2009: 51-52).

Whenever gasification becomes more flexible, the technology is expected to provide input-substitutes for oil within current infrastructures. R&D priorities favour gasification as a flexible way to fuel current transport infrastructure; it can generate ‘drop in’ solutions particularly in the difficult sectors of aviation and heavy goods vehicles. In both sectors, the Government has indicated biofuels should be prioritised because ‘no other solution is available,’ according to the government-funded National Non-Food Crops Centre (Tomkinson, 2012).

Another foreseen application is waste-recycling in ways localising energy production. Gasification is also promoted as a flexible means for more efficiently converting diverse biomass inputs into various outputs. This role complements the well-known ‘waste hierarchy’ for optimising GHG reductions (DEFRA, 2011b).

Gasification is expected to facilitate a shift to non-food feedstocks for novel biofuels, as well as employment creation. According to an expert study by the National Non-Food Crops Centre:

New technologies – like gasification and pyrolysis – allow biofuels to be made from a wide range of sustainable materials, such as household rubbish... Under favourable economic conditions and strong improvements in policy support, projections suggest advanced biofuels could meet up to 4.3 per cent of the UK’s renewable transport fuel target by 2020.... At this scale advanced biofuels would save the UK 3.2 million tonnes of CO₂ each year – equivalent to taking nearly a million cars off the road – and create 6000 full-time construction jobs and over 2000 permanent jobs supplying and operating the plants (Natrass et al., 2011).

Incorporating those expectations, the *UK Bioenergy Strategy* promoted gasification as flexible, especially for converting biowaste. Priorities will include R&D on yield improvements and technologies which can make better use of wastes. In particular, gasification-derived bio-syngas is an intermediary for converting diverse bio-wastes into various energy forms and uses (DECC et al., 2012a: 55).

To move forward gasification, the Energy Technologies Institute allocated funds for a demonstrator project, linked with the 2050 targets. Specifically, it announced

... a new £13 million project to help design and build a next-generation energy from waste demonstrator plant to convert typical wastes into electricity and heat. The ETI is focused on the acceleration of the development of affordable, clean and secure technologies that will help the UK meet its legally binding 2050 climate change targets... (ETI, 2012).

Such expectations also include a link to CCS. According to an ETI staff member:

gasification 'also enables carbon capture & storage, which is becoming a major topic across Europe as it delivers negative GHG emissions' (interview, ETI, 08.06.12). The priority for energy-from-waste anticipates that the UK could gain a competitive advantage in technology for this process. Gasification is also expected to make biowaste-CHP more economically viable: 'Gasification systems can also be used for small-scale heat and CHP applications, which are commercially deployed with support in some countries' (LCICG, 2012: 17).

Biowaste is spatially distributed, thus offering opportunities for decentralisation. Indeed, UK policy has advocated biowaste-CHP as a means to decentralise production, while also enhancing use of waste heat, thus saving GHG emissions (DECC, 2009a: 115). Nevertheless the prevalent design will provide input-substitutes for centralised infrastructure: 'Gasification plants will generally be in or near waste-handling facilities, which tend to be far away from potential heat users' (interview, ETI, 08.06.12). This design complements policy assumptions, e.g. about centralisation being more cost-effective and novel inputs remaining invisible to consumers.

BE-CCS

Bioenergy-carbon capture and storage (BE-CCS) already had a central role in the UK's 2011 *Carbon Plan* for fulfilling 2050 targets. Among three future scenarios, one expects to save even more GHG emissions through CCS by expanding bioenergy, thus compensating for greater imports of cheap natural gas (DECC, 2011: 17). Although BE-CCS is foreseen as more speculative than other pathways, its technical success would significantly lower the costs of UK carbon targets (DECC et al., 2012), according to widely shared expectations.

Moreover, the *UK Bioenergy Strategy* emphasised flexible deployment for negative emissions:

Bioenergy carbon capture and storage (BE-CCS) could produce bioenergy in the form of biopower, biohydrogen, bio-heat and biofuels, but most significantly permanently store underground the waste carbon from these processes that was taken from the atmosphere by plant growth, providing net carbon removal from the atmosphere or 'negative emissions' (DECC et al., 2012a: 42).

CCS would open up options for various sectors, including biohydrogen:

the priority should be for continued use of biomass resource in process heating, and in the transport sector, either through bioenergy hydrogen production with CCS or through biofuels for aviation and shipping if CCS is not available (DECC et al., 2012a: 41).

How would BE-CCS relate to current infrastructure? A localised small-scale design would facilitate biomass supply and enhance GHG savings, according to an academic study:

While biomass co-firing with coal offers an early route to BE-CCS, a quite substantial (>20%) biomass component may be necessary to achieve negative emissions in a co-fired CCS system. Smaller-scale BE-CCS, through co-location of dedicated or co-combusted biomass on fossil CCS CO₂ transport pipeline routes, is easier to envisage and would be potentially less problematic (Upham & Gough, 2011).

Nevertheless the prevalent design assumes that BE-CCS will complement centralised

infrastructure for fossil fuels, as promoted by major energy companies within the Energy Technologies Institute (ETI). Bringing together several major energy companies for common projects, ETI 'identified a specific opportunity to develop capture technology for new-build, pre-combustion coal capture based on physical separation of CO₂ from synthesis gas', i.e. initially in coal plants. It invited company proposals 'for full-scale demonstration by 2015 and adoption into full scale commercial power applications by 2020' (ETI, 2010). Biomass is foreseen as supplying a few large-scale centralised plants (interview, ETI, 08.06.12).

Moreover, eventually the negative emissions are expected to lighten the burden of GHG savings from fossil fuels. These emissions could then be used to offset fossil fuel emissions from other harder-to-decarbonise sectors (DECC et al., 2012a: 41). Put more explicitly: such negative carbon emissions could reduce the cost of low-carbon energy supply because we could go on using gas, possibly even using coal, and balance it out with CCS' (interview, DECC, 14.08.12; cf. ETI comment at bioenergy workshop, 20.11.12). Thus optimistic expectations for BE-CCS complement longer-term dependence on fossil fuel within current centralised infrastructure, regardless of whether or when BE-CCS materialises.

Conclusions

Let us return to the main question posed earlier: How do expectations for future technology mobilise resources for some innovation trajectories rather than others? This paper has shown that UK bioenergy innovation has been locked into current energy infrastructure through technological expectations, especially the reciprocal requirements of state bodies and industry.

The technological expectations literature generally analyses how innovators seek support for a specific technoscientific pathway by raising expectations, thus generating a promise-requirement cycle, with requirements to demonstrate technical progress and/or raise new expectations. By contrast, our case study has focused on technological expectations within a wider policy framework: For its renewable energy and GHG targets, UK bioenergy policy depends on future expectations for bioenergy innovation, though not on any specific pathway. The paper has analysed state-industry reciprocal dynamics: having raised innovators' expectations, state bodies face requirements to make long-term commitments for support measures.

By accommodating industry proposals, UK state bodies have promoted expectations that bioenergy innovation generally will help to fulfil targets for GHG savings in environmentally sustainable ways, among other societal benefits. These promises have been turned into requirements for industry to demonstrate technical progress, as well as for state bodies to make long-term commitments for support measures. Within those reciprocal dynamics, tensions have arisen among different policy aims, energy futures, innovation pathways and expectations for their benefits.

In particular state bodies have undergone various tensions among aims: first, how to incentivise industry and prioritise state R&D funds, while justifying these measures as necessary to fulfil several policy aims, especially GHG savings; second, how to make long-term commitments as incentives for industry investment, while leaving open future options which may be more environmentally sustainable; third, how to prioritise and justify innovation pathways as a 'low-carbon' future, especially in relation to current high-carbon infrastructural patterns of energy production and use.

Those tensions have been contained through technological expectations for bioenergy innovation in general, while ostensibly keeping open future options for state support and commercial development. UK policy language disavows any role in ‘picking winners,’ while attributing innovation choices instead to the market or technoscientific progress, as if they were external factors. Yet some potential futures have been favoured by new institutional arrangements, alongside policy documents drawing on expert reports.

Such arrangements closely link state bodies with industry, together seeking to de-risk R&D investment. UK Research Councils have offered a great influence over priorities to companies co-funding R&D. Company representatives mainly comprise the government’s Technology Strategy Board, in turn influencing R&D priorities. Large energy companies co-fund near-market technological scale-up as means to minimise or share financial risks in commercialising technoscientific results.

Although those arrangements disperse decision-making across various state bodies, consequent support measures have followed a common pattern: specific innovation pathways envisage bioenergy mainly as input-substitutes within dominant high-carbon centralised systems. State bodies have framed expectations for societal benefits according to those priorities. Although technical progress has encountered difficulties and long delays, expectations for economic benefits have helped to mobilise resources, while conflating national benefits with private-sector interests. Such expectations favour measures de-risking some potential innovations rather than others.

From those expectations, CCS has gained support as a necessary means to turn high-carbon systems into low-carbon ones. Even when more biomass substitutes for coal

inputs via co-firing, however, bioenergy-CCS will reinforce current infrastructure for electricity-only coal plants within centralised electricity systems. Moreover, ‘carbon-negative’ CCS is expected to offset GHG emissions from fossil fuels, thus reinforcing and justifying long-term dependence on high-carbon energy sources.

As regards the three longer-term ‘hedging options’ in the *UK Bioenergy Strategy*, expectations inform priorities as follows:

1. Biohydrogen: For the past decade, government policy has promoted hydrogen fuel cells as the preferable alternative to the internal combustion engine. This alternative is foreseen as even more environmentally sustainable if using biomass inputs for biohydrogen. But this pathway would require new infrastructure and perhaps undermine the dominant one; it has gained relatively less financial support for R&D.
2. Advanced biofuels: These have been strongly promoted for several aims – to build on UK technoscientific strengths, to gain intellectual property from those strengths, to avoid the ‘fuel versus food’ conflict and to avoid a lock-in of conventional biofuels. Yet any biofuels, especially the search for ‘drop-in fuels,’ reinforces the internal combustion engine and thus dependence on liquid fuels.
3. Gasification: This technology has been promoted for its economic benefits and flexible links with several other pathways. In particular, biowaste-to-energy conversion would turn an environmental burden into an asset. Yet gasification readily complements centralised infrastructure and is being envisaged along such lines.

Although UK policy documents mention several desired futures, only some are wishfully enacted by mobilising resources. These priorities complement broader policy assumptions as follows: Cost-effective, GHG reduction depends on inherent efficiencies of large-scale systems. National economic benefits arise from large companies selling novel technology or patents abroad, or with large-scale infrastructures maintaining or creating employment, or with research institutes competing against each other for foreign investment. GHG savings should not depend on behavioural changes, so input-substitution remaining invisible to consumers will be politically more reliable. These policy assumptions manifest a more general socio-technical lock-in of energy systems.

Thus technological expectations complement a path-dependent reinforcement of dominant infrastructures. This role has historical analogies with earlier technoscientific innovation. As Edgerton (2006: 210) put it:

Calling for innovation is, paradoxically, a common way of avoiding change when change is not wanted. The argument that future science and technology will deal with global warming is an instance. It is implicitly arguing that, in today's world, only what we have is possible.

By contrast to that foreclosure, government policy also has promoted expectations for bioenergy to decentralise energy systems along with community involvement. But such pathways have remained marginal in support measures. To realise those potential futures, state bodies would need stronger involvement of actors such as SMEs and local public-sector authorities.

In conclusion, this paper has analysed reciprocal requirements of state bodies and industry within technological expectations, while linking these with path-dependence, thus enriching both analytical perspectives. Through UK state-industry arrangements, technological expectations mobilise financial support for novel path creation within a fundamental path dependence. UK bioenergy strategy mentions efforts to avoid lock-ins, yet only some are explicitly called lock-ins. A fundamental path dependence is implicitly accepted by default, or is even sought as beneficial – as accommodating current energy infrastructures and consumption patterns.

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