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Spaces for sustainable innovation: Solar photovoltaic electricity in the UK

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ABSTRACT

This paper engages with recent research concerning the roles of niche spaces in the strategic management of sustainable innovations. Whilst a growing body of empirical investigation looks to developments within these spaces, it is surprising how little pauses to consider how the spaces themselves develop over time, what constitutes these spaces, and how their characteristics influence sustainable innovation. We explore such questions through a case study into the history of solar photovoltaic electricity generation over the last 40 years in the UK. Whilst we see evidence consistent with recent ideas about niche spaces shielding, nurturing, and empowering sustainable innovation, the main thrust of our analysis concludes that this arises in contested and compromised ways. Moreover, our analysis identifies niche space developing through the political ability of technology advocates recursively interpreting, representing, and negotiating between the content and contexts of innovation.

1. Introduction

After decades of fitful support and development, the generation of electricity from daylight using solar photovoltaic systems (PV) recently underwent a boom in the UK. Installed PV capacity grew from 26.5MWp in 2009 to 594MWp in 2011 [1]. Growth was underpinned by an above-market price guarantee for solar electricity, regulated through a Feed-in-Tariff (FIT) policy introduced by the Labour government in April 2010.

Rapid uptake under the FIT 'subsidy' alarmed the newly-elected (May 2010) Conservative-Liberal Democrat government. Influential sections of the mass media were becoming critical about 'green taxes' on rising energy bills during a time of economic difficulty. Concern reached such a pitch that Secretary of State for Energy Chris Huhne announced early, unscheduled tariff reductions and a general review of the FIT system. In response, a coalition of PV firms, installers, politicians, and PV investors (including households, community groups, and businesses) mounted a campaign to resist the proposals. All parties agreed PV costs were falling — thanks to cheaper components, learning and scale economies, and competition amongst installers. But projected trends were contested. Debate centred on what depth, timing, and character of FIT reform was reasonable, based upon different assumptions about the prospects of PV development in electricity systems and markets whose future structure was also uncertain.

Government cuts went ahead, but less sharply than originally envisaged. In the interim however this controversy cast uncertainty over PV development. Despite media-reported cost concerns, PV remains a popular technology in public surveys[1] and as evidenced by the take up of the FIT. In response, the Department of Energy and Climate Change (DECC) "appears to be bowing to general pressure from industry and NGOs" [2]; and in May 2012 government announced their updated Renewable Energy Roadmap will include solar PV, and that up

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[1] A survey of 2121 representative households by the Department of Energy and Climate Change in March 2012 found 83% support for solar (DECC, 2012).

to 22GW by 2020 is an 'achievable ambition' (DECC 2012, Press Notice 12/066). This is in stark contrast to positions prior to the FIT controversy, which made no specific provision for PV.

This episode reminds us that political debate about the roles and performance of technology are important for their future development [3]. In this paper we analyse how shifting debates over more than four decades about PV technological prospects helped open up (or close down) the 'spaces' available for PV innovation in the UK, and how the characteristics of those spaces influenced the developments that arose (and whose consequences were drawn upon in subsequent debates).

In analysing PV in this way, the paper engages with salient ideas about 'niches' and 'protective spaces' in the research literature on innovations for sustainable development, i.e. innovation with the potential to contribute towards more sustainable systems of production and consumption (section two). We suggest an approach that subsequent comparative research can use to address more general theoretical issues about the social construction of 'protection' in the research literature on 'strategic niche management' for sustainable innovation [4][2].

Our paper consequently addresses the following questions:

1. How did PV develop in the UK over the last four decades?
2. What implications can be drawn from this study for better understanding the dynamics of spaces for PV innovation?

Section two elaborates the background theory regarding niches for sustainable innovation, and elaborates our analytical interest in protection and PV development. Section three explains the methodology we used in studying PV. Section four presents our results in the form of an historical account of the development of PV in the UK. This is followed by analysis in section five about protective niche spaces and PV innovation, including a discussion on generalizability. Conclusions are drawn in section six.

2. Theoretical background: spaces for sustainable innovation

The innovation systems literature attributes innovative success to an ability of firms, policy-makers and others to link systematically knowledge, capabilities, resources, and markets [11]. Any successful innovation milieu – whether national, regional, sectoral, or technological – is explained by the forming of systems [12–16]. But what happens when neither policy nor commercial interest exists in building effective innovation systems? What strategies are available to aspiring technology developers who are weak, not well connected, and who fail to dislodge vested interests? How do innovations that are promising from the perspective of societal goals, such as sustainable development, develop in situations where those expectations are neither widely shared nor institutionalised amongst investors, policy-makers, and markets? Such was the situation for PV in the UK for decades. The short answer to these questions is that the innovation will fail because a system cannot develop — as diagnosed for PV in the Netherlands [17,18].

But perhaps this answer is too hasty? Even successful innovations suffer difficult periods; whilst 'hopeful monstrosities' can struggle for decades [19]. A second literature in sustainable innovation – strategic niche management – draws attention to the construction of 'protective spaces' where sustainable innovation can be initiated in the absence of fully-developed systems [20]. However, analytical attention tends towards technology development *within* niche protective spaces, and under-investigates *the provision of protection itself* [7]. Our approach to studying PV in the UK here is to address this neglected provision of protective space.

2.1. Spaces for sustainable innovation

Strategic niche management notes repeatedly show technologies that are promising on the grounds of environmental (and social) sustainability, can nevertheless be at a distinct disadvantage in the context of incumbent technologies and their associated institutions (including markets) and infrastructures. The development of the latter arose without sustainability finding full expression in more powerful economic and other criteria. In evolutionary terms, incumbent systems, such as large-scale, centralised, fossil-fuel electricity generation, constitute more structured and structuring 'socio-technical regimes' that present unfavourable selection environments for sustainability novelties like PV. As such, strategic niche management argues sustainable innovations need 'niches' in which to develop initially. Niches are defined in the literature as 'protective spaces' where real world experimentation and development of sustainable technologies can take place and supportive constituencies can be built [6]. Niche protective spaces shield the innovation against premature rejection by incumbent regime selection pressures, until the innovation is proven to be sufficiently robust to compete and prosper in unprotected market settings [5,6].

Market niches have long been recognised as providing limited yet commercially viable opportunities for technologies to find customers willing to pay (typically higher) prices for the new technology (and whose performance is usually poor compared against customary criteria of incumbent technologies). Here, we might think of green electricity consumers willing to pay higher prices for solar photovoltaic electricity, compared to the lower prices of conventional power stations. However, strategic niche management argues that in the case of sustainability, 'technology niches' need to precede or augment market niches. Technology niches are deliberately created protective spaces that seek to improve a cleaner technology through processes of social learning, expectation development and networking, so that its chances of diffusing (via market niches) into wide-spread, application are enhanced [6]. In addition to the support that users and suppliers give to niche technologies, public policy measures such as product subsidies, investment grants and preferential treatment in legal frameworks are mentioned as ways to intentionally shape technological niches.

[2] This paper is part of an ongoing ESRC-NWO research project in which solar PV is compared with off-shore wind energy and carbon capture and sequestration in the UK and the Netherlands. Hence, PV in the UK is the first case study in a series of six. Pointing to the construction of protective niche spaces in this way extends the policy considerations of 'strategic niche management' to include the conditions for its own implementation (though this is beyond the scope of the paper here).

Given this emphasis on *protective* spaces, it is surprising that the foundational concept of *protection* has received little systematic attention in the literature [7]. In her study of the PV niche in the Netherlands, for example, van Mierlo takes provision of demonstration projects as given (i.e. a protective space), because she (typically for the literature) focuses on learning processes and networking across demonstrations and their development consequences [10]. In other words, the space is presumed and only PV development kept in focus. Even responses to criticism from Hommels et al. [8, see 9], about the disadvantages of protection in innovation, have not prompted serious reflection about how protective spaces are constructed, who is involved in their construction, nor how the characteristics of protection affect the development of innovations for sustainability, and vice versa.

The analysis of PV below identifies protective spaces as constituted recursively through discursive and material activities: coalitions of PV actors construct narratives[3] in an attempt to draw attention and material resources towards potential sites of action for PV development, such as R&D programmes, industrial development strategies, building-integrated application of PV technologies, or developing country rural electrification projects (section four). The material consequences arising from these sites of action underpin (or undermine) subsequent narrative claims, and thus the spaces available for further PV development. The case of PV draws attention to the way constructing protective spaces iterates between innovation *contents* (socio-technical performance of PV) and innovation *contexts* (developments in incumbent energy systems and the wider social world of PV). It reveals how estimates and assumptions about developments in the technology and projections about its future, such as PV cell efficiencies or projected price reductions along learning curves, connect to debates about present-day and future electricity systems and markets, and with assumptions about the wider social world in which the technology might operate, such as future outcomes of climate change negotiations or industrial opportunities, or the creation of jobs.

Studying PV in Germany, Jacobsson et al. [21] demonstrate how an innovation system evolved through researchers, firms, lobbyists, environmentalists and politicians securing from the state first research programmes, then industrial policy, and later market deployment policies. Actors, networks and institutions forged a functioning system capable of: creating sufficient knowledge about photovoltaic materials and electrical systems; focusing direction for the development of promising applications; supplying capital and other resources, such as skills; creating positive network externalities to attract new entrants; underpinning market formation with tariff protection and regulatory frameworks; and incentivising entrepreneurship. In other words, PV innovation was not limited to technology development, but to the development of a broader socio-technical configuration [6].

What is striking about the study is how much work PV advocates had to dedicate to aligning their innovations with contextual conditions over time, and especially the political processes involved in such alignments. The study notes the significance of public policies in initiating, maintaining and expanding PV innovation in contexts otherwise dominated by the interests of actors in the centralised fossil-fuel electricity regime [22]. Indeed, Jacobsson et al. conclude (p.24; emphasis added):

> '[N]ew technologies need to be given a 'space' in which a learning process can take place. This space cannot be created by technology policy alone but requires measures designed to form markets in order to induce firms to enter into various points in the value chain … policy makers need to expand this space in order to strengthen the process of cumulative causation (e.g. induce even more firms to enter), and have the patience to maintain this *growing space* over an extensive period of time in a context where vested interests challenge the relevance of such support.'

Alliances had to be forged with advocates of other renewable energy technologies, and lobbying focused on the state in order to institutionalise policy measures that would encourage and help firms to develop PV. The policies were legitimised through arguments about wider social and economic goals that chimed with German political and economic contexts for energy (including concerns for energy security, addressing climate change, an alternative to nuclear power, and creating jobs) [23]. More recently, competitive pressure from Chinese PV module manufacturers, and lobbying from interests vested in other energy technologies is requiring renewed work on PV legitimacy.

2.2. Shielding, nurturing and empowering strategic niches

Strategic niche management emerged with a specific concern for the provision of spaces for sustainable innovation. In a recent review, Smith and Raven argue that effective protective spaces facilitate three important processes [7]. First, spaces *shield* against prevailing selection pressures (see also [24]). Shielding involves both the exploitation of relatively 'passive', pre-existing situations – such as the opportunities for PV in remote off-grid locations – or more pro-active shielding through deliberate policies that counter selection pressures, like the Feed-in-Tariff intervention in electricity markets.

Second, protective spaces also contribute to *nurturing* processes, which have become the focus in the literature [25] due to their immediate roles in socio-technical system building. Case studies indicate nurturing requires [see 25 for a review]: a) positive expectations that are robust (shared by many actors), specific and credible (substantiated by multiple projects); b) social networks that ensure support is broad (plural perspectives) and deep (substantial resource commitments); and c) social learning processes that not only accumulate facts, data and first-order lessons, but also generate second-order learning about underlying assumptions and values about an innovation and its application.

Drawing upon the theoretical literature, Smith and Raven [7] propose a third set of *empowering* processes next to shielding and nurturing. These take two distinct forms. The first form involves the niche innovation becoming competitive under prevailing selection environments: it is able to *fit and conform* into incumbent regimes. A clear example is the rapid cost price reductions in PV modules resulting from improved production processes, economies of scale and

[3] Narratives are stories expressed in various forms of texts, images and speech that try to account for events, developments and consequences in a meaningful way.

learning in the installation of PV systems, and improved PV module designs. Any legitimate need for protective space falls away, and the PV technology can compete in relatively open markets. The second form of empowerment involves protective measures influencing reforms to prevailing selection environments: the niche innovation is able to *stretch and transform* incumbent regimes. Measures constituting niche protective space become institutionalised into a reformed regime, including re-structured markets (e.g. that internalise environmental costs). Smith and Raven argue this latter empowering involves actors in processes that are *outward-oriented* (relative to the niche protective space) towards lobbying and change in the wider social world, compared to the *inward-oriented* processes of nurturing for competitiveness to improve competitiveness on conventional terms.

2.3. Constructing and contesting protective spaces through narratives

Conceiving protective space as functional to the development of sustainable innovations, and that ought to shield, nurture and empower them, appears reasonable from a strategic managerial perspective [27,28]. However, this downplays the socially constructed, and hence political, characteristics of opening spaces for sustainable innovation. The construction of protective spaces for sustainable innovations is likely to encounter confounding situations and actors with differing opinions [29–31]. Analysis is required that explores the negotiation, bargaining and compromises over spaces for sustainable innovation [32,33].

A relevant line of inquiry is offered by Law and Callon, who consider how technology advocates deploy narratives that recursively negotiate relationships between the context for a technology project and the content of the project [34]. The question becomes one of how PV advocates try to take arguments about past performance, the development realities currently, and future prospects, and connect them to contextual developments in incumbent energy regimes and broader socio-economic contexts. It suggests niche-building actors (a sub-set of technology advocates) are involved in the outward-oriented representation and negotiation of PV in the wider social world (cf. inward-oriented accumulation of knowledge across networks of projects). Narrative work tries to create opportunities through interpretations of technological contents in dynamic contexts that can be turned into material measures of support for PV development. An example here is the narratives around the creation of jobs resulting from PV industries, which in times of a global economic crisis may appear relevant to political decision makers. The political dimensions of these processes become apparent when we recall that the development, validation and recruitment of other actors to favourable narratives contends with competing narratives about other niche technologies, as well as with more widely accepted narratives in incumbent regimes of what constitutes reasonable techno-economic performance.

Reflecting on experience with PV in Sweden and Germany, Bergek and colleagues emphasise how arguments about the performance of a technology is important for the provision of spaces for its development [35]. In particular, they note how technology assessments play a key role in these arguments (see also, [36]). Increasing support of, and agreement amongst diverse actors about, assessment procedures helps ensure more robust, accountable, and persuasive narratives. Assessments with broad appeal mobilise support and policy behind the technology and hence open the space for its development (p.583).

Bergek et al.'s conclusion echoes Callon and Law [34]. All argue the negotiations in assessment processes are one form of a broader set of narratives used to provide a critical interface between the content of an innovation and the contexts that shape it [37]. So in turning to our PV study, we wish to explore whether and how protective space arises through the narrative work of actors negotiating between the contexts and contents of PV development [38], and whether this work shields, nurtures and empowers further PV development.

3. Research methodology

We adopt a qualitative case study methodology in order to answer our research questions. Longitudinal case studies have become a standard approach to the study of socio-technical transitions, where variables change qualitatively as well as quantitatively and where the aim is to trace processes of transformation, see for example [39–42] and other empirical papers in special issues of Technological Forecasting & Social Change 79(6), 77(8), 76(2), 72(6)). The attraction with this methodology is the way it permits contingencies to be set against more systemic forces, and bringing to the fore the concrete, context-dependent knowledge in which plural actors try to make sense of and participate in complex processes of change [43–45]. Our methodology follows Flyvbjerg's information-oriented and paradigmatic case selection for the testing and development of theory [46,47].

We followed Dilley for making 'context' empirically operational:

> "A phenomena is connected to its surroundings: contexts are sets of connections construed as relevant to someone, to something or to a particular problem, and this process yields an explanation, a sense, an interpretation for the object so connected. The context or frame also creates a disjunction between the object of interest and its surroundings on the one hand, and those features which are excluded and deemed as irrelevant on the other [48: 2]."

However, given the constructivist theoretical background we are drawing upon, i.e. the negotiations between innovation content and contexts, and similar in approach to Asdal and Moser, we were interested how 'contexts' were construed and articulated by institutionally-embedded actors, rather than us as analysts [38]. It is the various actor understandings of the energy system environment and wider social world at different points in time that interest us, and the way actors related this to spaces and processes for developing PV. As such, our purposeful selection of actors was based on proximity to and knowledge of PV developments in the UK (see below), including those with long-standing overviews, rather than randomised samples [49]. Interviews were used to trace the PV process, and corroborated with other data, rather than randomly selected in order to generalise to a population.

Given the long time-frame involved in our study, and the many sites of PV development over that period, it is impossible to present a very fine-grained reconstruction of multiple, individual actor-centred positions and contexts in a paper. We consequently took a more pragmatic approach that has tried to reconstruct key periods in the history of PV where the evidence suggests a general consensus over the prevailing contexts, and where it has been possible to identify several strategic responses or development activities amongst key actor groups in each period, such as technology advocates, policy-makers, research organisations, environmental NGOs, technology users, and politicians. The results are presented in section four.

We reconstructed this history through the triangulation of multiple sources of evidence. First, drawing upon grey literature and the (limited) research literature relating to PV development in the UK over the last forty years, we developed a working time-line of key developments in terms of activities such as demonstration projects, policies, technology assessments, key actors, actor statements, conferences, and research programmes. Second, using secondary literature on the history of the UK energy system more generally, including recent developments, we developed a good working knowledge of the broad contexts within which PV was situated over the same period. Third, identifying key periods of relatively intensive activity, we undertook a deeper search for key documents contemporary to that period and identified potential interviewees with first hand experience. This deeper analysis drew on scientific publications, industry documents, government reports and policy reviews; public data on deployment and R&D investments; and interviews with 14 key stakeholders involved in the development of PV in the UK (see Appendix A).

Interviews were in-depth and semi-structured, beginning with personal histories and roles in the development of PV, and then questions about energy contexts and spaces for PV development in the past, in order to try and assist with interviewee recollections, before moving to more specific questions about PV advocacy and activity. These more specific questions, adapted to the respondent and guided by their viewpoint, included the roles of pioneering installations, the conditions of their development, policy developments, broader events of significance to PV at the time, and other questions that provided multiple routes into the issue of understanding the dynamics in protective spaces for PV. Interviews were transcribed and coded using a qualitative data analysis software package. Open-ended coding on the basis of emerging themes was combined with codes predefined on the basis of theoretical concerns, e.g. evidence for shielding, protection, and empowering, or statements favourable to or challenging a specific context. These were triangulated against further interviews and documentary analysis for corroboration. Documents were also interpreted carefully on the basis of author positions, intended audiences, and contexts of production; and interpreted and discussed amongst research team members both for within-case validity and in comparison with the literature (section two). Points of doubt and uncertainty were returned to and the evidence interrogated afresh until we achieved stability in our historical account of the development of PV in the UK [47,50].

4. Results: PV development in the UK

Consistent with discussion so far, the results of our study provide an historical account that traces PV developments, protective spaces, contexts and narratives from the perspective of different actors involved in the technology [38]. Our history is punctuated into overlapping periods that approximate to qualitatively different mobilisations of context by PV advocacy, and associated developments in the PV content in the UK. In this way we explore how PV spaces related to those contexts, and how narratives generated shielding, nurturing and empowering processes (or not).

4.1. Alternatives to energy crisis — but limited opportunity in the UK

Whilst the research, development and use of PV electricity can be traced back to space satellite programmes [51,52], exploration for its terrestrial potential began in earnest after the energy crises of the 1970s. PV was amongst a portfolio of ambient energies being investigated. The new Department of Energy launched a UK renewable energy programme in 1974. Its advisory agency, the Energy Technology Support Unit (ETSU), undertook desk studies to assess the viability of different renewable energy technologies. They concluded PV was not relevant to the UK [53,54].

While other countries, notably the US and Japan, invested public funds into PV research and development (R&D), the UK government provided little funding (see Fig. 1)). ETSU's technology assessments, based on lab-based conversion efficiencies of PV *materials* and estimated engineering costs of scaled-up *modules*, underpinned the UK government position. Advocates maintained that methodologies developed for large, centralised power systems introduced bias against the potential of PV in decentralised systems — a theme that recurs to the present day [55,56].

Government R&D budgets funded "a small programme of work on solar cells because it recognised that they had major export potential" [54: 34]. Over a dozen universities began investigating solar PV (interviews 2; 3; 9; 11). These funds soon stopped (see below), and PV research had to proceed indirectly through materials science research grants and discretionary university funds. Researchers recall: “If you wanted to get a solar proposal through the research councils, you shouldn't mention solar cells anywhere in the bid. You should refer to light sensitive devices because solar was seen as irrelevant” (interview 3). “[Funding] only went into panels and materials science, never into R&D into the engineering of the system” (interview 9).

Whilst disappointed, PV advocates were undeterred. A UK section of the International Solar Energy Society (UK ISES) was founded in 1974 and had over 300 members within a year. High-profile conferences were organised on both solar thermal and solar PV [57]. PV associations and research teams began marshalling evidence (including from PV programmes overseas) and making a case about PV potential in the UK, e.g. solar incidence data, cell efficiencies, and electricity potential.

Slight commercial interest came began in 1975, with Lucas Aerospace selling US solar cells [56], for low-power applications in remote, off-grid locations, where the economics were viable. Applications included monitoring and control devices in the gas, electricity, meteorological, water and telecommunications sectors [52: 372], and niche markets in cathodic protection of pipelines, as well as power for yachts, caravans and remote communities (interviewees 2; 11; 12). There was sufficient activity for a Solar Trade Association to be

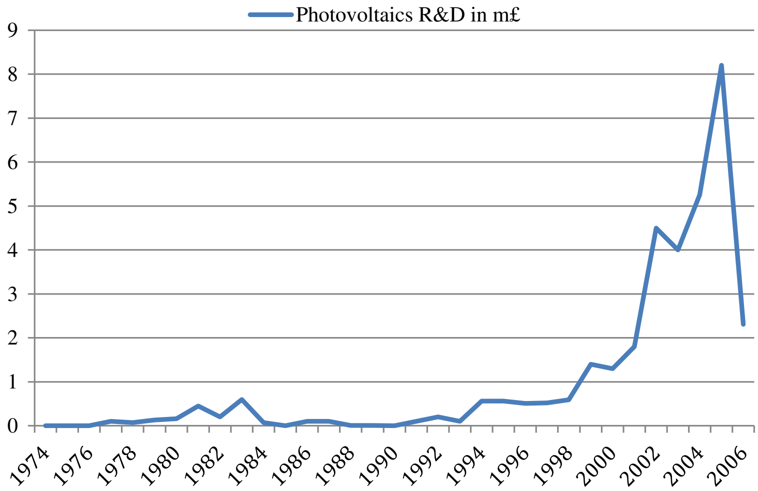

Fig. 1. Public R&D investment in PV in the UK in m£.
Source: own illustration, based on data from IEA (no data available from 2007 onwards).

established in 1978, though most trade was in solar water heating rather than PV. Some remote PV applications were attractive for oil company installations. Oil firms began investing small amounts in the technology (with the additional advantage of widening energy portfolios in ways helpful for public relations). BP opened a research lab at Sunbury, where 25 staff investigated different cell materials by the mid-1980s. BP bought Lucas' PV business in 1980, only to be sold-off in later years: a pattern of take-up and disposal that was to become typical. Solar remained very marginal compared to core investment and technological competences.

Some environmentalists experimented with very small, off-grid PV systems with batteries; and PV development remained part of the environmentalist narrative [58]. PV was envisaged operating alongside other small-scale renewable energy technologies under the control of 'low energy' communities. A nuclear-free, decentralised 'soft energy' future was contrasted with a securitised, centralised 'hard energy' dystopia [55]. The Centre for Alternative Technology (CAT) commissioned experts in renewable energy to develop an Alternative Low Energy Strategy for the UK in 1977 (and endorsed by the Astronomer Royal) [59]. Their report intended to be as technically proficient as an ETSU assessment, but informed by a different framing of priority parameters. Despite its scientific credentials, government ignored the strategy. Any space for arguing energy alternatives narrowed considerably with the discovery and opening of North Sea oil and gas. This removed energy security from the political and economic agenda, as the UK became an energy exporter in the 1980s.

Nevertheless, a collection of advocates and activities had emerged, and occasionally networking, e.g. through conferences. Within this space were a few PV installations for off-grid applications. Government remained dismissive. Official assessments used engineering cost-performance criteria typical for the larger, incumbent electricity generating technologies, and against which PV compared badly. ETSU analysis was a key gate-keeper to public support in this respect. Its conventional assessment methodology ruled out the broader narratives of environmentalists. Alternative appraisals, like that by CAT, exerted no influence beyond the environmentalist milieu. There was little scope for significant practical activity moving beyond the laboratory. All advocates could do was be hopeful and keep abreast of PV developments elsewhere.

4.2. Privatisation and liberalisation — but limited opening up for PV

The situation did not alter drastically over the 1980s. The Thatcher governments were hostile to public support for industries and technologies generally. Funding for renewable energy R&D was cut. Falling and relatively low oil and gas prices – and tax revenues from North Sea exploitation – diminished interest further. Two events dominated energy policy. First, a year-long miners' strike in 1984. This symbolised a more general cleavage in social and political ideas for the country. The miners were defeated, as was the political left, consolidating the government's neo-liberal agenda. Pit closures, that sparked the dispute, reduced the role of coal in UK electricity.

The second process was privatisation of the gas and electricity sectors. Government policy left energy to markets set by new regulatory institutions [60]. The privatised utilities turned to gas-fired electricity for new generation capacity over the following decade and cut in-house R&D [61]. These two events were a major preoccupation for government. They left little room for considering renewable energy (especially PV).

Occasional ETSU assessments continued to inform government. The view prevailed that "photovoltaic devices for power generation are unlikely to make a significant contribution to UK energy requirements, although there may be a limited market for specialised applications" [54]. PV remained a 'long shot' [R30, ETSU; cited in [62: 41].

Table 1
Pioneering PV projects in the UK.
Based on: [42,52; as well as interview evidence].

Project (year)	PV system installed	Actors involved	Funding
Marchwood (1984)	First grid connected PV installation in the UK (30 kWp)	CEGB; BP Solar	EC
Oxford Solar House (1995)	4 kWp fully integrated PV roof on domestic house; grid connected	Enthusiastic academic from Oxford Brookes University; BP Solar; CAT	Mainly privately funded by home owner; some funding from DTI
Northumbria University (1995)	40 kWp integrated PV façade; at the time largest installation in the UK	Northumbria University; BP Solar; IT Power; Ove Arup; Solapak	EU THERMIE (40%); DTI (9%); Northumbria University; Greenpeace; Northern Electric; Newcastle building society
Centre for Alternative Technology (1995)	12 kW roof integrated system	CAT; environmentalists	DTI
Doxford Solar Office (1998)	73 kWp building integrated system	Northumbria University; David Lloyd Jones; Schüko	DTI
Ford's Bridgend manufacturing plant (1998)	94.5 kWp system retrofitted to roof of automotive manufacturing plant	Ford; BP Solar; Ove Arup	Ford; EU Thermie; DTI

Nevertheless, some PV activity persisted. Work on low-power off-grid applications expanded through rural aid programmes to developing countries. Specialist engineering consultancies like IT Power worked with module providers like BP Solar and Solarpak in developing country installations. While physically distant from the UK, the projects provided further space for demonstrating PV systems-design capabilities and networking between PV practitioners, in addition to the small PV systems installed in the UK.

4.3. Opening space through demonstration programmes

Installed PV capacity in the UK was only 0.1MWp in 1992 (Dukes – Digest of UK Energy Statistics). However, UK membership of European Community research programmes changed the space for PV in the 1990s. The EC/EU THERMIE programmes[4] in particular supported a number of demonstration projects for building integrated, grid-connected PV systems (see Table 1)). Several UK partnerships bid successfully to these funds. They included IT Power, the Centre for Alternative Technology, BP Solar, all with track records in PV, but also brought in architects, building developers, and engineering consultancies like Ove Arup. Demonstration moved PV assessment from laboratories and desk-studies into real UK situations. PV advocates finally had a second opening to work on, compared to lobbying arbitrated by ETSU energy assessments.

ETSU appraisals began to reflect different socio-technical configurations of PV, and found some were promising (interview 3). Rural off-grid applications were deemed limited, given the extent of grid connection in the UK. Large solar arrays generating significant power in dedicated stations continued to be considered unrealistic. Government reconsidered PV (ETSU-R-50) and found most promise in the distributed generation of electricity from building integrated PV [53]. In all cases, public funds were needed. The government contributed funding to THERMIE projects to enable further monitoring [53: 116].

In enrolling architects, built environment professionals and planners, demonstration projects expanded the diversity of actors involved in local PV networks. Assisting and benefiting from this process was a widening in variety of narratives for PV. New narratives re-cast the economic (and political) potential of PV. Advocacy became more plural, opening up an interpretative flexibility [63] towards PV that linked it to salient discourses about environment, jobs and greening the economy.

4.4. Climate change and ecological modernisation creates space for PV

PV was also being re-considered favourably elsewhere. The US and Japan had been developing PV for some time, and Germany was beginning to invest too. The German city of Aachen pioneered the Feed-in-Tariff in 1994, which spread across the country. Intensive lobbying from industrial interests in PV (including Siemens) prompted the German SPD-Green government to adopt a 100,000 roofs programme in 1998 [64]. Industrial policy in these countries expanded the manufacturing base for PV. Module and component costs fell.

Manufacturing and markets overseas furnished UK advocates with another narrative. Whilst UK universities retained PV-relevant materials science capabilities, any UK PV sector risked falling further behind without policies to capitalise on this expertise. A Technology Foresight panel for energy, undertaken by the government's Office of Science and Technology, listed 'photovoltaic power generation … via development of thin film materials' as a priority opportunity for the UK. The panel rated building-integrated PV the highest renewable energy topic. The panel stressed the global export potential as 'attractively large' [65].

Others saw similar 'ecological modernisation' themes resonating with increasingly salient climate change goals. Over the course of the 1990s, Greenpeace had been increasingly campaigning along solutions-oriented goals for new green industries (interviewee 4). PV was adopted by them as a hi-tech exemplar fit for their purposes. Greenpeace brought professional campaign capabilities to the promotion of PV.

However, any industrial policy rationale for supporting PV jarred with neo-liberal commitments in government. Several

[4] The Programme for the promotion of energy technology in Europe (Thermie) ran from 1990 to 1994 and had funding of €350 m. It was followed by Thermie 2 which ran from 1995–1998.

interviewees confirmed that in the UK state policy was about generating electricity at lowest cost, not building industries:

> 'In Germany apart from security and climate change, industrial policy was key for PV. In the UK programme the balance was much less on that and more on how can we secure a component of our supply coming from renewable at a lower cost.' (interviewee 13).

> 'Germany has seen huge benefits regarding jobs, businesses, avoided environmental costs, avoided energy costs because of PV. UK policy makers just don't see these benefits' (interviewee 8).

The government's sustained opposition, justified on cost per kWh or cost per tonne of carbon saved, underscored just how dominant were static, short-term and narrowly framed cost-benefit considerations. Ideas about the ecological modernisation of industry, as argued by Greenpeace and others, had little traction with UK policy initially. And yet, industrial policy elsewhere was reducing the costs of imported panels through global economies of scale.

Meanwhile, the increasing political prominence of climate science provided a change in context with renewed impetus for renewable energy in ways similar to energy security before (e.g. interviewee 9). In May 1997 the Chief Executive of BP America, Lord Brown, accepted the possibility of climate change and saw solar PV as having a bright future: "I am convinced that we can make solar competitive in supplying peak electricity demand within the next ten years" (NATTA RENEW newsletter July-August 1997). Lord Brown pledged to "increase investment in solar from $100 million to $1 billion a year" [66: 5]. For PV advocates this 'was a real enforcement … [BP] made it respectable for big companies to invest in solar. It opened up the investor market and gave credibility' (interviewee 11).

Much later, in 2004, Sharp started producing solar panels in Wrexham, Wales. A 20 MW per year production line was set up initially, increasing to 500 MW and employing 1100 people by 2011 (interviewee 3). Whilst expansion was based on export-market growth, this manufacturing plant nevertheless reinforced advocates' ecological modernisation narrative.

In terms of socio-technical configuration, the networks and narratives supporting solar PV were able to draw on climate change and ecological modernisation discourse. Commitment by BP and Sharp provided business legitimacy. PV was portrayed as an exciting, high tech opportunity. Whilst still resisted in government, PV advocacy began to chime for some politicians. The opposition energy spokesperson, John Battle, was sympathetic; and when Labour was elected in 1997, committed to reducing carbon emissions, Battle instigated a review of energy policy.

4.5. Energy policy reviews open limited space for PV

The new Labour government entered office committed to the development of renewable energy. Various renewable energy policy initiatives and reviews were launched, culminating in the Energy White Paper 2003 [67]. The main policy instrument for renewables deployment at that time (the market-based Renewables Obligation, RO) did not help PV, because the RO price ceiling was too low to encourage investment in PV. However, policy reforms introduced a series of grant programmes designed to help PV and other smaller-scale renewables deployment (see Table 2)).

All these schemes were over-subscribed and the funds available depleted rapidly. Installers and PV suppliers complained that a glut of time-limited grants did not help their business planning and cast uncertainty over sector growth. Some limited replenishment of funds did not really address a stop-start dynamic in PV deployment. PV advocates joined others in arguing for the introduction of a German-style feed-in-tariff as a way of providing more stable supportive space for PV. However, the government remained committed to the RO and resisted calls for a FIT.

In response, PV advocates joined forces with other small-scale electricity generating technologies to lobby the case for 'micro-generation' (generating technologies smaller than 50 kW capacity). A number of studies found potential in micro-generation [68–70]. Findings repeatedly criticised the lack of attention to and support of micro-generation technologies in energy policy and pointed to regulatory and financial barriers similar to those identified in PV demonstration programmes. What was needed, said advocates, was a strategy for micro-generation technologies.

Microgeneration lobbying bore little fruit initially. A government Micro-generation Strategy in 2006 was a disappointing document. Called 'Power from the people', it proved to be long on rhetoric but short on immediate material support for PV. A civil servant involved in the process remembered a total mismatch between the ministerial foreword, which outlined a vision in which every home in the UK should have some sort of microgeneration, and the substance of the document, which didn't specify a budget or new instruments (interviewee 7). The strategy was widely criticised for not setting targets and not containing any new instruments

Table 2
Overview of UK government PV demonstration and deployment programmes.
Source: own illustration, based on a variety of sources including [1,58,59]; ENDS; NATTA.

Name	Years	Funding provided	Total capacity installed under the scheme
SCOLAR Programme	1998–2000	£1 m	100 small PV areas for schools and colleges (2-3 kW each)
PV Field Trials Programme	2000–2006	£9.4 million	1.5 MW
Major Photovoltaics Demonstration Programme	2002–2006	£31 million	8 MW
Low Carbon Buildings Programme	2006–2010	£13.4 (only for PV)	4549 projects
Feed in tariff	Since April 2010	£36 m (FIT payments for quarter from 01.10.-31.12.11)	594.9 MW (as of Dec 2011); 144,450 installations

(ENDS Report 375, April 2006, pp. 44–45). A senior DECC civil servant involved in this policy area for some time commented (in a way revealing of official attitudes): Ministers like the idea of micro-generation. Various times it has been seen as breaking the power of the big six, bringing energy generation back into people's hands, appeals to self sufficiency. It's the 21st century version of growing your own vegetables" (interviewee 7). Whilst frustrated by poor progress, the microgeneration lobby had nevertheless recruited an active group of back-bench Members of Parliament led by Alan Simpson, who were to prove significant later.

4.6. Deepening commitments to renewable energy, and a nuclear revival

Meanwhile, other developments in energy policy and politics were once more shifting PV contexts. Nuclear power had not featured prominently in the 2003 Energy White Paper: indeed, the government stated nuclear power was 'an unattractive option for new generation capacity' [67]. The nuclear lobby embarked on a campaign to reverse this situation, successfully convincing the Prime Minister to devote time and backing for the technology; and which culminated in a controversial 2007 Energy White Paper, in which new nuclear capacity returned to a key position in UK energy policy [71]. Having moved temporarily out and now back into policy favour, new legislative arrangements were needed to reform the electricity market in nuclear-friendly ways. As will become apparent, this presented both a challenge and opportunity for what had become the micro-generation lobby, including PV.

At the same time, European Union policy commitments to renewables were strengthening under the 20–20–20 targets adopted in 2008 (20% renewable, 20% cut in carbon, both by 2020). It became increasingly clear that additional policy action was needed in the UK to meets its EU-derived target of 15% renewable energy by 2020. Civil servants within DECC were concerned that while they were working on a renewable energy strategy, the 2008 energy bill "didn't have anything new for renewables … and we knew more was needed to meet European renewables targets" (interviewee 7). Large offshore wind farms were seen as a major component in meeting the target, but as with nuclear, additional legislative measures would be needed to underpin this policy commitment.

Support from Parliament was needed for this legislation, and this provided MPs favourable to micro-generation and FIT instruments with a bargaining opportunity. Instead of suggesting to replace the RO with a German style FIT, lobbyists changed their tactics and argued for FIT to complement the RO by focusing on micro-generation technologies. A new FIT instrument would be dedicated to small scale generation below 5 MW capacity, and the RO would continue for generation above that scale. Official government resistance to dismantling the RO could be side-stepped.

In this context lobbying really built up (interviewee 7). PV advocates organised a wide ranging coalition included people from the construction industry, roofing contractors, the solar industry as well as NGOs like Friends of the Earth and Greenpeace. Our interviewees say this was crucial for success. A dedicated website (http://wesupportsolar.net/) reinforced and spread the message. Actors in the coalition deliberately included those with no self-interest, and who represented concerns wider than PV firms, such as the national federation of roofing constructors: "they were key to get FIT" (interviewee 5). A public campaign by 40–50 Labour back-benchers (led by Alan Simpson) (interviewee 5) coincided with the new minister Ed Miliband needing to pass energy legislation. A political deal was struck: the backbenchers supported the government bill for nuclear and offshore wind reforms, in return for the inclusion of FIT in the legislation. In April 2010 the government introduced a FIT for small-scale renewable energy technologies. PV prospects changed immediately.

While the different grant programmes in the 2000s had led to some PV deployment (see Fig. 2), the FIT scheme spurred exponential growth (see Fig. 3).

In its first year (1 April 2010 to 31 March 2011) the FIT led to 28,608 registered PV installations which represent 77 MW of installed capacity. PV proved to be the most popular technology under the scheme, accounting for 72% of total FIT capacity. Wealthier householders liked the 5% return on investment; FIT enabled local groups to develop PV schemes as revenue generators for other community energy activities; companies developed 'rent-a-roof' and 'free solar on your roof' offers; local councils used FIT to generate income from their property, or to benefit residents in their social housing stock; and commercial investors partnered with farmers to propose larger-scale solar arrays up to the 5 MW FIT capacity limit. Overseas PV module suppliers and installation firms quickly began opening trading offices in the UK. A PV boom was underway. Most of the installations were small scale, grid connected systems which were retro-fitted onto domestic buildings — but a few proposals for large-scale arrays were to become controversial and convenient for critics of PV.

4.7. The 'solar farm threat', 'fat cats', and how the controversy about FIT shapes the future for PV

In February 2011, less than a year after the start of the FIT scheme, the Energy Secretary of the new Coalition government, Chris Huhne, announced an unplanned review of the scheme. He said the government was concerned about larger scale, 'solar farm' projects cashing in on generous FIT price for PV[5]. Farm proposals threatened to divert funds away from household installations [72]. This argument was controversial. The first UK solar farm, a 1.5MWp scheme, received planning permission only in September 2010 (ENDS Report 428, September 2010, p. 18). While more than 95% of the FIT supported capacity was to small scale installations. Cornwall had one other application for a solar park and 26 scoping requests for projects up to 5 MW.

The unscheduled FIT review suggested the maximum size of qualifying installations should be cut back from 5 MW to 50 kW. Support for PV would be focused on domestic scale installations. Climate Change Minister Greg Barker stated: "We want to see an ambitious roll out of solar panels on Britain's roof space but not all over the countryside" [73].

[5] The FIT guarantees a generation tariff and an export tariff for 25 years for PV. The tariff levels vary depending on the scale of the installation. For PV, the generation tariff rates varied initially between 41.3p for installations <4 kW (retrofit) and 32.2p for stand-alone systems and installations >100 kW–5 MW. All were more or less halved after April 2012.

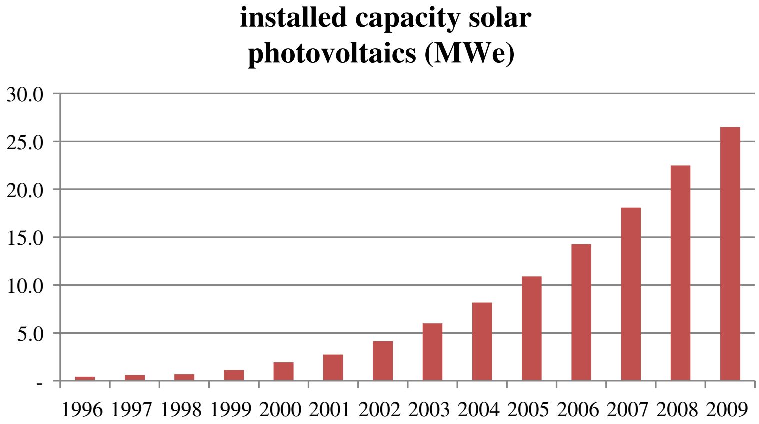

Fig. 2. Installed PV capacity before FIT.
Source: own illustration, based on data from Digest of UK Energy Statistics (DUKES).

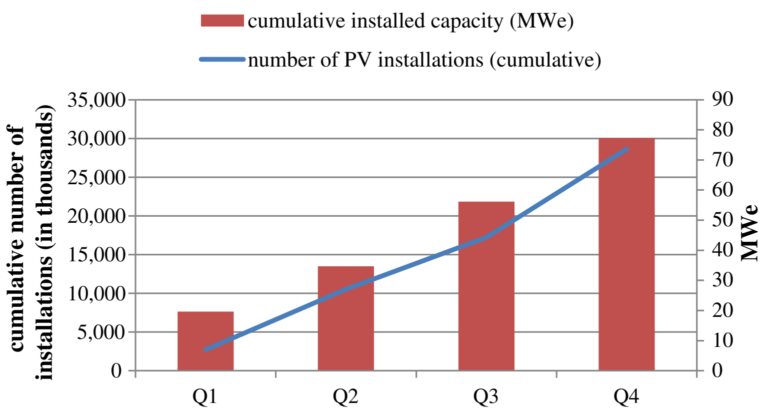

Fig. 3. New PV installations in the UK, 1 April 2010 to 31 March 2011.
Source: own illustration, based on data from Ofgem Feed-in Tariff Update, Issue 4, June 2011.

Media reports took this up and complained about ‘fat cat’ investors getting rich on FIT subsidies paid through household electricity bills.

This counter-narrative criticised the PV boom. One interviewee explained that politically, “large-scale PV … is more difficult to get acceptance because of associations with ‘gold rush, fat cats’ etc” (interviewee 5). A DECC programme manager acknowledged that the problem was “‘fat cats’ getting rich in the South of England. FIT was meant to incentivise ‘normal’ people.” (interviewee 14). But in addition to tighter eligibility criteria, the government wanted to reduce the tariff by up to 50% [74]. The cuts were justified by reference to a substantial fall of PV costs since the FIT was introduced, although scheduled reviews had already been written into the original legislation for this purpose, but which government saw fit to override [75].

This policy position created a division between two different forms of socio-technical configuration for PV: small, domestic household installations versus large-scale solar farms (and caught in the middle were community energy schemes above 50 kW). Whilst government presented the former as the intended target group, with some populist criticism of solar farm investors, this political position was not strictly accurate. Large investors were also profiting from ‘rent a roof’ schemes (effectively, solar farms distributed across many houses); whilst a 50 kW cap on installation size threatened many community energy schemes designed to enable less wealthy neighbours to benefit from PV and finance local energy demand-reduction schemes[6].

A ‘Cut Don't Kill’ campaign by solar industry advocates and supporters (incl. Friends of the Earth, Homesun, the Solar

[6] Interestingly, the narrative about solar farms being undesired appears at odds with the dominant dogma that government wants to support cost effective renewable energy technologies – large scale installations are more cost effective and receive less FIT subsidy.

Trade Association and Solarcentury) voiced considerable opposition to the proposals. The solar manufacturer Sharp, which had just doubled their capacity at their Wrexham facility and opened a training academy for installers, warned the government not to undermine the early success of the FIT. A manager pointed out that job growth would be affected and that capping the installation size at 50 kW “doesn't even allow for installations in large commercial buildings, schools and social housing project, which will cut the industry off at its knee” (SolarPowerPortal).

The government was persistent. However, their haste meant official procedures for consulting on policy changes had not been followed. Campaigners took the government to court, won their legal case and a delay to cuts. After a second, properly constituted consultation, government eventually published their final decision on solar PV tariffs, which applied to new installations after 1st April 2012. The support period has been reduced to 20 years and tariffs have been significantly cut (tariffs now range from 21p for <4 kW systems to 8.9p for systems >250 kW). Contrary to earlier proposals the installation size was not cut to 50 kW. The decision also includes a degression mechanism by which Ogfem will set the new tariff on a quarterly basis based on deployment statistics as well as energy efficiency requirements [76].

This episode shows the continuing significance of technology assessments and how claims and counter claims are made about PV. In justifying FIT reduction rates, DECC published reports on declining solar PV costs and future assessments [75]. These projections have been disputed on the grounds that the data used was out of date, that definitions are unclear, that different types of modules are confused and that the sources of data were not a solid basis for such significant decisions [77]. Arguments about ‘grid parity’ also proved influential over the long-term future of PV. Consultant reports from McKinsey and Ernst & Young both project the achievement of this goal within the next ten years, depending on the installation type, its location, and wider energy market considerations, but also, continued innovation through deployment support. As before, this is essentially a debate about the future contexts in which disputed PV will operate.

5. Analysis: constructing protective spaces for PV

Section two identified an under-theorised role for ‘protective spaces’ in sustainable innovation. Our results confirm the preliminary view that constructing these spaces is politically challenging. Even now, after 40 years, dispute persists about which, if any, socio-technical configurations of PV should receive support and how. Conceived as a niche, PV development occupies a dynamic and uncertain space. In this section we discuss three issues important in the construction of protective spaces for PV.

5.1. The role of technical assessments

Whilst changing contexts that challenge incumbent electricity regimes appear favourable to alternatives generally, such as the energy crises in the 1970s and low carbon goals now, they do not automatically open spaces conducive for specific technologies like PV. Technical assessments have been identified as important elements in the construction and negotiation of narratives. The official view on PV in the 1970s was as an expensive way to generate small amounts of electricity in centralised systems. Advocates were unable to underpin their decentralised vision with sufficient practical experience. Without such evidence, capable of challenging prevailing engineering-cost technology assessments, then the case remained weak. Other context developments, like exploitation of oil and gas fields in the North Sea, preoccupation with electricity privatisation, and government antipathy towards active industrial policy further undermined opportunities for negotiating protective space for PV development.

Given the way PV opportunities were framed in assessments, space for PV was limited to hidden corners of materials science research programmes. Advocates collected evidence and built a case through participation in conferences and keeping a watchful eye on international developments. Evidence for improved cell efficiencies and falling costs came through these networks. International aid programmes for low-power off-grid PV systems in developing countries provided space for UK developers to accumulate practical experience. Similarly with specialist remote applications where low maintenance put PV at an advantage compared to other technologies. Space for PV in the UK arose through engagement with dynamic contexts internationally.

Recalling Bergek et al.'s [35] emphasis on technology assessment, and Law and Callon's [37] on narratives, we see a significant moment for PV opening with the EU-derived demonstration programmes. This transformed the assessment of PV in the UK from a closed, desk-based exercise into practical experience involving a range of actors. Space for PV widened considerably. This was not primarily because of sudden advances inherent in PV technology (performance continued to advance incrementally), but because demonstration projects re-framed PV as a building-integrated technology rather than a power-station technology. Expectations shifted, and the basis for assessment could be opened to new criteria.

Where the ability to turn favourable contexts into material opportunities had largely proven elusive before, demonstration networks could mobilise new framings and interests in the technology. This also helped extend PV narratives into active engagement with other contextual developments arising from the late 1990s onwards, such as climate change and ecological modernisation.

5.2. Narratives mediating between content and context

Our PV history suggests that the active provision of protective space hinges upon iterations between the development of PV technology (somewhere) and its favourable representation to less committed actors with resources relevant for further PV development, but who are centred in a wider social world dominated by incumbent regimes. Concerns of the latter are not specific to PV, and so narratives need also to prompt re-interpretations of those concerns in ways that PV becomes relevant and attractive.

Niche networks had to play a role additional to inward-oriented, technology development processes in order for the latter to persist. Advocates had to engage in outward-oriented processes for securing flows of resources and

Table 3
Summary of narratives, actor networks and consequences for socio-technical configuration.

Narratives	Actor networks	Associated socio-technical configurations
'PV as part of diversification strategy away from oil and gas'	Shell, BP, ETSU, Department of Energy, Department of Trade and Industry, UK ISES, University research groups, environmentalists/green movement	Focus on large scale PV
'PV as small scale, off-grid technology'	IT Power, BP Solar, Solarpak, CAT, environmentalists	Potential for PV was seen in market niches such as remote telecoms installations or rural areas in developing countries with little grid infrastructure; or low energy communities
'PV as building material'	Researchers; Ove Arup; BP Solar; Architects; DTI	Building-integrated PV systems were seen as more attractive for economic as well as space reasons
'PV as climate mitigation strategy'	Greenpeace, PV companies like Solarcentury, BP, some Labour MPs; researchers; Sharp	Assessment of PV in terms of £/tonne of carbon saved; large scale solar parks look more attractive
'PV industry creating low carbon jobs'	Greenpeace, Solar Trade Association, some Labour MPs; Foresight panel; Sharp	Aim of attracting PV manufacturers to the UK; creating demand for deployment of technology; opening up of training academy for installers; accreditation schemes developed
'PV as micro generation option to break the power of the big 6'	Solar Trade Association, Micropower Council; Green Alliance; Academics; National Federation of Roofing Contractors; think tanks like ResPublica	Focus on small scale, domestic household installations to give 'power from the people'; former consumers become energy producers and actively contribute to climate mitigation

commitments to underpin inward-oriented processes of PV nurturing. Actors in the wider social world were less interested in the socio-technical minutiae of PV development compared to those involved in PV projects. More significant was what this meant for the roles PV might play in wider, mainly political and economic, concerns. So whilst the legitimacy-bestowing work of technology assessment identified by Bergek et al. [35] is confirmed for our PV history, we also find important narrative work operating at a broader scale in the wider social world.

Table 3 summarises the outward-oriented narratives used to expand the space for PV development and their associated socio-technical configurations.

The narrative work of PV advocates also involved countering anti-narratives, such as solar incidence in the UK being insufficient for PV, costs being too high, and the relevance of decentralised systems in centralised electricity systems. In all cases, information about detailed technical performance had to be translated into evidence that could persuade people about the credibility and veracity of narratives about PV's past development, its current status, and its future role and potential in society. Some PV narratives recur throughout the history, though fine-tuned to particular circumstances. As early as the 1970s, for example, the business potential of PV was identified in export markets. It was not until the 1990s, however, and in the context of an increasingly influential ecological modernisation policy discourse, that PV advocates could leverage support on the basis of business and jobs arguments. These commitments were limited compared to elsewhere, especially Germany, which reflects deeper reticence towards active industrial policy in the UK. Until this particular context condition changes, then some PV narratives will struggle to engage policy.

The above confirms narratives are influential in translating the content of PV development into stories and arguments relevant for the wider context. However, our PV history also points to narratives mediating causal relationships in the opposite direction. Narratives may have influenced interest in PV by policy-makers and, later, investors, but *commitments* arising from that interest were *conditional*. Those conditions constituted criteria that would still be assessed against the material performance of PV. Ministers wanted evidence of the jobs created by PV programmes, for example, and the 'cost' per job, or carbon emissions reductions per £ arising from the grants given. Advocates repeatedly mobilised narratives that contested or advanced particular framings of PV technology assessments. But ultimately, even these more sympathetic assessment criteria have to be delivered upon, and where the materials of PV have to play their part. The materiality of PV remains important[7].

5.3. Protective measures generate dispersed spaces for innovation

Evidence from the history of PV suggest practical measures and situations provide combinations of the conceptually distinct shielding, nurturing and empowering processes [cf. 7]. Table 4 provides examples of how measures important to PV were actually manifold in terms of their contributions to shielding, nurturing and empowering the niche over time. Table 4 further indicates that the development of PV has not been strategically managed, in the sense that a coherent space has been constructed, and whose shielding, nurturing and empowering processes have led to the cumulative development of PV in the UK. Rather, fragmented and sometimes fleeting spaces have emerged, accompanied by measures whose realisation over time addressed particular and immediate

[7] Interestingly, our PV history included an episode where this dynamic between narrative claims, conditional commitment, and material performance was suspended. Legislation reviving nuclear power and addressing large-scale renewable energy required back-bench votes; and a coalition of MPs used this inter-dependency, between their legislative consent and government authority, to bargain for FIT policy. Arguments and evidence for PV had not changed. Nor had attitudes in government. Introducing FIT meant the government could advance their nuclear and offshore wind ambitions, whilst placating opposition with measures for micro-generation. This was not narrative work: FIT was a political bargain during a period where PV advocates had an unusual gate-keeping role in wider political goals.

Table 4
The manifold features of protective space measures.

Niche-relevant measure	Shielding (moderating selection pressures)	Nurturing (improving the innovation)	Empowering (increasing influence over contexts)
Materials science research and development programmes	Passive shielding (though general research funding available from research councils which initially prohibited research labelled as PV); Active shielding (in industrial labs or large companies such as BP and Sharp; later limited PV specific public research funding available; now growing)	Very little funding but recent increases for next generation PV; Networks of enthusiastic researchers emerged in the 70s and 80s and was actively promoted later on; networking initially often took place at European conferences but research landscape has been claimed to be fragmented; Expectations about which PV material is most attractive are contested within the R&D community and number of rival technologies is high; Learning: diversity of R&D has made it difficult to achieve critical mass in any one area	PV research programmes institutionalised (e.g. as part of Supergen programme); Long struggle to get positive PV expectations established but recently powerful narratives about exploiting UK competitive advantage in materials science could be drawn upon which has enabled more nurturing to take place for next generation PV technologies (such as organic and thin film cells)
International aid for rural electrification/Niche market for low power in remote locations	Small specialist firms exploited niche market for off-grid power applications; driven by economic drivers; Remote locations without grid access as passive protective spaces	Few specific nurturing activities, including some Worldbank contracts for developing country applications such as water pumps; Off-grid space enabled network of small companies to work with PV and to be profitable without specific support; Space enabled technical learning about feasibility of PV and design of system	Off-grid applications and public support for such installations was sometimes connected to discourses around 'third world needs'; Off-grid installations do not compete with electricity system but with technologies such as diesel engines; PV was competitive (price, reliability)
Building Integrated PV demonstration programmes	Passive shielding (through values of dedicated solar advocates who wanted to produce energy themselves); Active shielding through establishment of DTI Solar programme, was a 'targeted assessment programme' of BiPV which provided funding for demos, monitoring, dissemination	Some specific nurturing taking place from the 1990s with funding for several demo projects (Oxford Solar House, Northumbria University, CAT); Projects brought together a range of actors, stimulated learning and provided performance data and experience; It has been difficult to integrate mainstream building regime actors into the networks despite some interest.	Some attempts at reframing PV cladding as a building material (rather than an energy technology) which will be cost competitive from 2000 on to increase fit with the building regime
PV grants and feed-in-Tariff	Passive shielding: some green activists install PV even with high costs and long payback time; Active shielding: grant programmes and FiT shielding against price disadvantage of PV compared to conventional generation	Expectations around achieving 'grid parity' contested between PV advocates and critics learning: installers' accreditation schemes hoped to ensure quality; Networks: new actors involved, including housing associations, schools, local councils, farmers, institutional investors etc. which widened the political coalition in favour of PV support; Positive expectations created through announcement of FiT which were shortly afterwards renounced as maximum size of installation capped to avoid solar farms specifically	Change in institutions (planning rules) in 2008 so no permit needed for retrofitting PV on domestic roofs. FiT institutionalises long term price support (for 25 years); PV advocates try to connect PV with climate change and energy security concerns but concerns about high cost of PV as carbon mitigation strategy persist; Support portrayed as temporary until grid parity reached (strategy of 'fit and conform'); Strong political backlash against 'fat cat' investors has made further empowerment of this space very difficult politically; 'Fat cat' rhetoric has been contested by some solar advocates; Mobilisation in defence of FIT indicates a popular PV lobby and secures bigger commitment to the technology from government in the longer-term

aspects of PV, and that were returned to and picked up when later measures provided further occasions for development.

The analysis identifies at least two instances in which the politics of creating protective space had a material impact on the socio-technical configuration of PV:

First, measures supportive of building-integrated PV materials initially nurtured PV in ways specific to that form of PV, e.g. cladding devices such as PV tiles and architectural issues, and tried to empower PV in that vein. It also influenced the networks of actors involved in these developments as pointed out above. But this measure also generated adaptable, less specific developments, such as lessons about grid connection and decentralised PV electricity relevant to configurations wider than building-integrated configurations alone, such as retrofit installations.

Second, experience with the FIT indicates how measures generate a politics of socio-technical configuration that affects the space for continuing development. So, despite solar farms being relatively cost-effective and receiving lower tariff rates, issues of ownership and perceptions of large aggregate payments going to a few investors nevertheless justified a FIT reform that altered the space for PV. Somewhat obliquely and opportunistically, questions as to the relative social iniquities of different PV socio-technical configurations have entered the debate. Indeed, claims for community ownership and householder ownership are fundamentally about the social justice of the differential socio-technical consequences arising from the measures in protective spaces.

Both of these instances can be seen as examples of how the processes of negotiating a protective space are evidence of what others have called the social shaping of technology [37,63]. Overall, the analysis reveals how solar PV remained contested within the niche network (e.g. ETSU, civil servants) even when specific, conditional measures to provide protective space were in place. Often PV was not considered a funding priority by government officials despite the interest in the technology by green NGOs, advocates, academics and the public. Measures for different socio-technical configurations have varied over time, as did the actors involved in the variety of spaces in which PV developments took place. Local networks were dispersed and favoured different socio-technical configurations, which undermined their ability to develop PV but also their political power. As Table 4 indicates these processes did not lead to a stable or consistent 'protective space' for PV in the UK as developments were dispersed and contested most of the time by relevant actors.

6. Conclusions

In presenting the equivocal development of PV in the UK we addressed the first research question of this paper, i.e. how did PV develop in the UK over the last four decades? This history in itself makes an important contribution to existing analyses, which to our knowledge only cover partial and mostly more recent developments.

With the study of PV in the UK we also explored some implications arising from more general and theoretical understandings of the dynamics of niche 'protective spaces' in strategic niche management (our second research question). There are of course constraints on the kinds of generalisation we can make from single-case study designs. If protective spaces for innovation were ever needed for sustainable energy technologies, then PV would be amongst those needing them due to its poor 'fit' with the institutions, infrastructures, and cultures of centralised- and large-scale electricity systems. Our empirical research does confirm the logical deduction that the construction of protective spaces was necessary for PV. Conversely, if 'spaces' had been found to be irrelevant for a case as critical as PV, then this would falsify a founding principle for niche-based approaches to innovation studies [46].

However, more specific patterns of niche processes should not be inductively concluded form this single case alone. As such, the following observations are more speculative, but nevertheless informative for theoretical scrutiny through future empirical studies.

Our first observation is that 'spaces' for sustainable innovation is a useful concept. Thinking about how favourable conditions for innovation are obtained in otherwise unfavourable contexts underscores the need for attention to socio-political processes beyond the narrow techno-economic development of an artefact. So in addition to *inward-oriented* activities aimed at the practical development of socio-technical configurations, PV networks are also engaged in *outward-oriented* activities of interpreting, representing, and negotiating PV in the wider social world. Such outward-oriented activity is absent in earlier theorisation of niche development [26].

Our second observation is that the narrative work in outward- and inward-oriented processes constitutes and characterises protective space. The distinction is overdrawn here, since in practice processes of shielding, nurturing and empowering folded into each other for PV. Moving from outside protective spaces inwards, broad narrative claims translate into conditional forms of support, which translate into criteria for more technologically-oriented assessments of performance. Material performance against these criteria informs what further developments are required. Moving from the inside outwards, interpretations of performance and requirements feed back up through assessments in ways that condition and revise narratives.

In combination, protective space can consequently be conceived as the combination of internal developments specific to PV and external representations meaningful to the wider social context (and where incumbent socio-technical regimes influence interpretations). Advocates develop a repertoire of narratives involving representations to key, resourceful audiences in the wider social world, and rendered credible (or not) by selectively drawing upon collections of more specific assessments of socio-technical performance that validate (or not) the narrative claims. Included in this narrative work are interpretations and arguments about changes in contexts relevant to that socio-technical performance.

In passing, we note how demonstration programmes become political exercises as well as technology assessment measures. Demonstration programmes provide opportunities for the build-up of advocacy, widening participation, introducing new framings and narratives, re-assessment of interests as well as the technology. Linking this to the original focus of strategic niche management – which recommended real world experimentation with sustainable innovations — our study suggests projects have to be seen as important political activities. But, our history also illustrates how these are not the sole occasions for constructing and contesting spaces, since research programmes, early application domains, and even a technology's emblematic role in social movements (e.g. for alternative energy) can prove significant for translating contexts into content.

In conclusion, our study of PV in the UK suggests that the actor networks that try to create and influence narratives for opening up protective spaces, and the spaces themselves, can be widely distributed socio-spatially and temporally. Their manifold characteristics will have a material influence on the socio-technical configuring that is possible, where that configuring takes place, who is involved, and how certain configurations are advanced for further development in particular locations. Even our limited focus on the UK points to widespread processes in the construction and contesting of protective space, including European research programmes developed in Brussels, German industrial policy towards PV, the development of PV systems in rural Africa, and even satellites in space. Nevertheless, it remains the case that attention still focuses on political jurisdictions, like the nation state, with the authority to instigate protective policy measures. What our history suggests is that spaces for sustainable innovation are socially constructed and hence politically contested.

Appendix A. List of interviewees

Interviewee	Position and organisation
1	Professor of Technology Policy, specialised in Renewables
2	Professor of Renewable Energy
3	Professor of Engineering
4	Former campaigner for environmental NGO
5	Representative of solar energy company
6	Representative of solar installation company
7	Senior Civil Servant, Department of Energy and Climate Change
8	Representative of solar manufacturing company
9	Former Technology Director of Public Sector Organisation
10	Professor of Architectural Engineering
11	Former BP solar employee
12	Solar PV entrepreneur
13	Former ETSU employee responsible for renewables
14	Programme Manager, Department of Energy and Climate Change

All interviews were conducted either in person or by phone between February and June 2011 and were recorded and subsequently transcribed. They normally lasted for between 45 and 90 min.

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