



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

The pursuit of interdisciplinary whole systems energy research

Insights from the UK Energy Research Centre

Citation for published version:

Winkel, M 2018, 'The pursuit of interdisciplinary whole systems energy research: Insights from the UK Energy Research Centre', *Energy Research & Social Science*, vol. 37, pp. 74-84.
<https://doi.org/10.1016/j.erss.2017.09.012>

Digital Object Identifier (DOI):

[10.1016/j.erss.2017.09.012](https://doi.org/10.1016/j.erss.2017.09.012)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Energy Research & Social Science

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.





Original research article

The pursuit of interdisciplinary whole systems energy research: Insights from the UK Energy Research Centre



Mark Winskel

Science, Technology and Innovation Studies Group, School of Social and Political Science, University of Edinburgh, Chisholm House, High School Yards, Edinburgh EH1 1LZ, United Kingdom

ARTICLE INFO

Keywords:

Interdisciplinary
Whole systems
Research
Energy

ABSTRACT

Interdisciplinary whole systems research (WSR) is attracting increasing interest as a way to address to complex societal challenges such as sustainable energy. However, WSR typically involves challenging research elements (*radical* disciplinary scope, *integrative* knowledge production and *transdisciplinary* design), which are seen by some as intellectually and institutionally flawed. Drawing on the interdisciplinary studies literature, this paper considers WSR strategy and practice in the UK Energy Research Centre (UKERC) over its first two phases (2004–14) and compares UKERC to other similar UK-based initiatives. WSR strategy and practice face a number of tensions: integration versus diversity, stability versus flexibility and independence versus engagement. The emphasis in UKERC was on integration in the first phase and diversity and flexibility in the second phase – a pattern largely imposed by funders, assessors and stakeholders, rather than by internal strategy. Though granted ambitious remits, WSR is often funded, practised and assessed in the margins of disciplinary based research systems, rather than as a distinctive research form. There is a need to better attend to the choices and trade-offs involved in WSR strategy and practice, drawing on the experiences of UKERC and other initiatives. As a guide, the paper introduces a number of interdisciplinary WSR archetypes.

1. Introduction

1.1. Background

Interdisciplinary research is often seen as a promising way to respond to urgent and complex societal challenges such as sustainable energy (e.g. [1–3]). The proponents of interdisciplinary responses to complex socio-technical problems tend to have in mind research which reaches across the physical, social and environmental sciences – sometimes referred to as ‘radical’ interdisciplinarity [4] – and which develops an integrated ‘whole systems’ perspective [5–7]. This is found, for example, in a number of recent energy research and policy initiatives aimed at ‘whole systems integration’ [8,9]. WSR approaches may also feature the strong involvement of non-academic stakeholders (policymakers, businesses and civil society groups) in research design and production – referred to a ‘transdisciplinary’ research [10]. Interdisciplinary WSR can therefore be defined as having distinctive *radical*, *integrative* and *transdisciplinary* elements, in various combinations.

Alongside the many advocates and enthusiasts for interdisciplinary WSR research are a few questioning or sceptical voices. Daniel Sarewitz has suggested that such research has very little actual capacity to solve complex problems, and often constitutes little more than hubris [11].

Jerry Jacobs has also questioned the value of integrated interdisciplinary solutions to complex societal problems [12]. Other cautionary voices include senior researchers who have led or reviewed WSR programmes, and who report-back on the difficulties encountered (e.g. [1,13,4,14]).

This mix of enthusiasm and advocacy alongside scepticism and caution suggests the need for empirical studies of WSR experiences. Drawing on the interdisciplinary studies literature, this paper considers the experiences of the UK Energy Research Centre (UKERC) over its first decade (2004–14), within wider WSR efforts on energy in the UK. In analysing the UKERC case, the aim here is to open-up the ‘black box’ of interdisciplinary research strategies and practices [15].

1.2. Design and method

The analytical focus here is the development of interdisciplinary WSR strategy and practice within UKERC (Fig. 1). The paper does *not* attempt to comprehensively assess UKERC’s research themes, projects and researchers. However, UKERC’s pursuit of WSR was greatly shaped by ‘external’ influences – funders, advisors and stakeholders – and these are also part of the analysis. The wider context for energy research – though an important backdrop – is outside the scope of the study, as are

E-mail address: mark.winskel@ed.ac.uk.

<http://dx.doi.org/10.1016/j.erss.2017.09.012>

Received 23 February 2017; Received in revised form 4 September 2017; Accepted 7 September 2017

2214-6296/ © 2017 The Author. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

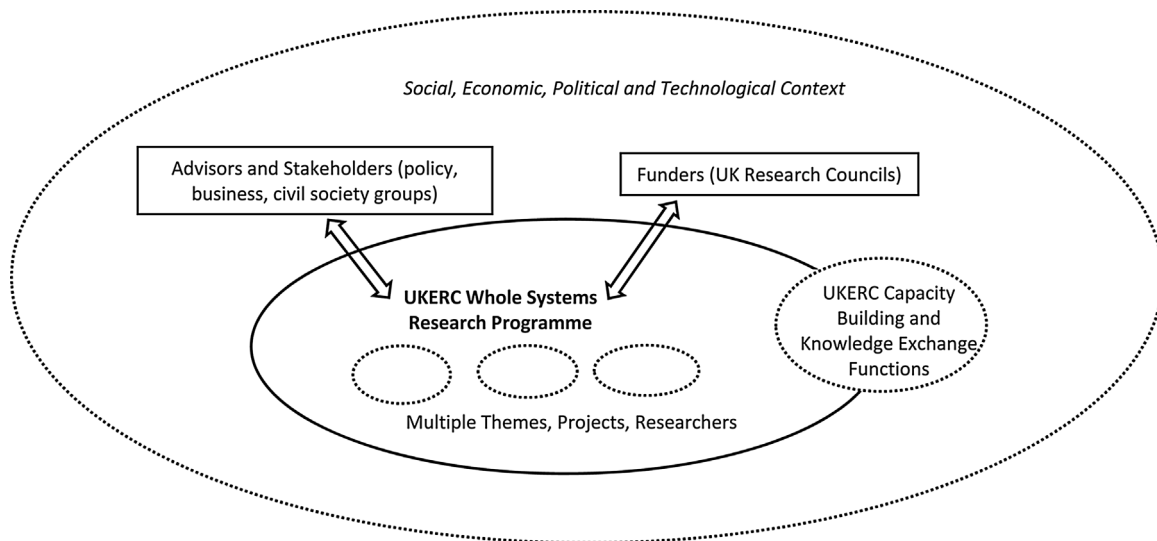


Fig. 1. Case Study: UKERC's Interdisciplinary WSR programme.

UKERC's 'non-research' activities.

The case study is based in-part on empirical fieldwork carried out towards the end of UKERC's first decade. (UKERC is continuing in revised form until 2019, but this 'Third Phase' is not studied here). Fieldwork included a residential workshop of interdisciplinary energy researchers ($n = 49$), a facilitated group discussion of UKERC researchers and stakeholders ($n = 15$), a survey of the UKERC research community ($n = 90$) and a series of semi-structured interviews with UKERC researchers, advisors and stakeholders ($n = 18$). (Fieldwork details are available from the UKERC website). The following codes are used for fieldwork participants:

- EC1, EC2 etc.: Early Career Researchers (PhD Students and postdocs with less than c.5 years' experience)
- MC1, MC2 etc.: Mid-Career Researchers (with at least several years of research experience)
- SR1, SR2, etc.: Senior Researchers (with senior roles and at least 10–15 years of experience)
- AA1, AA2, etc.: Academic Advisor (external academics with an advisory role in UKERC)
- EA1, EA2, etc.: External Academic (interdisciplinary academics with no role in UKERC)
- SA1, SA2, etc.: Stakeholder Advisors (senior figures from industry, policy etc.).

The fieldwork was aimed at soliciting both an inside and external view of UKERC's WSR strategy and practice. Although the fieldwork sample included many participants in the UKERC research programme, it also included many external academics and non-academic stakeholders (policymakers, business and third sector organisations) not directly involved: two-thirds of the interviewees, one-third of group discussion participants and three-quarters workshop attendees were not directly involved with UKERC. (Among those directly involved, most were only part-time and temporary UKERC members, alongside other academic responsibilities).

The case study has also involved a review of relevant internal, grey and public papers, and the personal experiences of the author, who was closely involved in UKERC's research strategy for most of its first decade. While this close involvement has enabled access to documents and a close working knowledge of the case, it may raise concerns about impartiality and objectivity. There are a number of responses: firstly, the paper has the benefit of 'historic distance': it reports UKERC experiences up to 2014, rather than an assessment of its ongoing operations (the author has a reduced role in UKERC Phase 3). Secondly, the

paper is not aimed at assessing UKERC's specific research *outputs* and *impacts* (a number of independent assessments of these were carried out over the period analysed here). The concern here is rather research *strategies* and *practices*, drawing on the views of a wide range of UKERC participants, advisors and observers, as well as the personal insight of the author, so as to contribute to a body of such research in interdisciplinary studies.

While the case study selection is partly based on pragmatism, UKERC is also a compelling case for a study of WSR strategy and practice: a relatively longstanding part of interdisciplinary energy research in the UK, with a particular remit and experiences across two distinct phases set against a changing context. While a number of other comparable interdisciplinary initiatives have published accounts of their interdisciplinary experiences (e.g. [1,13,16,17]), this is the first account of the UKERC experience, and interdisciplinary WSR remains a relatively under-researched topic in interdisciplinary studies.

Any single case inevitably reflects many specifics [18]. For example, UKERC may be expected to reflect a UK 'style' of energy research, involving a relatively fragmented and fluid set of organisations [19,20]. The energy sector also presents a distinctive setting for interdisciplinarity, with a set of pressing policy drivers and statutory commitments, (especially, for this case, the UK Climate Change Act; [21]). In terms of expertise, energy research has a traditional orientation to physical sciences, engineering and economics [22], although more diverse research efforts have developed recently, as UKERC itself exemplifies.

To help discriminate between case specifics and wider patterns (i.e. the 'generalisability' of case findings) the paper includes a review of the relevant interdisciplinary research literature, organised around the challenges of WSR (radicalness, integratedness, transdisciplinarity and institutional contexts) (Section 3). The paper also includes a structured comparison of UKERC and similar UK interdisciplinary initiatives (Section 5). While there are many forms of interdisciplinary energy research, the comparison in Section 5 is restricted to particular UK-based centres and programmes which, like UKERC, were funded by the UK Research Councils as coherent WSR programmes or centres, and which have a body of supporting documentary and empirical evidence, including fieldwork carried out as part of the UKERC case.

The next section (Section 2) presents a narrative, chronological account of UKERC's pursuit of WSR across two five-year phases, based on document analysis and fieldwork. Section 4 is an interpretative analysis of the case study based on themes identified in the interdisciplinary studies literature in Section 3. Section 6 concludes and offers recommendations regarding publicly funded efforts at WSR.

2. Case study: the UK Energy Research Centre (UKERC)

2.1. UKERC Phase 1 (2004–09)

UKERC was formed in the early 2000s as UK public spending on energy research was starting to increase from a very low base in the wake of energy industry liberalisation (Fig. 2). The main driver for this (at first) modest recovery was growing awareness of the need to decarbonise energy systems in the face of climate change [24]. UKERC's specific genesis was an Energy Research Review Group (ERRG) made up of senior figures from business, academic, policy and the third sector. The ERRG fed into to the UK's first major review of energy policy and research since privatisation [25]. Although it had a mainly techno-economic and supply side orientation, the ERRG called for the creation of a multidisciplinary national energy research centre:

The research challenges ... cross the boundaries of physical science, engineering, environmental science, socio-economic and socio-political sciences and life sciences ... A multidisciplinary approach is essential ... in the development of technological solutions to future energy supply ([26,p. 24]).

In accepting the ERRG's call, Research Councils UK (RCUK) (the Research Councils' umbrella body) emphasised the need for the new centre to focus its limited resources on WSR: 'the research challenges and opportunities required to underpin UK energy policy development demand whole systems integrated approaches' ([27,p. 1]).

Rather than a single-site centre, as the ERRG had envisaged, UKERC was created as a dispersed collaboration between eight partner universities and research institutes assembled from three rival consortia, with a small secretariat headquartered at Imperial College, London [28]. It was awarded a significantly smaller annual budget (around £2–3m) than ERRG's recommended £10m, provided roughly equally from three Councils: the Natural Environment Research Council (NERC), Engineering and Physical Sciences Research Council (EPSRC) and Economic and Social Research Council (ESRC) [29]. Like other relatively large awards (a number of technology-specific energy research centres had already been established by this time) UKERC was initially funded for 5 years.

UKERC was given a dual remit: running its own WSR programme and providing 'coherence, co-ordination and connectivity' for the UK's

wider energy research activities [27]. This latter role involved, for example, establishing a National Energy Research Network, an energy research data repository, a workshop facilitation capacity and an interdisciplinary doctoral studentship programme. The Research Councils suggested that UKERC should direct its resources equally between research and capacity-building activities, so that its annual research budget, to be shared among its eight academic partners, was only around £1.5m. Though often seen as the flagship part of the Research Councils Energy Programme (RCEP), UKERC was in practice a marginal addition (Fig. 2).

In setting out the new Centre's role, its Research Director highlighted the need to provide 'independent, authoritative guidance to government and other stakeholders' ([28,p. 25]) by developing a programme of whole systems, policy-oriented research: 'The Centre will address the energy system as a whole ... it will take a long-term perspective on the steps required to give effect to the ambitious goals of UK energy policy' ([28,p. 1]).

UKERC's research programme was organised around six themes, each led by a senior academic from a partner institute (Fig. 3) (an additional 'Technology and Policy Assessment' theme undertook systematic evidence reviews) [28]. Working under the Research Director (who had a policy and modelling background) and an Executive Director (who had an industrial engineering background) the theme leaders formed the UKERC 'co-Directorship'. The Centre's theme leaders and many of its researchers worked part-time for UKERC alongside other research and teaching responsibilities.

The envisaged mechanism for research integration was informal, bottom-up collaboration, along with 'procedural' measures such as regular meetings of theme leaders and researchers (interview, EA2). Early Centre-wide meetings provided a forum for debate about what WSR might involve and how it could be pursued. They revealed a mix of enthusiasm about the potential to deliver distinctive insights, and concerns about the risks involved, such as the low status of integrative research in prestigious journals [30,31].

By 2006 concerns within UKERC were also being expressed about the lack of interaction between technical and social research in the Centre, and between UKERC and the wider energy research community [31]. Some researchers now called for stronger top-down efforts at research integration, with a firmer emphasis on balanced disciplinary contributions and 'forced marriages' between disciplines [31]. The

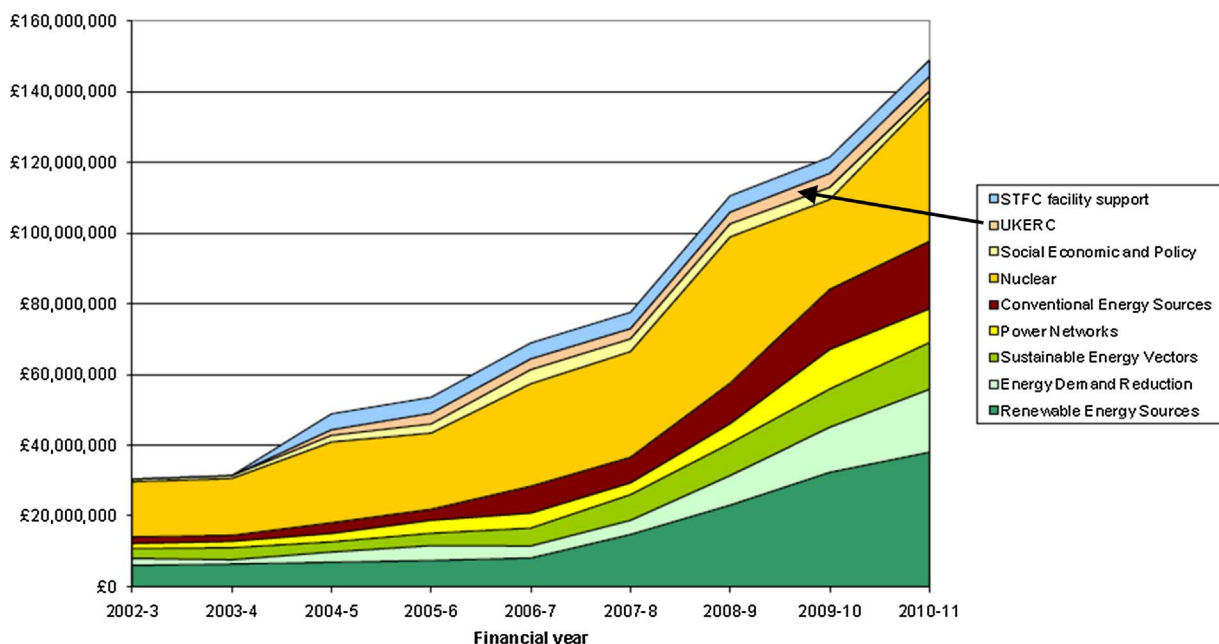


Fig. 2. Research Councils' Energy Programme, Annual Expenditure by Theme [23].

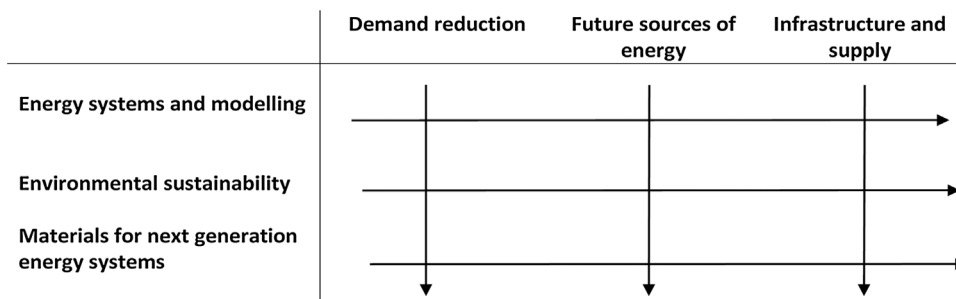


Fig. 3. UKERC Phase I Thematic Research Programme Structure (2004–2006) [28].

Research Director was also becoming aware that the informal and bottom-up approach to integration was failing to overcome disciplinary silos [32].

At the same time, UK energy policy became increasingly concerned about the challenges of reconciling decarbonisation with energy security and affordability, in a context of increased fuel import dependency and escalating global carbon emissions [33]. These internal and contextual drivers prompted the inception of a Centre-wide ‘integration project’, later called the *Energy 2050* project. The rationale was set out in an internal review:

One major challenge for UKERC has been to realise the ‘whole systems integrated approach’ ... A cross-Centre Integration Project ... will draw all the Centre’s themes and functions together ... Progress towards a ‘whole systems’ approach to energy research needs to be accelerated’ [31,pp. 1,4].

Energy 2050 was devised as a ‘social engineering’ initiative to create interdependencies between the Centre’s themes, disciplines and partner institutes (Fig. 4). The project involved changed ways of working for most researchers. Research activities (and all of the Centre’s regular meetings) were now designed around Energy 2050 cross-theme ‘working groups’, with input from non-academic stakeholders via advisory groups and workshops.

The Energy 2050 project involved devising multiple pathways consistent with UK energy policy goals for decarbonisation, security and affordability. Pathway development involved a combination of qualitative narratives and quantitative data assumptions for variables such as lifestyle and behaviour, technological innovation, public attitudes and environmental sensitivities. After several interim and component working papers, Energy 2050 culminated in two integrated outputs: a ‘synthesis report’ [34] and an edited book [35]. The synthesis report was co-authored by over 40 UKERC researchers – around two-thirds of the Phase 1 research community.

While it realised many of its integrative aims, the Energy 2050 project was seen ambivalently by those closely involved. One senior UKERC researcher concluded that ‘Energy 2050 was arguably the furthest ... that UKERC has gone; as an interdisciplinary exercise it was far from perfect, but it did force some useful interactions’ (interview, SR2). A particular concern was that pathway development became preoccupied with devising inputs for the systems models used in the project: ‘the Energy 2050 project ... ended up being very “Markal” [system model] focused, and there were some tensions’ (interview, EC1).

The central role of whole systems modelling also meant that Energy 2050 was oriented to a UK national scale and mainly techno-economic variables, with less focus on more disruptive and difficult to model aspects such as governance, decentralisation and investment risks. A number of these ‘blind-spots’ were pursued in UKERC’s Phase 2 research programme.

2.2. UKERC Phase 2 (2009–14)

Towards the end of Phase 1 the Research Councils indicated their

intention to support a UKERC second phase. The context for energy research was changing: UK policy was formalised with the Climate Change Act [21], but the UK economy was experiencing a sharp decline in the wake of the financial crisis. In late-2008 UKERC issued a new mission statement to reflect the changes, replacing: ‘what are the options for and implications of achieving a secure low-carbon energy system?’ with: ‘how do we make the transition ... given a deeply uncertain world which will not develop along smooth trajectories?’ ([36,p. 1]).

The recommissioning process involved a lengthy period of consultation and iteration between the Research Councils, senior UKERC researchers and stakeholder groups. A recurring issue was the need for both continuity and change. At the outset, the Research Councils emphasised continuity: ‘The existing UKERC structure and management has resulted in very good progress in fully interdisciplinary research in energy ... an open competition would be counterproductive, given ... the urgency of addressing ... energy challenges’ [37,p. 3]).

UKERC’s Directors were therefore invited to submit a second phase five year proposal with a broadly unchanged remit: to conduct ‘a strongly visionary and integrating whole-systems work programme focused on inter-disciplinary research’, while also continuing to capacity-build for the wider research community ([37,p. 5]). Although the RCEP was now expanding rapidly (Fig. 2), Phase 2 was funded at around the same level as Phase 1 (c.£3.5m p.a.). NERC requested that around 40% of UKERC’s budget be dedicated to networking and capacity building, leaving an annual research budget of around £2m.

The Councils also stipulated that around half of the Centre’s research budget be allocated through a series of open and competitive research calls. The aims of the new ‘Research Fund’ were to involve a wider range of researchers and disciplines and respond to emerging policy and research concerns [37]. In the course of recommissioning, independent academic and stakeholder advisors requested that the Fund enable the greater involvement of social and environmental researchers, reflecting perceptions that Phase 1 was dominated by a techno-economic perspective (interview, EA2; [38]).

At the outset of Phase 2 the UKERC research programme reverted to a broadly similar structure to the first half of Phase 1, with themes on Supply, Demand, Systems, Environment and Technology & Policy Assessment. However, two of Phase 1’s more technically-oriented themes (Future Sources of Energy and Materials) were discontinued, given concerns that monodisciplinary, ‘underpinning’ research had struggled to engage with the Centre’s WSR remit [31,39,40], and also, that the halving of the Centre’s core research budget to accommodate the Research Fund meant that such work would now be better funded elsewhere [36].

The Research Fund was allocated over four open calls for proposals, each based on topics specified by UKERC after wider consultation. The call specifications identified the interdisciplinary dimensions of the research, likely participating disciplines and the intended contribution of the research to the Centre’s WSR programme. After independent review, each selected project was allocated to one of UKERC’s research themes. Anticipating the managerial challenge involved, UKERC set-up a small co-ordination team to enable ‘sustained commitment and effort’

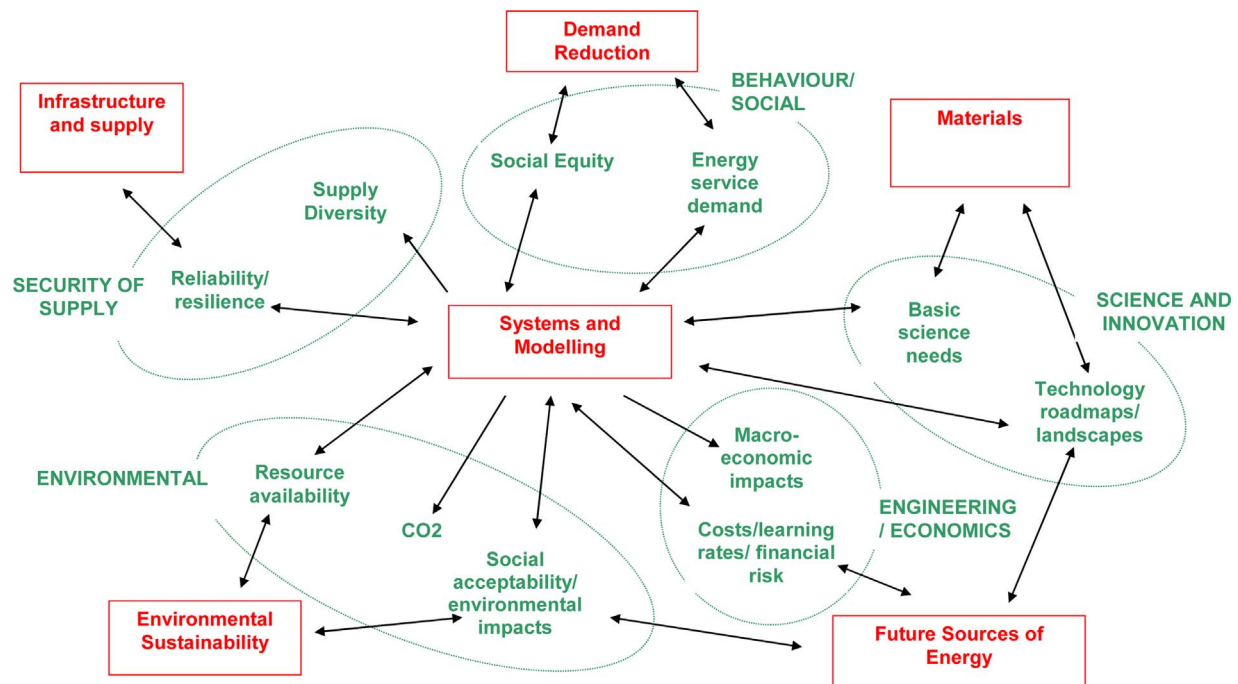


Fig. 4. UKERC Phase I Energy 2050 Research Programme Structure (2007–09) [32].

on research integration [36]. In addition, a Committee of independent academics was created to oversee the Fund and assess overall research programme progress.

The new funding arrangements led to a more diverse research community, as a similar overall budget to that in Phase 1 was spread around many more institutions and disciplines. Over 160 investigators, researchers and students became involved, equivalent to 50 full-time staff at peak. Most were only temporary and part-time members, as Research Fund projects ran for no more than two years. Although the Research Fund projects involved multi-disciplinary teams, the majority (10 out of 16) were led by social scientists [67].

The Research Fund was seen ambivalently by UKERC's researchers and advisors: some highlighted its benefits, in terms of flexibility, impact and 'keep[ing] core researchers on their toes' [interview AA2]. Others noted its operational challenges: 'the more people, the more of a challenge to integrate those people effectively' [interview, SR1]. A particular challenge was embedding new projects into themes – a 'cuckoo in the nest' problem for theme leaders [interview, EA2]. Managing the Fund meant that the Research Co-ordination team were limited to 'remedial' efforts on Centre-wide interaction in the first half of Phase 2, with less proactive cross-theme working [interview, EA2].

Nevertheless, two cross-theme 'flagship projects' were undertaken in the later stages of Phase 2: 'UK Energy in a Global Context' and 'UK Energy Strategies under Uncertainty'; the latter provided an integrated analysis of the main uncertainties facing UK energy policy to 2030. Both projects culminated in UKERC synthesis reports [41,42] and academic outputs: an edited book from the 'global' project and a journal special issue from the 'uncertainties' project. Around 40 researchers contributed to the synthesis reports – a similar number to the Energy 2050 report, but a much smaller proportion of the total UKERC research community. Most Phase 2 researchers were not involved and continued working in their themes and projects, and a number of flagship project contributions were commissioned from researchers outside the Centre. Survey results suggested that interdisciplinarity was more commonly experienced in smaller scale project-level activities [survey, Q. 11].

3. Interdisciplinary studies and WSR

Interdisciplinary research carries significant intellectual

assumptions, amounting to a 'philosophy of knowledge' [43]. While the term 'interdisciplinarity' tends to be used to describe any research which crosses traditional disciplines, many different types of exchange are identified in the literature [44]. Within this, WSR has received little attention as a conceptually distinctive form. However, its characteristic elements: radicalness, integratedness and transdisciplinarity, have received significant attention, and this section is organised around these three themes, with an additional section on institutional contexts for WSR.

3.1. Radical interdisciplinarity

A distinction is often made between 'cognate' interdisciplinarity, operating *within* macro disciplines (e.g. physical, environmental and social sciences) and 'radical' interdisciplinarity *between* macro disciplines [4]. Radical interdisciplinarity raises a number of conceptual and practical concerns. Rouse (in Hannon et al., [47]) described it as a meeting of physical science's positivist laws and determinisms and social science's interpretivist hermeneutics. Others have detailed the many differences involved: problem definition; data, evidence and proof; research methods; unit and scale of analysis; the role of non-academic stakeholders; and funding and reward structures (e.g. [4,45]).

Given these differences, the imposition of a single research design is likely to lead to antagonism and marginalisation. In practice, radical interdisciplinarity may be preframed in mainly technical terms, with social scientists expected to embrace positivism [4]. On the other hand, engineers and physical scientists may be reticent participants in research framed in 'post-positivist', constructivist terms [46].

A number of interdisciplinary energy-related research initiatives have encountered these tensions. Petts et al. [4] concluded that although it was widely seen as virtuous, radical interdisciplinarity was rarely seen in practice, as disciplinary boundaries were often quickly reinstated. Hargreaves and Burgess [14] found 'an almost total divide' between natural and social scientists' expectations of radical interdisciplinarity, with physical scientists tending to be more enthusiastic, but on rather unreflexive terms. Longhurst and Chilvers [16] and Rouse (in Hannon et al., [47]) both also reported greater scepticism among social scientists.

Alongside these concerns is recognition of the possibility of more

amenable and productive exchange. Rouse (in Hannon et al. [47]) noted that within a long-term collaborative context it is possible to overcome many of the divides and establish common grounds, such as a shared commitment to empirical evidence.

3.2. Integrative interdisciplinarity

As Jacobs [12] pointed out, much interdisciplinary research is *not* aimed at integration, and equally, integrative research can be narrowly pursued *within* disciplines. Even so, interdisciplinary knowledge integration is an underpinning tenet of much interdisciplinary effort [6,44]. Brewer [46] argued that academic specialisation and reductivism, though it had brought impressive results, had incurred costs (including environmental damage), suggesting the need for integrative interdisciplinarity.

Some view knowledge integration more sceptically. Barry et al. [48] argued that although integration and synthesis was the dominant mode of interdisciplinarity in climate and environmental research, other modes were possible, including *subordination-service* exchange (seen, for example, when social science plays a subservient or ‘gap-filling’ role); and *agonistic-antagonistic* exchange (with an explicit attempt at oppositional exchange, possibly leading to disciplinary transcendence). Others have considered different integrative research methods, including model-, product-, and dialogue-based forms [68].

In an explicit critique of integrative interdisciplinarity, Sarewitz [11] contended that reductive monodisciplinary research was a far more important engine of social transformation than interdisciplinary holism: while the former generated powerful context-independent knowledge and artefacts, the latter vainly sought to explain complex and non-deterministic systems – an ultimately political pursuit. Holistic knowledge claims reflect arbitrary acts of boundary drawing, Sarewitz argued, encoding some concerns above others, mobilised to support or undermine particular political positions. Rather than independence and objectivity, such research is infused with self-interest and conflict, and only a modest and pragmatic form of knowledge synthesis is tenable.

In a similar vein, Jacobs [12,p. 128] argued that the assumption that complex problems required integrated interdisciplinary solutions ‘melts under closer inspection’. Instead, he suggested, such problems can often be tackled through partial and specialised solutions that are only later assembled into a larger whole. Jacobs also noted the different contexts for knowledge integration across policy and research communities: while policy solutions may require an integrative approach, research programmes may not.

3.3. Transdisciplinarity

Transdisciplinarity is a distinctive form of interdisciplinarity, with an active role for non-academic stakeholders and/or wider publics as co-designers and perhaps co-producers. As such, it transgresses expert, stakeholder and lay divides [49] and conflates knowledge production and exchange [44,17,45].

There has been a notable turn to transdisciplinary research in the UK and internationally [10], with some accompanying conceptual and practical concerns. For example, Jacobs [12] argued that a ‘vogue’ for transdisciplinary research institutions designed to respond to particular social problems threatened academic independence, as instituted in more linear forms of production and exchange, and also the pursuit of long-term research with uncertain payoffs, as enshrined in disciplinary-based departments.

Transdisciplinary research is more likely to be funded by non-traditional and perhaps overtly political organisations [43]. It may also challenge the primacy of academic peer review [49]. Hulme [13] positioned transdisciplinarity as occupying a middle-ground between ‘curiosity-driven’ and ‘call-down’ research, but with concerns about co-production sliding into consultancy.

Lyll et al. [10] found that genuinely transdisciplinary research remained rare in practice. Hulme [13] concluded that co-production was much harder to realise than its rhetoric suggested, with a gulf between stakeholder expectations and researchers’ ability to respond. Harris and Lyon [45] noted the cognitive and practical challenges of managing diverse transdisciplinary consortia. Within this, there is a risk of privileging stakeholder views: just like academics, stakeholders have partial and limited understandings of the ‘real world’ [10].

3.4. Institutional contexts

Interdisciplinary initiatives tend to be institutionally fragile and lack means for their reproduction [50,51]. Their initial appeal is often replaced by growing awareness of their challenges, with funding and researchers migrating back into established disciplinary structures [52]. Within academia, interdisciplinary research may be seen as superficial and undisciplined [10], and having a ‘real world’ orientation may also be viewed negatively [53].

Researchers need manageable research objects [18] and a secure home disciplinary base [54], but interdisciplinary researchers are confronted with a complex landscape across research, funding and stakeholder groups [4,14]; there are particular risks for less established early career researchers [52,45,55]. In addition, universities now face a competitive market for research, spanning consultancy firms, think-tanks, industry associations, civil society organisations and pressure groups [43].

In responding to these challenges, a degree of organisational detachment may be beneficial [50,51]. Brewer [46] argued that interdisciplinarity was best suited to organisational ‘interstices and marginal spaces’ rather than the academic mainstream. Harris and Lyon [45] concluded that there was an optimal size for transdisciplinary consortia, with larger and more dispersed initiatives tending to perform less well than smaller, bounded networks.

Another recommendation is to link together strategic *aims*, financial *means* and management *methods* (Nowotny, 2006, cited in [10,see also 14]), and to generate discrete, recognisable outputs for different funders and stakeholders [45]. There is also a need to provide dedicated time and space (and co-ordinating roles) for interaction and mediation, although academic research is often conducted in a context of competition rather than collaboration [50,56,4,16].

Funding and assessment procedures exert a powerful influence on research practice [49,53,15]. Interdisciplinary proposals may face inconsistent assessment processes and criteria, and judgement by assembled disciplinary experts rather than experienced interdisciplinarians [56,1,15]. Hulme [13] concluded that research funders were ‘instinctively disciplinary’, and Petts et al. [4] noted that even in pooled-funding initiatives each funder seeks a distinctive imprint.

4. Case study analysis and discussion

4.1. UKERC and radical interdisciplinarity

Different forms of exchange between physical, social and environmental sciences were evident in UKERC at different times, with a broad orientation to techno-economic positivism and mainly quantitative methods in Phase 1, and more diverse epistemologies and methods in Phase 2. This pattern was largely imposed by funders and commissioning panels rather than internal strategic choices.

By the later stages of Phase 2, a view had emerged that UKERC had become dominated by social science: ‘One thing missing in Phase 2, and that has been lost, is a strong dialogue between social science and engineering; the engineering aspects have become very narrow.’ [FGD, SA1]. One suggested barrier to more balanced radical interdisciplinarity in Phase 2 was the dispersal of limited funds across a much expanded energy research community: ‘For engineering, the limited size of UKERC grants is a barrier; engineers would rather spend

valuable time preparing grants for larger awards [FGD, SR1] ... and you don't have the transaction costs of interdisciplinarity ... it's not so surprising that it's been more difficult to engage engineers in Phase 2' [FGD, MC5].

While UKERC's initial commitment to techno-economics may suggest a subservient role for social sciences, the Centre's declared mode of interaction was *integration and synthesis*. In practice, different modes of exchange were interwoven, and while social sciences tended to play a 'service' role in Phase 1, Phase 2 saw some instances of engineering subordination to social science. There were also some (undocumented) *antagonistic/agonistic* exchanges. For example, in the course of *Energy 2050*, tensions arose between two different energy system models. While it had been hoped that these differences would be a source of productive analytical tension, they proved difficult to reconcile and only one of the models was ultimately used for project integration. There were also occasional tensions between positivist and constructivist epistemologies, and qualitative and quantitative methods. These antagonisms were played out by circumvention and disengagement, rather than the more constructive learning anticipated by Barry et al. [48].

Beyond a tacit commitment to techno-economics, disciplinary identity in Phase 1 was left largely unexamined – the emphasis was on 'working with people who have the passion and drive to work in interdisciplinary research' [interview, SR1]. The Phase 2 Research Fund provoked more explicit attention on disciplinary identity, with a tendency to 'gap-fill' by creating new projects for specific disciplines, especially (previously underrepresented) social sciences. Research Fund calls for proposals explicitly sought participation from psychologists, political scientists, geographers, management scientists, risk studies experts and media studies researchers [67].

The tension between transgressing and upholding disciplinary identities was recognised in the group discussion: 'It's great ... [that] there are single people who span the disciplines [FGD, MC5]; ... [But] doesn't the policymaker want to be assured about where they get their advice from, their credentials? ... Belonging to a particular discipline gives you credibility [FGD, SA2]; ... Academia is based on expertise, so ... we are expected to be disciplinary [FGD, MC3].

Some survey respondents saw interdisciplinary researchers in UKERC as lacking disciplinary credibility: 'although many people and projects involve aspects of social science ... most people have a hard science or engineering background' [survey, Q.12]; 'although there are lots of "engineers" within UKERC, I think their research is often at a higher systems level ... [rather] than being involved in the application of technologies' [survey, Q.12].

4.2. UKERC and integrative interdisciplinarity

UKERC's creation in the early 2000s was shaped mainly by technocrats, with an essentially instrumental approach to interdisciplinary integration i.e. designed with specific types of benefit in mind – especially, enabling the smoother progress of energy supply technologies, rather than a more tentative and reflexive approach.

However, there was initially little consideration of integrative means and methods. This deficit provoked discussion of research practice and design in early UKERC meetings, as the Centre gradually built up its activities. These discussions showed support for the pursuit of WSR, but also concern for the difficulties involved. More recent fieldwork suggests continuing ambivalence; some described the value of a WSR framing in terms of 'understanding interconnectedness' [interview, SR2] and 'ensuring one does not simply look at one sector in isolation ... to make sure [some] policy goals are not set at the expense of others' [interview, SA3].

Others were more sceptical, seeing WSR as an 'imported' term from environmental science, with little relevance for interdisciplinary energy research [interview, EA2], or as difficult to operationalise: 'the problem is drawing the boundary – you need to think about "systems of

systems" to understand how interactions propagate' [interview, AA3]. For another interviewee, WSR was an inherently limited, technocratic framing: 'There is more to "whole systems" than people normally mention ... all sorts of social phenomena as well as physical kit ... Interdisciplinarity goes beyond whole systems ... [to ask] what counts as a system?' [interview, EA1].

Mid-way through Phase 1 a more strongly integrative research form was devised, reflecting growing concerns about the limits of an organic and bottom-up approach. The ability of the Centre to reinvent itself mid-phase was predicated on the strategic discretion awarded to the Research Director. The ambivalent judgement on the resulting Energy 2050 project reflects the strengths and weaknesses of this more 'forced' type of WSR, and the use of whole system modelling as an integrative tool. While Energy 2050's more general insights have endured (such as the trade-offs and synergies between different aspects of system change) many of its more specific findings, such as the anticipated contribution of different supply technologies, soon proved to be erroneous.

Although Phase 2 was established with the same high-level commitment to integrative WSR as Phase 1, research programme integration was in practice given reduced priority alongside variety and flexibility. The Research Fund required significant strategic and management effort, and UKERC's co-Directors were left with reduced strategic authority and discretion. One senior UKERC researcher highlighted the different balances struck in different phases: 'Phase 1 was quite integrated, but it was seen as an "exclusive club"; Phase 2 tried to be more inclusive, but ended up with a not particularly well integrated programme' [interview, SR2]. One senior advisor highlighted the trade-off: 'UKERC needs to decide whether to focus and concentrate on a few institutions or be very open; if it's being asked to be very open, it needs more funding' [interview, SA4].

4.3. UKERC and transdisciplinarity

UKERC was established to offer an independent and authoritative research voice, and although its research was shaped by ongoing consultations with funders, business, policy and civil society representatives, it placed less emphasis on co-design and co-production than some other initiatives; rather than transdisciplinarity, the Centre sought a balance between engagement and autonomy.

In Phase 1, the 'independent and authoritative' pursuit of interdisciplinary WSR was underpinned by wider institutional stability and political consensus – albeit with a privileging of some types of knowledge and disciplines above others. Later on, this became more challenging as energy policy knowledge production proliferated and political consensus weakened. More researchers, consultants and campaign groups became involved in energy research, bringing diverse interests, viewpoints and normativities. While contested politics and fragmented institutions may bring greater demands for independent and authoritative research, it also diminishes the likelihood of any agreed evidence and expertise base. One senior UKERC advisor noted that 'public policy needs clear messages, and interdisciplinary research is difficult to convey' [interview, SA3].

Within UKERC, tensions grew between independence and engagement, and even as the impetus for co-design and co-production gathered, the independent Research Committee promoted academic-led research commissioning and assessment. Some academics and stakeholders argued for deeper dialogue with stakeholders: 'There's a need to involve stakeholders ... more directly than in advisory groups – that would give more credibility to research' [interview, AA1]; 'industry engagement ... needs to be embedded in the whole organisation' [interview, SA4]; 'Academics [need] to see the problem from a policymaker's perspective ... a step-change is needed in the quality of research-policy exchange' [interview, SA2].

However, a number of UKERC's academic advisors and researchers rejected calls for a stronger transdisciplinary commitment: 'Co-producing research means you could lose control of your research agenda'

[interview, AA4]; ‘UKERC must retain its identity as an academic institution – there’s a danger that [it] becomes too much like a consultancy’ [FGD, SA2]; ‘It wouldn’t be appropriate for the whole of UKERC [to] invite ... stakeholders to comment on everything we do’ [FGD, SR2]; ‘Stakeholders want to answer questions that are directly relevant to their benefit ... [it’s] better to maintain flexibility to determine your own project’ [interview, MC1].

Some argued that tensions between independence and engagement could be reconciled by focussing on *co-design* rather than co-production: ‘I’m in favour of ... identifying agreed research priorities ... but there are concerns about co-production, especially in more contested areas’ [interview, AA3]; ‘industrial partners ... should be involved at early stages ... involve them, but don’t follow them’ [interview, AA2]. Another interviewee suggested that academic independence could be fostered by allowing a trade-off between different stakeholder views [interview, EA2].

4.4. UKERC and institutional contexts

Although UKERC was heralded as a major new initiative and a cornerstone of UK public energy research, it was from the outset marginal to Research Council spending. For most participating academics their UKERC role was supplementary to established teaching and research activities. Rather than being able to occupy an autonomous or protected space for WSR, UKERC had to work largely within the confines of mainstream academic institutions. As one senior researcher noted ‘UKERC can’t change how our home institutions, or stakeholders, or funders, organise themselves; we have to work with the way they are’ [FGD, SR1].

UKERC’s multi-Council funding also imposed an institutional imprint on its pursuit of WSR, with a tendency to devise discrete and recognisable activities and outputs for each Council [interview, EA2]; it also had to navigate the distinctive commissioning and assessment practices of each Council, with some Councils strongly shaped by their academic communities while others operated with greater discretion. One interviewee noted the difficulties of explicitly addressing funder-researcher relations: ‘Discussing the terms of trade ... between Research Councils and UKERC and its various stakeholders would be regarded as extremely impolite’ [interview, EA1].

Another challenge for WSR in Phase 2 was the emergence of wide-ranging multisectoral ‘nexus’ research agendas, spanning food, water and climate [57]. Recent policy framings have also embedded energy in broader agendas such as industrial strategy, localism and inequality (e.g. [58,9]). These challenge UKERC’s ‘energy only’ framing: ‘Given where the political discourse is and the imperatives on the funding

bodies ... UKERC will have to expand into ... the role of energy in the wider economy’ [FGD, MC5]. One advisor suggested that these re-framings meant that UKERC should abandon its pursuit of ‘independent and authoritative’ scholarship and embrace a more constructivist approach: ‘[UKERC] should be more open about contending notions of value, and how they might be reconciled through collaborative research’ [interview, EA1].

Research assessment also exerted a powerful imprint. The focus on disciplinary-based, individual assessment in the UK Research Excellence Framework (REF) is a recognised inhibitor of inter-disciplinarity [54], as several fieldwork respondents reaffirmed: ‘REF relies upon discipline-based panels that struggle to assess interdisciplinary papers [interview, SR2]; “REF is a disincentive ... [you] have to justify ‘mixed’ papers to a discipline-specific submission panel” [survey, Q.19].

UKERC was also assessed in a number of dedicated assessment exercises, including mid- and end-phase reviews. These typically involved assembled senior academics and stakeholders, and tended to raise particular disciplinary- or domain-based concerns. For example, a Phase 2 review concluded that UKERC was weak in underpinning and integrative social science research [59] – criticisms which were disputed by the Centre’s senior researchers [60].

UKERC also featured in reviews of the wider Research Councils’ Energy Programme (RCEP). One prominent review identified a lack of coherence across the RCEP, with competition between funding bodies and poor career prospects for interdisciplinary researchers [61]. The review called for ‘a single, well defined cross-Council energy research budget’, with larger centres to be funded for no less than 10 years to provide greater continuity ([61], p. 2, 24).

5. UKERC in context: comparison with other interdisciplinary WSR initiatives

This section compares UKERC’s pursuit of WSR with a handful of other broadly similar UK-based initiatives. The section draws on two types of sources: firstly, the published accounts of senior researchers involved in the different initiatives [56,1,13,5,62,14,16,17,7]. Secondly, original fieldwork conducted for the UKERC case study: as well as their UKERC-based experiences, several of the fieldwork participants were involved in one or more of the other initiatives discussed here, and the fieldwork explicitly solicited comparisons between UKERC and these other initiatives.

The comparative assessment helps to discriminate UKERC case specifics from wider patterns. The comparison has involved identifying some of the main factors involved in shaping WSR practice: funding

Table 1
Selected UK Interdisciplinary WSR Energy Related Research Initiatives.

	Main Funder(s)	Overall Budget ^a	Disciplinary Diversity	Programme Flexibility	Programme Integration	Programme Transdisciplinarity
UKERC 1 (2004–09)	NERC EPSRC ESRC	c.£18.5m	Medium (across physical, social and environment sciences)	Low	High	Low
UKERC 2 (2009–14)	NERC EPSRC ESRC	c.£15m	High (across physical, social and environmental sciences)	High	Medium	Low
Tyndall Centre (Phases 1 and 2; 2000–10)	NERC, EPSRC, ESRC	c.£19m	Medium (mainly social and environmental sciences)	Medium	Medium	Medium
Transition Pathways (Phases 1 and 2; 2008–16)	EPSRC (& <i>e.on</i> in Phase 1)	c.£6.6m	Medium (mainly physical and social sciences)	Low	High	Medium
Rural Economy and Land Use (RELU) (2004–12)	ESRC, BBSRC ^b NERC	c.£22m	Medium (across environmental, biological and social sciences)	High	Low	High

^a Including non-research activities.

^b BBSRC = Biotechnology and Biological Sciences Research Council.

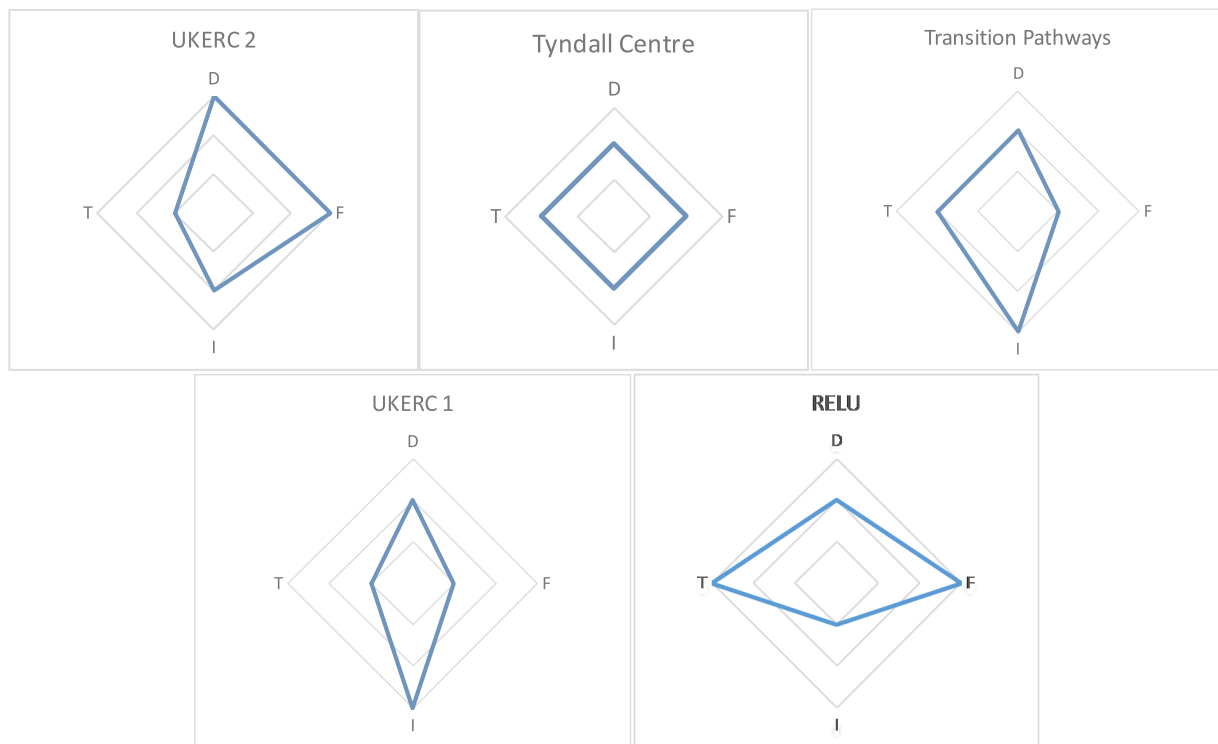


Fig. 5. Mapping UK Interdisciplinary WSR Energy Related Research Initiatives. (D = Diversity; F = Flexibility; I = Integration; T = Transdisciplinarity).

sources and budget, disciplinary diversity, research programme flexibility, programme integration and transdisciplinarity (Table 1). The assessments are based on evidence from published and fieldwork sources, and the author's longstanding working knowledge of the different initiatives (as an advisor, workshop/conference participant and research colleague).

The assessments have been made on a consistent basis: e.g. a 'high' flexibility rating indicates that a substantial proportion of the overall funds were allocated on an open and competitive basis; a 'high' integration rating indicates research processes and outputs that encompassed the majority of the staff involved; a 'high' transdisciplinary rating indicates that non-academic stakeholders were co-designers or co-producers across most of the research programme.

Fig. 5 maps the five initiatives in Table 2 against four criteria: diversity, flexibility, integration and transdisciplinarity. (These are the three elements of interdisciplinary WSR identified earlier, plus an additional 'flexibility' criterion, reflecting the tension in WSR programme design between fixed funds and membership versus more flexible, emergent arrangements). The analysis suggests that under limited funding there are some pervasive tensions in interdisciplinary WSR strategy and practice. For example, the only two initiatives with highly integrated practice and outcomes (UKERC 1 and Transition Pathways) both operated with closed networks, suggested a trade-off between integratedness and openness.

Case particularities shaped these experiences. For example, single-Council funded initiatives such as Transition Pathways were not faced with deriving distinctive outputs for multiple funders; the Transition Pathways consortium was also permitted greater continuity between phases than larger centres such as UKERC and the Tyndall Centre. RELU was distinct in that, although it developed a reflexive interdisciplinary research strategy, it did *not* seek to develop integrated programme-wide insights across its programme: 'RELU [was] less explicitly "whole system" oriented than UKERC; we avoided a single methodological or modelling approach ... we tried opening-up systems models to different disciplines and stakeholders' [interview, EA3]. Reflecting its strong

transdisciplinary commitment, RELU emphasised contextual, local knowledge rather than UKERC's orientation to more 'authoritative' knowledge and expertise; this suggests another inherent trade-off in WSR design and practice: between stakeholder engagement and independence.

UKERC had a unique role as the Research Council Energy Programme's national co-ordination centre [63]. While this was largely pursued by 'non-research' parts of the Centre, it carried some implications for senior UKERC researchers: for example, in commissioning and leading facilitated research conferences and stakeholder workshops. These expectations of 'good academic citizenship' arguably prioritised external relations above internal co-ordination.

Strategic choices were also involved. UKERC gave less explicit attention to its WSR 'aims, means and methods' than some other initiatives. For example, both Transition Pathways and RELU research designs explicitly included interdisciplinary tasks, methods and resources. Among fieldwork respondents with experiences of multiple initiatives, UKERC was judged positively in terms of disciplinary breadth and application (i.e. bringing together different disciplines to address 'real world' problems), but less positively in its WSR design and methods: 'Transition Pathways was more consciously interdisciplinary ... more thought was placed on the actual process' [Interview, EC1]; 'RELU was the best example I know of ... building a community of practice' [interview, AA3]. Although UKERC's less formal approach lent strategic flexibility, it also meant fewer planned opportunities and dedicated resources for interdisciplinary exchange.

Looking more broadly, the UK's interdisciplinary energy research efforts during this period involved multiple public and private sector initiatives, each created for particular purposes at particular times. The resulting pattern is accumulating, overlapping and piecemeal [64]. While a dispersed, polycentric research system has its merits – such as reduced institutional lock-in [19] – it also brings costs, with a danger of 'reinventing the wheel', as similar underlying challenges are discovered anew by each initiative. For UKERC, this institutional churn has meant adapting its strategy as newer initiatives were created (for example,

Table 2
Interdisciplinary WSR Archetypes.

	Strengths	Weaknesses
Integrated WSR (e.g. UKERC 1, Transition Pathways).	Able to pursue centre-wide integrated research across disciplines, with shared designs and outputs. Fosters strong interdisciplinary relationships. Outcomes may command high levels of authority and independence.	May be based on a closed network, with limited disciplinary perspectives and research methods. May lack direct relevance for policy and stakeholders, and be unresponsiveness to changing contexts.
Diverse and Flexible WSR (e.g. UKERC 2)	Able to engage across a broad disciplinary range, and to adapt its research in response to changing policy needs and societal drivers. May be seen as highly inclusive for different researchers and funders.	May have weak integrative capacity, leading to fragmented outcomes. Managing flexibility is resource demanding. Diversity may span inconsistent analytical framings and offer unclear advice for stakeholders.
Transdisciplinary WSR (e.g. RELU)	Research designs and outcomes designed to directly reflect interests and framings of decisionmakers, stakeholders and publics. May command high levels of interest, relevance and impact for non-academics.	Dangers of being 'stakeholder-led', with a lack of independent, critical analysis. Knowledge produced is likely to be embedded in particular contexts, and may lack wider authority.

reducing its efforts on whole systems modelling and end use energy demand); more broadly, it is also at odds with calls for long term stability in major research initiatives.

Further research is needed to compare the different interdisciplinary WSR strategies and practices, beyond the cases covered here, across different combinations of disciplinary breadth or focus, research programme flexibility or integration, and engagement or independence. Table 2 offers a summary of WSR model archetypes, as a guide to researchers, commissioners and assessors.

6. Conclusions and recommendations

Despite attracting increasing interest as a response to complex societal challenges, interdisciplinary WSR is under-recognised as distinct research form among researchers, funders, stakeholders (and interdisciplinary analysts). As a result, it tends to operate in the margins of disciplinary-based research systems. Though it can be designed and practised in different ways, interdisciplinary WSR is likely to involve a combination of radical disciplinary breadth, integrative programme design and transdisciplinary ambition. However, these elements are not easily reconciled, and funders, assessors and leaders of WSR initiatives should give careful attention to the choices and trade-offs involved.

To help better understand WSR as a distinct interdisciplinary form, this paper has considered the experiences a prominent UK initiative over a decade of changing strategies, practices and contexts. The UKERC case illustrates the tensions between disciplinary diversity and interdisciplinary integration, organisational stability and flexibility, and academic independence and engagement. In its first phase UKERC's pursued an integrated form of WSR across a stable research community. In Phase 2, despite having a similar remit, the emphasis was on diversity and flexibility. There was strikingly little attention to these different forms among research funders, commissioners and strategists.

To help consider the generalisability of the case study, the paper offered a short comparative assessment of several energy-related interdisciplinary WSR initiatives in the UK. This comparison, and the wider research literature, indicates the pervasive nature of WSR challenges and trade-offs, yet among more recent UK initiatives (e.g. [65,8]) there is little explicit reference to earlier experiences, suggesting a lack of reflexivity and learning. The comparative analysis was also used to generate a set of interdisciplinary WSR archetypes as a guide to funders, researchers and further interdisciplinary studies.

Interdisciplinary WSR can offer distinctive insights on complex societal challenges, but it is a fragile and often elusive form – as Mike Hulme noted over a decade ago: 'difficult to fund, difficult do and to evaluate' ([1, p. 16]). The UK Government has recently introduced a more unified structure for interdisciplinary research [66] – a long-standing request by some interdisciplinarians. Any revised structure will bring new concerns, for example, the suggested closer coupling between business and academia, and many other intellectual and institutional forces will continue to present challenges to interdisciplinary

WSR strategy and practice. Rather than abandoning such research in the face of these challenges, however, the need is to better acknowledge its distinctive role and dependencies.

Acknowledgements

The research supporting this paper was in-part undertaken for the UK Energy Research Centre, supported by the UK Research Councils awards NE/G007748/1 and EP/L024756/1. The author wishes to thank three anonymous *Energy Research and Social Science* reviewers and the Editor in Chief for their detailed comments, and also a number of UKERC advisors who kindly commented on earlier versions of the paper. Thanks also to Ioanna Ketsopoulou and Tim Churchouse who helped carry out the fieldwork. The views expressed are the author's own.

References

- [1] M. Hulme, Break moulds to recognise value of interdisciplinary research, *Res. Fortn.* (November) (2006) 16–18.
- [2] C. Lyall, A. Bruce, J. Tait, L. Meagher, The role of funding agencies in creating interdisciplinary knowledge, *Sci. Public Policy* 40 (2013) 62–71.
- [3] B.K. Sovacool, S.E. Ryan, P.C. Stern, K. Janda, G. Rochlin, D. Spreng, M.J. Pasqualetti, H. Wilhite, L. Lutzenhiser, Integrating social science in energy research, *Energy Res. Soc. Sci.* 6 (2015) 95–99.
- [4] J. Petts, S. Owens, H. Bulkeley, Crossing boundaries: interdisciplinarity in the context of urban environments, *Geoforum* 39 (2008) 593–601.
- [5] A. Watkinson, A journey in inter-disciplinarity, in: M. Hulme, A. Minns (Eds.), *Truly Useful: Doing Climate Change Research That Is Useful for Both Theory and Practice*, Tyndall Centre, Norwich, 2006, pp. 9–11.
- [6] V. Boix Mansilla, Learning to synthesize: the developments of interdisciplinary understanding, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 288–306.
- [7] P. Lowe, J. Phillipson, K. Wilkinson, Why social scientists should engage with natural scientists, *Contemp. Soc. Sci.* 8 (3) (2013) 207–222.
- [8] Energy Systems Catapult, *Welcome to the Future of Energy*, Energy Systems Catapult, Birmingham, 2016.
- [9] Scottish Government, *Scottish Energy Strategy: The Future of Energy in Scotland*, Scottish Government, Edinburgh, 2017.
- [10] C. Lyall, L. Meagher, A. Bruce, A rose by any other name? Transdisciplinarity in the context of UK research policy, *Futures* 65 (2015) 150–162.
- [11] D. Sarewitz, Against holism, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 65–75.
- [12] J. Jacobs, *In Defense of Disciplines: Interdisciplinarity and Specialization in the Research University*, Chicago University Press, Chicago, 2013.
- [13] M. Hulme, Identifying and mobilising the UK's academic capacity, in: M. Hulme, A. Minns (Eds.), *Truly Useful: Doing Climate Change Research That Is Useful for Both Theory and Practice*, Tyndall Centre, Norwich, 2006, pp. 5–8.
- [14] T. Hargreaves, J. Burgess, *Pathways to Interdisciplinarity: A Technical Report Exploring Collaborative Interdisciplinarity Working in the Transition Pathways Consortium*, University of East Anglia, Norwich, 2009.
- [15] C. Lyall, I. Fletcher, Experiments in interdisciplinary capacity-building: the successes and challenges of large-scale interdisciplinary investments, *Sci. Public Policy* 40 (2013) 1–7.
- [16] N. Longhurst, J. Chilvers, *Interdisciplinarity in Transition? A Technical Report on the Interdisciplinarity of the Transition Pathways to a Low Carbon Economy Consortium*, University of East Anglia, Norwich, 2012.
- [17] J. Phillipson, P. Lowe, A. Proctor, E. Ruto, Stakeholder engagement and knowledge

- exchange in environmental research, *J. Environ. Manage.* 95 (2012) 56–65.
- [18] W. Krohn, Interdisciplinary cases and disciplinary knowledge, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 31–49.
- [19] L. Anadón, Missions-oriented RD & D institutions in energy between 2000 and 2010: a comparative analysis of China, the United Kingdom, and the United States, *Res. Policy* 41 (10) (2012) 1742–1756.
- [20] M. Winskel, J. Radcliffe Skea, X. Wang, Remaking the UK's Energy Technology Innovation System: from the margins to the mainstream, *Energy Policy* 68 (2014) 591–602.
- [21] HMG (Her Majesty's Government), *Climate Change Act*, TSO, Norwich, 2008.
- [22] S. Sorrell, Improving the evidence base for energy policy: the role of systematic reviews, *Energy Policy* 35 (2007) 1858–1871.
- [23] RCUK, *Energy Programme Overview*, Presentation at RCEP Town Meeting, Birmingham, 18th January 2012, Research Councils UK, 2012.
- [24] RCEP, *Energy, The Changing Climate*, Royal Commission on Environmental Pollution, London, 2000.
- [25] PIU (Performance and Innovation Unit), *The Energy Review*, Cabinet Office, London, 2002.
- [26] ERRG, *Report of the Group: Recommendations to Inform the Performance and Innovation Unit's Energy Policy Review*, Office of Science and Technology, London, 2001.
- [27] (House of Commons Environmental Audit Committee) HCEAC, *Memorandum from the research councils (RCUK), appendix B0, energy white paper? Empowering change? Eighth Report of Session 2002–03*, HMSO, London, 2003.
- [28] J. Skea, *Case for Support: Research Programme of the UK Energy Research Centre*, Policy Studies Institute, London, 2003.
- [29] RCUK, *Research Councils UK Review of Energy in the United Kingdom: Evidence to the Panel*, Research Councils UK, Swindon, 2010.
- [30] UKERC, *Proceedings of the UKERC Annual Assembly 2005*, Keble College, Oxford, 6–8 July. London: UK Energy Research Centre, 2005.
- [31] UKERC, *Note on UKERC Discussion Groups*. UKERC Annual Assembly, Edinburgh, 4–6 July, London: UK Energy Research Centre, 2006.
- [32] J. Skea, *An Integrating Research Agenda for UKERC*, UK Energy Research Centre, London, 2006.
- [33] DTI, *The Energy Challenge: Energy Review*, Department of Trade and Industry, London, 2006.
- [34] J. Skea, P. Ekins, *Making the Transition to a Secure and Low-carbon Energy System: Synthesis Report*, UK Energy Research Centre, London, 2009.
- [35] J. Skea, P. Ekins, M. Winskel, *Energy 2050: Making the Transition to a Secure Low-Carbon System*, UK Energy Research Centre, London, 2011.
- [36] UKERC, *Response to UKERC Phase II Moderating Panel*, UK Energy Research Centre, London, 2008.
- [37] NERC, *Specification for Providing Work to Continue Activity of the UK Energy Research Centre (UKERC) 2009–2014*, Natural Environment Research Council, Swindon, 2008.
- [38] NERC, *UK Energy Research Centre: Report of Moderating Panel Meeting to Assess the UKERC Phase 2 Proposal*, Natural Environment Research Council, Swindon, 2008.
- [39] UKERC, *Light Touch Review*, UK Energy Research Centre, London, 2006.
- [40] UKERC, *Case for Support: UK Energy Research Centre: Phase II 2009–2014*, UK Energy Research Centre, London, 2008.
- [41] P. Ekins, J. Watson (Eds.), *UK Energy in a Global Context: Synthesis Report*, UK Energy Research Centre, London, 2014.
- [42] J. Watson, R. Gross, I. Ketsopoulou, M. Winskel, *UK Energy Strategies Under Uncertainty: Synthesis Report*, UK Energy Research Centre, London, 2014.
- [43] P. Weingart, A short history of knowledge formations, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 3–14.
- [44] J. Klein, A taxonomy of interdisciplinarity, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 15–30.
- [45] F. Harris, F. Lyon, *Transdisciplinary Environmental Research: A Review of Approaches to Knowledge Co-production*, University of Sussex, Brighton, 2014.
- [46] G. Brewer, The challenges of interdisciplinarity, *Policy Sci.* 32 (1999) 327–337.
- [47] M. Hannon, A. Rhodes, J. Skea, *The research councils and the energy innovation, Landscape, Energy Strategy Fellowship Report No. 4*, Imperial College, London, 2012.
- [48] A. Barry, G. Born, G. Weszkalnys, Logics of interdisciplinarity, *Econ. Soc.* 37 (2008) 20–49.
- [49] J. Holbrook, Peer review, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 321–332.
- [50] D. Rhoten, Interdisciplinary research: trend or transition, *Items Issues* 5 (1–2) (2004) 6–11.
- [51] C. Calhoun, D. Rhoten, Integrating the social sciences: theoretical knowledge, methodological tools, and practical applications, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 103–118.
- [52] J. Graybill, V. Sheridas, Doctoral students and early career academic perspectives, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 404–418.
- [53] K. Huutoniemi, Evaluating interdisciplinary research, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 309–320.
- [54] British Academy, *Crossing Paths: Interdisciplinary Institutions, Careers, Education and Applications*, British Academy, London, 2016.
- [55] B. Mallaband, G. Wood, K. Buchanan, S. Staddon, N.M. Mogles, E. Gabe-Thomas, The reality of cross-disciplinary energy research in the United Kingdom: a social science perspective, *Energy Res. Soc. Sci.* 25 (2017) 9–18.
- [56] K. Anderson, Integrating decarbonisation research for system-level analyses, in: M. Hulme, A. Minns (Eds.), *Truly Useful: Doing Climate Change Research That is Useful for Both Theory and Practice*, Tyndall Centre, Norwich, 2006, pp. 13–14.
- [57] R. Cairns, A. Krzywoszynska, Anatomy of a buzzword: the emergence of 'the water-energy-food nexus' in UK natural resource debates, *Environ. Sci. Policy* 64 (2016) 164–170.
- [58] BEIS, *Building Our Industrial Strategy*, Green Paper, Department of Business, Energy and Industrial Strategy, London, 2017.
- [59] RCUK, *Natural Environment Research Council Evaluation Panel Report: Evaluation of the UK Energy Research Centre (UKERC)*, Research Councils UK, Swindon, 2012.
- [60] UKERC, *Evaluation of the UK Energy Research Centre, April 2012 and Management Response from the Research Councils, February 2013: Response from UKERC*, UK Energy Research Centre, London, 2013.
- [61] RCUK, *Progressing UK Energy Research for a Coherent Structure with Impact: Report of the International Panel for the RCUK Review of Energy 2010*, Research Councils UK, Swindon, 2010.
- [62] P. Lowe, Interdisciplinarity and integrated research approaches: lessons from the rural economy and land use programme, *UKERC Annual Assembly 2007: Meeting Report*, London: UK Energy Research Centre, 2007.
- [63] RCUK, *The Research Councils' Response to the Report of the International Panel for the 2010 RCUK Review of Energy – 2012 Progress Update*, Research Councils UK, Swindon, 2012.
- [64] IEA, *Energy Technology Perspectives 2012: Pathways to a Clean Energy System*, International Energy Agency, Paris, 2012.
- [65] CESI, *National Centre for Energy Systems Integration*, (2016) Available at: www.ncl.ac.uk/cesi/about/.
- [66] BIS, *Success as a Knowledge Economy: Teaching Excellence, Social Mobility and Student Choice*, Department for Business, Innovation and Skills, London, 2016.
- [67] UKERC, *Report for the NERC Review of UKERC*, UK Energy Research Centre, London, 2012.
- [68] G. Hirsch Adorn, C. Pohl, G. Bammer, Solving problems through transdisciplinary research, in: R. Frodeman, J. Thompson Klein, C. Mitcham (Eds.), *The Oxford Handbook of Interdisciplinarity*, Oxford University Press, Oxford, 2010, pp. 431–452.