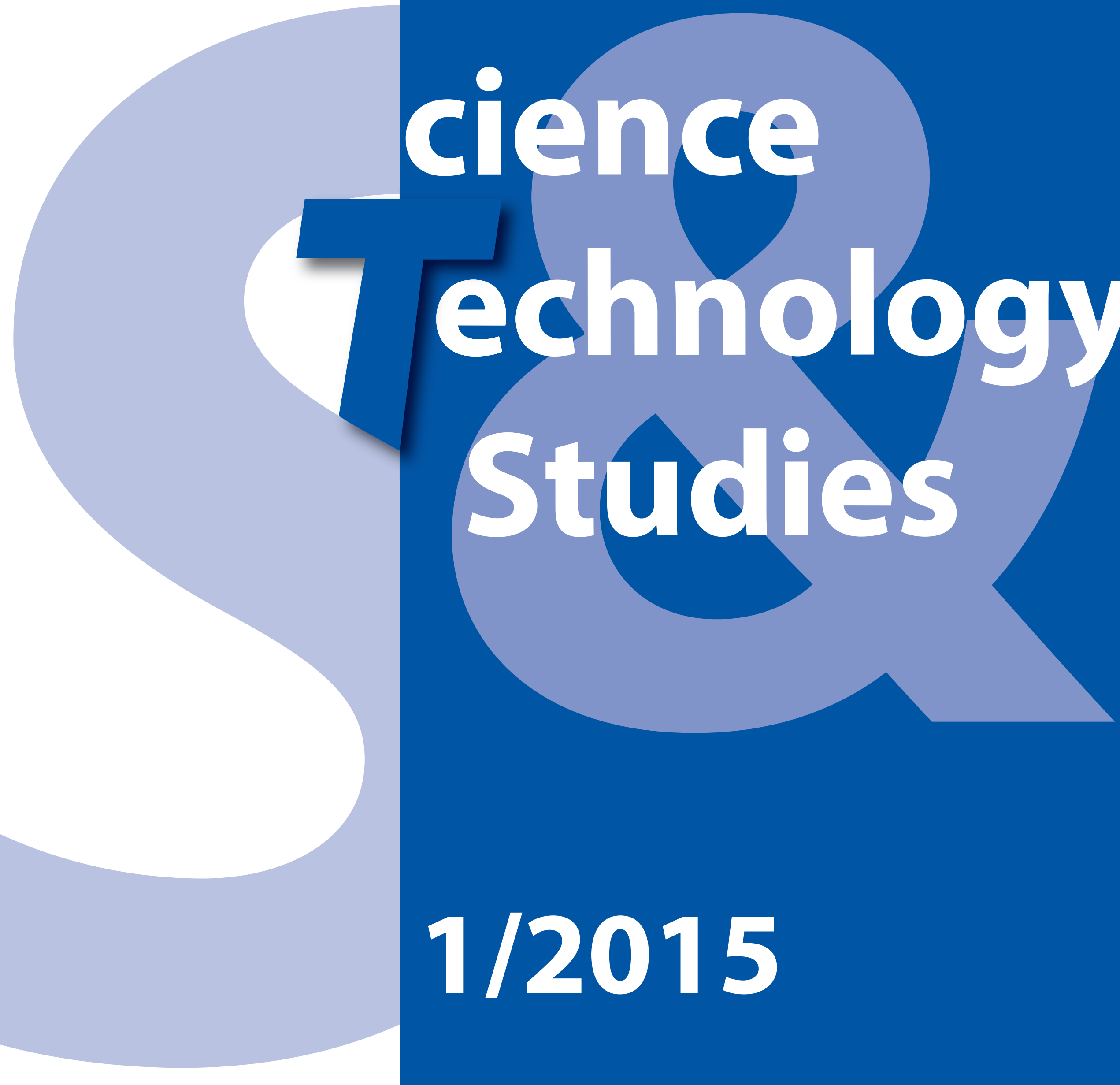

Science & Technology Studies

1/2015

Science & Technology Studies

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2243-4690

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Science & Technology Studies

Volume 28, Issue 1, 2015

Guest Editorial: Second Part

Articles

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Guest Editorial: Second Part

The Politics of Innovation for Environmental Sustainability: Celebrating the Contribution of Stewart Russell (1955–2011)

This is the second part of the special issue of *Science & Technology Studies* on the *politics of innovation for environmental sustainability,* initiated by a colloquium held at Edinburgh University to recognise Dr Stewart Russell's contribution to Science, Technology and Innovation Studies (STIS). The papers in the first part of the special issue, *Science & Technology Studies 27(3),* revolved around issues which preoccupied Russell for much of his academic life: the rescaling and decentralising of energy systems, and the role within this of district heating and combined heat and power. The papers explicated Russell's core intellectual project and considered how this had contributed to contemporary theoretical debates in STIS. As part of his theoretical contribution Weber (2014) fleshed out Russell's specific multi-level approach with its particular interest in political and institutional contestation.

The four articles that make-up this second special issue cover a wider range of sustainable technologies, innovations and transitions across energy, transport and buildings. They share Russell's concern to develop detailed but incisive understandings of the dynamics, barriers and resistances to sustainable innovation, using STS-based and wider sociological analytical resources (Williams et al., 2014). The papers focus on a range of sociotechnical innovations with environmental benefits as they attempt a transition from an 'alternative' to more 'established' or, to use the language of the Multi-Level Perspective (MLP) from 'niche' status to 'regime'. In doing so, they pay attention to both absent voices as well as those present; to those technologies which fail to become established as well as those which succeed; to the relative resources available to different actors; and to the ways in which the social and environmental characteristics of sustainable innovations may be transformed (and in some respects lost) in the course of their development.

Collectively, the papers thus provide an opportunity to explore Stewart Russell's contribution in relation to a wider range of developments in the field of STIS. After briefly introducing each of the papers below, we then draw together their shared concerns under three themes: the barriers and resistances to sustainable innovation; the transformation of green innovations in the course of their diffusion; and lessons for researching and intervening in the politics of innovation for environmental sustainability.

In the first paper, Knut Sørensen seeks to develop an understanding of the long-term challenges of achieving the systemic changes in technologies and practices needed for environmental sustainability. He does this by a retrospective examination of how some cleaner and greener technologies moved from being part of the 'alternative technology' movement of the 1960s and 1970s to part of the present-day mainstream. Sørensen considers the fortunes of three alternative technologies – wind turbines, electric vehicles and ecological architecture – in terms of their development in response to more recent concerns, such as climate change. Sørensen uses the concept of 'sociotechnical mainstreaming' – the transformation of radical niche technologies by dominant interests and institutions – to explore the differing patterns of change. His comparative analysis highlights four different technological and institutional forms of mainstreaming: pragmatic, expansive, dominant design and conceptual.

The second paper, by Graham Spinardi and Rebecca Slayton, also offers a multi-case historical analysis of the fortunes of 'green' innovations. However, while Sørensen considers cross-sectoral patterns, the empirical terrain here is narrower, focused on a single sector. Spinardi and Slayton present three case studies of innovation in aviation (engine designs, advanced materials and wing design) to develop an STS-based account of the resistance to radical sustainable innovation seen in risk-averse sociotechnical systems. In doing so, they also critique the Multi-Level Perspective and suggest ways in which it may need to be extended. They argue, as did Russell, that in 'opening the black box' of innovation the MLP should give greater attention to technological specificities. In the aerospace sector, for example, technologically-specific risks and a conservative regulatory system (with a complex suite of tests and standards built around established proven technologies) present significant barriers to certain kinds of radical (greener) innovation.

The third paper by Kean Birch and Kirby Calvert, critically considers the prospective role of biofuels in the US transition to a low carbon economy. Drawing particularly on Timothy Mitchell's diagnosis of 'carbon democracy' (the deep-rooted dependencies of Western political economy on fossil fuels) Birch and Calvert attend to a wider range of sites, actors and timescales than is commonly the case in studies of innovation. In doing so, they call into question any portrayal of bioenergy as a 'drop-in' fuel – a socio-technical solution to climate change requiring only limited disruption to broader energy systems. The barriers and resistances to prospective sustainable innovations, they argue, are rooted in the deep entanglement of our political, institutional and economic, as well as technological systems in the current carbon economy. Moving away from fossil fuels will require not just technological change, but also new political machinery, new forms of economic knowledge and accounting practices. This echoes arguments in papers from the first part of this special edition by Hawkey (2014) and Webb (2014) who highlight how governance and market structures, respectively, may need to be reformed for more decentralised energy innovations. This raises still unresolved issues about how readily such institutional barriers may be overcome (a point we return to below).

Whilst the first three papers span relatively large scale and long term sociotechnical processes, the final paper, by Christian Clausen and Wendy Gunn, is concerned with micro-level structure and agency, and the more immediate temporalities of design practice. Prompted by some longstanding concerns among STS scholars on the absence of user perspectives about the design process, and the gap between technical solutions and user practices, Clausen and Gunn focus on the use of ethnographic-based interventions to create ‘temporary spaces’ for more meaningful participatory innovation. Drawing on their own efforts to promote awareness of sustainable innovation in the building sector, they explore the scope to reconfigure the metaphorical and literal spaces in which innovation players – developers and users – may interact.

The Barriers and Resistances to Sustainable Innovation

As was evident from Russell’s work on combined heat and power, and from the articles in the first part of this special issue, superior environmental performance is no guarantee of the adoption of a technology, even where there appears to be a strong sustainability imperative. Studies of such ‘failures’ are still far less common than analyses of successful adoptions, but they can provide important insights into the politics of sustainable innovation.

Spinardi & Slayton’s analysis of the lack of adoption of a number of environmental innovations within the same sector is interesting in this context. Given the strength of concern over climate change, one might have expected the aviation industry to be vigorously pursuing innovations which promote better environmental outcomes. However, factors such as the close alignment of players within the industry and the strongly risk-averse context and associated regulatory controls are shown to favour incremental developments over radical innovations. The analysis of the different cases is used to unpick further the dimensions of the widely adopted concept of ‘radical innovation’ – for example in terms of the engineering knowledge involved, or the issues it poses for particular technology adopters or users.

Birch & Calvert’s analysis provides a different perspective on the barriers to environmental innovation created by powerful institutions, actors and embedded infrastructures – what Gregory Unruh referred to as ‘carbon lock-in’ (Unruh, 2000). Focusing on the energy sector, they critique the advocacy of a particular ‘version’ of bioenergy: ‘drop-in’ biofuels. Though this is seen as attractive by some because it promises a non-disruptive transition, the authors argue that this fails to recognise wide and complex socio-technical associations, particularly in relation to land use and transportation. While Spinardi & Slayton offer a call for a detailed elaboration of specific forms of sociotechnical lock-in, Birch and Calvert criticise the narrowness of much techno-economic energy analyses which engage only with immediate barriers to change, and call for attention to more pervasive but perhaps more decisive forms of socio-cultural-technology lock-ins. These ‘hidden’ resistances to sustainable innovation are found *within* and *across* the systems often analysed in sustainable innovation studies research.

What Can Be Lost When Sustainable Innovations Are Taken Up?

In the 1970s proposals for environmentally beneficial ‘green’ innovations were often also seen to have other desirable social characteristics, – such as promoting craft skills and local production. Alternative technologies were thus conceived as a challenge to the dominant industrial regime, which, with its emphasis on specialisation, centralisation and economic imperatives, was seen as having caused and therefore unable to resolve contemporary social and environmental problems. The papers included here present a more complex picture.

Sørensen’s paper poses a general question about what may be lost as an initially politically-radical innovation, geared towards widely distributed local capacities, becomes taken up in a more conventional mainstream industrial and commercial framework. Sørensen finds that those projects which continued to emphasise critical outsider perspectives seem to have been less ‘successful’, in terms of being taken up on a large-scale basis (or merely surviving). However, in more ‘successful’ projects, the radical social goals seem to have been abandoned in the process of institutionalisation and wide diffusion, and a relatively narrow pursuit of climate change mitigation rather than more radical socio-economic sustainability agendas.

Birch & Calvert also critically engage with the suggestion that, in order to be successful, sustainable technologies should be made acceptable to the mainstream. Promoting ‘drop-in’ solutions to environmental problems, they argue, not only favours existing institutional actors in terms of preserving current structures, it also constrains the resources available to different actors to engage in decentralised political action. They contrast this to a scenario with more decentralised energy provision based on biofuels. Rather more explicitly than Sørensen, Birch & Calvert argue that ‘genuine’ sustainability (social, economic and environmental) requires a broader and more radical approach to innovation. A possible counter argument here is that efforts to realise broad disruptive sustainable transitions may increase uncertainties and resistances to climate change mitigation. Winskel and Radcliffe (2014) have argued, similarly, that the increasing urgency of climate change mitigation in UK energy policy had led to a focus on continuity-based change.

At a different scale and locus of analysis, Clausen & Gunn also show that pursuing apparently environmentally superior technologies without regard to their social context – and in particular to those who will be using the technologies – is likely to compromise their environmental credentials. They explore the ways in which the engineering and marketing expertise that drive product development can lead to technologies which are ill-suited to the way people wish to control their indoor climate. The implication here is that users will either fail to adopt or appropriately use such environmentally benign technologies. As with Russell’s (2005) work on representations of use on ‘intelligent’ polymers as well as Birch & Calvert and Sørensen in this volume, the lesson here is that the contexts and processes for the uptake and use of technologies can undermine the envisaged sustainability transition. Assessing the sustainability benefits of new technology requires critical social analysis regarding its likely appropriation patterns, contexts and practices, and calls for continued interventions in the course of their typically extended development periods.

Researching and Intervening in the Politics of Innovation for Environmental Sustainability

These concerns raise questions about the advantages and disadvantages of particular strategies for achieving socio-technical change. For some of the authors their research has led to a critical engagement with the highly influential Multi-Level Perspective that has, under the term Transition Management (TM) (Rotmans et al., 2001; Geels, 2002; Geels & Schot, 2007), achieved wide currency in discussions of promoting an environmentally sustainable society. The appeal of the MLP schema, with its readily intelligible templates that tacitly convey a sense that sustainability transitions could be anticipated and managed, contrasts with the empirical complexity of actual development pathways revealed by historical and sociological studies – as many

MLP-based case studies have themselves illustrated (Winskel & Radcliffe, 2014).

Rather than the MLP's typologies of change, Sørensen argues that the concept of *mainstreaming* captures the complexity of interactions and resistances – for example, in how 'alternative' ideas are transformed and incorporated within dominant institutional frames. Stewart Russell, though broadly supportive of the MLP-TM project (Russell et al., 2012) which he saw as exemplifying his call for analysis which attended to the interaction between local developments and 'layers of context' (Russell & Williams, 2002: 59), also called for attention to be paid to the intricacy of these interactions – which could reveal particular impediments as well as opportunities for policy and intervention. The maintenance of theoretical commitment in the face of complex and perhaps ambiguous empirical evidence was a recurring theme in Russell's work.

From the outset STS articulated a critique of the factors shaping traditional technology design, accompanied by a vision that design and development processes could be redirected to achieve alternative (e.g. human-centred or greener) technologies (Russell & Williams, 2002; Stewart & Williams, 2005). However, in the early stages of STS there was very little practical experience of intervention to change design practice and outcomes. Some decades later, greater experience of attempts to intervene in and redirect technology innovation have highlighted the difficulties in achieving this, given the complexity of interactions involved. Clausen and Gunn's work exemplifies the sustained efforts of STS scholars to engage with technological practitioners – efforts which yield very different understandings of the character of innovation processes, how they are shaped, and the scope to intervene therein.

The papers presented here all illuminate the complexity and situatedness of 'transitions' in practice, both in relation to the adoption of effective environmentally sustainable technologies, and, in cases where adoption does occur, in links with other social values.

As well as emphasising the value of research studies of 'failed' or 'incomplete' transitions, these papers also raise questions about the strategies which could be pursued by those concerned with achieving more sustainable, and equitable futures – be that through high-level policy interventions or at the level of design and development.

One reading of Sørensen's cases might suggest that those wanting to see environmentally sustainable products break out of their 'alternative' or 'niche' status will need to accept that their diffusion will require them to be reshaped by institutions in ways that may lead to a loss of wider social characteristics. However, the variety of ways in which such 'mainstreaming' is shown to have occurred by Sørensen perhaps opens up alternatives paths, which retain such characteristics. In a related way, Birch & Calvert's paper underlines the importance of paying attention to the wider 'political materialities' of energy if we are concerned about social outcomes and the ability of diverse – and currently largely absent – actors to have a stake in policy debates.

Together, the papers represent lines of conceptual development and empirical enquiry which resonate strongly with Stewart Russell's own concerns: the need to analyse sociotechnical change and sustainable innovation in specific institutional and practice contexts; to empirically study contestation over sociotechnical outcomes under the influence of individual and collective actors; and to hold structure and agency (and theory and empirics) in tension rather than favouring one over the other to understand the dynamics of innovation.

We close this review by highlighting a broader feature of Stewart Russell's intellectual project – his concern to promote the health and vibrancy of our still emerging field of STIS. In its early stages its striking intellectual dynamism was characterised by proliferation of empirical studies and conceptual schema – benefitting enormously from pathbreaking inputs by some outstanding individual scholars.

However, developing a field of enquiry is not just an individual task but is a community achievement. It involves different kinds of intellectual work. As well as empirical and conceptual extension, there is also an important, but often unheralded, job of work in integrating and systematising our understanding. Concern that this vital task had not been adequately pursued by the STIS community prompted Stewart Russell to develop a Glossary of "some key social shaping concepts" (Russell & Williams, 2002: 108). Here, he proposed a principled approach to such a project: rather than impose one particular analytical tradition and ignore other schools, Russell argued for the need to attend to and engage seriously with other intellectual traditions within and outwith STIS.

Focusing upon "Confluences and tensions" Russell and Williams (2002: 97) argued for a conception of STIS as a broad church, valuing diversity and debate as a source of creative tension. The papers in this special edition can, we hope, be seen to contribute to this project in two ways. First, they point to the productive interleaving over time of contributions amongst a diverse intellectual community around a broadly shared programme of enquiry. Second, the papers testify to the value of contributions that, while empirically engaged, are able to stand back from particular empirical studies and reflect upon the longer-term evolution of sociotechnical domains, and the changing ways in which we have sought to understand and to shape them.

We hope, through this special edition, to have enabled a more effective understanding of the distinctive analytical contributions of a valued colleague to important ongoing theoretical and policy debates within our field.

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From 'Alternative' to 'Advanced': Mainstreaming of Sustainable Technologies

Knut H. Sørensen

This paper revisits some technologies that, in the 1970s, were considered as 'low-tech' alternatives to mainstream versions, but more recently have been developed using high-tech elements. This change from alternative to advanced is analysed as a process called sociotechnical mainstreaming, whereby technologies are transformed by the dominant R&D institutions and/or industry. The paper aims to clarify what is involved in such processes of mainstreaming, and how they affect the fate of the alternative technology legacy, not only in terms of being ecological but also their production being craft-based, decentralised and with some form of local control. This is explored through three examples: wind turbines, electric cars, and ecological architecture. Four mainstreaming processes are identified: pragmatic, expansive, dominant design, and conceptual. More empirical research is called for to further develop the concept of mainstreaming.

Keywords: alternative technology, mainstreaming, sustainable transitions

Introduction: A Point of Departure

Most of today's sustainable energy technologies have in some way emerged from what used to be thought of as alternative technologies in the 1970s and 1980s. While they still are alternatives to the entrenched, fossil fuel based technologies, the dynamics of their development have changed. It was expected that alternative technologies would be made differently from the dominant industrial regime with its emphasis on advanced design, mass production and centralisation. Alternative technologies were supposed to be based on low or intermediate technology elements and designs developed outside the industrial and technological centres. In contrast, present-day efforts make use of advanced elements and designs and take place at the very centres of technological development. This paper uses the concept of mainstreaming to help understand and describe this change.

What perception of technology was characteristic of the alternative technology discourse? Langdon Winner (1977) chronicles the many roots of critical appraisal of technology, in particular the idea of an autonomous technology developing from its own logic, more or less out of control of humanity. This admittedly pessimistic outlook was supported by observations that industrial technologies were endangering, even destroying the conditions of human life through massive pollution and reckless exploitation of natural resources (see, e.g., Dickson, 1974). The interest in alternative technologies emerged from these fears, as a strategy to regain human control of technology as well as achieving more environmentally friendly designs. In addition, a concern for third world countries' need for cheaper and locally manageable designs was important.

At the heart of the argument was technological determinism: the idea that technology represents a force developed outside of society with the ability to reshape social relations. The fear that advanced technologies would increasingly display unwanted but unavoidable properties was used to support the alternative technology agenda. However, as Stewart Russell (1993) noted, technological determinism is difficult to reconcile with a critical or alternative technology policy. To accept determinist arguments limits strategic choices to two main options: either to protest against the hegemonic technological regime and dismiss new technologies, or to try to create protected spaces where alternative technologies may be developed. The 1970s and 1980s saw examples of both – for example industrial actions to stop new technologies and efforts to create alternative life styles. Though the strategy of simply dismissing new technologies attracted little political support, ideas of fostering alternative technologies were more popular (Winner, 1986). The radical social movements of the period engaged in resistance, as well as making efforts to modify proposed technological projects.

As we shall see, what was usually understood as alternative technology grew out of a belief that the dominant trajectory of technological development could not help to solve social and environmental problems. How could the hegemonic technology be used to manage the problems that it had produced itself? Thus, the interest in alternative technology was linked to the perceived possibility of making artefacts that were environmentally friendly and socially desirable, without being caught in the wheels of advanced engineering embedded in large-scale, wasteful and alienating industry.

We now observe that alternative technologies seem to be appropriated by advanced engineering; what has happened? An interesting line of inquiry is suggested by Winner (1979). He made an early attempt to take stock of the achievements of alternative technologies and argued that developing new assessment criteria was more important than constructing new technologies:

> [T]he ultimate promise of alternative technology has little to do with the new hardware that it may happen to develop. Indeed, if the success of the field is to be measured solely in terms of new inventions to solve the energy crisis, then it will have done little that is significantly new. [...] A sign that alternative technology has reached a meaningful point of sophistication would be its ability to move logically from a set of critical, evaluative principles towards specific criteria of technological design. (Winner, 1979: 83)

Consequently, mainstreaming of alternative technology could be understood as the application of its design criteria in a high-tech context; what were these criteria?

What Was Alternative Technology?

As Winner (1986) argued, the roots of the alternative technology movement are found in a complex combination of the politics of the period, diverse theoretical sources and practical experiments. Dickson (1974) describes the ambitions as characterised by utopian thought, to break with established patterns to seek new principles for development and use of technology. The main idea was that the alternative technology should be 'soft', environmentally friendly and economical with respect to resources:

> [Alternative technology] should function most effectively at the lowest level of society; […] the poorest people should be able to use it; […] it should be based primarily on ecological and social considerations, rather than those of economic efficiency; […] it should allow the possible evolution of small, decentralized communities; and […] it should require relatively small amounts of resources (Dickson, 1974: 101).

Thus, it was important to transcend the dominant industrial regime that emphasised large-scale design and standardisation as keys to growth and efficiency. E. F. Schumacher, one of the best known spokespersons at the time for a different way of developing technology, formulated the alternative in a simple and rhetorically effective manner – 'Small is Beautiful':

> The system of mass production, based on sophisticated, highly capital-intensive, high energy-input dependent, and human labour-saving technology, presupposes that you are already rich […]. The technology of production by the masses, making use of the best modern knowledge and experience, is conducive to decentralisation, compatible with the laws of ecology, gentle in its use of scarce resources, and designed to serve the human person instead of making him the servant of machines. (Schumacher, 1973: 143)

Clearly, Schumacher's approach to alternative technology was based on a critique of then current big industrial technology as wasteful, hostile to the environment, and alienating. At the same time, he linked the need for alternative or intermediate technology particularly to developing economies as a corrective to the dominant approach to technology transfer as based on advanced, industrially oriented solutions.

Dickson (1974) perceived alternative technology as a socialist strategy, as a way of building a different type of society. Schumacher (1973) was more pragmatic and saw 'intermediate technology' as a realistic, preferable option of reforming technology transfer. It is important also to note that he specified alternative technology as something in-between the advanced and the primitive. Intermediate technology should be an improvement to already existing artefacts but at the same time be manageable in local communities of developing economies.

Jéquier (1976) proposed a distinction between three varieties: (1) low cost technology, (2) intermediate technology, and (3) appropriate technology. The third of these labels seems to have been the most widely used (Carr, 1985). This reflected the emphasis placed upon the need for new technologies to be adapted to local conditions:

> Appropriate technology […] represents what one might call the social and cultural dimension of innovation. The idea here is that the value of a new technology lies not only in its economic viability and its technical soundness, but in its adaption to the local social and cultural environment. (Jéquier, 1976: 19)

The argument that technology should be appropriate gained some support in the discussions about transfer of technology to developing economies. However, the idea that technology should be locally manageable was seen as important also to industrialised countries (Dickson, 1974; Winner, 1986). Regardless of the actual interpretation of the concept, alternative technology discourses stressed the importance of increasing the possibility for decentralised local communities to develop their own technologies according to local skills and local resources. Ideally, it should be possible to make the technologies locally; at least their running should be manageable for local people.

Underlying this view was the presumption that local communities engaging with alternative technology would encompass a fairly broad share of the population. Equally, innovation competence should be more evenly distributed. The communities pursuing alternative technology were believed to need a relatively high general level of mechanical skills and proficiency with machines. Accordingly, we find a comprehensive engagement with practical technological possibilities in books on alternative or appropriate technology (see, e.g., Carr, 1985; Darrow & Saxenian, 1986).

The idea that technologies should be locally embedded and with broad public participation signalled the need to break with the universalising approaches of the hegemonic engineering sciences. At the same time, the concept of intermediate technology emphasised that alternatives did not need to be primitive or low-tech – they should just not be ‘advanced’ according to the dominant premises of the engineering sciences.

In the early 1980s, the alternative or appropriate technology movement more or less disappeared (Pursell, 1993), although the concept of appropriate technologies has continued to play a role in technology transfer and technology dynamics in developing countries (Kaplinski, 2011; Murphy et al., 2009). Winner (1986) also noted the demise and thought that the enduring legacy of the appropriate or alternative technology was in the making of some of its concepts like sustainability more of a commonplace to planners, engineers, and the public; this assumption is also found in approaches like ecological modernisation (Mol et al., 2009).

What were the main ideas of the alternative technology movement? Adrian Smith (2005) suggests four requirements: (1) craft-based, (2) local participatory control (3) small-scale and decentralised, and (4) ecologically sound. To what extent have these criteria been taken on board in the mainstreaming of alternative technology? When studying this issue, we are warned by Winner (1986: 73) that “the set of criteria upon which this vision of good technology rests [...] may not be compatible. Hence, it is not obvious that decentralised technologies are necessarily sound”. In addition, the criteria are not unambiguous: even with respect to ecological soundness or sustainability, assessments may be framed in different ways (see, e.g., Jørgensen, 2012; Skjølsvold, 2013).

The paper does not address the latter problem. Primarily, it explores some efforts to mainstream alternative technologies, and if and how the four above-mentioned criteria have been part of the transformation process, but not whether the outcome may be considered environmentally friendly. Additionally, the paper examines if there are clear links between the original alternative technology ideas and the more high-tech outcomes of the transformation.

Mainstreaming Alternative Technologies

Evolutionary innovation theory puts learning – in a variety of articulations – at the centre of technological change (Lundvall et al., 2002). This includes standard-setting and other forms of regulatory actions that may mediate between, for example, environmental concerns and innovation efforts. At an abstract level, we might see influence from alternative technologies as related to some form of learning, perhaps through search processes initiated as a response to environmental regulations. However, we need more knowledge about this, including conceptual development.

Inspired by Berker (2010), the processes through which alternative technology ideas are integrated into mainstream technological development is referred to here as mainstreaming. Berker borrows this concept from the literature on gender equality, where gender mainstreaming denotes a strategy to transform organisational processes by introducing concern for gender equality as a mandatory consideration (see, e.g., Benschop & Verloo, 2006). He contrasts mainstreaming to substitution as a strategy of implementing sustainable energy technologies. Substitution designates a top-down approach of 'creative destruction' where new, science-based designs replace existing technologies. Mainstreaming, according to Berker, involves bottom-up, incremental improvement of compatible technologies.

There are other approaches that may be used to study such transformations. For example, David Hess (2007) puts social movements at the centre of the making of alternative pathways for scientific and technological development. He differentiates between industrial opposition movements, which aim to stop a particular technology, and technology- and product-oriented movements that work to develop alternative systems of technology and products. With some reserve, Hess (2007: 236) argues that "agents of social change often find, to their chagrin, that they have made history, but not exactly according to their original vision. Rather than achieving a full victory, they usually become caught up in a more complex dance of partial success and co-optation".

This view raises questions about the nature of co-optation processes and their outcomes. Hess (2007: 237) describes the potential successes of the technology- and product-oriented movements as related to the incorporation and transformation of ideas by established industry: "as the mainstream industry shifts from resistance to incorporation, the companies may acquire the innovating entrepreneurial firms or develop new product lines, and they often redesign alternative technologies". However, the problem with concepts like co-optation is the underlying suggestion that when alternative ideas, actors or social movements gain influence, they usually are modified to become less radical or even rendered harmless. 'Mainstreaming' does not make such presumptions, although co-optation may be a form of mainstreaming.

Another approach that focuses on the way environmental concerns are made to shape modern societies is ecological modernisation. Here, the focus is on environmental reform to make such ideas mainstream in industry, government, etc. Thus, policy-making is given particular attention (see, e.g., the contributions in Mol et al., 2009). My emphasis in this paper is on the role of sociotechnical transformations, which means that the ideas that are to be mainstreamed, in addition to catering for environmental concerns, also may include suggestions regarding other aspects of design, such as size, shape, and resources. This is different from the more general environmental criteria promoted through ecological modernisation and also in approaches like clean technology or clean innovation (see, e.g., Markusson, 2011).

The idea of moving environmentally friendly innovation into mainstream development is also important in the 'multi-level perspective' on sustainable transitions. This approach distinguishes between three levels: (1) niches, where innovations may be nurtured and protected; (2) sociotechnical regimes, that refers to the rules that shape development of technology; regime is the mainstream of development of technology; and (3) socio-technical landscapes, which represent contexts beyond the direct influence of niche and regime actors, like macro-economic or macro-political developments (Geels, 2002; Verbong & Loorbach, 2012). From the multi-level perspective, sustainable sociotechnical transitions mainly take place when sustainable innovations make their way from the niche to the regime or mainstream level. This may happen through different pathways that are produced through different forms of interaction between the three levels (Geels & Schot, 2007). Smith (2005) proposes that alternative technologies like wind power or local organic food may be niches that make their way into the mainstream regimes.

The multi-level perspective has gained considerable popularity as a way of studying sustainable transitions, possibly due to its rather formulaic features. However, its proposal to study sustainable transitions as produced through the interaction of the three levels creates analytical difficulties: first, there is the issue of how to distinguish empirically between the three levels; second, the underlying systems approach tends to give actors and action less attention. This has resulted in oversights with respect to the role of political and other controversies as well as a lack of consideration of the strategies of involved actors. Geels' (2014) effort to remedy some of the problems by indicating how politics and power may be analysed at the regime level illustrates the difficulties with the idea of system-generated transition pathways.

The mainstreaming concept avoids some of the problems with the multi-level perspective, because it uses a 'flat', action oriented approach. The advantages of this way of thinking are argued by Latour (2005) in a general sense and Jørgensen (2012) specifically with respect to sustainable transitions. Rather than seeing sustainable transitions as results of niche innovations being nurtured to grow into the mainstream regime, mainstreaming of alternative technologies is viewed as a co-production of niche and mainstream developments. What needs to be clarified is the nature of such co-productions and the role and effect of alternative technology criteria, including the strategies of participating actors and the conflicts that may take place.

The analysis here starts from an assumption that mainstream technological development is embedded in technologically advanced engineering. This is not to say that this development is science driven but that it draws upon scientific insights and new artefacts that are made from such insights. Thus, mainstreaming is seen as a process where ideas and concepts from the alternative technology tradition are used to change the direction of mainstream technological development. For example, the alternative idea of using wind rather than fossil energy has been picked up by companies that use their competence in making technology for offshore production of oil and gas to contribute to the design of offshore wind parks (Steen & Hansen, 2014).

However, alternative ideas and concepts themselves change through mainstreaming, and over time, some aspects of the alternative thinking may become less important or even disappear. For example, within the field of new renewable energy sources, it is mainly the ideas about alternative energy sources that are retained, while the first three characteristics identified by Smith (2005) – craft-based, local participatory control and small-scale decentralised – tend to fade out of sight.

Cases and Method

The remaining part of the paper explores the ability of 'mainstreaming' to make sense of the transition from 'alternative' to 'advanced' by discussing three cases: wind turbines, electric cars, and ecological architecture. These have been selected in order to look for diversity in mainstreaming processes. Wind turbines were considered an alternative technology, but have become a well-established concern of a technologically advanced industry as well as public R&D institutions. Electric cars were for a long time a marginal phenomenon, a technology for those with particular interests and developed by actors outside the established automobile industry.[1] Ecological architecture is a field with considerable technological diversity, but where particular ideas have played an important and controversial role in the development of strategies for sustainable buildings.

The three cases are based on re-analysis of secondary sources; most of them published scientific studies. The wind turbine case is focused on Danish experiences, which have been considered particularly important in the development of wind turbine technology and so have been quite widely studied. The electric car case is mainly concerned with developments in Denmark (Munch, 2002) and Norway, in particular the Norwegian Think efforts (Undheim, 2002; Kårstein, 2010). However, these sources have been supplemented by a search using the news media database retriever.no to update the information about Think. The case of ecological architecture is based mainly on Norwegian publications (especially Ryghaug, 2003, 2007).[2]

Thus, the three cases are based on sources using different methods. The wind turbine case is based on primarily written sources. In the electric vehicle case written sources using interviews as well as documents are combined with newspaper articles. The ecological architecture case is based on publications using interviews with architects. The case material has been analysed in an 'abductive' manner, which means that the analysis has moved between conceptual deduction and empirical induction (see, e.g., Reichertz, 2007).

The selection of the cases and the data sources raise some issues. First, the three cases clearly differ with respect to their maturity. Wind turbines are fairly well established, electric cars seem to be in the midst of a fairly rapidly changing development, while ecological architecture is less mature, and still on its way to take-off. The analysis has consciously tried to take into account differences in mainstreaming due to differences in the stage of development. Second, the cases involve different types of actors and contexts. However, this allows for analysis of the mainstreaming concept under diverse circumstances. Third, there are in places insufficient original or detailed data to allow a closer study of specific mainstreaming processes. Even so, the available secondary data has allowed for a preliminary comparative analysis.

Wind Turbines: The Alternative Technology that Ousted the Advanced

After the oil crisis in 1973, many industrialised countries began searching for alternative sources of energy. Wind power emerged as one of the most promising options, but it was pursued in different ways.

Industrial communities in Germany and the US thought they could use advanced engineering competence, in particular from the aerospace industry, to design large and light-weight wind turbines. Danish actors followed a rather different development pathway. (Heymann, 1998; Nielsen, 2010)

The German and US efforts met with serious technological difficulties, and after a while they were outdistanced by the Danish wind turbine industry. Danish actors conducted R&D to explore the possibilities of high-tech wind turbine design, but did not follow the trajectory of advanced, science-based engineering. Rather, wind turbines were constructed by a locally embedded mechanical industry with a strong craft tradition, and the turbines were largely bought and operated by Danish farmers. Thus, initially, wind turbine development was characterised by small enterprises and local ownership. This facilitated close interaction between users – mainly farmers – and the emerging wind turbine companies. In turn, this meant that the industry could make use of user experiences to improve the products (Jørgensen & Karnøe, 1995).

Garud and Karnøe (2003: 296) described the Danish development of wind turbines as a bricolage-like approach "that begins with a low-tech design but ramps up progressively". This contrasted with the strategy pursued by the German and US actors – aimed at a high-tech breakthrough by providing a completely new design, linked to industrial, large-scale production of electricity. Thus, the Danish experience appears to be an example of how technological innovation based on an alternative path may outstrip and substitute high-tech engineering science – at least for a while. The alternative technology criteria (Smith, 2005) were in the Danish case met through reliance on intermediate technology solutions: use of local resources and local embedding of the activity. However, Garud and Karnøe (2003) show that this is only part of the story. Gradually, some companies began to construct wind turbines for export, particularly to California; these companies grew larger, and the local foundation of their operation became weaker. Increasingly, the technological development of wind turbines became based on high-tech engineering science. Today, to characterise the Danish wind turbine industry as low or intermediate technology would be very misleading.

Kemp et al. (2001), working from a multi-level perspective, interpret Danish wind turbine development as a result of policy interventions. Clearly, policy was important, not the least the introduction of a fairly generous feed-in tariff, technological standards and, later, investment subsidies. In addition, the planning system was beneficial (Buen, 2006; Munksgaard & Morthorst, 2008; Petterson et al., 2010). Jørgensen and Karnøe (1995) also remind us that the political climate was favourable, not the least through support from the anti-nuclear movement. The mainstreaming of the alternative wind turbine technology was facilitated by the political and administrative context. However, it is unclear how important this 'landscape effect' actually was.

When we analyse the Danish wind turbine story as a mainstreaming narrative, there are some other striking features. It begins as an account of the strength of alternative technology relative to more high-tech efforts, not least through the pragmatism of alternative technology actors. However, its continuation shows the unfolding of a high-tech mainstreaming. When Danish companies reached a share of 40% of the world market of wind turbines it was because they had been at the technological forefront for some time (Nielsen, 2010). The path of development has become unequivocally high-tech.

The mainstreaming was therefore a co-production of the niche of wind turbines as alternative technology and mainstream engineering, merging into the present-day high-tech wind turbine industry.

The early stage of the Danish development of wind turbine technology arguably satisfies all four of Smith's (2005) criteria. However, after the mainstreaming process, the Danish wind turbine industry at best meets only the fourth criterion, of ecological soundness; none of the other three are met today. Standard wind turbine technology is not simple and craft-based, it cannot easily be made anywhere, and its design and development is embedded in high-tech engineering science. Interestingly, the rapidly growing wind turbine industry in India and China today follows a high-tech track, not an intermediate strategy (see, e.g., Lewis, 2007).

To summarise, the development of wind turbine technology during the last 3–4 decades began when the use of an alternative technology approach in the context of Denmark provided a fruitful point of departure for designing robust, functional turbines with a stepwise innovation strategy. The subsequent further development of larger and more efficient turbines was increasingly supported by R&D and high-tech engineering, resulting in technologically advanced products from a technologically advanced industry. Is this a typical path for alternative technologies if they extend beyond their alternative niche?

Electric Cars: Alternative Technology or Alternative Mobility?

Electric cars played a prominent role in the early development of modern mobility (see, e.g., Mom, 2004). However, they were outstripped by combustion engine cars in the early 20th century. When they re-emerged as a concept in the 1970s, it was more as a curiosity and a special niche vehicle than a real challenge to the standard automobile (Fogelberg, 2000). Thus, the electric car of the 1970s and 1980s was an alternative technology, satisfying the criteria of being small-scale, decentralised, ecologically sound, maybe also craft-based, but without local participatory control. The cars were made in small numbers by small companies, and they differed from standard combustion engine cars not only in terms of the motor, but in the whole design. This meant not only that they were more environmentally friendly, but also that they were based on an alternative concept of mobility, namely short distance driving in and around cities. Thus, electric cars were an urban niche phenomenon.

Increasingly, however, the large automobile manufacturers are offering electric models as alternatives to combustion engine cars. The number of electric cars in the streets still remains relatively small, but the sociotechnical context of the development is radically different. When the concept of electric cars re-emerged in the 1970s, most efforts to design and build them came from actors outside the automobile industry (Maruo, 2000). The Norwegian inventor Lars Ringdal is a typical example. Ringdal was primarily engaged in making of plastic boats but in the wake of the so-called oil crisis of 1973, he developed a conceptual design of a small car, cast in plastic and running on an electric engine. This idea was picked up later by a small Norwegian company Pivco in their construction of an electric car that eventually became Think. (Undheim, 2002)

Developments in Denmark and Norway illustrate particular features of the niche-like development of electric cars, in terms of how they were manufactured, and their patterns of use.[3] In Denmark, several models of electric cars, meant for short-distance, city driving, were produced in the 1970s and

1980s. However, none of the models of this generation of electric cars were produced in more than 50 units. The total production increased somewhat in the next decade but never became large. The most popular model of the 1980s was the Ellert, which was marketed more extensively than the previous models, but sales were no more than around 700 vehicles. (Munch, 2002)

We may safely characterise the Ellert as an alternative, intermediate effort. It was relatively environmentally friendly, and the production was substantially based on locally available resources and skills. Moreover, electric cars in the Danish context were made for a particular group of users (public institutions), for a particular purpose (driving short distances in cities), and with a different design (small, lightweight vehicles with relatively low top speed). Thus, it was made for an 'alternative' audience, which remained small.[4]

To what extent do we observe mainstreaming efforts? In the early 1990s, new ideas emerged about how to design electric cars and how they could be marketed. In Denmark, the electric Kewet Citi-Jet car was made to be as much like a normal car as possible. Its maximum speed was 75 km/h, and the range was 80 km (Munch, 2002). The Kewet Citi-Jet represented a break from the idea that this alternative technology should be linked with alternative mobility – driving short distances only. Even more important was the shift in thinking about what should be demanded from users:

> The putative users of a Kewet were ordinary people who wanted a well-functioning, easy to drive, noiseless vehicle, performing so similarly to a conventional car that they did not have to make major adjustments of their driving patterns and practices (Munch, 2002: 74).

The Norwegian company Pivco used the conceptual drawings of Lars Ringdal as a basis for designing an electric car with an all-plastic vehicle body, eventually called Think. The name was chosen because the car was promoted to represent an alternative form of mobility – meaning less driving – while a lot of effort was put into the design of the car body to give it a suitably 'alternative' look. Even if the body was made of plastic, neither the car's technology nor its production was alternative in the sense that it was low or intermediate technology. Think was a professionally constructed car with some high-tech qualities, and its maximum speed and range was about the same as the Kewet City-Jet (Undhjem, 2002). It could be considered as a niche product in an early stage of sociotechnical mainstreaming, with a goal of being environmentally friendly.

The detailed story of Pivco and Think is fairly complex, with multiple bankruptcies, shifting ownership and discontinued strategies (Kårstein 2010). A couple of observations will have to suffice here. Most striking was the fact that one of the world's largest automobile companies, Ford, became a majority owner of Pivco and Think in 1999, in response to California's Zero Emission Vehicle (ZEV) policies (see Hoogma et al., 2002). When Ford's CEO at the time, Jack Nasser, announced the transaction, he stated that:

> This car not only will give us immediate access to a whole new market niche, it will provide a wealth of new ideas for us to develop. We are particularly interested in new concepts in the use of plastic body components, as well as low-volume and flexible manufacturing. (Quoted from Hoogma et al., 2002: 84–85)

Ford helped to accelerate the mainstreaming process of Think, and thus of the electric car; between 1999 and 2003 Ford invested around 200 million dollars to develop a production line for a new model, Think City, which was more similar to combustion engine cars than the previous model. However, Ford sold off Pivco soon after California modified their ZEV policy in 2003, stating that they rather would explore options related to hydrogen and fuel cells. Nevertheless, the mainstreaming of Think's design continued with new owners. Their new concept car, Think Ox, signalled that the original ideas of Pivco to make Think a car for alternative, mainly urban, mobility had been abandoned.[6] Mainstreaming resulted in efforts to make the electric car more like conventional cars. While Pivco learnt from Ford, it remains unclear whether Ford learnt from Pivco, as Nasser intended.

Compared to the wind turbine case, the mainstreaming of electric cars was more complex, with greater uncertainties. The development received little or no support from any social movement. Pivco began by providing something that definitively was an alternative car, technologically as well as with respect to use. It was marketed as a new form of mobility, as a lightweight vehicle with limited range, to be leased to companies and public institutions. Pivco was a small company located in a fairly small community some 50 kilometres outside Oslo. Initially, there was local control and a base in craft skills but no participatory interaction with users. In the mainstreaming process, local control was lost, together with most of the alternative design concepts except environmental friendliness. With respect to Smith's (2005) criteria, this is an ambiguous case.

Arguably, the main contribution of Pivco and other actors in their efforts to make electric cars was to revive the concept of electric mobility, emphasising short-range, low emission, low noise, and low speed driving. According to Maruo (2000), several producers of electric cars were acquired by traditional auto companies looking for ideas about how to design electric vehicles, similar to Ford's relationship to Pivco. Furthermore, Sierzchula et al. (2012) argue that the field of such vehicles is transitional, with many new entrants. In some places, like California and Norway, supportive policies are in place (Brown, 2001; Ryghaug & Toftaker, 2014). Overall, it appears that the established automobile industry may be learning from alternative efforts, but the mainstreaming of the electric car seems increasingly to be influenced by the image of the standard automobile with an emphasis on speed and range but also with strong similarities with regard to design. Criteria of craft-based, local participatory control and small-scale decentralised have been lost in the mainstreaming process.

Ecological Architecture: From 'Knitted Houses' to Glass and Steel

While wind turbines and electric cars were alternative products, ecological architecture has been a reform programme in the mainstream building industry rather than an alternative technology, with quite diverse conceptions and pluralist practices (Guy & Moore, 2007). Even so, ecological architecture largely fulfils Smith's (2005) alternative technology criteria. Compared to wind turbines and cars, the building industry is to a greater extent characterised by small-scale, locally controlled activities. Thus, the mainstreaming of ecological architecture could have been less disruptive than the two other examples. In practice, ecological architecture has proven controversial, making mainstreaming difficult.

When it emerged in the 1970s, ecological architecture differed from dominant approaches with respect to design and choice of materials. Ecological buildings were environmentally friendly, preferably built of local resources and using low or intermediate technology elements. However, the majority of practicing architects in Norway perceived ecological houses as badly designed (Ryghaug, 2003, 2007). Ecological buildings were considered personal statements with a home-spun character, associated with the use of 'outdated' building materials like earth or bales of straw. Ecological houses were criticised for looking too much like traditional mountain cottages. The design was described by words like chubby, hairy, dishevelled, organic, knitted, or as having a 'barefoot out in the woods' style. The architects interviewed by Ryghaug criticised the use of many different angles and curved lines in ecological buildings. One architect described the approach in the following way:

> These earthen houses where pee, poop and plugs are recycled and comes out of the kitchen tap [...] after four turns of purification. This is something different, then, like pigs on the roof and goats in the basement. This is the backyard ecology from Berlin in the 1970s that was further developed also in Norway. (Quoted in Ryghaug, 2007: 221, English translation by the author)

The blunt dismissal by the large majority of architects clearly made ecological architecture difficult to mainstream. How then to consider its relationship with the emerging high-tech sustainable architecture? To begin with, this latter effort shares some aesthetical preferences with traditional architecture, but it is at the same time experimental and oriented towards energy efficiency and environmental friendliness, for example by using double glazed facades and complex ventilation systems (Andresen et al., 2007). This also means that technologically advanced ecological architecture is at the research frontier and to a substantial degree shaped by elements made by engineers. Some architects fear that the visual expression of such buildings thus becomes sturdy and boring (Ryghaug, 2007: 222). Nevertheless, this type of ecological architecture is increasingly popular among architects as well as builders, and probably will influence a growing number of new buildings (Kongsli et al., 2008 Hojem et al., 2014).

High-tech ecological architecture shares some features with the traditional ecological approaches, such as local control and an experimental approach. The lack of public standards for ecological buildings in Norway, except with respect to energy efficiency, means that the local contexts as well as the ideas of the project actors are important (Kongsli et al., 2008 Hojem et al., 2014). However, the high-tech architects use advanced technology to signify sustainability in the visual expression of the buildings, rather than organic elements (Kongsli et al., 2008; Hojem et al., 2014).

Has traditional ecological architecture really been mainstreamed? As a reform programme, the original ecological architecture made little impact upon the building industry. As we have learnt, it was controversial and marginalised (Ryghaug, 2007; see also Smith, 2007; Guy & Moore, 2007), and it is still practiced as a fringe phenomenon. Moreover, the local qualities of both traditional and high-tech ecological architecture reflect characteristics of the building industry more generally.

The ideas that buildings should be energy efficient and sustainable have been drivers of the development of high-tech ecological architecture (Andresen et al., 2007. Did this idea come from traditional ecological architecture? Judging from accounts of building industry actors, the idea has mainly been picked up from the general discourse about environmental and climate issues (Kongsli et al., 2008. However, Smith (2007: 106, original emphasis) observes that "green" design of buildings in the UK has been a niche, "likely to be only a source of debatable ideas for mainstream sustainable development, not a model for mainstream transformations". This seems a fair assessment of the Norwegian situation also.

Thus, the idea of traditional ecological architecture that buildings should be sustainable has been mainstreamed, but not the alternative architectural practices. Arguably, a more comprehensive mainstreaming was made difficult by the blunt dismissal by mainstream architects of alternative aesthetics. When mainstream architecture has taken on board environmental concerns, it has done so by going for high-tech solutions. There are also policy issues to consider; with respect to sustainable architecture, new and stricter building codes have not paved the way for traditional ecological architecture, or made it more influential. Rather, new building codes have supported the emerging high-tech ecological architecture, which draws on traditional ecological architecture with respect to environmentalism, traditional architecture as a source of ideas about aesthetics, and engineering science as a source of new building technologies and new kinds of visual elements. The result, considered attractive by traditional architects and high-tech ecological architecture, may eventually become a new, distinct mainstream.

Conclusion: The Diversity of Mainstreaming

As we have seen, the alternative technology movement of the 1970s and 1980s called for increased emphasis on craft skills, decentralisation, use of local resources, engagement by users and ecological thinking. This paper has examined what may happen to such ideas and related practices when technologies considered alternative are (partially) appropriated by high-tech communities through mainstreaming.

The alternative technology movement did not succeed in achieving a fundamental change away from what was seen as an ecological harmful advanced technology path. Rather, alternative technologies – or at least some of them – have been made advanced in the sense that they have become part of mainstream high-tech paths of development. What was involved in such processes? Following Winner's (1986) suggestion, mainstreaming can be seen primarily as a picking-up of ideas, of alternative design criteria. This would also be in line with the ecological modernisation approach (Mol et al., 2009). Is this a reasonable understanding of the three cases discussed in the paper?

The cases reviewed here suggest that mainstreaming is not just a process where alternative ideas are picked up or co-opted by established industrial or technoscientific communities, but that there is more going on. The cases of wind turbines and electric cars involve alternative technology communities pragmatically integrating high-tech elements into their designs; this may be called pragmatic mainstreaming.[7]

The Danish wind turbine industry then developed into what we may call expansive mainstreaming, and in the process, the once alternative industry was transformed so that the industry lost its anchoring in local skills and engagement and so most of its alternative qualities. However, the process should not be seen simply as co-optation or a transfer of ideas. The 'ramping up' of the Danish wind turbine industry was a process of learning, deeply embedded in what originally was an alternative industry. Moreover, wind power is still generally considered sustainable, even if there are conflicts with respect to some developments.

The case of the electric car is different. Until about 2000, as we saw, production took place in communities outside of the automobile industry. More advanced technological elements were increasingly introduced to extend the range and improve safety and comfort as an instance of pragmatic mainstreaming. The take-over of Pivco by Ford signalled the beginning of another form of mainstreaming where the dominant design (Abernathy, 1978) of the automobile industry became a strong shaping factor. As we observed with the changing design of Think, and even more so with the electric cars that have been produced by the established automobile industry after 2010, the electric car was transformed from an alternative vehicle for urban mobility to become a standard car with a non-standard motor, an example of dominant design mainstreaming.

What we observe here is closer to the notion of co-optation in that the established automobile industry has appropriated the idea of an electric car, and has tried to combine design features important for standard cars, like range, speed and safety, with criteria from alternative electric vehicles (use of electric motors, improved batteries and lightweight bodies). While we do not know the extent to which the established industry learnt from the alternative one, it seems clear that more has been transferred than just going electric.

The case of ecological architecture is more complex, because low-tech ecological architecture continues to co-exist with emerging high-tech practice.[8] The emergence of high-tech ecological architecture seems to have been based on the concept of sustainable buildings and not on any 'ramping-up' in the low-tech community. Thus, we observe conceptual mainstreaming. This is different from dominant design mainstreaming because visually, high-tech ecological architecture is only moderately influenced by traditional buildings, using high-tech building elements to signify environmental consciousness (Hojem et al., 2014). Further research is needed to examine how different this is from more traditional aesthetics.

Thus, we can identify four types of mainstreaming: pragmatic, expansive, dominant design, and conceptual. They may be combined – probably in more ways than we have seen in this paper – and there is no reason to believe that these four are the only ones possible. This conceptual plurality suggests a diversity of mainstream logics. Berker (2010) proposes two logics: bottom-up approaches and incremental improvements. While incremental improvements seem to be a feature of all four types of mainstreaming, the bottom-up logic is only seen in pragmatic and expansive mainstreaming, not with dominant design and conceptual types. Other suggested logics to be observed in the three cases in this paper include environmental criteria, efficiency, and hybridisation; more work is needed to identify and elaborate such logics.

Should we rather have considered the three cases as processes where we see transition pathways produced through systemic interaction, on the lines suggested by Geels and Schot (2007)? Already suggested difficulties implementing the multi-level perspective appear to be supported by the cases covered in this paper. For example, how to empirically distinguish between the niche, the regime and the landscape level? What constituted the regime level in the case of wind turbine development? In the case of electric cars, can we really identify a transformative niche innovation that made its way into the automobile industry? By comparison, the mainstreaming concept facilitates observations of actor strategies and conflicts in sociotechnical transformations – the co-production and the acting-out of mainstreaming logics.

One weakness could be that mainstreaming needs better conceptual explanation. Do we need ecological modernisation or the multi-level perspective for this purpose? Clearly, the kind of mainstreaming studied in this paper happens in a favourable context of increasing demand for sustainable technologies. Still, it remains a matter of controversy which transitions actually are sustainable, which technologies should be preferred and how such preferences should be established (see, e.g., Jørgensen, 2012). At least, more empirical work is needed to see how mainstreaming is supported.

The exploration of mainstreaming in this paper has been based on revisiting a set of studies of past developments conducted by many authors with different goals and foci. To carry the analysis and understanding further it is desirable to undertake primary research directed towards explicating detailed mainstreaming processes. This would provide an opportunity to address issues such as the interactions and learning between traditional and high-tech approaches. Such research may also lead to the discovery of other types of mainstreaming and mainstreaming logics.

Acknowledgements

A first version of this paper was presented at "Symposium to celebrate the contribution of Dr. Stewart Russell", March 30, 2012, at The University of Edinburgh. The present version has benefitted from valuable comments from participants at that symposium, Heidrun Åm, three anonymous reviewers, and the editors of this special issue. The work has been supported by grant #185397 from Research Council of Norway.

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Notes

1 Recently, the latter industry is increasingly offering such cars but the links to alternative actors are more obscure than in the case of wind turbine technology.

2 In the two latter cases, I was familiar with the most frequently used sources because they have been produced through research in which I have participated.

3 The development of EVs did not follow a strategic niche pattern (Geels & Schot, 2007) but took place in a setting outside of competition from the established automobile industry due to special interests of the producers and a small number of customers.

4 In addition, Munch (2002) points to safety rules as a special challenge. The Danish electric cars were usually made from lightweight materials, like plastic, their top speed was low, but they were still considered to be dangerous with unacceptably inadequate levels of safety.

5 An update is found in ‘Eventyret endte i tragedie’ (The adventure ended tragically), Adresseavisen, October 24, 2012, p. 18.

6 See, e.g., ‘Denne bildesignen er ekte norsk’ (This car design is genuinely Norwegian), Verdens Gang, November 29, 2010.

7 Pragmatic mainstreaming may also have happened with respect to ecological architecture, but this is not clear from the evidence reviewed here.

8 The extent to which low-tech ecological architecture has engaged with pragmatic mainstreaming need to be further studied.

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Greener Aviation Take-off (Delayed): Analysing Environmental Transitions with the Multi-Level Perspective

Graham Spinardi and Rebecca Slayton

In the past fifty years, long-range commercial airliners have changed only incrementally from the paradigmatic design – a tube fuselage with swept wings and mostly-aluminium construction. Reducing the environmental impact of airliners may require radical innovations and a new paradigm, but the transition to a new paradigm is fraught with risks. This paper analyses how key risks have shaped and limited efforts to transition toward three types of radical innovations that would significantly improve airliner fuel efficiency. We use these three cases to reassess the dominant framework for analysing sociotechnical transitions – the multi-level perspective (MLP) – in light of methods and theoretical perspectives drawn from Science and Technology Studies (STS). We argue that if the MLP is to provide a robust framework for analysing sociotechnical transitions, it must be refined in three ways. First, it must 'open the black box' to account for the ways that technologically-specific risks shape the transition process. Second, rather than predefining particular innovations as radical or conservative, 'mature' or 'immature,' it should attend to how actors conceive of such terms; an innovation which appears 'mature' to one group may appear 'immature' to another. Third, the MLP would be strengthened by additional case studies such as ours, which examine incomplete or failed transitions.

Keywords: Green Aviation, Transitions, Multi-Level Perspective

Introduction

At the beginning of the 21st century, amid growing concerns about anthropogenic climate change, an authoritative study concluded that two innovations – laminar flow control (LFC) and a 'flying wing' aircraft design – offer "the greatest aerodynamic potential for reducing the contribution of air travel to climate change" (Greener by Design, 2003: 9). Remarkably, one of the UK's then leading aircraft manufacturers, Handley Page, had proposed precisely the same thing nearly fifty years earlier – a flying wing with LFC. The Handley Page 117 (HP, 117) would have consisted of nothing but wings carrying passengers inside, rather than wings with a fuselage for passengers. It would also have used LFC to reduce drag. Handley Page claimed that together the flying wing design and LFC would have maximized the lift to drag ratio and increased fuel efficiency, cutting operating costs in half.[1]

However, today both the flying wing and LFC remain technologies of the future. In fact, for over fifty years, long-range commercial airliners have changed only incrementally from the paradigmatic design – a tube fuselage with swept wings, mostly-aluminium construction, and turbofan engines – despite considerable work on more fuel-efficient designs. For example, lightweight materials such as carbon fibre have been under development since the 1970s, but only recently began to displace aluminium in large structural components. Advanced turboprop engines could nearly match the speed of turbofans while operating much more efficiently, but despite decades of development, such engines have not seen operational use in airliners.

Why haven't any of these innovations become operational, even after decades of interest in reducing fuel consumption and carbon emissions? Many other approaches to greener aviation are possible, including the use of biofuels, solar power, airships, and improved air traffic management (Cohen, 2010: 460). Moreover, improving fuel efficiency may not increase sustainability, as more efficient and thus cheaper-to-operate airliners may make flying less expensive and more common (the Jevons paradox, see, for example, Owen, 2012). As Ozzie Zehner (2012) has argued, behavioural changes will be needed to achieve sustainability. Nonetheless, we focus on three technologies for improving energy efficiency – more fuel-efficient engines, lighter aircraft, and more aerodynamic designs – because they dominate contemporary studies of greener airliners (Greener by Design, 2005; Green, 2009). Why, despite growing interest in energy efficient aircraft, have these technologies not been widely adopted?

Lack of radical change in airliner technology reflects the persistence of what evolutionary economists have called a *technological regime*: a rule-set that governs decisions about how to develop and produce new technologies. As initially described by Nelson and Winter (1977, 1982), technological regimes encourage engineers to pursue incremental improvements along a technological trajectory rather than radical innovation (see also Dosi, 1982). Kemp and Rip expanded the notion of regime to include the rules shared by technology's selection environment (Rip & Kemp, 1998), while Geels has used 'sociotechnical regime' to describe a broader set of relationships and investments "embedded more widely in the knowledge base, engineering practices, corporate governance structures, manufacturing processes and product characteristics" (Geels, 2002b: 1260). This paper defines sociotechnical regimes broadly to include artifacts and organizations, a usage that is common in the literature (see e.g. Kemp et al.,1998), and explicit in Gabrielle Hecht's notion of 'technopolitical regimes' (Hecht, 2001; Allen & Hecht, 2001).

The dominant framework for understanding how regime transitions occur is the Multi-Level Perspective (MLP) (Geels, 2002b, 2005; van Driel & Schot, 2005). The MLP conceptualizes transitions according to three levels: niche, regime, and landscape. Because regimes tend to pursue incremental innovation, radical innovations are nurtured only in small market niches. The landscape includes economic, political, and environmental pressures that are beyond the direct influence of regime or niche actors, but that may encourage regimes to nurture and adopt niche technologies.

The MLP explains transitions as a result of "linkages between co-evolutionary dynamics at multiple levels", rather than seeing them as driven by price/performance improvements (Geels, 2006: 1014). It characterizes transition pathways by two aspects of interactions between the levels: i) the timing of niche, regime, and landscape developments (especially whether or not the niche technology is mature relative to landscape pressures), and ii) the degree to which niche and landscape developments threaten or reinforce the regime (Geels & Schot, 2007).

Thus, the MLP would explain slow, incomplete, or non-existent transitions such as those explored here as a consequence of immature niche innovations and/or insufficient landscape pressures. But this explanation leaves deeper questions unanswered. How do regime actors decide whether or not a niche technology is sufficiently mature? What does it mean for landscape pressures to be sufficiently large, and for whom? And what happens when key actors related to different dimensions (Lettl et al., 2006: 252) of an innovation frame technology differently?

This paper addresses these questions through the core principles and methods of science and technology studies (STS), as exemplified by Stewart Russell's work (e.g. Russell, 1993; Russell & Williams, 2002). Indeed, Russell's emphasis on the ways in which complex interdependencies affect sociotechnical change anticipated the MLP (see discussion in Weber, 2014). We argue that STS can extend the MLP in three ways.

First, we follow STS's injunction to 'open the black box' of technology by considering how the inner workings of technology shape social outcomes, and vice versa (Pinch & Bijker, 1987). Although the injunction to open the black box is not new, the MLP has yet to fully incorporate this perspective into its framework. As Russell and Williams (2002: 81) note, close attention to "the *specificity* of processes in different areas of technology and different domains of application" (italics in original) is crucial to a full understanding of the social shaping of technology. However, the MLP does not account for the content of technological design in any systematic way.

For example, the MLP's typology of transition pathways specifies transition pathways solely in terms of the maturity of niches relative to landscape pressures, and the degree to which the niche innovation threatens or reinforces the niche. Yet we have reason to expect that transition pathways will be shaped by aspects of technological design. For example, many communications technologies, by their very design, are exhibit in strong economies of scope, or positive network externalities. Because products which capture an early market share enjoy increasing returns if the network grows, firms have strong incentives to introduce products early as well as to invest in them heavily only if the network then grows. It is also riskier to introduce a product late than to introduce it with a few glitches.[2] By contrast, the consequences of failure for technologies such as airliners and nuclear power plants are extremely high. Because such large physical systems confront huge start-up costs, a commercial failure is enormously expensive. Additionally, technological failures in such systems can cost not only money but also hundreds or thousands of lives. Thus, from the perspective of an aircraft manufacturer, the risks of introducing a new airplane before its safety is demonstrated are far greater than the risks of being rendered obsolete by a competitor while research and development continues.

The differences between technologies such as computer network protocols and airliners illustrate that technological specificity can shape transition pathways by giving meaning to the notion of technological maturity. Accordingly, the MLP would be strengthened by incorporating some dimensions of technological design into its conception of how transitions occur. Here we suggest that the type of risk associated with innovation is one key facet, but other aspects are undoubtedly important.

Second, STS explains technological change in part by the unique ways that social groups frame technology—that is, the assumptions that they bring to bear upon new artifacts. This agent-oriented approach has been criticized (with some justification) by MLP advocates, who argue that the MLP "is strong in combining STS sensitivities about micro-processes with long patterns and processes" (Geels & Schot, 2010: 35). However, these authors also acknowledge that the global theory of the MLP "needs to be complemented by local theories which help to analyse how actors navigate, struggle and negotiate on specific alternatives" (Geels & Schot, 2010: 101). Similarly, MLP advocates acknowledge that the structuralist approach of the MLP needs to be complemented "with an actor-oriented approach working 'from the inside out' " (Geels, 2004: 43).

The need to work both 'from the inside out' and 'from the outside in' was advanced much earlier by Russell and Williams (1988: 4, 11). Adopting such an 'inside out' approach, Höyssä and Hyysalo (2009) and Hyysalo (2010) argue that an understanding of how specific actors perceive 'innovativeness' – including the degree to which specific technologies are novel, the dimensions of its novelty and how they relate to different actor groups, and the locus of innovation around the new products – is critical to understanding transitions. Here we build on this argument by considering how different actors – such as design engineers, operators, business analysts – understand what it means for a new innovation to be 'radical' or 'conservative,' 'mature' or 'immature.' We argue that achieving an appropriate balance between agency and structure requires analysts to not predefine particular innovations as radical or immature, but rather to study how different actors themselves conceptualize these terms with respect to specific technologies and their dimensions of novelty. While advocates of the MLP acknowledge the importance of agency, they do not generally consider how actors construct concepts such as 'radical' innovation or 'mature' technology. As we will see, an innovation that seems radical to one group may seem quite conservative to another.

Third, we help to correct a bias in MLP studies by following STS's 'symmetry principle,' in which success and failure both require sociological explanation (Pinch & Bijker, 1987). The MLP has tended to treat success, but not failure, as a matter for sociological analysis (for a recent exception, see Wells & Nieuwenhuis, 2012). Although aspects of the MLP framework have been used to assess on-going transitions (see e.g. Hofman & Elzen, 2010; Elzen et al., 2011; Grünewald et al., 2012), the MLP framework has been developed primarily using historical case studies of successful transitions. Geels and Schot (2010: 79) acknowledge the need to "correct the bias towards winners and novelty". Russell's (1986, 1993) early work on combined heat and power in Britain exemplifies STS accounts that focus on failure, and thereby help to correct the bias towards success stories. This paper builds on Russell's legacy by examining transitions that have, we might say, stalled.

In what follows, we first discuss how a very low tolerance for risk shapes innovation within the aviation regime. We then provide three historical case studies of innovations for more fuel-efficient airliners, showing how the 'maturity' of the innovation is socially constructed by actors that may have different tolerances for risk, and by different conceptions of what constitutes ‘radical’ innovation.

Risk in the Aviation Regime

In commercial aviation, radically new technology entails many risks. The process of moving from early stage technology development to a marketable product is very expensive. For example, the Boeing 787 airliner is estimated to have cost around $16 billion to develop (Gates, 2011). By contrast, the Toyota Prius cost about $1 billion, a typical cost for new cars (Taylor, 2006). The sizable majority of mobile apps cost less than $100,000 to develop (Furnas, 2013). High airliner development costs, along with the difficulties of entry have produced an oligopoly in which a very small number of manufacturers (just Boeing and Airbus for large airliners) participate in the design of new aircraft. Competition between these manufacturers is fierce, but the high stakes of new aircraft development leave companies favouring incremental innovation.

The (potentially) large risks associated with airliner innovation – including the reputational damage that could ensue from a major crash – are exacerbated by high uncertainties. In early stages of research and development, feasibility, producibility, regulatory acceptance and market appeal are all uncertain. High technological complexity amplifies these uncertainties. While computer simulations are helpful for predicting likely performance, the performance of new designs can ultimately be determined only by building and operating a full-scale product. Airline manufacturers try to minimize uncertainties through an extremely conservative innovation strategy. Since deductive models are of limited value for predicting future performance, manufacturers base judgments about the feasibility of future aircraft on extrapolation from decades of engineering experience – data on wind tunnel testing, operational performance of existing airplanes, and the tacit knowledge and intuition of experienced engineers.

Regulators also rely heavily upon past data and conservative innovation. American aircraft certification is carried out by the Federal Aviation Administration (FAA) (working in conjunction with its European counterpart). The certification process has become increasingly challenging as the complexity of aircraft design has increased. In 1998, a study by the U.S. National Research Council noted:

> A major airframe manufacturer may employ as many as 8,000 engineers, flight test pilots and inspectors to design, develop, and certificate a new wide-body passenger jet. These large staffs are necessary to investigate the design complexities of modern aircraft. The number of labour hours invested by a manufacturer in designing a large new jet may be several hundred times greater than the number of labour hours the FAA has available to verify the safety of the aircraft design. (NRC, 1998: 38)

As the National Research Council (NRC) noted, these disparities raise questions “about the FAA’s ability to analyse independently new aircraft designs and locate safety-related design flaws” (NRC, 1998: 38).

The FAA attempts to manage this problem by co-opting the aircraft engineers themselves to self-regulate, and by drawing on the past record of the aircraft manufacturers and of the aircraft that they built (Downer, 2010). As Downer notes:

> Reliability assessments of new civil aircraft lean very heavily on inferences from the – statistically well-established – data from earlier, different, aircraft designs. This is viable because the architects of new aircraft are highly conservative when developing new models. [...] Innovations are extremely modest, with new technologies being withheld until their reliability has been well-established in other contexts (in military aircraft, for instance). (Downer, 2011: 279).

In short, the main barrier to the development of radically more fuel-efficient airliner technology is the extremely conservative innovation process that is particular to the aviation regime. This conservative approach is rooted in socially and technologically specific views on what it means for innovations to be radical or disruptive of the airliner regime, and thus calls for the analytic framework and methods of STS.

In what follows, we analyse how this conservatism has shaped three approaches to making airliners more fuel-efficient. The first approach is to replace turbofan engines with more efficient turboprop or propfan engines. The second is the adoption of carbon fibre composites, a transition that is now finally underway despite having been feasible for decades. The third approach is to achieve greater aerodynamic efficiency through LFC and/or flying wings. In each case, the MLP provides a partial explanation of how these innovations gained a niche. However, to explain why these approaches have not caused a regime change, we adopt a more micro-level perspective. We show how different social groups adopted varying views of what ‘radical’ or ‘mature’ innovation meant, and how these different framings ultimately limited the adoption of more fuel-efficient technologies.

The Turbo Revolution: The Birth of the Modern Airliner Regime

Edward Constant’s (1980) study of the ‘turbojet revolution’ is often cited as an example of how radical innovations can transform a stable regime. Thus Geels (2002a, 2006) illustrates the MLP through the shift from the propeller piston-engined, straight-wing regime (e.g. the Douglas DC-3), to the turbojet-engined, swept-wing regime (e.g. the Boeing 707). A ‘landscape’ development – the looming threat of war in the 1930s – nurtured the turbojet niche because the higher speed of turbojets was identified as a valuable asset for fighter aircraft. Fighters with turbojets could be rapidly ‘scrambled’ from ground stations when enemy aircraft were spotted. Although only a few turbojet fighters saw action in WWII, turbojets were preferred in post-war fighters.

Military applications thus provided a niche in which turbojets could mature sufficiently to be considered for civil applications. After WWII, many manufacturers continued with incremental improvement of piston-engined airliners, but the turbojet provided an opportunity for new entrants to gain competitive advantage. For the UK, building a turbojet-engined airliner was a way of overcoming the growing US dominance of the industry, and the De Havilland Comet was the world’s first jet airliner to enter commercial service in 1952. The initial success of the Comet quickly dissipated due to fatal crashes in 1954 (as discussed further below). Nonetheless, the Comet demonstrated that there was public demand for such a technology. The interest stimulated in airline operators led Boeing to convert its Dash-80 refuelling jet into the Boeing 707 airliner, which entered service in 1958 (Geels, 2006: 1012).

The development of turbofans – a variation of turbojets which reduces noise and increases efficiency – further increased commercial aviation's interest in 'jet' engines. As Geels (2006) has discussed, several adaptations in the aviation regime (such as longer runways, pilot training, and new aircraft control methods) enabled turbojets to displace piston-propeller aircraft. However, Geels provides only a partial historical account because he does not explain how another engine technology – turboprops – flourished alongside turbojets and turbofans, albeit on a lesser scale.

From an engineering perspective, turbofans and turboprops are both incremental innovations upon turbojets, both of which aim to optimize the mass and final velocity of the air moved. Because the energy consumed in an engine scales with the mass of the air multiplied by the velocity squared (mv^2), while the momentum produced by the engine is equal to mv, engines can produce momentum most efficiently by moving larger masses of air more slowly (i.e. increasing m while decreasing v). A 'pure' turbojet gains all of its propulsion from high-speed gases produced by combustion in the engine core. By contrast, turbofans use the jet's combustion to power a fan, which accelerates a larger volume of air to a lower velocity. The air accelerated by the fan bypasses the engine, so the ratio of this slower air mass to the faster air mass accelerated by engine combustion is called the *bypass ratio*. Efficiency increases as the bypass ratio grows. Because noise tends to increase with higher velocity air, the high bypass ratio of turbofans offers not only more efficiency, but also less noise than pure turbojets.

Closely related to the turbofan is the turboprop. Whereas the turbofan uses a gas turbine to spin a ducted fan, a turboprop uses the gas turbine to spin a propeller more slowly than the turbine. Turboprops are most efficient at low speeds because they can move larger masses of air more slowly than turbofans. But at high speeds, turboprops become less efficient than turbofans because the tips of the propellers are moving close to the speed of sound, generating shock waves that increase drag and friction. Turboprops are typically slower and noisier, but much more fuel-efficient than turbofans.

The first turboprop to fly was the British Rolls-Royce Trent, which was tested on a Meteor I aircraft in 1944 (Anonymous, 1950: 489). Although turbofans became dominant in long-range aircraft, the greater fuel efficiency of turboprops soon made them the preferred engine for short-range aircraft, where passengers were unlikely to notice the lower speed. By the 1960s turboprops were completely dominant in aircraft with less than 50 seats, and had approximately an equal share of aircraft with 51–90 seats. The oil crisis of the early 1970s made energy efficiency an even greater priority, encouraging further demand for turboprops. Additionally, the deregulation of the US market in 1978 encouraged the hub-and-spoke model for airline operations, thereby increasing the number of short-range flights and the associated demand for turboprops (Bonaccorsi & Giuri, 2000: 855–857).

Thus, the commercial aviation regime developed a mixed character with respect to engines, with both turbofans and turboprops establishing patterns of incremental innovation. In this sense, it might be more accurate to discuss a 'turbo revolution' than a 'turbojet revolution.'

High oil prices enabled an even more fuel-efficient 'advanced turboprop,' or propfan, to find an R&D niche during the 1970s and 1980s. The propfan consisted of thin swept blades that resembled a pinwheel, and aimed to achieve similar efficiencies to conventional turboprops, but without generating the turbulence that eroded efficiency at high speeds (Ethell, 1983). Although fast and efficient propfans posed several engineering challenges, they represented an incremental innovation from standard turboprops. Propfans were first suggested in the 1950s, but the materials at that time were not strong enough to create propfan blades, and the low cost of fuel meant that efficiency was not a priority.

In what follows, we show that while the MLP partially explains how propfans found an R&D niche, it does not fully explain why propfans have not been adopted by airlines. To explain this non-transition, we show how specific social groups – airlines, and passengers – framed propfans as too revolutionary and immature for operational use, despite the fact that they represented a kind of incremental innovation.

Propfans and the Advanced Turboprop Project

The dominance of the turbofan in long-range aircraft was such that NASA had ceased research into propeller technology by the early 1970s (Hager & Vrabel, 1988: 1). However, the 1973–1974 oil crisis saw aviation fuel prices increase from twelve cents a gallon to over a dollar in the U.S., and fuel increased as a proportion of airline operating costs from about a quarter to over half (Bowles & Dawson, 1998: 326). Responding to this changing landscape, NASA began investigating propfans in 1974, and accelerated work after February 1976, when the U.S. Congress funded NASA's new Aircraft Energy Efficiency (ACEE) programme. Three of the six projects funded concerned propulsion systems, and were managed by NASA's Lewis (now Glenn) research centre in Cleveland, Ohio. NASA and several industry studies all agreed that the Advanced Turboprop Project (ATP), which focused on propfans, had the highest potential payoff of the three propulsion projects, with estimates of fuel savings ranging from 30% to 50% (Bowles, 2010: xii, 13; Hager & Vrabel, 1988: 3). The challenge was to develop a propfan that could match the speed and altitude of the turbofans used on most airliners – 0.8 Mach at 30,000 feet – whilst maintaining satisfactory levels of noise, comfort and reliability.

The ATP's initial funding was held up, according to John Klineberg, later director of Lewis Research Center, "because it was considered too high risk and too revolutionary to be accepted by the airlines" (quoted in Bowles & Dawson, 1998: 329).

Table 1. Comparison of different types of turbine-based engines

Type	**Source of Propulsion**	**Efficiency and Noise**
Turbojet	Combustion gases	Least efficient below Mach 1
Turboprop	Combustion gases turn a propeller, which moves air	Most efficient below Mach 0.6[3]
Turbofans	Combustion gases turn a ducted fan, which moves air	More efficient than turboprops above Mach 0.6
Advanced Turboprop; Propfan; Unducted fan	Combustion gases power specially-designed propeller, which moves air	Most efficient above Mach 0.6

In February 1975, NASA's newly formed Aircraft Fuel Conservation Technology task force noted that aircraft manufacturers were disinclined to develop high-speed turboprops (or propfans) because of the "perception of turboprops as an old-fashioned, troublesome device with no passenger appeal" (quoted in Bowles & Dawson, 1998: 328). Studies by Boeing, McDonnell Douglas, and Lockheed also raised questions about noise, potential maintenance costs, and whether the propeller could remain efficient at speeds exceeding 0.6 Mach (Hager & Vrabel, 1988: 5).

Significantly, the propfan was too 'high risk' and 'revolutionary' primarily from a passenger and marketing perspective. From an engineering perspective, the ATP represented an incremental improvement upon lower-speed turboprops. As proof of the viability of high-speed turboprops, engineers could point to the Soviet development of long-range turboprop aircraft such as the Tupolev TU-95 'Bear' bomber, which had a 0.75 Mach cruise speed. This Soviet achievement was used to gain support for the ATP by raising concerns about the Soviet Union being ahead in the Cold War technology race (Bowles, 2010: 19, 125). Although the TU-95 (and its civil airliner derivative, the TU-114) demonstrated the feasibility of achieving high speeds and altitudes with turboprops, they were reportedly very noisy and relied on complex gear-systems for the contra-rotating propellers with consequent high maintenance requirements.

By the time the ATP was formally launched in 1978, NASA had demonstrated high efficiency at Mach 0.8 in a scale model (Hager & Vrabel, 1988: 8). However, it remained to be seen whether such performance could be achieved with acceptable cabin noise levels. Since the addition of acoustically insulating materials to reduce noise would add weight and thereby reduce the efficiency of turboprops, there appeared to be a trade-off between noise and efficiency.

The ATP research programme also aimed to alleviate industry anxieties about safety. For example, at a meeting of the Industrial Advisory Board at NASA, an air accident advisor expressed concern about the "safety aspect of propellers breaking away from the engine and the damage caused by their impingement into the fuselage" (quoted in Bowles & Dawson, 1998: 333). To dispel these anxieties, engineers at NASA Lewis carried out and commissioned studies into propeller damage, concluding that turboprops posed no unique safety risks (Bowles & Dawson, 1998: 333).

As NASA's project continued, another spike in fuel prices influenced developments at General Electric (GE), one of the world's big three engine producers (the others being Pratt & Whitney and Rolls Royce). The Iran-Iraq war that began in September 1980 led to an even more dramatic increase in oil prices than that of 1973. GE's internal predictions were for aviation fuel to rise to $2 or $2.20 a gallon by the mid to late 1980s (Sweetman, 2005). As a result, GE set up a team in 1981 to investigate more efficient engine designs, including its own version of a propfan.

First announced in 1983, GE's unducted fan (UDF) engine came as a surprise to the ATP team. The UDF was bigger and more powerful than NASA's effort, and was planned to be ready sooner, in late 1986 (Sweetman, 2005). A non-functioning mock-up of GE's UDF engine was unveiled to the public at the 1985 Paris Air Show, and first ground-tested in August that year (Sutcliffe, 1987: 11). It was the key to greater fuel efficiency in Boeing's proposed 150-seat 7J7 airliner, slated for delivery within seven years. Boeing promised that the 7J7 would be twice as fuel-efficient as the

Airbus A320 that was then almost ready for delivery (Sweetman, 2005).

The first test flight of the UDF, carried out on a Boeing 727 airframe, came on August 20, 1986, with the first public flight on a McDonnell Douglas MD81 following in September 1988 at the Farnborough air show. The test flights were considered encouraging: noise levels were higher than desirable, but manageable: 'acceptable and certifiable', according to GE (Anonymous, 2007). The way forward appeared clear, as a 1987 *Washington Post* article stated: "The aircraft engine of the future has propellers on it" (Hamilton, 1987).

Advanced Turboprops Stall

Thus, by the mid-1980s, major landscape changes had apparently destined propfans for widespread adoption. However, a key risk-averse social group – airlines – viewed propfans as too uncertain, and therefore too immature, against the changing landscape. Boeing's attempts to market its proposed 7J7 – a 727 employing the UDF instead of turbofans – were not successful. In order to reduce noise from the UDF, the engines would be installed in the back of the plane. However, this increased the weight of the plane, and maintenance costs for a novel engine remained uncertain. Thus, operations engineers were cautious. Bob Conboy, a market analyst at GE recalls: "We'd talk to the planning people and they'd say 'When can we have it?' But we never got an enthusiastic response from the operations people" (quoted in Sweetman, 2005).

Future fuel prices also remained uncertain, and were another reason (in addition to the potential maintenance and weight issues) that Airbus did not adopt the UDF. Airbus' chief planner, Adam Brown explained that the advantages of the UDF "depended very much on the price of fuel […] . With the projections that we were most comfortable with at the time, they couldn't beat the A320." (quoted in Sweetman, 2005). Although the A320 could not offer the fuel efficiency claimed for the 7J7, it used more familiar turbofan engine technology while still improving over the previous generation of midsize airliners.

One of Boeing's own aircraft also undermined support for the 7J7. The 737 was a late-1960s midsize airliner that struggled to achieve decent sales during the 1970s. But in 1981, a new version, the 737-300, was introduced with a more efficient and quiet CFM56 turbofan engine developed by GE and the French SNECMA engine developer. Sales of the 737-300 grew rapidly, with over 1000 sold by the end of 1987 (Sweetman, 2005). With the CFM56 engine becoming the dominant engine in this important and growing airliner sector, GE saw little need to pursue the UDF development. According to Brian Rowe, then GE's senior vice president in charge of engine development: "When the CFM56 took off, we thought, What the hell? All we'd be doing [by launching the UDF] is killing our own business" (quoted in Sweetman, 2005).

The other main potential user of the UDF was McDonnell Douglas, whose rear-engined MD-80 was proving uncompetitive with the Boeing 737 and Airbus A320. A UDF engine was tested on an MD-80 airframe in late 1987, and McDonnell Douglas had plans to launch UDF-fitted models the following year. The UDF-equipped MD-80 was flown to the Farnborough Air Show in September 1988,[4] but without firm orders, GE was unwilling to commit to further development (Sweetman, 2005). The MD-80 was also flown with an ATP-inspired engine developed by Pratt & Whitney and Allison, but again there was insufficient commercial interest.

Wither the propfan? By the late 1980s, the landscape conditions that had led to the ATP and to GE's UDF had ameliorated.

Using non-inflation adjusted dollars, the cost of oil had soared from $3.39 per barrel in 1970 to $37.42 per barrel in 1980; by 1988 it was down to only $14.87 per barrel (Bowles, 2010: 134). In inflation-adjusted 2012 dollars, this did translate into a significant increase – from approximately $11 in 1970 to $35 in 1988 (BP, 2013: 15). But the commercial aviation regime viewed these prices as tolerable, and the risks of further increases as survivable. The commercial case was thus undermined. The manager of NASA's ATP, John R. Facey, believed that the manufacturing costs would exceed operational fuel savings: "An all new aircraft with advanced avionics, structures and aerodynamics along with high-speed turboprops would be much more expensive than current turbofan-powered aircraft, and fuel savings would not be enough to offset the higher initial cost" (quoted in Bowles, 2010: 134).

Facey's comments represent a risk calculus – a belief that extra manufacturing costs would probably outweigh future fuel savings. These financial risks make propfans radical from a business perspective. Yet from an engineering perspective, the physical concepts behind propfans are not radically different from those behind the well-established turbofan and turboprop.

In the past decade, growing pressures for more energy efficient aircraft have reinvigorated research into propfans. Europe's Clean Sky Joint Technology Initiative, a partnership between the European Union and industry, has continued to pursue propfan research and development (Clean Sky, 2013). GE continues to develop propfans, and currently anticipates reducing the noise to acceptable levels by 2030 (Croft, 2012).

In sum, landscape changes – spikes in oil prices – nurtured development of propfans. However, these pressures were too transient to overcome the risk aversion of some of the key actors in the civil aviation regime – business concerns about image and initial manufacturing costs, and operational concerns about maintenance and noise. By examining propfans from an STS perspective that focuses on the technologically and socially specific risks associated with new engine designs, we can better assess obstacles to a transition. In particular, the adoption of propfans may depend on locating airports further away from urban centres or a significant shift in public attitudes towards aircraft noise, which until recently has been *the* key environmental driver for aero engine development (Greener by Design, 2005: 5).

Lighter Materials: The Development of Carbon Fibre

Whereas more efficient engines are stuck in laboratory development, lighter materials (most notably carbon fibre) have found a substantial market niche. Although the MLP helps to explain how lighter materials have seen growing use, it does not fully explain why a more complete transition to composite construction has not occurred. In what follows we use the MLP to frame the initial adoption of carbon fibre, and then show how an actor-oriented understanding of what it means for innovative materials to be 'mature' is necessary to explain the limits of adoption.

High strength carbon fibre was first developed in the 1960s and quickly found application in rocket casings and military aircraft (Spinardi, 2002). Military aircraft, and the gradual introduction of composite components such as tailfins and control surfaces in airliners, provided a niche for developing stronger, lighter-weight, and more reliable composites. Carbon fibre was first used for airliner secondary structures (such as spoilers, airbrakes, rudders, and wing edges) in the early 1980s. Sharp rises in oil prices nurtured the carbon fibre niche, and in 1981, one production engineer predicted that aircraft would be more than 50% composite construction by the end of the 1990s (King, 1982). Similarly, in 1983, the Dutch aircraft company Fokker announced that its next commercial aircraft, to be introduced in 1992, would consist of 50–65% composite materials by weight (Feazel, 1983). Yet by the turn of the millennium, no commercial airliner had more than 20% carbon fibre construction.

Why was carbon fibre not adopted more widely earlier? The MLP would suggest that landscape pressures were insufficient, or that carbon fibre was not yet mature. But to understand what it means for landscape pressures to be large enough or for carbon fibre to be mature enough, we must adopt an STS 'inside out' perspective, and consider how different regime actors framed different kinds of risks associated with novel materials.

The *safety* risks of new aircraft materials are well illustrated by the experience of the Comet, the first aluminium pressurized fuselage to enter service. On three separate occasions in the mid-1950s, Comets broke up in mid-flight as the pressurized fuselage explosively decompressed (Marks, 2009). Although the Comet had been subjected to the most rigorous safety testing available to that time, engineers did not fully understand how the process of pressurization and depressurization would fatigue the metal, leading to cracks around the plane's square windows, and eventually structural failure (Hansard, 1955).

The Comet experience led to better testing procedures because it "stimulated enormous research efforts aimed at understanding and avoiding fatigue cracking" (Vlot, 2001: 11). It also heralded a shift towards conservatism in the airliner innovation system. Technological advances in aviation had been rapid over the first half of the twentieth century, with clear benefits in the speed and comfort of long-distance travel, but there were trade-offs between these benefits and the risks involved in pushing new technology. Once turbo-powered aircraft such as the Boeing 707 came into service, and large aircraft such as the 747 made long-range mass transit economical, it was not clear that further leaps forward in airliner technology were worth the risks associated with novelty. Notwithstanding experiments with faster aircraft such as the Concorde, most airline manufacturers and operators agreed that the paradigmatic 707-type aircraft was good enough.

The adoption of carbon fibre thus proceeded very incrementally. It was not until 2002 that Boeing announced that its next generation airliner would use unprecedented levels of carbon fibre – nearly 60% (Wallace, 2001 Smith, 2001; Staff, 2001). What eventually became the Boeing 787 is the first airliner to use carbon fibre for large structural components (i.e. fuselage and wings).[5] Concerns about the safety of such large composite components became very public after engineer Vincent Weldon claimed that Boeing fired him over his criticisms of carbon fibre. Boeing claimed that he was fired because of threatening and racist comments he made towards a manager, but Weldon nonetheless drew public attention to the risks of new materials. In a 2007 letter to the FAA, Weldon warned that aluminium has "far fewer failure modes" than carbon fibre.

Significantly, Weldon's criticisms centred on the risks generated by a relative lack of experience with carbon fibre, noting that "there is far less proven knowledge than for aluminum structure," and that "the less mature composite structure data base, compared to that of aluminum, is of concern". A 2011 investigation by the US General Accounting Office echoed these concerns, acknowledging "limited in-service experience with composite materials used in the airframe structures of commercial airplanes and, therefore, less information [...] on the behavior of these materials than on the behavior of metal" (GAO, 2011: 28). However, the GAO report concluded that the FAA's certification process had been satisfactory, citing expert opinion "that while not every risk can be known, the use of composites is not revolutionary; rather, it is a new application of technology that has a history in military and general aviation applications" (GAO, 2011: 28).

Although government regulators concluded that carbon fibre was mature enough from a *safety* perspective, Boeing discovered new *manufacturing* risks when it attempted producing those structures. While aluminium components are produced by cutting the metal and then assembling parts, carbon fibre components are fabricated at one and the same time that the composite is created. Carbon fibre components are typically made through a labour-intensive process: a tool modelling the shape of the part is created; carbon fibre plies that are pre-impregnated with resin are carefully placed on the tool, using a precise alignment that is designed to optimize the final strength of the part; the entire assembly is carefully covered with materials to ensure that the plies lay flat; and then the entire part is cured under heat and pressure (Younossi et al., 2001). Composite components can reduce the need for assembly processes, but they are often slower and more expensive to produce. Furthermore, because composites cannot be reshaped after fabrication, they must be produced to very precise tolerances (Vosteen & Hadcock, 1994).

Because the composite material does not exist apart from the part that it constitutes, a much larger component is effectively a different material. Boeing discovered this the hard way in June 2009, when ground tests simulating the stresses of flight showed unexpected structural weaknesses. When pressure was applied to the wings of the test aircraft, titanium fasteners did not transfer the load properly, causing delamination of the carbon fibre plies and deflection inside the fuselage. The failure was especially troubling because computer models had not predicted it. The data that was the basis for engineering the entire aircraft suddenly appeared to be flawed (Mecham, 2009). The 787 finally entered service in 2011, years late and over budget, largely because of unexpected difficulties that came with new fabrication processes.

Although the Boeing 787 appears to be on its way to commercial success, the transition to carbon fibre remains incomplete. In 2008, Mitsubishi Heavy Industries, the company responsible for manufacturing the 787 carbon fibre wing box, announced that it would be manufacturing a lighter-weight, more fuel efficient regional jet (the Mitsubishi Regional Jet). But Mitsubishi chose not to use composites for the fuselage or wings, because it did not expect the weight savings on a smaller-sized airplane to justify the risk of higher manufacturing costs (Tabuchi, 2013).

Thus, the current commercial aviation regime remains mixed between carbon fibre and aluminium, and it is unclear whether a transition to carbon fibre will be completed. This incomplete transition cannot be fully explained by the MLP, which would suggest that the carbon fibre niche is immature relative to landscape pressures. By contrast, the methods of STS explain this partial transition by reminding us that the maturity of carbon fibre is a matter of perspective. While regulators have deemed carbon fibre to be safe, manufacturers continue to be wary of production-related risks and uncertainties related to recouping costs.

Radical Aerodynamics: Flying Wings and Laminar Flow Control

A third area in which aircraft can be made more efficient lies in aerodynamic advances that maximize the amount of lift that can be obtained from a given amount of power. The aerodynamics of the classic 707-type aircraft has changed only incrementally since their development in the late 1950s. Considerable advances in aerodynamic efficiency have been achieved by fine-tuning this design through wind-tunnel testing and computational fluid dynamics. Additionally, winglets – small, nearly vertical wing extensions which increase the lift-to-drag ratio – have produced small improvements. However, far greater improvements have long been known to be possible through flying wings and laminar flow control (LFC). Consistent with the MLP, these 'radical' innovations have been nurtured in the niches of military research and development. However, to understand why flying wing designs and LFC have yet to become operational, we must again move beyond the structural approach of the MLP and consider how specific actors – most notably airlines and passengers – construct the 'maturity' of these innovations.

Flying Wings

A flying wing seeks to get rid of any aircraft structures (in particular the fuselage) that do not provide lift, thus maximizing the overall lift to drag ratio of the airframe. The flying wing concept is almost as old as aviation itself. Hugo Junkers patented a wing-only aircraft concept in 1910 (Pletschacher & Junkers, 2004: 144). The closest Junkers came to realizing this ideal was the 1930 G-38 airliner whose all-metal structure involved a huge 148 feet wide and six foot deep wing (with space for passengers to sit in the wing space next to the fuselage looking forward). However, the G-38 had a long fuselage after the wing leading to a biplane tail, and a stub of a fuselage at the front. *Flight* magazine noted that the aircraft "does not realize the ideal of the 'flying wing,' although it goes some way towards it" (Anonymous, 1929).

Others in Germany and the UK experimented with flying wing designs, but the concept found its fullest expression in the USA, where Jack Northrop was an avid supporter. Military aviation – a sector with greater risk-tolerance than civil aviation –provided a niche for Northrup's designs, starting with the 1940 N1-M. The aerodynamic efficiency predicted for such designs would enable bombers to fly longer distances and/or to fly faster – goals, which had great appeal during WWII. With feasibility demonstrated, in 1941 Northrop won a contract from the Army Air Corps to develop a large flying wing bomber. Known as the XB-35, the first aircraft was due to be delivered in 1943 (Baker, 2001: 201).

Northrup promoted the XB-35 for having "considerably less drag than a conventional airplane, which means that the same comparative speed can be obtained with less horsepower or that the speed may be considerably increased using the same horsepower."[6] It also claimed 'extensive' cost savings, "as the Northrop aircraft consists essentially of a thick wing in which there are virtually no structural complications, and in which there is ample room for the installation of the many auxiliary component parts which make up the modern airplane."[7]

However, Northrop's optimistic sales talk proved wide off the mark. The XB-35 programme was plagued by production and technical problems. The first XB-35 did not fly until June 1946, three years late and 400% over budget (Baker, 2001: 202). Much of the XB-35's difficulty stemmed from its counter-rotating propeller engines, and after 1947 Northrop focused on the YB-49, a modified

XB-35 in which the propeller engines were replaced by turbojets. Again production proved challenging, and the resulting aircraft had much less range than planned (mainly because the of the fuel-hungry turbojet engines), had insufficient payload capacity, and suffered from instability in pitch and yaw that made bombing much less accurate than conventional aircraft. Even worse, a test flight on June 5, 1948 provided fatal evidence of the YB-49's propensity to stall (Baker, 2001: 205). Northrop was unable to meet the production schedule, and the RB-49 was cancelled in 1949 due to budgetary constraints and a preference for more proven technology (Baker, 2001: 210).

Thereafter, advocates of flying wing aircraft struggled to argue that the benefits would surpass the extra costs and risks in comparison to conventional designs. In January 1947 *Flight* magazine predicted that: "Some day the flying wing will emerge as the accepted form of a passenger air liner" (Anonymous, 1947), but in 2015 that day still appears some way off. The technical maturity of a flying wing design is no longer in doubt; the US B2 'Stealth' bomber proves that stability problems can be managed using complex computer algorithms. Flying wings have survived in the niche of military aviation, with military support demonstrating the feasibility of the flying wing.

To understand why flying wings have not been widely adopted, we must move beyond the MLP to consider technologically specific features of commercial aviation – in particular, risk aversion in commercial dimension of the regime. Commercial airlines continue to view flying wings as too radical and high-risk because of concerns about cabin pressurization and the integration of passengers in a flying wing (i.e. passengers like to look out of windows). Instead, recent work has focused on a compromise approach known as a 'blended wing' which retains some fuselage blended into a large wing in order to provide windows (Greener by Design, 2005: 19–20).

Laminar Flow Control

The other much-touted aerodynamic innovation – laminar flow control (LFC) – likewise has a long, frustrating history. When an aircraft moves through air, friction with the surface causes a thin boundary layer of air to be dragged along with the surface. This boundary layer is laminar when it is comprised of thinner layers that slide past one another with no mixing, thus creating minimal drag. However, flow over large surfaces tends to become turbulent, dramatically increasing drag. Approximately half of fuel consumed in commercial aircraft goes into overcoming this turbulent drag (Bowles, 2010: 114).

The goal of LFC or 'laminarisation' is to keep this boundary layer laminar rather than turbulent. When leading edge surfaces are angled such that pressure decreases as the boundary layer moves towards the trailing edge, laminar flow occurs naturally. However, to keep the flow laminar near the rear portion of the surface, pressure must increase as air moves towards the trailing edge. This requires active LFC, which is typically obtained using suction through small perforations in the surface of the airfoil.

The efficiency gains of active LFC were first discussed by Griffith and Meredith of the UK Royal Aircraft Establishment in a 1936 paper.[8] They calculated that LFC by suction could reduce five-sixths of the power loss caused by friction between the aircraft's skin and air.[9] In the 1950s and the 1960s, the rapid growth of air travel (a 'landscape development') prompted some companies to study LFC as a means of reducing costs and further expanding markets. In June 1960, Handley Page acknowledged that supersonic air travel was "a new and inevitable development", but argued that high costs would only make it more exclusive: "passenger air transportation can be expected to remain the preserve of the expense account traveller or the wealthy, and a significant increase in air passenger traffic is unlikely without a correspondingly significant reduction in fares."[10] Thus, Handley Page proposed the HP 117 aircraft as a way to enable long-range air travel for the masses. The HP 117 design used two techniques for reducing drag: laminarisation and a flying wing design, thus affording "the full exploitation of low drag associated with laminar flow in combination with the low structure weight of the all-wing aeroplane."[11]

Although Handley Page gained government support for early research on the HP 117, it could not obtain funding to build a full-scale operational LFC aircraft. The sociotechnical landscape – notably the low cost of aviation fuel and efficiency gains from high-bypass turbofan engines – did not favour LFC in the 1960s. Crude econometric studies suggested that LFC would only offer a worthwhile benefit for very long-range aircraft, and with no such requirement envisaged, UK funding was stopped in the late 1960s.

Notably, this decision was not based upon a clear-cut cost-benefit analysis. Rather, it involved judgments about the probable costs and benefits of LFC. Deliberations by the Aeronautical Research Council's Aerodynamics Committee regretfully noted that this decision was based on "purely arbitrary estimates and so, as on many occasions in the past, the discussions have highlighted the difficulties of making any accurate assessment of the possible performance advantages from laminarisation in the absence of reliable and substantiated data on manufacturing and maintenance costs."[12] This decision illustrates a typical catch-22 for radical innovations: they present high uncertainties until they are developed and operated, but these same uncertainties deter sufficient investments in development to provide operational data.

Support for LFC was more substantial in the USA. In the early 1960s, Northrop obtained Air Force funding for a flight test programme with an X-21 aircraft. This initially revealed several difficulties associated with LFC, including unexpectedly high levels of turbulence across wing surfaces, and the loss of LFC in certain weather conditions due to the formation of ice crystals. The X-21 eventually achieved laminar flow over 95% of its laminarised surfaces, but the project was cancelled in the late 1960s, reportedly because of dwindling Air Force support and the distractions of Vietnam (Braslow, 1999: 12).

Interest in LFC was revived by the 1973 oil crisis. Although many at NASA believed that earlier research had demonstrated the impracticality of LFC, a 1974 workshop by the American Institute of Aeronautics and Astronautics (AIAA) indicated that progress in related technologies warranted renewed attention to LFC. In September 1975, a NASA-sponsored task force published their conclusion that LFC should be supported, and a Laminar-Flow Control Working Group was immediately established at NASA Langley Research Center (Braslow, 1999: 14). The LFC project eventually became one of the six projects to be supported by NASA's ACEE.

The task of the 1970s LFC group was even more challenging than that of the 1960s LFC researchers because NASA aimed to develop technology for the civil airliner industry, where costs are more important than they are in military applications (Braslow, 1999: 15). A wide range of activities, from basic research to flight-testing, sought to establish the practicality of LFC. Key concerns included insect contamination and the consequent in-flight loss of laminarisation, along with extra maintenance costs. Flight tests on a relatively small aircraft demonstrated that LFC could be maintained over a portion of the wings under operational conditions that were typical of commercial airliners: “during four years of flight testing from November 1983 to October 1987, no dispatch delays were caused by LFC systems” (Braslow, 1999: 25).

Despite these findings, the risks of extra maintenance costs and in-flight loss of LFC have deterred airliner manufacturers from using LFC operationally (Braslow, 1999: 1). Both Boeing and Airbus have flight-tested hybrid LFC, in which a combination of natural and active laminar flow control provides a more reliable, though less efficient solution than active LFC. This has now been implemented on the latest derivative of the 787 (Kingsley-Jones, 2014 Mecham, 2012). Nonetheless, an airliner with extensive suction-LFC does not appear to be a near-term prospect.

In sum, while landscape pressures such as high oil prices have helped to provide a niche for LFC research and development, they have been insufficient to cause a regime change. To explain this insufficiency, we must go beyond the structural MLP analysis to consider how specific social groups conceive of ‘maturity’. While engineers have proven that LFC can operate reliably on small aircraft, manufacturers and commercial airlines require more experience and full-scale demonstrations before they consider LFC to be mature.

Discussion and Conclusions

Why do some innovations enable transitions, while others find only limited market niches, and still others remain in the research and development phase? The case studies described above illustrate both the utility and limitations of the MLP in answering such questions. The MLP provides insight into how the timing of landscape, regime, and niche dynamics allowed the turbofan to displace propeller-pistons in long-range aircraft. The landscape pressures of WWII nurtured the military turbojet niche and made it sufficiently mature to replace the propeller-piston regime when new landscape pressures – the U.S.-British post-war rivalry in commercial aviation and the rapid expansion of air travel – grew sufficiently strong.

Yet the mere presence of niche resources and landscape pressures is insufficient to explain how or why transitions occur. As we have seen, other radical aviation technologies – including advanced turboprops, flying wings, and laminar flow control – have been supported in niches and nurtured by landscape developments, but have not caused transitions. Cold War technological competition created a niche for both carbon fibre and flying wings. Propfan and laminar flow control niches were nurtured by the landscape development of the oil crisis and consequent government R&D programmes. In recent years, concerns about a new landscape pressure – climate change – have continued to nurture all of these niches.

Why, then, have niche and landscape developments not caused a transition towards these more fuel-efficient innovations, as they did for the (extremely inefficient) turbojet? The MLP provides a preliminary answer: the niche was not mature enough, and/or the landscape pressures have not been sufficiently strong or sufficiently consistent to lead to full market introductions and maturation of innovations. But to understand why some innovations cause transitions while others do not, we must consider what it means for a niche development to be sufficiently mature, what it means for landscape pressures to be sufficiently large, and for whom. We also need to follow the 'symmetry' principle by analysing a spectrum of outcomes (success, failure, and partial adoption), rather than focusing solely on past successful transitions. Future work on the MLP framework could benefit from a more comparative approach that considers successful, partial and failed transitions within the same regime and between different types of regime.

What our case studies show is that different social groups could evaluate the same innovation as 'conservative' or 'radical,' 'mature' or 'immature.' In the engineering dimension of innovation, propfans were not very radical, but in a business and consumer dimension, they represented significant departures from what had come to be accepted as the appropriate speed, noise level, and appearance of a long-range airliner to the social groups primarily concerned with these aspects of air travel. The case of carbon fibre is just the opposite: the engineering and manufacturing of carbon fibre components is radically different than that of aluminium components, but a carbon fibre airliner such as the 787 looks nearly identical to other Boeing or Airbus aircraft. Similarly, laminar flow remains a 'radical' engineering challenge, and its development poses significant economic risks, though consumers would hardly notice it in operation. Flying wings are radical from virtually all dimensions of innovation – engineering, business, policy, and consumer acceptance – and this is a principle reason that they are not even on the drawing board for any near-term airliner.

These cases suggest that technologies which are more radical in the engineering dimension of innovation than from a business or consumer dimension are likely to find a niche in research and development laboratories, but will be slower to find a market application. Such technologies include cold fusion nuclear reactors and carbon sequestration technologies. Markets for cheap, safe electricity and carbon footprint reductions exist, but the engineering of such systems remains stuck in the laboratory. By contrast, technologies, which are primarily radical in a business or consumption dimension, but are conservative from an engineering dimension, are more likely to find a market niche. Examples of innovations in this latter category include car sharing schemes (such as Zipcar, RelayRides, and Getaround) and 'smart' electrical meters. In these latter cases, regimes may take on a mixed character, in which two or more technologies see a pattern of incremental development.

These conclusions have implications for policy as well as for future research. As we have seen, the transition from niche to regime is often limited by actors' risk tolerances, but these tolerances vary greatly. Simply nurturing a niche is far from enough, even when landscape pressures appear to be supportive. Instead, the specific concerns of specific regime actors need to be addressed. Manufacturers find it safer to build upon established consumer preferences than to enter radically different markets. Consumers are wary of new and unproven products. The process of taking early-stage research into the market is long, arduous, and above all else, risky. In the case of high-risk technologies such as laminar flow and flying wings, neither increasing landscape pressures nor nurturing niches is likely to enable a transition. Rather, policies should aim to reduce or disperse the specific engineering, business, and regulatory risks associated with different technological options for radically green aviation.

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Notes

1 Handley Page 117 Laminar Flow All-Wing Transport for Lowest Cost – Longest Range. Handley Page Ltd, June 1960. UK National Archives [NA], DSIR 23/28151.

2 This is one reason that computer software is often put on the market with glitches and security flaws (Anderson, 2006).

3 See 1992 Figure from Rolls Royce: http://ocw.mit.edu/ans7870/16/16.unified/propulsionS04/UnifiedPropulsion3/UnifiedPropulsion3.htm

4 A short clip of it flying can be found here: https://www.youtube.com/watch?v=1BMNaXc1rL8

5 Carbon fibre comprises 50% of the Boeing 787 by weight, and enables over 3% of the 787's 20% fuel savings. Weight savings contribute to 3% of the efficiency gains, and carbon fibre also enables aerodynamic streamlining and systemic efficiency improvements. Combined with more efficient engines, these material-related savings make the 787 20% more fuel efficient than previous comparable aircraft.

6 Official Northrop Press Release, enclosed with letter from British Air Commission, October 31, 1941. NA, AVIA 10/363.

7 Official Northrop Press Release, enclosed with letter from British Air Commission, October 31, 1941. NA, AVIA 10/363.

8 Royal Aircraft Establishment, 'The possible improvement in aircraft performance due to the use of boundary layer suction,' by A. A. Griffith and F. W. Meredith, March 1936. NA, AVIA 6/8595.

9 Royal Aircraft Establishment, 'The possible improvement in aircraft performance due to the use of boundary layer suction', by A. A. Griffith and F. W. Meredith, March 1936. NA, AVIA 6/8595.

10 Handley Page 117 Laminar Flow All-Wing Transport for Lowest Cost – Longest Range. Handley Page Ltd June 1960. NA, DSIR 23/28151.

11 Handley Page 117 Laminar Flow All-Wing Transport for Lowest Cost – Longest Range. Handley Page Ltd June 1960. NA, DSIR 23/28151.

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Rethinking 'Drop-in' Biofuels:
On the Political Materialities of Bioenergy

Kean Birch and Kirby Calvert

A sustainable transition is premised upon moving from a carbon energy regime to a renewable energy regime; a highly contested political-economic transformation, to say the least. In places like the United States and European Union the main form of renewable energy is bioenergy, especially biofuels. Recent policy and industry efforts are focusing on the development and implementation of what are known as 'drop-in' biofuels, so named because they can be incorporated into existing distribution infrastructure (e.g. pipelines) and conversion devices with relatively few, if any, technical modifications. As with carbon energy, bioenergy has particular materialities that are implicated in the political-economic possibilities and constraints facing societies around the world. These political materialities of bioenergy shape and are shaped by new energy regimes and therefore problematize the notion of a drop-in biofuel. Thus further examination of the political materialities of bioenergy, and of renewable energy more generally, is of critical importance for successful sustainable transitions.

Keywords: political materialities, drop-in biofuels, bioenergy, sustainable transitions, bio-economy

Introduction

Climate change is not only a major crisis facing the global community but also – and perhaps more crucially – a seemingly intractable political-economic problem for which governments, businesses and consumers are unwilling to accept responsibility through remedial action. These observations are made across the political, environmental and scholarly spectrum. For example, Lord Nicholas Stern, who authored the influential *Stern Review* (HM Treasury, 2006), increased his prediction regarding the likely rise of global average temperatures from two degrees to four degrees centigrade (The Observer, 2013). In *Rolling Stone* magazine, Bill McKibben (2012) pre-empted Stern by arguing that a four-degree rise is inevitable. Importantly for our paper, McKibben highlighted the ongoing enrolment (or complicity if we accept non-human agency) of political-economic technologies – notably resource and asset accounting and calculation criteria – in this process. Specifically, McKibben argues that a 2 degree centigrade increase in temperature will result from the release of another 565 gigatons of carbon dioxide. While a daunting observation on its own, he then points out that carbon reserves (e.g. oil, gas and coal) currently held by companies and states around the world represent approximately 2,795 gigatons of CO_2; or, five times what McKibben considers a tolerable threshold. The most frightening part of McKibben's assessment is that these reserves are "already economically aboveground – it's figured into share prices, companies are borrowing money against it, nations are basing their budgets on the presumed returns from their patrimony". In other words, in the absence of a willingness to write off "$20 trillion in assets" these 2,795 gigatons of CO_2 have already entered the atmosphere as a result of how we account for and calculate our (carbon-based) natural resources.

As environmentalists and scholars in this area are likely to point out (e.g. Lohmann, 2010), this carbon needs to stay in the ground if we are to have *any* chance of transitioning to a low-carbon future which will stabilize global temperature rises. However, we face significant obstacles to any social and economic transition. For example, Boykoff and Randalls (2009: 2299) argue that "carbon-based activities dominate [our] economies and societies in ways not seen before in human history"; thus it makes sense to talk about a *carbon economy* in which human action, institutions and infrastructures are entangled with the very materiality of natural and environmental processes relating to the discovery, extraction, processing, distribution and consumption of carbon resources. Moreover, as Timothy Mitchell (2011: 1) has argued we can also talk about a *carbon democracy* in which the materiality of "[f]ossil fuels helped to create both the possibility of modern democracy and its limits" (see also Mitchell, 2009, 2010). In particular, Mitchell (2011: 7) notes that one of the key limitations represented by carbon energy – especially oil – "is that the political machinery that emerged to govern the age of fossil fuels, partly as a product of those forms of energy, may be incapable of addressing the events that will end it".

It is clear that we need to de-carbonize our political-economies (see Jackson, 2008). The alternative is further 'carbon lock-in' (Unruh, 2000) and dramatic environmental and social impacts from rising temperatures. De-carbonization, however, entails more than the research, development and promotion of low-carbon innovation, including in the Global South (e.g. Tyfield & Urry, 2009). Indeed, a systemic shift in political-economic technologies (e.g. accounting) is needed as well in order to untangle our polities, societies and economies from the materialities of carbon as an energy regime (see Bradshaw, 2010). How we go about doing this is a critical issue and the subject of much heated debate (pun intended).

As this special issue attests, these concerns with energy politics and economics are not new to STS. In his research on the politics of combined heat and power back in the 1980s and 1990s, Stewart Russell's (1986, 1993) work prefigured much of the recent work on the politics of transitions and renewable energy. With regards to our own arguments, Russell highlighted several key issues that arise repeatedly, including: the problem of barriers to entry created by incumbent or prevailing energy producers (amongst others); the relationship between techno-scientific and political-economic knowledges (e.g. economics of energy); the politics of energy supply and use (e.g. energy decentralisation); and, especially, the decisions and choices that go into the shaping of energy pathways (e.g. techno-scientific exclusion).

Bioenergy represents one pathway towards a low- or zero-carbon future. Bioenergy is both an old form of energy (e.g. wood stoves) and new form of energy (e.g.

liquid biofuels). The idea of an emerging bio-energy regime has become popular over the last few years, and implies a transition to what is being called a *bio-based economy* or *bio-economy*; that is, an economic system in which societal needs and desires are met through institutions and infrastructures that enable the production and conversion of biological matter into various energy and non-energy products (see OECD, 2006; EU Presidency, 2007; CEC, 2012; White House, 2012).[1] It is not our intent to get into a discussion of this emerging bio-economy here; instead, our primary aim is to theorize the political materiality of bioenergy. We aim to highlight that this bio-economy, similar in process (though not in form) to a carbon-economy predicated on fossil energy, represents a political-economic project configured and conditioned by the particular biophysical and technoscientific materialities of bioenergy such as biofuels. Moreover, the bio-economy is likely to prove highly disruptive to the current carbon economy given the vastly different materialities between the two energy resources. It is hardly surprising, then, that more recently there has been greater emphasis placed on the development of technologies like 'drop-in' biofuels, so named because of their ability to be used in existing distribution infrastructure and conversion devices with relatively few, if any, technical modifications compared to conventional biofuels. We aim to question this notion of a drop-in biofuel, largely because it focuses only on downstream applications of bioenergy (i.e. conversion and consumption) and completely ignores the considerable upstream disruptions they will likely require for implementation.

We want to be clear at the start that our paper is programmatic in nature. Using empirical material from the Canadian province of Ontario to illustrate our claims, we are concerned with thinking about the problems that might surface during a transition from a carbon economy to a bio-economy, especially where the latter is predicated on disrupting the former as little as possible. This is the key research question and focus for our article. In order to build our arguments we first discuss the material politics of energy by drawing on the work by Timothy Mitchell (2009, 2010, 2011). We then discuss the relationship between renewable energy and systemic, sustainable transitions as they are currently conceptualized, before identifying a series of gaps and omissions in the promotion and development of bioenergy, especially biofuels, as an alternative energy to carbon within Ontario, Canada. We use Ontario as an illustrative case study because of its recent and continuing support for bioenergy and biofuels through several key policies including the *Ethanol Growth Fund* (enforced as of 2005), *Ethanol in Gasoline Regulation* (enforced as of 2007) and *Green Energy and Green Economy Act* (enforced as of 2009). We finish with a conclusion that outlines the implications of our arguments to the development of drop-in biofuels.

Political Materialities of Energy

We are concerned with the political materialities of energy in this paper, especially the role of bioenergy in any transition to a low- or zero-carbon energy regime. These sorts of concerns with the politics of material technologies are not new to science and technology studies (STS). In STS materiality has been used to reference the material agency of objects, technologies and even nature itself in shaping technoscience and technoscientific practices, and vice versa. This interactive process brings us to the work of Timothy Mitchell (2009, 2010, 2011), whose approach we use to examine the energy-politics nexus.

In Mitchell's (2009: 399) words, "fossil fuels helped to create the possibility of twentieth-century democracy and its limits" – or what he terms *carbon democracy* (also Mitchell 2011). As a starting point, Mitchell (2009, 2011) interrogates the claim that oil-producing countries tend to be less democratic because they suffer from a 'resource curse' – more specifically, an 'oil curse'. According to Mitchell, the claim that countries suffer from an oil curse largely ignores "the ways oil is extracted, processed, shipped and consumed, the forms of agency and control these processes involve or the power of oil as a concentrated source of energy" (Mitchell, 2009: 400). What Mitchell is getting at is that (democratic) politics is bound up with the very materialities of fossilized carbon itself, since these materialities shape the forms, participation and constraints of political engagement or dis-engagement. In addition to the simple physical characteristics of coal or oil, it is the material apparatus of energy production (e.g. mines), distribution (e.g. pipelines) and consumption (e.g. power stations) that shapes political power and, ultimately, the capacity for political and social change. Hence, it is critical to consider the materialities of bioenergy, as we do in this paper, since bioenergy is meant to represent a key alternative to the fossil fuel regime that Mitchell concentrates on in his work. Before we come to bioenergy, however, we want to properly outline Mitchell's broader argument.

The key to Mitchell's (2009) argument is that the materialities of carbon energy (e.g. coal, oil) create possibilities for and limits on political action, which have to do with the biophysical characteristics of hydrocarbons themselves as well as the material (e.g. transport) and epistemic (e.g. accounting) apparatus needed to bring them into use. According to Mitchell (2009), the existence and recovery of coal made it possible to transport and therefore centralize large quantities of energy and to generate motive power on a large scale (e.g. steam engines). These materialities were crucial for (re)distributing political power relations that were central to colonization, industrialization and urbanization. Mitchell argues that these political materialities of coal are evident in the rise of mass democratic movements driven by labour organizations during the 19th century and early 20th century (also Agustoni & Maretti, 2012). More specifically, Mitchell argues that the growing dependence on coal was accompanied by the rising power of the labour movement because workers could disrupt key junctures in the transport of coal (e.g. railway terminals, ports, coal mines) and therefore threaten the material basis of these political-economic pursuits. The power of workers was not limited to coal miners, moreover, since other workers could also blockade these key transit sites (e.g. railway workers, dockers, sailors). What this meant was that workers could shut down the flows of hydrocarbon energy on which industrial societies had become dependent and hence they were able to make political demands which had to be met, whether this was for higher wages or political franchise.

While coal represented one specific form of political materiality, oil represented another form according to Mitchell (2009, 2011). Mitchell argues that the pursuit of oil as an alternative energy source was partly a response to the growing power of labour. Indeed, the biophysical and energetic qualities of oil, as a liquid energy carrier that is of higher energy density than coal, meant that the man-power required in order to extract, refine and distribute energy was greatly reduced. In Mitchell's terms (2009: 407), the qualities of oil meant that:

> [I]t required a smaller workforce than coal in relation to the quantity of energy produced. Workers remained above ground, under continuous supervision of managers. Since the carbon occurs in liquid form, pumping stations and pipelines could replace railways as a means of transporting energy.

All of this entailed a different political materiality, involving a new technological and epistemic apparatus. First, Mitchell (2011: 46) points to the "development of technologies for transporting oil that took advantage of its liquid form and eliminated most manual labour from the movement of energy". Oil can be transported within buried pipelines and fractionated into useful products through automated processes. Workers therefore had fewer opportunities to disrupt the flows of energy so that the political power of labour was dramatically reduced (see also Huber, 2013), while the control of energy depended on control over "a comparatively small number of sites" including "major oilfields, pipelines and terminals, and the handful of bulk tanker fleets" (Mitchell, 2011: 67). Ultimately then, oil limited the development of democratic movements as it reduced the power of workers to back up their demands with acts of disruption.

Second, Mitchell highlights the necessary convergence of the materiality of oil with the epistemic practices and technologies of economics during the early years of the 20th century. In earlier work, Mitchell focuses on how 'the economy' has been constructed through epistemic practices in the discipline of economics (e.g. Mitchell, 2005). In relation to carbon democracy, Mitchell takes his argument further by examining not only the materiality of fossil fuels "but also the related networks, of international finance, for example, of technical knowledge, and of economic theory that different forms of energy depended upon and made possible" (Mitchell, 2010: 190). This *carbon economy* – or, perhaps more precisely, *carbon economics* – entailed a wholesale transformation of economics as a discipline, according to Mitchell (2011: chapter 5), from a focus on natural resource depletion (regarding coal in 19th century) to the treatment of oil (post World War II) as an 'inexhaustible resource' that reinforced the fiction of ever-rising national economic growth (also Boyer, 2011). Here epistemic practices are entangled with the different materialities of coal and oil; the latter became bound up with new forms of national accounting (e.g. GNP), Keynesian demand management and a focus on prices (i.e. "petroknowledge") which presaged new economic technologies of calculation, price-setting and so forth that "were built into the new financial institutions" (Mitchell, 2011: 135).

We will return to the importance of epistemic practices when we consider the implications of the political materialities of bioenergy since, and if we accept Mitchell's arguments, it is clear that an epistemic transition will be a necessity with any transition to a low- or zero-carbon economy. In coming back to how Mitchell relates to bioenergy, in general, it is crucial to consider his argument "that the political machinery that emerged to govern the age of fossil fuels, partly as a product of these forms of energy, may be incapable of addressing the events that will end it" (Mitchell, 2011: 7). Or, more simply, we cannot rely upon a political apparatus underpinned by fossil fuels to engender and drive a systemic transition to a new energy regime based on renewables, bioenergy included. New forms of energy entail new political machinery and new epistemic practices, which involve a completely different perspective to the carbon age. Any analysis of systemic energy transitions will necessarily involve an understanding of what Boyer (2011: 5) terms ‘energopolitics’; this is more than the politics of access and control, it also concerns “interrogating the magnitude and methods of energy usage that carbon statecraft institutionalized”.

Sustainable Transitions and Bioenergy

The reason that the political materialities of energy are important goes back to the discussion in the introduction about the emerging and growing policy, political and academic emphasis on low- or zero-carbon transitions (e.g. Jackson, 2008; Tyfield & Urry, 2009). One important technological pathway towards a sustainable transition is bioenergy; it is meant to offer a win-win solution in which transition can be allied to a new energy regime which will de-carbonize our economies (Frow et al., 2009; Birch et al., 2010). For the purpose of this paper, bioenergy refers to the conversion of biomass from plants and waste streams into various forms of energy (e.g. electricity, heat) or energy carriers (liquid, gaseous, or solid fuels)

The last decade has been characterized by a significant push behind bioenergy and specifically liquid biofuels (e.g. bioethanol, biodiesel) as a key sustainability solution to climate change. Moreover, bioenergy and biofuels are an important (and dominant) form of renewable energy in major world economies like the Unites States and European Union. In the US, for example, biofuels have a long history stretching back at least to the *Energy Tax Act* (1978), which was concerned with US energy security following the oil crises in the 1970s (Kedron & Bagchi-Sen 2011). More recently, and as a result of the *Energy Policy Act* (2005) and *Energy Independence and Security Act* (2007), the US overtook Brazil as the world’s leading biofuels producer (Smith, 2010). Thus it is no surprise that bioenergy now represents nearly half of the USA’s renewable energy production (Zimmerer, 2011). In the EU, bioenergy also represents a significant proportion of renewable energy production, over half in 2010 (ClientEarth, 2012). Again, in the EU bioenergy mainly relates to biofuels, primarily biodiesel, and support for biofuels has been integrated into the *Biofuels Directive* (enforced as of 2003) and *Renewable Energy Directive* (enforced as of 2009).

Bioenergy is a dominant renewable energy source in the USA and EU primarily because of policy support for biofuels in the transportation sector – a major greenhouse gas (GHG) emitter. As mentioned, this support dates back to the 1970s in some cases, largely as a response to the oil crises and fears about energy security (WorldWatch Institute, 2006). The rationale behind promoting biofuels has since evolved a number of times in both the US and EU; it has moved through several policy justifications including energy security, rural economic development, energy efficiency and, finally, GHG emission reductions following the *Kyoto Protocol* (1997) (e.g. Charles et al., 2007; Mol, 2007). It is no wonder that biofuel production quadrupled in the period between 2000 and 2006 (see Mol, 2007; also WorldWatch Institute, 2006), although this has largely been concentrated in the USA (ethanol) and EU (biodiesel) (Ponte, 2014).

Post-Kyoto, both the USA and EU began to articulate a sustainability rationale for promoting biofuels in legislation like the US *Biomass R&D Act* (2000) and the EC *Biofuels Directive* (2003) (Charriere 2009; ClientEarth 2012). There are plenty of analyses of the (positive and negative) impacts of these pieces of legislation and later policy decisions like the EU *Biofuels Strategy* (2006), US *Farm Bill* (2002), US *Energy Policy Act* (2005), and others (e.g.

Charles et al., 2007; Londo & Deurwaarder, 2007; McMichael, 2009, 2012; Gillon, 2010; Bailis & Baka, 2011; Kedron & Bagchi-Sen, 2011; Levidow et al., 2012b; Levidow & Papaioannou, 2014; Ponte, forthcoming); however, it is not our intent to go into these debates in any detail here. What we want to highlight is the importance of bioenergy and especially biofuels as a key renewable energy source for these major economies.

In the last few years, however, major media outlets have reported on the uncertainties surrounding biofuels, especially whether they will actually achieve their proposed environmental and socio-economic benefits (Smith, 2010). This uncertainty reflects growing criticism in the scientific literature about the ecological and social benefits of biofuels derived from primary agricultural products (e.g. corn, soy). Criticism from scientists in 2008, with several papers in *Science* (Fargione et al., 2008; Hill et al., 2006; Searchinger et al., 2008), spread quickly to mainstream media when policy concerns relating to the impact of biofuel production on food prices was highlighted in a World Bank report leaked to *The Guardian* newspaper (Mitchell, 2008). These criticisms largely focus on indirect land-use change (ILUC) as biofuels production in places like the US force changes in land-use in other parts of the world (cf. Harvey & Pilgrim, 2011). As a result there has been a policy push behind so-called ‘second generation’ or ‘advanced’ biofuels for which net energy returns are greater and which are derived from non-food crops (e.g. switchgrass, miscanthus) or biomass grown on non-agricultural land (e.g. forest residues) (Pimentel, 2009; Sims et al., 2010; Stephen et al., 2011), and hence can be considered as more ecologically and socially sustainable (Bailis & Baka, 2011; Levidow et al., 2012b). Given uncertainties surrounding, and impediments to, the development and commercialization of these second generation biofuels (O’Connell & Haritos, 2010; Tyner, 2010a, 2010b; Stephen et al., 2011), policy support is also increasing for research on new types of biofuels with higher energy contents (e.g. butanol). These third or fourth generation biofuels are derived from algae or synthetic biology (Ferry et al., 2012), and can be designed to ‘drop-in’ to prevailing infrastructures used by fossil fuels (Tyner, 2010c; Savage, 2011).[2]

What this brief discussion of bioenergy and biofuels is meant to illustrate is that these forms of energy are important alternatives in major national and regional economies to the carbon economy theorized by Mitchell (2009, 2011) and others (Boykoff & Randalls, 2009; Bridge, 2011). The prominence of bioenergy as a key renewable energy resource in both the USA and EU has been reinforced recently by the ‘bio-economy’ strategies produced by these states in early 2012 (e.g. CEC, 2012; White House, 2012). Whether or not bioenergy and biofuels will or can engender a sustainable transition to a low- or zero-carbon future is open to question. It is our argument that whether this is likely depends upon the political materialities of bioenergy and the constitution of a *de-carbonized democracy*. It is to this issue that we now turn.

Political Materialities of Bioenergy: The Case of Ontario

Our analysis in this section builds on Mitchell’s (2009, 2010, 2011) arguments about the political materialities of carbon energy; what we do here is apply his insights to bioenergy, especially liquid biofuels. In order to help illustrate the political materialities of bioenergy and to contrast them against the political materialities of carbon energy, we focus, in particular, on the Canadian Province of Ontario. Our interest in Ontario stems from the

Provincial Government's recent and very active role in promoting sustainable energy transitions through various policies, which in many cases build on previous Federal Government policies. These include, but are not limited to, Ontario Provincial policies (e.g. *Ethanol Growth Fund*, 2005; *Ethanol in Gasoline Regulation*, 2007; *Ontario Green Energy Act*, 2009) and Canadian Federal policies (e.g. *Alternatives Fuels Act*, 1995; *Biomass for Energy Program*, 2000; *Action Plan on Climate Change*, 2000; *Ethanol Expansion Program*, 2003; *ecoENERGY for Renewable Power Initiative*, 2007; *NextGen Biofuels Fund*, 2007; *Federal Renewable Fuels Regulation*, 2011) (see Charriere, 2009; Puddister et al., 2011; Mabee, 2013). More recently, however, the Federal Government has all but halted the promotion of renewable energy; mostly for political reasons relating to the dominance of the Conservative Party and Alberta tar sand interests (Winfield, 2012). As a result, Ontario has taken a significant lead over other Canadian provinces when it comes to bioenergy and biofuels (CanBio, 2012).

Until recently, Ontario was heavily dependent upon fossil fuels for transport and electricity generation (Ontario Power Authority, 2010). The transition to renewable energy and especially bioenergy has been driven by several of the policies highlighted above. We focus here on three in particular. The first policy is the 2005 *Ethanol Growth Fund* (EGF) which was established to finance capital investment in ethanol production and assist producers in the face of market uncertainties, as well as fund R&D into biofuels. The EGF forms part of Ontario's plan to introduce a renewable fuel standard (RFS), which is the second policy and is represented by Ontario's 2007 *Ethanol in Gasoline Regulation* (EGR). This was originally announced in 2004 as a provincial RFS, reflecting moves in other countries to introduce RFS based on biofuels (see Bailis & Baka, 2011) and building on agreements with British Columbia and California to reduce GHG emissions (Charriere, 2009). The emphasis on volume mandates can be seen as part of a wider shift away from excise tax exemptions, which were highly variable between countries and even provinces (de Beer, 2011). The EGR stipulated a 5% minimum ethanol blend by volume for all gasoline sold in Ontario from 2007 – there is now a similar Federal RFS introduced by the *Renewable Fuels Regulation* (2011). The EGR has effectively created a market for over 880 million litres of ethanol for Ontario producers – a benefit of a RFS mandate over excise tax exemptions – most of which is produced from the conversion of starch from corn and wheat and is financially supported by the EGF. The investments through the EGF have resulted in the installation or construction of over 1000 Ml of ethanol production capacity in Ontario (Canadian Renewable Fuels Association, 2011). According to de Beer (2011: 21), Ontario's EGR policy was at the time of its enactment unique because it contains (albeit weak and so far ineffective) provisions to encourage advanced biofuels in Ontario, especially cellulosic biofuels from non-food plants (e.g. forestry), as part of this RFS mandate.[3] The provincial government has also financially and politically supported an increasing number of wood-pellet production facilities as well as commercial and pre-commercial advanced or drop-in biofuel production facilities through support for capital expenditures as well as licensing agreements on forest resources.

There are also moves to encourage bioenergy production in the electricity sector through the 2009 *Green Energy and Green Economy Act* (GEGEA). This legislation follows declarations and actions toward the closure of all coal power plants in Ontario by 2014 and investment in renewable energy sources like wind, solar and bioenergy; the latter is expected to reach 10,700 MW by 2018 (Ontario Power Authority, 2010). The main mechanism for promoting renewable electricity generation is through a feed-in-tariff, which guarantees a secure pricing structure for producers; the GEGEA also has a domestic context requirement meaning that a majority proportion of technology inputs need to be sourced from Ontario thereby linking sustainable innovation to the creation of new jobs in Ontario (Ritson-Bennett, 2010). The feed-in tariff rates for bioenergy are 13.8 cents per kWh for biomass-based electricity plants under 10 MW and 13.0 cents for those over 10 MW (Ontario, 2010).

These three policies in Ontario are representative of state interventions designed to promote sustainable transitions and the de-carbonization of the economy. They imply not only a significant rethinking of the organization and configuration of energy production, distribution and consumption, but also a rethinking of political formations and technologies. Changes could be undertaken within the current energy regime by integrating renewables and bioenergy into prevailing infrastructures and institutions, or they could be pursued by totally disrupting the current energy regime. As Mitchell (2011) points out, the latter is considerably less likely because the 'political machinery' associated with fossil fuels is biased against the introduction of new energy systems. The main reason for this is that any new energy regime (e.g. bioenergy) entails new political machinery which will necessarily contradict the political machinery of any prevailing energy regime (e.g. fossil fuels) – this new political machinery will be tied to the biophysical and energetic qualities and characteristics of bioenergy. This is especially the case if jurisdictions wish to achieve a scale of production that is able to replace entirely our existing fossil-based energy systems (Richard, 2010).

These political changes are frequently presented as socially, economically and politically positive because they are expected to encourage things like local control and autonomy, decentralized decision-making and cohesion, and localized economic benefits like new jobs, new investment etc. (e.g. Green New Deal Group, 2008). The positive impacts of bioenergy are more evident when we consider a range of possible bioenergy scenarios (see Upham et al., 2007 for examples). Deciding how biomass resources are best used is an inherently political choice with different political-economic implications in terms of end-users as well as patterns of production. If a given society chooses liquid biofuels or follows an export-oriented path for pellets, for instance, then production facilities will necessarily occur in large centralized facilities due to the need for economies of scale. If biomass is diverted instead toward combined heat and power or district heating systems, then it is more likely that a distributed pattern of development will occur because it is simply not possible to transfer heat over long distances. Such a bioenergy scenario would be more amenable to community-based ownership models similar to local cooperative models employed in the wind sector.

As Russell (1993) highlighted in his work, these questions of energy decentralization and distribution are tied up with political-economic decisions and not limited to technical issues. However, what we want to emphasize is that both of these bioenergy scenarios entail particular political materialities; unfortunately we cannot compare these different scenarios and materialities in this article for want of space, so instead we focus on the political materialities that will be important, regardless of the scenario considered. While we do not want to directly contradict the claims made about renewable energy regimes and especially bioenergy regimes, we do want to unpack the 'new political machinery' that will be necessary to facilitate a transition toward bioenergy while at the same time problematize the assumption that they necessarily entail positive political change. The emergence of bioenergy has significant material implications and impacts that necessitate an examination of the political materialities discussed by Mitchell (2009, 2011) in reference to oil and coal.

We are going to focus on three key issues in this regard, bringing together in our analysis a consideration of the physical materialities of bioenergy with the political machinery these materialities both enable and limit, and are, in turn, enabled and limited by. First, we discuss the implications of (bio-)energy flows in order to illustrate how they are different from fossil fuels. Second, we discuss the mobility of unprocessed bioenergy resources relative to fossil energy and whether this will have impacts on political machinery. Finally, we discuss the transboundary nature of bioenergy in relation to sustainability concerns and economic practices.

Mitchell's (2011: 12) concept of carbon democracy is based on "buried sunshine" in the form of coal, oil and gas. In stark contrast, bioenergy and biofuels can be considered "grown sunshine". This is the first crucial difference in the materiality of biomass as opposed to fossilized carbon. When it comes to differentiating between the materiality of bioenergy and carbon energy, it is evident that biomass has relatively low energy density (i.e. GJ/t) compared to fossil energy resources and it grows at relatively fixed rates. On average, approximately 1.5 tonnes of biomass, grown aboveground, are required in order to replace the energy equivalent of one tonne of coal, which is recovered from subterranean deposits. Replacement values can be as high as 2–4 tonnes where petroleum and natural gas is concerned. Further, the rate at which biomass can be extracted from any given area must be limited in order to maintain ecological integrity at the site, including soil quality and niche habitats.

These materialities are central to sustainable transitions involving bioenergy for two reasons. First, the low energy density of biomass indicates the need to reduce societal energy usage if bioenergy (and other renewables) are going to entirely displace fossilized hydrocarbons. In fact, biomass could not possibly be used to power all sectors (e.g. heat, motor fuels, electricity) under existing rates and trends of global energy consumption – i.e. almost all estimates suggest that there is just not enough solar energy being converted into biomass quickly enough, nor can biomass be extracted intensively enough, to allow that type of scenario to be sustainable (for a global-level perspective, see Berndes et al., 2003; for a local level perspective, see Mabee & Mirck, 2011). The shortfall grows larger when one accounts for the fact that biomass would also need to replace petroleum as an input into the production of chemicals and plastics. Second, even the most productive regions of the world will not produce enough biomass to support a bio-economy, so each society must greatly expand the land-footprint of its energy system in order to realize the full potential of bioenergy.[4]

Whether or not the land-intensive nature of bioenergy production entails specific blockage points along bioenergy flows – like coal in Mitchell's (2011) argument – is an open question, and depends on the political-economic conditions under which bioenergy systems are developed. On the one hand agriculture and forestry are sectors with low employment levels and traditionally low-levels of unionization, meaning that there is less likelihood of worker disruption. On the other hand, biomass has to be grown, cut down, moved, processed, refined, etc. in large quantities meaning that there will be plenty of blockage sites for disrupting these flows if workers so choose. The isolation of agriculture and forestry from urban centres is likely to limit the impact that workers can have at particular points of the bioenergy flow, which means that agricultural and forestry workers are less likely to be able to instigate political change by themselves as was the case for centralized and integrated coal workers. But there is also a shift from public to private resources that must be considered. Fossil energy resources in Ontario (and in most other states with the exception of a few notable countries such as the U.S.) are by constitutional law publicly owned. Much of the land from which biomass will be procured for bioenergy production however (e.g. agricultural land and privately owned woodlots) is privately owned. This not only requires new political technologies (e.g. contracts and agreements between hundreds or thousands of owners rather than a single owner) but might also add a new layer of complexity to the political relationship between suppliers and producers. We further reflect upon this relationship below.

The second and related material characteristic of bioenergy is that it is geographically distributed and relatively immobile. The low energy density (by weight and volume) of biomass means that it is not worthwhile in monetary or energetic returns to transport unprocessed biomass resources long distances from cultivation area to processing plant (Hamelinck et al., 2005). Bioenergy resource extraction and processing activities must therefore occur at the same site or in sites very close to one another in order to achieve viable and relevant production scales. Furthermore, the procurement radius for a given facility and therefore the land-based transport requirements are generally much greater (remembering that bioenergy production scales with land area). Biomass co-firing projects in the USA, for instance, "require supply chain managers to expand procurement from 2 to 3 coal suppliers supplying 16 million tonnes of coal to include 120 biomass suppliers supplying only 90,000 tonnes of biomass" (Wolf, 2012: 46, citing Johnson, 2012; see also Richard, 2010).

Three things matter here. First, the spread of bioenergy across a wide area and consequent spread of blockage points mean that the power of workers to affect political change may be significantly curtailed as there will be numerous sources of inputs (e.g. biomass); thus it will be relatively easy to shift from one sourcing site to another if bioenergy flows are disrupted. On the other hand, however, an existing bioenergy production facility might have less flexibility to switch suppliers because they cannot procure from a very long distance without incurring heavy economic costs. In other words, the friction of distance in bioenergy supply chains might bring some power balance between suppliers, producers and workers. This highlights the crux of the chicken-and-egg situation that is stalling many bioenergy investments: growers will not grow without a secure market and the market will not develop without a guarantee of a minimum supply at a fixed and acceptable price within a relatively small procurement radius. Second, and related to this point, a range of local upstream actors (e.g. growers, land managers, biomass aggregators) must be coordinated long before and long after project implementation in order to secure the resources that are necessary to keep a bioenergy system operational. This is in many ways different from all other renewable energy systems for which sustained human activity is not as crucial to maintaining resource flows (e.g. sunlight, wind). Third, oil can be moved by pipeline and coal from mine-to-facility by rail, while biomass must be collected from a wide geographical area and trucked to a rail terminal or shipping port prior to bulk transportation. This higher traffic activity associated with biomass transport and processing is a source of local resistance to project development (Sampson et al., 2012).

It is important to note that our discussion thus far has assumed that raw biomass will ultimately be consumed locally. This is not always the case. Processing biomass into a densified bioenergy carrier or biofuel (e.g. pellets, bio-oil, bio-gas) makes it possible to distribute bioenergy within international and global transportation networks, thereby extending the geographic reach of bioenergy supply chains. In all such cases, however, the upstream components of the supply-chain are distributed, land intensive, and require a significant new draw on local forest and agricultural resources. Furthermore, any such pre-processing incurs extra environmental and monetary costs that must be considered. Life-cycle analyses of long-distance transport of pellets between British Columbia and Europe, for example, reveal that ocean transport increases the energy costs of production and distribution by 54 per cent, raising the total energy costs to 40 per cent of the embodied energy of the biomass and lowering the net energy recovered well below that of locally consumed pellets (Magelli et al., 2009). Furthermore, these long-distance flows of bioenergy are entirely dependent on strong economic pulls or willed markets created by subsidies or carbon taxes in consumer jurisdictions.

Regardless of the development scenario – whether in many small or few large production facilities and whether focusing on heat, electricity, or fuels – bioenergy production systems are localized and land-intensive systems. What's more, the distribution of bioenergy products will operate at much smaller geographic scales than fossil energy products such as coal, especially if they are going to be cost effective and limit environmental impacts as much as possible. The impact that these bioenergy systems will have on local landscapes are, therefore, likely to be considerable; the extraction, distribution, and conversion of energy will be more visible to a greater proportion of the population than is currently the case under a fossil energy regime (Calvert & Simandan, 2010). In this sense, there is likely to be considerable resistance to the creation of new energy landscapes (Pasqualetti, 2011), not least because new energy regimes threaten existing livelihoods as well as lifestyles. As Mitchell (2011: 6) suggests:

> [C]itizens have developed ways of eating, travelling, housing themselves and consuming other goods and services that require very large amounts of energy from oil and other fossil fuels.

There is more to it than changing societal expectations and habits, however. While it might be possible to avoid some of these disruptions to lifestyles by importing biofuels, this would simply displace the problems onto other countries and defeat one key reason for promoting bioenergy in the first place (i.e. sustainability). Thus the political materialities of bioenergy are likely to be highly localized and distributed since they are entangled with different publics at and in many bioenergy sites.

The political capacities of these (largely rural) publics are as important when considering bioenergy as are the potential capacities of (largely rural) workers to affect social change (see earlier); in fact, the former could represent a significant (and possibly regressive) political force in contrast to the progressive political force presented by Mitchell (2009, 2011) when it came to coal and other workers.[5] For example, rural inhabitants have the capacity to block the installation of bioenergy facilities and thereby block bioenergy flows just like coal and other workers had the capacity to block carbon energy flows. Consequently it is important to acknowledge that the material immobility of bioenergy shapes and will continue to shape how different publics engage with bioenergy resources (Walker & Cass, 2007). Indeed, attempts to create new technologies of political governing in response to the move toward localized resources for energy production are already evident in the use of 'community energy plans' in Ontario (e.g. St. Denis & Parker, 2009). Such plans reflect broader moves in places like Denmark and Germany to enrol local communities in renewable energy developments throughout the decision-making process and within ownership models (Yappa, 2012).

New technologies of governance are especially critical where bioenergy processing, production and consumption are *not* localized with biomass cultivation precisely because the potential economic benefits of localized bioenergy processing and production will not accrue to the affected, local population. Thus the materiality of bioenergy and biofuels (i.e. land-based and relatively immobile) entails new technologies of political governance to enrol local publics in local decision-making and in the ownership of local production facilities, in order to enable public engagement in decisions that are likely to be highly disruptive as much as to forestall the highly disruptive capacity of local publics themselves.

Finally, we want to consider the transboundary nature of bioenergy and biofuels, not only in spatio-temporal terms (e.g. daily or seasonal variability) but also in socio-economic terms (e.g. price and commodification variability). Generally, the transboundary nature of bioenergy can be characterized as the *overflows* that happen between spatial and political jurisdictions (Giordano, 2003); these can constitute overflows of economies, energies and sustainability. Elsewhere ClientEarth (2012: 16) characterize such overflows as 'geographical' and 'sectoral' loopholes in accounting for carbon emissions and emissions reductions from biofuels.

Firstly, socio-economic transboundary issues are critical to bioenergy and to understanding the need for new technologies of governing (i.e. political machinery in Mitchell's terms). There are major differences, for instance, between excise tax exemptions and RFS mandates which make the latter more attractive as a policy mechanism to promote bioenergy. On one hand, RFS mandates are often supported by production incentives to develop local or 'home-grown' industries which are generally more acceptable to local citizens and associated with a higher 'willingness to pay' among the public (Upham et al., 2007). On the other hand, tax exemptions simply promote the redistribution of bioenergy products from low-cost producing areas toward areas where tax exemptions have created a market advantage for bio-based energy feedstock. This helps to explain why the Ontario Provincial Government removed the biofuels tax exemption and used the resultant tax revenue instead to fund local ethanol producers through the EGR, which meant that Ontario was no longer paying international producers.

Secondly, the producer receives the sustainability credit when it comes to accounting for the contribution of biofuels to GHG emissions reductions. Anyone producing biofuels, for example, could ship them to a country with an excise tax exemption and benefit from market advantage while any sustainability credit or economic development benefits would remain with the exporting country (ClientEarth, 2012).[6] Capturing these energy flows and sustainability credits necessitates new forms of accounting and calculation (i.e. political-economic technologies) which supersede those highlighted by Mitchell (2010, 2011) when it comes to the carbon economy, especially the oil economy. Thus, and like other energy regimes, bioenergy is bound up with particular political-economic practices and expertise to account for things like transboundary overflows of economic and sustainability benefits; this reflects how materialities are tied to political and epistemic machinery as argued by Mitchell (2011: 110) in reference to carbon.

When it comes to bioenergy there is a significant tension here. It is bound up with new political-economic technologies (e.g. sustainability accounting) that enable some countries to claim credit for the sustainable benefits of bioenergy. Such sustainability credit has to be determined as a political-economic consideration in global agreements because the sustainability benefits are global (i.e. declining emissions benefit everyone) and therefore countries have tried to find ways to integrate calculations of climate change mitigation or adaptation into bioenergy flows. However, this has not always been successful or sensible. In the Kyoto Protocol, for example, CO_2 emissions released by bioenergy are assigned to the country of origin (i.e. producers) rather than combustion (i.e. users) (ClientEarth, 2012). This makes a major difference in terms of who benefits from sustainability credit since user countries can simply discount these emissions by importing bioenergy, whether or not they have actually increased their emissions. This means that major economies like the USA and EU can increase their emissions as long as they import bioenergy from other places where any emissions reductions are assigned.

Overall, the political materialities of bioenergy necessitate a rethinking of economic practices that make “no distinction between beneficial and harmful costs” such as “the increased expenditure required to deal with the damage caused by fossil fuels” (Mitchell, 2011: 140). As highlighted in the introduction (e.g. McKibben, 2012), one prime example of what needs to be done is new ways to calculate the damage done by carbon energy and to assign responsibility (i.e. costs) for that damage to those who extract and use fossil fuels (e.g. oil companies, consumers). This is likely to entail significant struggle over knowledge claims, to say the least, especially in how to account for the costs associated with an increasingly bankrupt carbon democracy (Mitchell, 2009).

Conclusion

In examining the political materialities of bioenergy, we have hopefully pushed forward the work of Stewart Russell (1986, 1993) on the politics of energy and environmental sustainability. Our particular focus has been on the promotion of a green or sustainable transition in order to shift societies and economies away from dependence upon fossil fuels. These transitions are frequently represented as an almost entirely positive transformation of society towards low- or zero-carbon energy, jobs and economies. However, our discussion of the political materialities of bioenergy raise very troubling issues. While the notion of a bio-economy has clear benefits related to sustainability and in some cases stimulates new investments in forestry and agricultural regions, there are real and perceived negative impacts associated with its implementation that, as we have shown, are directly related to the materialities of biomass and how these materialities impact energy supply-chains as well as societal interaction with energy production, distribution and use.

Attempts to integrate bioenergy into prevailing infrastructures and institutions are likely to be problematic, not only because this will merely reinforce the carbon economy but also because the materialities of bioenergy will disrupt existing energy systems as well as regional economies, land-use systems, and transport infrastructure. The materiality of biomass/bioenergy, therefore, necessarily problematizes the notion of 'drop-in' biofuels. Although these fuels have been processed (e.g. de-oxygenated, reformed into long carbon chains) to mimic carbon fuels and therefore be compatible with existing infrastructure for fuel distribution (pipelines) and conversion (internal combustion engines), there are significant upstream changes that need to be made as well. These include: the way land is used and valued; where production facilities will be located; the sheer number and spatial distribution of resource (land) owners that must be considered; and increasing transportation requirements (i.e. for biomass). These things cannot be so easily 'dropped-in' to a carbon economy.

The reason this is important is that the carbon economy actually liberated most of our land and most of our transport infrastructure from supplying energy resources, since we could find them in relatively few sub-surface pools or deposits located great distances from population centres and distribute them in bulk via railways, pipelines and tankers. In contrast, bioenergy is dependent upon the collection of biomass from large areas of land compartmentalized into thousands of woodlots or farms, many of which are privately owned, and trucking that material to numerous, dispersed and relatively smaller processing or energy generating plants which makes energy production activities more visible to a greater proportion of the general public. Furthermore, bioenergy has socio-economic transboundary qualities that require a specific (rethinking of) policy mechanisms to capture energy and sustainability; for example, who gets to claim any GHG emissions reductions: producer or consumer?

These political materialities shape and are shaped by new energy regimes and are therefore of critical importance to sustainable transitions. We need to more closely examine these political materialities in order to understand the potential and limitations of any bio-economy or bio-based economy, and in order to fully grasp the ways in which the relations between society, technology, and environment will co-evolve in the process of a sustainable transition.

While we have found Mitchell's perspective useful as a starting point, we recognize there are limits to his analytical approach. Perhaps most importantly, the world Mitchell outlines is – not surprisingly – built on the notion of social groups pursuing their material interests (e.g. elites want control of energy while workers resist control for concessions). However, social mobilization is driven by more than material interests (e.g. nationalism, religion, culture, politics, etc.). In short, Mitchell's analysis is sometimes just too 'neat' – obviously he cannot cover everything, which means his arguments are often broader than perhaps merited.

Underpinning this flaw is a lack of clarity by Mitchell on how relations between society / social movements, technology, and environment are conceptualised: are these relations deterministic, contingent or co-productive? If the biophysical characteristics of fossil fuels determine particular forms of political mobilization and action, and limit others, it is not clear why the reverse cannot be true as well. For example, do particular forms of political mobilization and action determine access to certain types of energy?

These shortcomings aside, Mitchell's analytical lens has helped us to explore the possibilities and limits on social action, and anticipate the opportunities and challenges that might arise as efforts to transition toward a bio-economy proceed. Continuing this vein of research and thought will help to form the basis of new political technologies that might be required in order to expedite the transition toward sustainability, while at the same time ensuring that the costs as well as the benefits of technical innovations toward a sustainable energy future are considered.

Acknowledgements

We would like to thank the three anonymous referees and the special issue editors for their suggestions and comments on our paper. The usual disclaimers apply.

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Notes

1 There is increasing academic debate about the emergence of a bio-economy or bio-based economy as well; see, for example, Birch et al. (2010), Birch & Tyfield (2013), Levidow et al. (2012a, 2012b), McCormick & Kautto (2013), Ponte and Birch (2014) and Staffas et al. (2013).

2 Bioenergy production facilities could be fitted with carbon capture and storage technologies (CCS). Using IEA (2013) numbers, approximately 3.4 Gt CO_2/year would need to be sequestered which represents 1,804 bcm (assuming a density of 1.9kg/m^3), or 52 per cent of the total volume of gas that is currently produced in the world. In other words, it requires an addition of half of all pipelines that are currently in the ground to service the distribution of natural gas fuels. In the case CCS is deployed with biomass systems significant additions of infrastructure would need to be distributed over a wider geographic area, as our analysis has shown. The addition of CCS infrastructure on generating units lowers the efficiency of production, thereby requiring higher rates of resource extraction per unit of useful energy consumed. In other words, as a GHG-mitigation strategy, CCS is best considered independently from bioenergy production.

3 The provisions in the EGR related to cellulosics are a 'blending adder' for all ethanol derived from cellulosics so that 1L of cellulosic ethanol is equivalent to 2L of starch-based ethanol. To date, only a small (2Ml/yr) pre-commercial cellulosic ethanol plant has been developed in Ontario compared to more than 800 Ml/yr of starch-based ethanol.

4 We acknowledge that technical innovations will reduce the operational footprint of bioenergy systems where land-area is concerned (see Lynd et al., 2007). The fact remains, however, that even an advanced bioenergy regime will require a greater proportion of local land base than a fossil hydrocarbon based energy regime for an equivalent unit of power. This is a function of the aboveground and relatively immobile nature of bioenergy resources. We discuss the immobility of bioenergy resources later in the paper to further clarify this point.

5 It is possible that 'local' people will not necessarily be key actors in social mobilization and protest against rural-based energy infrastructure as evidenced in responses to the siting of nuclear waste in Germany (see Blowers & Lowry, 1997). Instead, it is possible that 'urban' dwellers will lead protest and mobilization efforts.

6 In many countries with a carbon tax, for example Finland, the tax is applied at the facility (e.g., the emissions leaving the smoke stack of a district heating system) and not to the fuels themselves. This means that the embodied carbon content of a fuel is not captured in the carbon accounting equation. As such, pellets shipped from Canada are considered equivalent as far as carbon content is concerned compared to pellets produced locally, even though they are clearly more energy intensive from a life-cycle perspective (Magelli et al., 2009).

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From the Social Shaping of Technology to the Staging of Temporary Spaces of Innovation –
A Case of Participatory Innovation

Christian Clausen and Wendy Gunn

This paper addresses recent developments within the social shaping perspective, specifically the forward-looking and political dimensions of intervening in processes of innovation. With a focus on the concept of 'temporary spaces' as an analytical framework we present a study of a case on participatory innovation concerned with indoor climate practices in the building sector. Based on an analysis of the travel and uptake of narratives derived from field studies in industrial and research environments, we discuss the role of intermediaries such as ethnographic provocations concerning user practices in the staging of these temporary spaces. While the direct uptake of qualitative knowledge on user practice in the engineering worlds of indoor climate is limited, the paper highlights the role of staging temporary spaces and intermediary objects in collaboration with stakeholders as a way of reframing conceptions of indoor climate practices.

Keywords: temporary spaces, participatory innovation, indoor climate practices

Different Approaches Towards a Social Shaping of Technology

This paper examines recent developments within the social shaping of technology research that explore temporary spaces in which innovation processes may be promoted, shaped and reshaped. Innovation increasingly takes place across sequential intersections of design and use. The research discussed here focuses on a temporary space, which is both transitory and improvisational in character. We explore the potential role of such intersections for intervention in the social shaping of technologies.

The focus of the paper is on the role of intermediaries in the movement of knowledge via participatory innovation, which emphasises particular knowledge objects, and practices. We draw upon action oriented approaches to social shaping of technology with particular attention to their discursive and political dimensions exemplified with the analytical notion of sociotechnical spaces for innovation (Clausen & Koch, 2002; Clausen & Yoshinaka, 2007). The notion of design labs

(Binder & Brandt, 2008) is incorporated as a way of addressing the staging of a temporary space, including the mobilization of findings from field and design practices.

The staging of participatory innovation practices is illustrated and analysed through a case study concerned with the social shaping of indoor climate conceptions and solutions. Shove (2003), Jaffari and Matthews (2009) and others have presented indoor climate practices as an important but difficult case for sustainable transitions due to path dependent developments sustained by dominant sociotechnical regimes. While we do not present a case of regime transition, we have been looking for new lines of inquiry concerning conceptions of user practice and whether these could lead towards a potential reframing of the way the social shaping of indoor climate solutions is being constituted.

The research involved collaboration between the TempoS project on Performing Temporary Spaces for User Driven Innovation at Aalborg University and SPIRE's research on participatory innovation at University of Southern Denmark (Buur & Matthews, 2008; Buur 2012; Gunn & Clausen, 2013). The aim of this particular collaboration was to trace and investigate the travel, translation and uptake of user knowledge about everyday indoor climate practices, via a series of participatory innovation workshops, into industrial organizations, engineering indoor climate research institutions, and engineering practices.

Our aim is to investigate how the movement of knowledge from local indoor climate practices to the worlds of engineering in the building industry and indoor climate research institutions may be facilitated through such interventions. Our question is concerned with the staging and politics of the design of such temporary spaces and whether these may lead to the reframing of user conceptions and their uptake in industrial and research organisations.

From Social Shaping to Processes of Innovation

From a social shaping perspective, technology is seen as an outcome of processes of negotiation between social actors, artefacts, interests, and diverse framings of problems and solutions. Previous analyses have focused on the identification of players, their visions and strategies and interactions with technological problems, solutions and technological and knowledge objects. The main concern has been with sociotechnical content and processes and has focused on settings and actors where technology can be analysed and influenced (Sørensen & Williams, 2002; Russell & Williams, 2002). A number of studies have focused on the synthesis of diverse types of knowledge along an unfolding trajectory of sociotechnical development (Akrich et al., 2002; Gish & Clausen, 2013). Other studies have sought to trace the journey (or biography) of technological artefacts or management concepts while they move or extend across time and space (Hyysalo, 2010). A primary research interest has been the building of constituencies, socio-technical ensembles, actor networks, and the processes of stabilization or destabilization within these. The social shaping perspective has often taken the outset of the sociotechnical journey as a mirror of dominant practices. Users and intermediaries (Stewart & Hyysalo, 2008) have often been relegated to the role of appropriation, domestication and shaping a trajectory (Sørensen & Williams, 2002). In this paper, we respond to the concerns articulated by Stewart Russell (1986) that one should not just analyse dominant developments, but also investigate and even demonstrate the possibilities of changing the course of events. Following Russell's attention to the uneven potential for influence between societal players, we argue for the need to make space for voices and user practices often ignored within current innovation practices.

Spatial metaphors have been widely used within a social shaping of technology tradition. For example 'laboratories', 'ensembles', 'development arenas', and 'niches' have been presented (Russell & Williams, 2002), pointing to the ambition of developing political dimensions of the social shaping perspective. The 'development arena' (Jørgensen & Sørensen, 2002) is presented as a metaphor for the space where political, social and technical performances related to a specific technological problem take place. A development arena is defined as "a spatial imagery that brings together heterogeneous elements that seem distant in geographical and conventional cultural space" (Jørgensen & Sørensen, 2002: 200). This notion addresses the space that holds together settings, situated practices, and relations comprising the context and content of product and process development.

Socio-technical spaces (Clausen & Koch, 2002; Clausen & Yoshinaka, 2005, 2007) also encompass socio-material, political and discursive practices and emerging configurations of socio-technical ensembles and networks. Here, political dimensions are key as the spatial metaphor sensitises our attention to the inclusion and exclusion of actors, interests, and meaning as well as content in socio-technical developments. This concern mirrors key elements in the configuration of a design project as Bucciarelli (2005: 64) reminds us when he asks "Who's in? Who's out?". These developments may concern design processes on project, organizational and inter-organizational levels where intended change is the typical case. By bringing attention to political processes in the creation of boundaries delimitating but also enabling certain innovation processes, the notion of the socio-technical spaces provides a focusing instrument and sensitising device for studies of innovation and reflexive action in the social shaping tradition. Sociotechnical spaces may indeed harbour active elements like engineering practices, design approaches, project templates and management concepts which appear to play a key role in the (re-) configuration of a design or project space and the performance of its actors.

Innovation increasingly involves movements through and across a number of temporary spaces that include actors outside R&D departments, including from other areas of corporate life, various companies in a supply chain, design bureaus and consultancies, aspects of everyday life and use practices. The notion of a design lab as presented by Binder and Brandt (2008: 116) is suggested to "capture a relevant framing of design research where stakeholders collaboratively explore possibilities [...] in a transparent and scalable process". Participants in a design lab are able to cut across organisational and institutional boundaries and include a repertoire of facilitating instruments and designed objects to enable assumptions that may otherwise be taken for granted, to be questioned. The design lab is intended to generate knowledge in some documented form and explore design spaces to engage multiple stakeholders within collaborative practices based upon different understandings of everyday use. By referring to the laboratory metaphor, the design lab also emphasises an ambition of staging a chain of ideas and designs to allow their translation into more stable innovative solutions. It is still unclear however whether (if at all) the outcome of such design labs results in innovations in the form of products, markets or alternative practices (Rohracher, 2003) or the formation of stable networks across institutional and professional boundaries (Jørgensen et al. 2011). Also, reports from the living lab tradition discuss challenges concerned with the scaling of local collaborative design practices into broader organisational and institutional transitions in the public sector (Carstensen & Bason, 2010). In an analysis of three Danish user oriented intervention projects, Elgaard Jensen (2012) suggests that such projects may perform as mediators between users and development projects and challenge taken for granted assumptions concerning the user. He describes such projects as 'intervention-as-composition' where the role of the mediator is seen as key focus. We see the participatory workshops discussed in our paper as a related form of intervention but use the term 'staging' to focus on the specific elements and types of interaction brought together in the workshop. The notion of temporary spaces is chosen to sensitise our analysis of the staged intervention through distributed, shifting and temporary locales for mediation across institutionalised boundaries such as between diverse organisations, knowledge practices or between development and use.

The ways in which innovative ideas are moved and shaped across temporary spaces have also been embodied in the notion of intermediaries. Howells' (2006) review of the literature on intermediaries points to the important role of intermediation in innovation and the wide and growing role of intermediaries, including brokers, third parties, and agencies that are involved in supporting the innovation process. Focus is given to the influence intermediaries have through the services they offer to suppliers in enabling knowledge to flow to and from markets and technology. The role of intermediaries as facilitators of user innovation and the linking of user innovation into supply side activities have been extensively discussed by Stewart and Hyysalo (2008). They refer to the wide ecology of diverse intermediaries playing key roles in the social learning, shaping, and configuration of emerging technologies and the importance of identifying and nurturing user side intermediaries. Innovation intermediaries are here considered as organisations or individuals attempting to "configure the users, the context, the technology and the 'content', *but they do not, and cannot control use or the technology.*" (Stewart & Hyysalo, 2008: 297, original emphasis). The authors emphasise that intermediaries are themselves shaped during the process as they perform as translators of interests and meaning between worlds of design and use and/or between supply, development, and emerging markets. The political dimensions of intermediaries are made explicit as they configure a space for certain kinds of meaningful interaction including considerations concerning support, access, award structures, and legitimacy.

Stewart and Hyysalo (2008) portray innovation intermediaries as persons or organisational entities, which may take on roles as actors. Callon (1991), in contrast, makes a distinction between actors and intermediaries with his focus on the intermediary objects. Here intermediaries are defined as "anything passing between actors which define the relationship between them" (Callon, 1991: 134). Actors define each other in interaction – in the intermediaries that they put into circulation. Callon identifies four main types of intermediaries: texts, technical artefacts, human beings and their competencies, and money. From a design anthropology perspective Vinck and Jeantet (1995) similarly coin the notion of intermediary objects, pointing at the heterogeneous nature of intermediaries as networks of social actors and objects mediating between stages in design processes. Accordingly, whether the intermediary object will perform as a stable platform for transmitting knowledge across boundaries or whether it translates or mediates knowledge in a transformative way will depend on the stability of the objects, the social actors involved and their interrelations (Vinck & Jeantet, 1995).

From these perspectives, we have found it interesting to explore how intermediaries are staged within temporary spaces and how they perform in practice. We use the notion of intermediaries not just at social entities but also to include material and other objects. By taking intermediaries as heterogeneous assemblages or networks we intend to trace how their performance depends on how they are becoming configured. The term 'temporary space' refers to the participatory workshops discussed below, which can be seen as part of the 'design lab' approach discussed previously. The workshops were set up and staged by the research team and included the use of ethnographic provocations (Buur & Sitorus, 2007).

It is also intended to draw attention to the more metaphorical notions of space captured in the 'development arena' and 'sociotechnical space' literature by signalling the wider range of networks engaged through the workshop process. We are interested in what kinds of knowledge outcomes are generated through purposely staged interactions between designers, design anthropologists and engineers in a temporary space and whether we can trace the uptake of knowledge into companies and organisations having a stake in designing indoor climate. How then is knowledge generated, packaged, transported and unpacked across such sociotechnical spaces from user domains to the 'home' organisations of the participating stakeholders?

Staging a Temporary Space

To illustrate the travel and/or mediation of user oriented knowledge we report on a case concerned with participatory innovation within the designing of indoor climate. Our report draws on original accounts of the workshops including working documents, published conference papers as well as our own observations as participants in the workshops and follow up interviews with project partners. The case is drawn from a Danish government funded research and development program in user driven innovation and was carried out within the SPIRE research centre at the University of Southern Denmark. The core idea of this particular project was to "take the perspective of the 'user' – the occupants of homes, offices and institutions – rather than the usual position of the engineers who design, build and control indoor climate" (Buur, 2012: 5). The project set out to investigate: a) what the notion of comfort in indoor climate means to people and how people experience comfort during their everyday use practices b) what innovation potential rests in an appreciation of peoples' everyday practices and accounts of these practices. The project exemplifies the Participatory Innovation approach developed by the SPIRE centre, which "seeks to combine the strengths of participatory design and design anthropology, while expanding towards a market orientation" (Buur & Matthews, 2008: 268). One of the key mechanisms in a participatory innovation project is to generate knowledge about users or customers in a format that inspires company employees to reflect on the relations between product, producer role, and company identity and to generate business opportunities (Buur & Matthews, 2008).

The case study enables us to trace the movement and transformation of user knowledge from user sites to confront established configurations of users in worlds of institutionalised indoor climate research and development. The groups included were: the SPIRE participatory innovation research team, engineers from an indoor climate research unit from a technical university, engineers from companies developing and manufacturing components for indoor climate solutions such as windows, ventilation and control systems, insulation material etc. The SPIRE research team organized a series of consecutive interactive stakeholder workshops and included activities such as sense making of field study material and exploration of innovation potentials. Three of the workshops were dedicated to co-analysis of material (excerpts from interview transcripts, video clips, photographic stills etc.) from field studies of indoor climate inhabitants and their practices carried out with people in their homes, offices and nurseries during the spring of 2009. The workshops were organised to instigate co-analysis between project partners and SPIRE researchers. SPIRE researchers would present a selection of surprising and provocative instances from the field sites supported by stories, design materials, quotes from interviews, and situational photographs for one or two company partners or climate research engineers. The groups were then asked to respond by participating in various activities mapping out their responses to the materials.

Engagement of the engineers and researchers in (joint) sense making of field study material reflected a key navigational decision made by the SPIRE researchers to refrain from reliance upon established engineering concepts and understandings of comfort and indoor climate. The implication was that problem framings and design strategies based in the participating organizations were only indirectly included in the sense making process and not foregrounded in workshop interactions. On the contrary, throughout the workshops, the SPIRE team encouraged the participants to engage with the material to develop a notion of indoor climate that challenged their usual perspectives.

Methods for presenting and analysing empirical material varied across the workshops, from using stories over transcripts and video clips to the use of performative tools for co-analysis aimed at analysing the framing of problems and solutions as response to carefully selected user statements. According to an account of the workshops from members of the SPIRE team (Jaffari et al., 2011) a shared understanding of indoor climate practices gradually developed across engineering and design disciplines. In this sense, a form of learning took place during a process, in which the engineers were engaged with their own future imaginings. As one engineer remarked while engaged in making sense of the field material: “if we had to see it from the user’s point of view…”. (Jaffari et al., 2011: 6).

An intermediate outcome of this collective learning took the form of so-called ‘comfort themes’. The ‘comfort themes’ included a package with six small booklets aimed towards moving into the spaces of uptake inhabited by the participating engineers. They provided the engineers with statements and selected field study material and user statements to work with in their own organizations to aid the generation of innovative ideas concerning indoor climate solutions. Each ‘comfort theme’ was presented with a corresponding statement presenting an ethnographic provocation derived from field studies followed by typically three questions exploring a theme. For example in the booklet, ‘Being Healthy’ the authors asked: ‘How would you enable people to act on and learn from their feelings of health within an indoor climate system of control?’. Underpinning another theme ‘Comfort is a political construct’, the conception of indoor climate as a neutral standard based on ‘what the experts say’ was challenged.

During the workshops the facilitator pressed for the exploration of how these ‘comfort themes’ might translate into innovation potentials (Gunn & Clausen, 2013). Here the facilitator presented a selected version of the comfort themes focusing on reconceptualising agency attributed to inhabitants of indoor climate. As expected by the facilitator, some of the comfort themes caused controversial debate during the workshops bringing to the fore a clash between opinions of how user knowledge could be a source of innovation potential. These instances of conflict were an important part of the staging of the workshop whereby ethnographic provocation played a central role (Buur & Sitorus, 2007).

A key priority in the design of workshop activities and outcomes was to challenge the dominant engineering understandings of indoor climate and avoid an engineering focus on technological objects such as climate models and building components like insulation materials, ventilation installations, control equipment or windows (Buur, 2012).

Our uptake study was initiated in the wake of the development of the comfort themes in order to a) improve the understanding of stakeholder positions and potential outcomes in terms of innovation and b) to inform the navigational process of the remaining workshops. Our interviews sought to trace the indoor climate end user voices in the format of narratives of user practices from the participatory workshops into the realms of companies manufacturing building components and an established indoor climate research environment. We asked how user knowledge derived from field studies interacts with systems of expert and generalized knowledge in the generation of innovation potential. Our aim was to analyse how the qualitative user knowledge was taken up, rejected or transformed in the participating organizations and their practices. In-depth 2:1 semi-structured interviews were carried out by the authors with six engineers from three companies[1] from the Danish building sector and a university based climate research centre – all being active in the SPIRE participatory innovation workshops. During the interviews the engineers were asked to describe the characteristics of the dominant knowledge practices of their organizations and compare them with the kinds of knowledge received through collaboration with SPIRE researchers. As a next step we asked the interviewees to comment on and relate to the comfort themes in the form of photographic sheets showing a series of video stills and statements from the differing field sites of people’s practices of indoor climate use. As described above, the company partners had been previously introduced to the materials in various formats throughout the SPIRE workshops. During the interviews, the authors referred to the comfort themes as a way to remember what individual participants had learned through participating in SPIRE workshops. Specifically, we were interested in how perceptions of the innovation potential of end user indoor climate practices changed as a result of the collaborative activities and how (if at all) the project partners had been able to pursue within their organizations what was learned during their participation in the workshops.

Challenging Model Based Research Practices

Three of the engineers participating in the workshop series were affiliated with a Danish university based research centre for indoor climate. The research centre for indoor climate has been an important player in the development of research based indoor climate models and represents an internationally highly recognised research environment. The centre promotes itself as an important provider of knowledge to governmental regulation of building requirements as well as industry standards and practices in indoor climate.

During our interviews, the engineers from the research centre stressed how different the knowledge practices at the centre were from the local and qualitative knowledge they were confronted with in the SPIRE workshops. Here their modelling practices stand out as a main reference point when comparing the differences between knowledge practices. The ambition of climate model research has typically been to describe the general relations between certain indoor climate factors (often temperature, air quality, light and noise) and a measure of general satisfaction with the indoor climate. The first climate models were based on laboratory experiments with test persons in an artificial, but controlled environment. Here, the inhabitants of indoor climate were represented as a generalised human being as made up across the variety of a test sample.

Over the years, such models have provided an important frame of reference for building requirements and engineering standards in industrialised countries. These models have been criticised (Shove, 2003; Jaffari & Matthews, 2009) for framing a particular knowledge base, fuelling the development of an industrial indoor climate control regime based on uniform global industrial standards for indoor climate solutions independent of local climate and the local cultures.

As one senior engineer from the research lab said:

> Our group has always been thinking about humans in our research, and have involved people in our research by asking them how they perceived indoor climate [...]. But, even if we ask people what they feel, it is another question entirely what they actually do to control their environment. This opens up the question: Should we design a centrally controlled indoor climate environment or should we delegate the control to people? [...] This is an important topic in our research community, as it is now, it is a one size fits all, and it seems like there is an increasing tendency to challenge this.

While this statement points towards configuration of key social and political dimensions in modelling work, it is also clear that the tradition has a tendency to detach ideas of the social from engineering design practices (Harvey, 2010) and even to remove any space in the models for certain kinds of qualitative knowledge. This has resulted in an understanding of the indoor climate user as being passive rather than active while negotiating indoor climate.

As mentioned previously, the SPIRE indoor climate research project was viewed as an opportunity to extend the research agenda of indoor climate modelling and further develop the understanding of social aspects of indoor climate. Over the last decades, traditional factors defining indoor climate have been gradually extended and studied in detail based on quantitative methods. Compared to this tradition, analysis based on field studies outside controlled test sites was welcomed as a new approach to include more knowledge on ‘the human behaviour side’ of indoor climate. Here it is important to remember emphasis is placed upon an understanding of human behaviour based on behavioural psychology. Similar conceptions are reported from engineering practices concerned with users within the energy sector (Løgstrup et al., 2013).

Our senior engineer from the research lab continued to discuss the difficulties of incorporating what was learned within SPIRE workshops in his research investigations:

> What we have learned from SPIRE workshops here is also to look at end users as individuals. We have to be careful with generalising across individuals, and I am convinced that people are different. But it is difficult to judge how much this lesson feeds back on our research at this moment. We will have to see…

Similarly one of the younger researchers from the same lab commented:

> For a long time, the climate models developed here were based on laboratory experiments with test persons in an artificial but controlled environment, but this did not represent real life situations. Recently, we have become more interested in human behaviour because you cannot explain or predict energy consumption in a house with natural ventilation without taking the human aspect into consideration.

Here, there is a clear indication that a movement in knowledge practice would be possible based on a conscious linkage between the new energy saving agenda and a challenge of the current generalised user construction accentuated by the SPIRE workshops. Field studies may, according to the lab researchers, add new dimensions to understanding how people are using buildings and why they behave as they do, how they are affected by and how they influence indoor climate. But again, the qualitative field study material was mainly seen as providing input to define new research hypotheses. However it was important for the lab team to remember that, “[i]n the end we will have to test these hypotheses through quantitative surveys”.

While the younger research lab engineer experienced the SPIRE workshops as highly revealing and inspiring for future research, he also recalled the difficulties in following an ethnographic approach.

> With our engineering background we were actually not really able to interpret the video stills, video clips and narratives from field studies but were dependent upon the SPIRE researchers […]. These experiences have opened up for some movements in our knowledge practices… I have learned a lot and I will certainly take up the qualitative methods while conducting interviews as part of my future projects, as it gives a much better understanding of why people act as they do.

Key dimensions in these engineers’ construction of an image of indoor climate users have been based on a research design focusing on the selection and distribution of test persons or survey respondents and a search for factors or parameters expected to have measurable effects on human well-being or on performance indicators. These laboratory settings form a certain kind of epistemic culture (Knorr-Cetina, 2001) allowing only certain framings of research questions. Often these practices, according to the younger researcher, assume an application of the results in specific engineering design practices based on single factor design requirements.

The current indoor climate modelling practices are furthermore an integral part of a larger engineering system with its infrastructure defining a chain of user constructions, indoor climate definitions and practices of usage in regulation and engineering design. This particular epistemic culture signifies the relevance of research as to whether it can be successfully translated into design recommendations in engineering practices and/or by defining a building design category. But the offering of clear cut design recommendations also poses some dilemmas as indicated by one senior research lab engineer:

> The industry has been asking us to combine the diverse climate dimensions into one single measure, I don't know whether it is feasible or at all possible.

A younger research lab engineer working in the same lab supported this:

> Building engineers often expect a single figure in order to make design easier for themselves, but they often fail to understand the limitations and underlying complexity of indoor climate models.

Here, our young engineer refers to practice in certain engineering worlds, where engineers are reluctant to take on design responsibility and prefer to automate decisions or make rule based decisions.

We also registered a movement away from the current and prevailing generalised understandings of end users of indoor climate. But this movement was rather vague and constrained by established ideas of producing single dimensions and even a single figure as a design recommendation and the expectation of providing explanations and predictions of *user behaviour*. In this sense the user is still reduced to a variable in the engineering calculation. And the idea of seeing the user as a co-constructor/designer of indoor climate not to say a key player or subject in the control of indoor climate solutions can hardly be addressed within such a practice.

Marketing Strategy Confirmations

Similar difficulties in taking forward the distinctive perspective from the workshops can be seen in the context of inputs to product development and marketing. The engineer participating in the workshop from the skylight window manufacturer is located in a group of engineers and architects at the company headquarters. Their task is to provide technical marketing support to a global sales organization of a large (10,000 employees) Danish multinational company and to provide analysis and knowledge support to management decisions. The company is specialized in the development, manufacturing, marketing, and sales of one product – a skylight window – in a number of variants. This particular product has a strong position in a niche market globally and the company is the main branch of a leading Danish group in the building sector.

When the engineer from the skylight company compares the knowledge traditions of the SPIRE group and the company, he first of all refers to the unique company history and its organizational culture:

> This company has a very long tradition for quality and trustworthiness. Every statement from the company, therefore, has to be based on sound evidence. And here I mean based on technical arguments or on numbers… Only quantitatively based arguments are recognised as valid in top management and in the sales and marketing department. The

> same is the case when we want to present our point of view in standardisation committees and revision of building regulations... We have a strong relation to research institutions like the Danish university based research centre for indoor climate where it is important to be able to base your arguments in research based data.

Many of the engineers in the company are recruited from the Danish research centre for indoor climate previously discussed and have similar engineering backgrounds and perceive arguments originating from this research as the hard currency in political arguments for the building industry and its regulatory bodies. This observation underlines the existence of shared knowledge practices in an engineering world cutting across several organizational borders. Our engineer from the skylight engineering company expresses a strong awareness of these rules for making accounts in the organization. He was also aware, however, that the same rules were a strong barrier for the dissemination and sharing of knowledge from the SPIRE user oriented project in the organization.

On the other hand, our engineer is also on the lookout to bring new approaches into the organization and tries to make an opening for anthropological knowledge by stressing the important role scientific institutions play in producing credibility in his organization. As he said:

> I noticed that the methods SPIRE used were also based on scientific arguments, and I like the idea that more university units contribute to research in indoor climate.

Actually, the company had recently employed an anthropologist to do user studies, which indicates that several knowledge practices could potentially co-exist in his organisation though the value of these accounts might vary according to circumstances.

This diversity and co-existence of multiple practices was also evident as the company is not a knowledge producing research unit, but an organization geared to promote a product by seeking the best support of scientific arguments for the marketing of a product. The strategic implication is to seek a mutual alignment between product features, the dominant sales argument and current indoor climate discourse. The implication being that the main framing of how the user oriented qualitative knowledge is received stems from the product. The skylight window engineer presented the company's interest in the indoor climate project:

> You have to understand, we are not selling windows, we are selling daylight and fresh air.

Accordingly, his immediate comment to the field study informant statements picked from the comfort themes was:

> I was so happy to see the picture of the woman standing there with the open window and the statement, 'Indoor climate does not stop at the window'. But also the statement that 'indoor climate is something you make'. These statements are quite important to us, because it confirms that people want to be able to open their windows, and that it is an important part of the indoor climate.

In this case, the user articulations are closely associated with the skylight manufacturers' current marketing strategy in so far as it underlines the very framing of their product. Consequently the engineer was receptive to the SPIRE approach, as there happened to be an alignment between differing perspectives on this issue.

The engineer from the skylight manufacturer clearly appreciated the engagement with qualitative knowledge, but as he also points out, there seems to be a very limited uptake in the wider organisation. Especially when it comes to the identification of innovation potential, the engineer has difficulties in pointing out where innovation takes place in the organisation. In this instance, field based material is most often confined to address, and to be appreciated in, the marketing processes and not in the front end of innovation. The company had a small front-end unit focusing on the development of new business areas, but this unit did not seem to pay much attention to findings from collective sense making generated within the SPIRE workshops.

Future Business Opportunities

The mechanical window manufacturer is part of the same multinational concern as the skylight manufacturer and the framing of their product is expressed in similar terms: 'We are selling natural ventilation'. This means that they see their main competitors as companies promoting and selling mechanical ventilation and consequently are on the lookout for arguments supporting natural ventilation solutions.

During the interviews we realized that the reception of user narratives and workshop exchanges did, in fact, lead towards the generation of ideas for further development of existing product programmes and services. This was most obvious when our engineer from the window control manufacturer began to discuss his company's focus on selling natural ventilation. His future business proposition was concerned with the control of indoor climate in office buildings, as the company manufactured and offered control systems and motors to operate windows. The definition of indoor climate is important here as it enters business calculations and directly informs the design criteria applied in the design of solutions. As he said:

> It is free of cost to open the windows compared to operating a mechanical ventilation system so we represent a different philosophy based on natural ventilation.

Still, while the philosophy is based on natural ventilation, by offering a system perspective, natural and mechanical ventilation are often balanced in order to be able to meet the required indoor temperature in all seasons. In order to support the concept, the company has developed a configuration model where the effect of a number of design variables such as room size, façade design, temperature, and ventilation are simulated and compared to a calculated temperature and air quality (CO_2 content) distribution.

The engineer from the window control manufacturer emphasizes the diverse origins of their knowledge: governmental prescriptions, property owner demands, and experiences from the practical implementation and use of their systems. He points to the 'optimization department' as the company's primary collector of user insights and experts in making contact to real world settings. One important lesson for the engineer in control manufacturing drawn from the indoor climate project is concerned with the conceptualization of the user. The company would normally negotiate solutions with architects, engineers, and property owners. After installation, private end users, typically represented by facility managers in an office building or school, would be instructed on how to use the system. Here, facility managers are expected to fulfil a mediating role between end users and designers of indoor climate solutions. But, as SPIRE field studies attended to where, when, how and why people negotiate indoor climate on a daily basis, our engineer observed that there could be a conflict between the facility managers' more economic view and the inhabitants' idea of comfort and the ability to control it. Again, meeting with traces of how people negotiate indoor climate in their everyday situated practices of use appeared distant from the worlds of engineering. As one engineer observed,

> I was surprised to see that the users often do not know how to work the systems.

This observation leads the engineer to further consider a need in his organization to incorporate broader local user knowledge in the configuration of ventilation solutions and how to convince the owner and 'administrators' of the value of such a user involvement. A further idea would be to consider the innovation potential in the adoption of a user-oriented service related to the advice on configuration and implementation of ventilation systems. A less radical perspective concerning user involvement – which the engineer from the ventilation control manufacturer saw as more realistic – would be to inform users on the system functionalities and how they might control the indoor climate more efficiently.

However, the observation from the field studies attracting most attention from the SPIRE project partners – and clearly indicated in the comfort themes – was the limited possibilities for control of indoor climate by the end users. Consequently, the window control manufacturer could imagine developing new control devices including temperature, CO_2 and humidity, and also how a new device might support an exchange of different views and perceptions of indoor climate quality and control. A major barrier for innovation of this type, according to the engineer from the window control manufacturer, is that company product development in this area is purely market driven. The implication being that a demand has to be demonstrated through company sales channels before a development is initiated.

New Collaborations Across Businesses

One of SPIRE's project partners was head of development from an international insulation manufacturer. She was concerned with the use of their products and how the use and markets could be extended. Continuously changing building regulations stipulating higher demands for energy saving were, of course, seen as an important driver for the general extension of the market for building insulation. Her position as head of development offered a more direct link to innovative activities compared to other partners involved in the SPIRE project.

Still, she pointed at the limited innovation in new products within the building sector and how many companies in this sector only innovate along existing paths of development. Ambitions to break with these dependencies seem to have very limited opportunities. These strong path dependencies (Garud & Karnøe, 2001) based on single dominant product designs and concerns for the protection of established market relations are paralleled with the highly embedded institutionalized knowledge practices in the building sector and its regulation in the western world. The implication of this being that the development of new business areas are hardly considered, in particular if the assumed business models involve multiple stakeholders in the designing of indoor climate.

Based on these observations, our engineer from the insulation manufacturer suggested a different way to overcome innovation barriers in the sector. She pointed to the ongoing dialogue in the SPIRE workshops as an opportunity for developing a new platform for innovative collaboration including research and development activities between the diverse companies. In this sense, the insulation manufacturer's representative understood participation in collaborative workshop activities as a means of aligning differences concerning innovation potential across the industry.

The engineer from the insulation manufacturer also recognized the challenges faced because of a limited sharing of knowledge in the wider building sector and the difficulties in making diverse products (insulation, windows etc.) fit together to form improved indoor climate solutions. Many players in the sales channels, especially the timber yards, and many small construction companies do not even take up the engineering knowledge available, never mind knowledge generated through people's everyday situated practices. Accordingly, by finding ways of working together across companies it should be possible, she suggested, to develop constructive advice and coordinated concepts. These could include more holistic building regulations, a new coordinated platform or standard for combining and fitting diverse construction elements in a cross-company recommendation of how to achieve a 'good indoor climate for people to inhabit'.

From this position, the end user is not just a variable social component separated from the material world but a competent player who innovators may relate to. Still, while the user is implicated in the innovative process, the user is not necessarily intended to have an active role, but rather to be a figure to be educated and informed.

Uptake of User Oriented Knowledge

The previous sections have discussed how a temporary space was created and how it enabled partial connections between everyday situated practices of negotiating indoor climate of the individual private end user with individual engineers performing roles in the worlds of indoor climate engineering. We have described how the SPIRE researchers in close interaction with engineers within this temporary space staged a number of intermediary objects, in the form of 'comfort themes' – forms of knowledge embodying narratives based on a practice oriented perspective on indoor climate and its inhabitants. The aim was to instigate reflexivity upon indoor climate engineering research and design practices and provoke reflection challenging current engineering conceptions of the user within indoor climate research, manufacturing, and business towards alternative future design of indoor climate. We have then traced the uptake of aspects of these comfort themes by following the engineers participating in this temporary space back to their home organisations.

Our interviews showed how the engineers' unpacking of the 'comfort themes' within the organizational and engineering worlds were highly selective and how the received understanding of user practices was reinterpreted and translated in the light of established engineering knowledge practices. In particular, the assumptions of the end users role in the design of indoor climate and the role end users can (or could) play in designing indoor climate were challenged. But, while our engineers readily engaged in a deliberation of the possibilities for an increasing engagement with end users appreciating these as competent players with relevant knowledge, the engineers were rather hesitant about the possibilities of assigning users more active roles in the design of indoor climate solutions. The engineers we interviewed mainly related comfort themes to (enact) existing products, marketing, and business strategies and infrastructures of engineering models and systems. While this is not surprising we observed a variety of patterns of uptake of qualitative understandings of user practices. In cases where the user practices identified confirmed strategic concerns in the company or research unit, and where user knowledge was in line with dominant framings, as in product marketing, we found an unproblematized application of the 'new' user insights.

By reinterpreting the knowledge base of established user constructions, a number of current framings of users embedded in institutional structures and knowledge infrastructures and their associated taken for granted assumptions became challenged through the engineers' participation in the temporary space. A reframing of what innovation could be has only taken place in the few cases where something is at stake such as when the engineers express the difficulties of designing energy saving solutions across unfitting products and unaligned business strategies or the controversies related to the development of new building regulations. In these cases the engineers' articulation of ideas of reconfiguring actors and infrastructures could be an indication that some movement in terms of reconceptualising the end user has occurred as a result of participating in SPIRE workshops. Generally, we found the movements in understandings of users and use practices within the organisations to be rather limited. It seems like the participating engineers' own conceptions were highly challenged, but their new insights clashed with established practices and made changes in engineering practices in the project partner organizations difficult if not impossible.

How, then, did the 'comfort themes' discussed previously establish a broader way of thinking in the organizations about the end user of indoor climate and the potential for innovation within the designing of indoor climate? In the following, we discuss these issues by focusing on the role and configuration of the temporary space, the nature and design of the intermediary objects involved in collaborative activities, and movement of the inscribed knowledge into subsequent design spaces along a potential innovation journey.

Temporary Spaces

Temporary spaces as a notion is inspired by the design and innovation oriented concepts like 'design labs' (Binder & Brandt, 2008) and 'participatory innovation' (Buur & Matthews, 2008) while also drawing on the more analytical stance highlighted in concepts such as development arenas and sociotechnical spaces. The notion of temporary spaces is especially aimed at sensitising our attention towards the configuring, political and discursive elements of distributed spaces for user oriented innovation outside or on the fringes of institutionalised practices. Key configuring elements of a temporary space resemble the sociotechnical and innovative space described by Clausen and Yoshinaka (2007) and Brønnum and Clausen (2013). In our case this would encompass:

1. The defining content and meaning of the space as it is defined in the purpose and idea of the project set-up where the participants are

enrolled. This includes 'taking the perspective of the user rather than the usual position of the engineers in designing indoor climate solutions'.

2. The inclusion of participating engineering domains related to indoor climate, company partners from component manufacturers, and engineering consultants and the non-inclusion of 'real' users.
3. The institutional underpinnings as a public funded research and development project within the highly profiled Danish government, 'User Driven Innovation' programme and hosted by a university research team.
4. The specific re-presentation of field studies in the form of design materials involving traces of user voices and practice narratives into the space.
5. The design approaches to the staging of interactions, the methods employed, and competences of the facilitators setting up the space.
6. The navigation of the discourse and political agenda defining meaning and content of the space.
7. The collaborative design of intermediary objects, where the comfort themes turned out to be a key focusing device for staging interactions in the temporary space and the wider travel of the gained insights out of the space and into the partner organisations with the participating engineers.

Few studies have been concerned with how such spaces are created and become configured. In their analysis of four distributed user-inclusive innovation communities, Heiskanen et al. (2010: 508) conclude that successful innovation communities demand a certain level of commitment within which a mutually beneficial alignment of resources and interests falls into place. Their cases show how much effort it takes to sustain even a limited collectivity. While these innovation communities mostly draw on already established sustained communities of practices, the innovative space we have been studying was highly temporary and only sustained through a limited number of meetings within the timeframe of an externally funded project. Furthermore, the indoor climate space was deliberately set up as an intermediary project intersecting and with the purpose of linking together engineering worlds from a diversity of industrial organisations with their vested strategic interests as well as diverse research traditions within indoor climate. Although the engineering participants were part of the same indoor climate engineering community of which several shared educational backgrounds, the SPIRE project partners represented just corners of larger organisational and institutional networks. Still, they had a shared interest in exploring indoor climate user practices, as this was considered relevant within the societal expectations of reducing energy consumption to which their organisations were inclined to respond.

A temporary space refers to an assembly of actors from a diversity of worlds being able to foster significant but limited steps along a potential, innovative journey (Garud et al. 2013). These temporary spaces can hardly be expected to synthesise or transform engineering knowledge with a practice-based view of indoor climate use into full-blown innovative ideas for new products, systems or services. But, as in our case, they may include designing and framing intermediary objects which move forward ideas or convey knowledge being able to travel to other design areas for further innovative treatment and co-development iterations. What we have seen in the SPIRE case is how a temporary space has problematized indoor climate conceptions and initiated a process towards raising awareness of the limitations of current knowledge infrastructures and constructions of users, which currently constrain and determine development activities in doing business. In this sense an outcome of this particular space may be the opening up of certain possibilities through the co-existence of several constructions of users and framing of design problems and alternative designs in the future compared to the single engineering model based quest for certainties which have been the norm.

Returning to Stewart Russell's (1986) concern for political intervention in innovation, we have to admit that our case does not directly 'demonstrate the possibility of changing the course of events'. In line with Elgaard Jensen (2012) we demonstrate that dominant conceptions of the user has been challenged, but we cannot point at direct changes in design or knowledge practices in the participating companies. In many ways our findings echo studies of innovative work in larger mature companies (Dougherty, 2008; Brønnum & Clausen, 2013; Gish and Clausen, 2013) where uptake of ideas from users to R&D or knowledge transfer across knowledge domains is indeed difficult and demand a sustained effort over time, especially if these ideas are challenging taken for granted and entrenched knowledge practices. To accomplish changes in practice, a problematization of user conceptions have to be translated into ideas and product concepts through several subsequent temporary spaces of design. The concept of temporary spaces is offered as a sensitising device to help reflect on and improve strategies for staging such interlinked interventions. Here, the design of intermediaries and configuration of the temporary spaces including the navigation of interests, established knowledge infrastructures, and pressing societal discourse and strategic considerations should be of concern.

Nature and Design of Intermediary Objects

What can we learn from the staging of the temporary space of the workshops and its configuration? How did the 'comfort themes' with their inscribed practice-oriented framing of indoor climate perform as an intermediary object moving across these diverse worlds? While the intermediary seems to perform a successful transformation of established user understandings within the temporary space, further attempts to reframe the relation between the private end user and the SPIRE partner organizations operating in the worlds of indoor climate engineering seem much less successful. Similar observations stem from studies in other sectors and organizations even where concerns for user practices are articulated (Løgstrup et al., 2013; Brønnum & Clausen, 2013).

The knowledge inscribed in the proposed 'comfort themes' from the workshops were not taken up as a simple and uniform appropriation of 'sticky' user knowledge (von Hippel, 2005) or as the outcome of building relations with users (Heiskanen et al., 2010). Instead, the comfort themes we have discussed in this chapter instigate reflections on the notion of the user(s), which seems to be constructed and framed in diverse ways, mirroring the specific spaces of uptake. User constructions are abstractions, but these abstractions are constructed and appear as contestable terrain, whereby actors from the diverse companies and the indoor climate research institution seek to position themselves according to how they frame professional or strategic interests. They are not just neutral elements of organizational intermediaries that mediate between spaces of use and design (Stewart & Hyysalo, 2008) but rather travelling knowledge objects based on narratives and video stills of what users do while negotiating indoor climate.

The 'comfort themes' can be viewed as heterogeneous intermediary objects (Vinck & Jeantet, 1995) where the stability of the object depends on the staging and ongoing stability of the participants engaged in the temporary space. While being influenced by the participating engineers from the temporary space into the partner organisations, SPIRE researchers and memories of others everyday use practices become more distant while the engineering, organisational and research practices became evermore present. The level of movement of knowledge such intermediary objects can perform varies substantially across the diversity of organizational worlds. Organizational worlds where something is at stake (business opportunities, external pressures for reduction of energy consumption etc.) seem to be more prone to influence what can be taken up concerning 'the implications for design' of practice oriented 'comfort themes' (Dourish, 2006, 2007). These findings resemble Carlile's (2002) observation that boundary objects in product development are only being effective (transformative) in cases where something like a political issue or meeting a performance goal is at stake.

The Travel Along Design Spaces

The unfinished nature and interpretative flexibility of the comfort themes also allowed for a diversity in the uptake of a practice oriented user perspective in the different organisational worlds. This becomes visible when we turn to the way our engineers relate to and enact knowledge objects and relations in their organisations. While they explain what the practice oriented 'comfort themes' can mean to their organisations, they simultaneously draw our attention to how their role, including their bounded possibilities, are configured as part of their world of uptake including its specific frame of references. They make associations with certain actors and specific parts of knowledge objects to define their space. A number of significant diversities can be observed in the commitment of the engineers to their respective worlds of uptake. They vary in their historically developed knowledge practices, in the discourses they refer to on user constructions (Akrich, 1995), in the role assigned to diverse knowledge objects, and to other groups of people in their respective worlds.

Co-analysis of interview materials indicates a number of commonalities in the engineers' understanding across their social worlds (Clarke & Star, 2008) in the sense that they refer to common discourses on indoor climate definitions and the overall needs for reduction of energy consumption. The engineers indicate the existence of a shared engineering infrastructure (Clarke & Star, 2008: 115) across the diverse organisations, which tend to reproduce a certain construction of design–use relation. The chain of knowledge flow originating from research negotiated in the standardisation committees, informing governmental building regulations to end up as design requirements in the engineering design of indoor climate systems and building solutions, indicates a common reference point in a technological infrastructure. Some of the engineers involved in the temporary space questioned the linear assumptions behind such an engineering infrastructure, pointing at its proven inability to respond to current challenges on the use side and to a lack of interest in end users' difficulties in negotiating indoor climate products and systems of control.

Another engineer involved pointed at the missed opportunities of learning from experiences in the user end of the supply chain and the possibilities for exchange of knowledge(s) along the chain. In other words, the limited movement in knowledge practices can be partly explained by how the engineers refer to a practice across the social worlds of design and use, where problem definitions at the engineering end are given much greater attention than considering a design space in the user end of the relation.

Conclusion

We have shown how a design staged intervention in indoor climate design in the form of a temporary space was set up by a research team and how it helped challenge and, under certain circumstances, even reframe existing engineering and model oriented user conceptions towards a more user practice oriented perspective. But our study also shows that, due to strong path dependent innovative practices in the participating organisations, a direct uptake of a different understanding of user practices beyond the temporary space proved limited. Path dependent innovative practices, business strategies and dominant designs add to the lack of relevant spaces for innovation within, or across, the participating organizations where supposedly 'new' insights might be turned into 'new' product ideas.

The temporary space is suggested as a sensitising concept in the staging of the minor but important steps involved in design staged interventions. By pointing at the role of temporary spaces and intermediary objects we have argued that intermediaries can be subject to ongoing changes in both the design process and the interventions made, while at the same time remain responsive to the changing and specific conditions across different sites of indoor engineering practice. The design of intermediary objects in close interaction between fieldwork methods, design practices and engineering oriented knowledge practices, together with key stakeholders, seems important for the configuration of temporary spaces and the reframing of user conceptions. It appears that the configuration of the temporary space and the design of intermediary objects are closely intertwined and mutually dependent.

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Notes

1 Company A was a large Denmark-based multinational skylight window manufacturer; company B was a Danish mechanical window manufacturer specialised in natural ventilation and control systems; and company C was a Danish subsidiary of a large European insulation manufacturer.

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Science &
Technology Studies

Volume 28, Issue 1, 2015