The Success and Failure of Combined Heat and Power (CHP) in the UK, Germany and the Netherlands: Revisiting Stewart Russell's Perspective on Technology Choices in Society

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Stewart Russell's research work on combined heat and power / district heating (CHP/DH) in the UK was among the first empirical contributions to demonstrate that technological change is not just determined by seemingly objective technical and economic performance characteristics, but rather the result of social choices. His rich conceptual thinking is reconstructed in a coherent framework, and its explanatory power explored by analysing the innovation diffusion paradox of CHP/DH: in spite of very similar technical and economic characteristics, the patterns of innovation and diffusion differ significantly across countries. To this end, the evolution of CHP/DH in the UK, Germany and the Netherlands is compared. Russell's ideas can be regarded as a predecessor of recent multi-level approaches to the analysis of socio-technical change. He put much emphasis on studying power relations for explaining the (non-) occurrence of socio-technical change; an issue that is still debated today.

Keywords: technology choices in society, power and conflict, combined heat and power

Introduction: Characteristics and Diffusion Patterns of CHP/DH

Science and technology studies have their roots in a range of research strands in economics, sociology, political sciences and history that converge on the conviction that technologies do not just emerge as a result of their objective superiority in terms of technological or economic performance, but as a result of the social shaping of mental and conceptual frameworks as well as organisational, institutional and political conditions in which they are embedded.[1] This debate started in the 1980s, based on selected evidence from historical studies, but it took several years to take coherent shape.

One of the first thorough empirical studies of a technology that was guided and inspired by a focus on social relations, in the analysis of technology addressed the case of combined heat and power, and specifically its application to district heating, in the UK (Russell, 1986a). Drawing upon a thorough empirical foundation, it integrated many of the – then current – debates about the socially and politically shaped nature of technology, and can thus be regarded as a pioneering piece of research.

The underlying principles of Combined Heat and Power (CHP) are rather simple. CHP means the simultaneous generation of electric power and useful forms of heat in the same process. It is an established technology that has been used since the beginning of the twentieth century, but has undergone several changes and improvements over past decades, for instance in relation to prime movers (engines, turbines, fuel cells, etc.) or the control systems to optimize the operation of CHP systems (load management, remote monitoring, etc.). Two main application areas of CHP can be distinguished. First of all, district heating, i.e. the centralised supply of hot water or steam, which represents a very efficient way of providing heating to residents. Large-scale local plants tend to be used for this purpose because heat cannot be transported without major losses over long distances. Secondly, industrial sites often need large amounts of high-grade heat, and if heat production can be coupled to power generation, either for their own use or for export to the power grid, the internal energy of the fuel can be exploited more efficiently than in separate processes. Sometimes, low temperature heating networks can even use the residual heat from high-temperature industrial applications. Until the early 1990s, these two types of CHP applications were mainly based on comparatively large-scale industrial and district heating plants. More recently, small-scale CHP systems have been developed that can be used for heating (and also cooling) purposes in large individual buildings such as hospitals, schools, public administration or residential areas down to the level of individual households, as well as for smaller industrial plants.

The compelling advantage of CHP is that it allows a much more efficient use of the internal energy of the fuel than in power-only production. Heat-only plants can also be highly efficient, but generating electric power as a particularly valuable form of energy entails major energy losses, dispersed as waste heat. In other words, the key argument in favour of CHP is that it allows high-value electricity to be produced in a way that avoids wasting at least 50% of the internal energy of the fuel, and instead uses it for heating or industrial purposes.

CHP thus seems to be an obvious example of a superior technology from an environmental and potentially also from an economic point of view, in comparison to power-only or heat-only plants. However, since it was first developed in the early decades of the twentieth century it has played a marginal role only in several European countries, whereas it flourished in others.

The diffusion patterns of CHP in Europe show some striking differences across countries (Raven & Verbong, 2007). For a comparative analysis, the UK, the Netherlands and Germany are chosen here as country cases. The developments over the past thirty years in the Netherlands and the UK are particularly interesting, because both countries had a quite low level of CHP capacity on the 1980s. The Netherlands managed to increase its CHP capacity by a factor of almost four in about fifteen years, the UK saw a much more modest growth of CHP, though also mainly in industrial applications. The situation in Germany is different in that CHP has a quite long-standing history of both industrial and district heating applications, with slow, but continuous growth over the past decades.

How to Explain the Innovation Diffusion Paradox of CHP/DH?

This diverse picture raises the question of why such a seemingly promising technology is highly successful in some countries, but not in others. Explaining the differences between countries requires explanations that go beyond traditional technological or economic frameworks. In increasingly open energy and energy technology markets in Europe, the technology used in the UK does not really differ from that in the Netherlands or Denmark. In fact Dutch companies started exporting their small-scale CHP technology to the UK in the mid-1990s, showing that the technical systems used do not differ significantly between countries.[2]

How can this paradox be explained? From an STS perspective, the immediate answer is rather straightforward and stresses the influence of social, organisational, cultural and institutional factors. The basic tenets of the STS perspective were already recognised when Stewart Russell (1986a) reconstructed in his PhD research the changing history of CHP and district heating in the UK since the 1930s as a process of social and political shaping. His research work raised in a thorough and empirically grounded way, many of the issues that have subsequently been debated by STS scholars. With his empirical work, he contributed to sharpening the understanding of the social shaping of technological trajectories, with a particular emphasis on the role of the *political* shaping of CHP and the influence of structural factors shaping innovation. His particular concern was with the ways in which particular possibilities failed to become expressed. In contrast to micro-sociological approaches this was seen not as a result of explicit conflict, but rather of historically grown structures and path-dependencies that systematically excluded certain options. While he derived clear methodological guidelines for his empirical work from the theoretical building blocks he used, he was less explicit in terms of formulating his conceptual framework.

Against this backdrop, a first objective of this paper is to revisit and reconstruct Stewart Russell's theoretical perspective on socio-technical change. Secondly, the aim is to explore the explanatory power of his framework by applying it to the aforementioned paradox, i.e. to explain the differences that can be observed between different countries in their adoption of particular forms of CHP.

The paper is structured as follows. In the next section, Russell's perspective is revisited and re-constructed by extracting his main lines of reasoning from his major publications. By relating his thoughts to later STS work on CHP/DH, his perspective will be embedded in the context of the wider STS debate. Section 3 uses this framework to look comparatively at the empirical examples of three countries (UK, the Netherlands, and Germany) with their very distinct innovation and diffusion patterns of CHP/DH. The aim is to explain the CHP paradox on the basis of Russell's main theoretical lines of reasoning. The final section draws some conclusions on the positioning of Stewart Russell's scientific contribution, and gives an outlook on a research agenda that flows from it.

STS Perspectives – Russell's Conceptual Framework

Russell's main interest was in the way choices are made about technologies in society, and in particular the political nature of these choices. As he argues that if technology is seen as socially shaped, then it is essential to understand how technology choices are made (Russell & Williams, 2002: 39). He understands technology as a social product, but admits that there are a number of constraints imposed on the choices to be made – constraints which should not be ignored in the sociological analysis of technology. These limits to social choice are due to several different factors, including available skills, materials and tools, scientific and other forms of understanding technology and its unforeseen consequences, the physical reality around us and the constraints imposed by existing systems (Russell, 1986a: 21–23). Most of these constraints, however, are the result of previous choices made in society. Russell's key point in this regard is that social divisions are decisive for the choices made in the past and the present, and they point to the question of who is ultimately in control of these technology choices. Matters of power and control are a central element of Russell's thinking.

In his early work, Russell (1986a: 16) was not intending to develop a comprehensive theory of technology choices in society, but several of his guiding ideas were innovative at the time and influenced later debates. He also formulated the kinds of requirements that a theory of technological choice in society should meet, namely

> to provide a structured, historical and dynamic account of a social formation; explain the specificity of social phenomena; and allow engagement with the general forms and changes in technological ensembles and the detailed content of specific artefacts and techniques[…]. Russell, 1986a: 18.

In his later work, his theoretical approach and framework became more explicit and coherent in the sense that he was seeking to resolve some of the tensions in the prevailing STS debates (Russell & Williams, 2002).

In what follows, an attempt is made to identify the key arguments around which Russell's conceptual thinking was built. These will then be integrated into a multi-level conceptual framework that picks up levels of analysis proposed by Russell himself to guide his empirical analysis and interpretation. This conceptual framework provides a blueprint to analyse and understand how technology choices in society are made, and how ultimately the dynamics of socio-technical change come about.

The first of the seven subsequent key arguments is the most fundamental one in that it focuses on the overarching logic driving socio-technical change, whereas the six other arguments refer to specific features and determinants of that change process.

Socio-Technical Change as Complex Process of Creation and Destruction

Russell's perspective is rooted in a broadly Marxist analytical approach and substantive social model. The Marxist perspective on social transformation, focusing on the realm of production and the role of labour, had to be adapted to the issue of technology choice. Russell (1986a: 19) argues that

> cutting labour costs is only one of the uses to which technology can be put. It may also be used to reduce the cost of production plant; to economise on raw materials, component stocks of energy; in devising radically new techniques to supersede traditional production routes; in creating new products, improving existing ones incrementally or making superficially different products, to compete; and in reducing the time taken to get revenue through improvements in communications and transport.

Technology choices are thus seen as part of a broader process of socio-technical change and transformation; a process, in which differences in power and interests are the key driving forces. Russell broadens the Marxist perspective by stressing that technology can be put to work for ends other than cutting labour costs and employment. Socio-technical change, in this sense, is about both the creation of the new and the (partial) destruction of the old.[3] Or to put it in Russell's (1986a: 26) words:

> Each option will to a differing extent require the destruction, replacement, enhancement or modification of already entrenched structures necessary for production, maintenance and options in the system of which it is to be a part.

Russell acknowledges that the observable dynamics of change are the result of complex mechanisms, resulting from the interdependence of social change and technological change, and from the path-dependencies, lock-ins and network externalities inherent to the socio-technical system in question (Russell & Williams, 2002: 55–60). This kind of reasoning is in line with similar arguments raised at about the same time by evolutionary and neo-Schumpeterian economists, as well as by later proponents of the multi-level perspective on socio-technical change (Geels, 2002).

Bridging Between Structure and Agency – Structures as Frames for Technology Choices

The duality of structuralist and behaviouralist perspectives on social change has a long tradition, and trying to reconcile both perspectives has been a recurrent struggle in the STS literature. Russell (1986a: 61) recognizes the limitations of established structuralist and action-oriented approaches to the study of social change and suggests relating the two levels of analysis by arguing that

> if it is accepted that social systems are in some sense structures of relations involving human action, an adequate framework must explain the role of action in creating, reproducing or changing these structures.

Building in particular on Jessop (1982), Benton (1981) and Giddens (1979), he favours a dialectical approach in which

> to take structures as imposing limits within which agents act, still essentially free-willed but with restricted scope. (Russell, 1986a: 61)

In seeking to understand his empirical material Russell (1993: 51) noted:

> I find it necessary [...] to argue the need for several different levels of analysis in the social systems within which technological development is situated [...].

With this statement, he is stressing that it is not enough to just trace actors and their networks, but that one needs to take into account also the social structures and contextual developments in which they are embedded. He argues against the then very influential micro-sociological perspectives on the social shaping of technology (Pinch & Bijker, 1984) which he criticizes for being mainly descriptive and not providing "an adequate explanation of why we have particular technologies and not others" (Russell, 1993: 50), for transferring naively categories from the sociology of science to the social analysis of technology (Russell & Williams, 1988), and for ignoring the need to embed specific social groups in their wider historical and structural context

(Russell, 1986b).[4] In particular, the partial emphasis on the micro-level is criticized

> in response to the action paradigm of the micro-sociologists, we find ourselves in the position of having to reassert the importance of the macro, and to argue the need for several different levels of analysis of the social systems within which technological development is situated[...]. (Russell & Williams, 1988: 2)

Patterns of centralisation and decentralisation, the existence of large incumbent players and the absence of smaller ones, or the formal competencies assigned to certain actors may be traced back to earlier choices and path-dependencies in society, but they cannot be ignored in the analysis of current choices. According to Russell, it is only within the confines of what structural and institutional contexts allow that behavioural forces can unfold to create and establish new technologies. Or, as Russell (1993: 52) puts it with regard to CHP:

> A contextual analysis [...] is necessary if we are to understand whether the exclusion of this technology has been accidental [...] or systematic [...].

In his work, Russell stresses the importance of the wider structural and institutional context in which micro-level interactions take place. His arguments foreshadow lines of reasoning that were later on proposed by other scholars studying the emergence of technology who also see structural conditions as enabling or preventing new types of behavioural and technological options. This view has become particularly prominent in the STS literature since the turn of the millennium, with the research strand on transitions using a multi-level perspective on long-term processes of socio-technical change. Here, the emphasis on the interplay between context, structures, institutions, organisations and behaviour is presented as a novel type of multi-level perspective (Geels, 2002), using the concepts of socio-technical landscape, technological regime and niches to denote three distinct levels, with the latter being essential for enabling experimentation and learning in protected spaces.

Interestingly, the multi-level perspective as introduced by Geels has also been used recently to analyse the emergence of CHP in the Netherlands (Raven & Verbong, 2007; Raven, 2007). Other attempts to bridge between structure and agency recur to a systems language, such as the TIS (Technological Innovation Systems) approach, which has been adopted by Hawkey (2012) to revisit the situation of CHP in the UK. There are without a doubt important differences between Russell's perspective and the new multi-level and TIS perspectives, in particular with regard to the understanding of how change comes about. However Russell's lines of reasoning can nevertheless be regarded as a precursor for the resurgence of interest in addressing different layers of determinants of socio-technical change.

Organisational, Institutional and Cultural Embedding of Technology

Russell recognises the particular importance of the organisational, institutional and cultural characteristics of the 'terrain' – as he puts it – in which a particular technology is embedded. This terrain refers to the sectoral context, but also to national level features, of relevance to the technology under study.[5] Large socio-technical systems can be organised in a more centralised or a more decentralised manner, thus favouring certain kinds of technologies over others. The balance between the operation of market forces and regulation is another feature that frames and guides technology choices. Finally, the level of integration or separation of service supply streams characterises the terrain, and it is an aspect of particular importance for CHP. According to his empirical analysis, the institutional and organisational environment of the energy sector in the UK, was highly detrimental to the uptake of CHP/DH.

> The second aspect is the necessity of understanding the institutional structure of the sector. The key absence has been an organization with national responsibility for heat supply or even conservation, so that CHP and DH have been left to organizations with other major responsibilities, for which they would be additional and marginal activities with precarious financial and political support. (Russell, 1993: 52.)

Now, more than thirty years after the introduction of institutionalist perspectives and innovation systems approaches, paying tribute to the importance of institutional and organisational determinants of technological change seems almost trivial. At the time Russell published his work however, these kinds of arguments were controversial and counter to prevailing lines of debate in the energy sector and in energy policy in particular. He argues that without a 'carrier organisation', that bundles interests associated with a specific technology, it is unlikely that this technology will succeed in a context of incumbent technologies and organisations. This argument went clearly beyond the usual technical and economic arguments used in the debates.

Interests and Power in Relation to Technology Choices

The structural, institutional and organisational determinants define the configurations in which the interests and power positions of the different organisations can be brought to bear. The ability of individual organisations to behave strategically, to pursue their specific interests, and to use their power positions to enforce them is key to understanding actor behaviour and change in socio-technical systems. This was a central conviction of Russell's (1980: 97) argument from his very early works:

> Any theory which takes technology as a starting point is in danger of obscuring the human intention behind it. The very act of conceptually abstracting technology tends to sever social links or mask its social content.

The notion of interests is in itself a complicated one. According to Russell (1986a: 75, 80–81), it is important to distinguish objective from subjective interests, i.e. those that are located in the structure of social life from those that are the result of interpretation by an observer. Moreover, interests depend on the structural location of actors, as well as on the specific circumstances of interaction. Interests usually refer also to potential outcomes and identities, and by referring to the future are inevitably contradictory. Power, against this background, is then the ability to secure these 'fuzzy' interests.

It is not a trivial task to identify 'interests' in practice. Interests must be understood as being related to existing arrangements as well as potential changes at different levels. They need to refer to subjective expectations as much as to seemingly objective organisational concerns. A typical strategy to safeguard an organisation's particular interests is to channel them through seemingly technical debates. Russell (1993: 52) had identified this mechanism very clearly in his work:

> The terms of appraisal were clearly dependent on the performing institutions and the precise constraints on it. It is not sufficient to ask whether the option was 'economic'. We need to ask for whom its economics was assessed, and why narrowly defined economic criteria were used and whether they were appropriate.

With the help of these and other mechanisms, alternative options can be systematically excluded, if they challenge established interests of the incumbents. In order to understand their interests, it is necessary to take a broader perspective on organisational objectives and strategies as embedded in a sectoral context:

> The electricity industry was not always actively opposed to CHP; but nor was it ever a strong supporter. We need first a broad picture of the major objectives and programmes it had defined for itself, and its evolving relation as a nationalized industry with government and with the rest of the sector. (Russell, 1993: 52.)

On such a broader basis it is possible to understand better why certain organisations oppose or support a new technology, and why certain selection criteria have been introduced, while others have been excluded.

The importance of organisational interests and power structures has been confirmed by later authors, and also specifically with regard to CHP in different countries (Summerton, 1992; Hard & Olsson, 1995; Weber, 1999). They all stress that in order to reap the benefits from synergies between different socio-technical systems it is essential to integrate them under the roof of a single organisation, as a way to overcome major conflicts of interests.

Knowledge Dynamics and the Assessment of Technology

An important role is assigned by Russell to the use that can be made of knowledge in its various forms in political debates about technology choices. In fact, knowledge, and the control over knowledge, is a key element for understanding how power is exercised and interests defended. Power and knowledge are regarded as the two facets of social action, which is why it is essential to consider how "content" is produced under the influence of interests and power:

> It is clear [...] that debate is a significant component of struggle; that knowledge in some form informs all practices and actions; that the dominance of certain views cannot be explained by the 'facts'; that knowledge is an important resource in interactions; and that its possession, deployment or withholding is significant in determining outcomes. In disputes over scientific and technological issues in particular, ostensibly technical arguments are widely recognised to be aligned to institutional interests in terms of optimism, interpretation of evidence, and so on, though protagonists generally deny such a connection. Thus the problem in explanation is: what status should be attributed to technical arguments and their resolution in explaining outcomes, and what should the disposition of the analysis be towards the content of contending positions? (Russell, 1986a: 87.)

Russell pursues a middle way of neither following positivism (i.e. the belief in the objective quality of knowledge) nor relativism (i.e. the rejection of entering into a substantive debate about the pros and cons of technical arguments). According to Russell (1986a: 95), it is important to be aware of the social, normative and sometimes even ideological influence on decisions, but it still matters to understand the substance of debates:

> […] the role of an argument is to be analysed specifically and with reference to its content […], showing in particular how elements of knowledge – scope, form and substance – are drawn on as resources in the process of formation and deployment.

At the same time, knowledge in relation to new technology is always uncertain in many regards (e.g. in technological and economic terms, but also with regard to the context of technology use), and this uncertainty raises a further complication, also known as the Collingridge dilemma (Collingridge, 1980).[6] In brief, it states that any attempt to actively influence and shape the unfolding of a specific technology is confronted with a fundamental dilemma: early on in the process of a technology unfolding, we know and understand too little about it to assess its potential impacts and influence its trajectory, but later on in the process, once we know and understand enough about it to be able to influence it in an informed manner, the trajectory has already become so entrenched that it can hardly be influenced any more. The recognition of this dilemma calls for a continuous interaction and learning process between the actual realization process of a technology and the social and political decision-making around it. It implies that any assessment of a technology in the making must accept uncertainty as an undeniable condition of decision-making. In fact, Russell and Williams (2002: 54) go even further in arguing that this inherent uncertainty requires new forms of policy learning and monitoring:

> Our understanding of the co-evolution of technologies and social forms shows that treating technological development and the occurrence of 'impacts' as separate processes is severely limiting. It highlights the need to integrate policies and programmes for innovation with those for evaluation and regulation. The emergent and unpredictable nature of sociotechnical transformations points again to the value of flexibility and constant monitoring, maintaining channels of communication and arenas of debate, and avoiding disincentives to open appraisal.

Russell's understanding of how seemingly technical debates influence and even dominate the shaping of evaluations and assessments of new technology is pertinent here. Institutional structures matter a lot, but so do professional communities and their role in influencing economic and political groups. Their claimed monopoly on technical expertise may easily lead to a reinforcement of prevailing technological paradigms (Dosi, 1982) and thus reinforce their path-dependency, to the detriment of other non-conventional alternatives.

According to Russell (1986a: 91), assessing the merits or not of a technology thus calls for a critical position with regard to any claim of 'rational' evaluation; any evaluation needs to be related to context and interests, and to the question of how debates are structured:

> [T]he construction of technical knowledge is particularly important here. It depends on the relation of technical experts to political arenas, and the process of negotiation between them over the objectives of their work, affecting not only the adaptation or transformation of knowledge but its very content.

Embedding in Broader Debates and Expectations

Russell recognized the importance of looking at a broader frame of reference than just the concrete choices about particular technologies. The specific issues associated with CHP were embedded in wider debates about future policy objectives in a range of adjacent policy areas. In his writings, he points out that

> [before liberalisation] CHP found itself at the intersection of a number of debates in Britain: on energy strategies, the environment, conservation, and alternatives to nuclear power; on the role of coal, the maintenance of markets for it, and the defence of the industry against run-down; on fuel poverty, living conditions and degenerating housing stock; on problems of the nationalised industries, alternative forms of public ownership and [...] the devolution of centralised state functions to regional and city levels; and on criticism of the electricity supply industry over its nuclear programme, over-forecasting and excess capacity[...]. (Russell, 1994: 19)

Reducing the debate about CHP to one single arena is thus not appropriate. With the broadening of the range of actors having a say with regard to a technology, the range of arenas and arguments in which an issue is embedded is equally broadening. The notion of 'terrain' as used by Russell reflects this multiplicity of co-existing arenas in which an issue is dealt with. Some of these arenas may at first glance appear entirely disconnected from the issue at stake, but they nevertheless touch upon a range of debates, arguments and expectations that matter. One of the biggest challenges in this regard is how to manage and coordinate the arenas on this terrain, with their fragmented responsibilities and lines of reasoning.

Russell already recognised the importance of taking views and expectations about the future of the terrain into account, even if these expectations are subject to a great deal of uncertainty. This implies that the question how well a technology is embedded in future expectations (for instance about broader energy issues such as oil prices or institutional frameworks), which are often determined at national, European or even global level, needs to be considered when assessing its future perspectives.

In the STS literature, the importance of the role of future expectations for the shaping and diffusing of new technology has been re-discovered in recent years (Borup et al., 2006; van Lente & Rip, 1998). In fact, expectations at different levels of abstraction can reinforce each other, showing that the embedding of expectations with regard to a specific technology in wider expectations, for instance related to energy supply or climate change, can strengthen the potential of a technology to diffuse (Budde & Konrad, forthcoming). In other words, a technology's future prospects not only depend on the expected performance of that technology, but on how well it fits into broader future visions and debates around energy supply, and the expectations associated with them.

The Role of the State in the Governance of Technology

The history of energy supply is also a history of energy policy. Energy supply has been dominated for decades by public sector and state-owned organisations at national, regional and local level, and technology development was strongly influenced by government policy as well. This kind of political shaping of technology is a central element in Russell's thinking and it has been taken up in STS debates as well.

By rejecting linear thinking and acknowledging complexity, Russell calls for a more modest conception to what government policy can actually do and achieve, and how under these conditions "strategic social objectives can be formulated, pursued and maintained" (Russell & Williams, 2002: 145). He calls for a process-oriented perspective on the governance of technology; a perspective that is interactive (i.e. mediating between use and supply) and reflexive in order to handle unanticipated and undesirable consequences, and that stresses the importance of modulation and orchestration as the main roles of government policy in order to ensure continuous learning to take place:

> Thus technology steering will look much less like the traditional picture of omnipotent and omniscient central direction. It will be much more like modulation and orchestration of the existing dynamics of innovation or technology management. (Russell & Williams, 2002: 139.)

Russell's argument about the need to embed specific technology debates in a broader frame of reference extended to a range of policy areas and levels. In the case of energy supply and CHP/DH, the role of local authorities is particularly noteworthy because their range of autonomous competencies is decisive for their ability to make local energy choices and thus create opportunities for CHP.

The recognition of the complexity of energy choices in a multi-level, multi-policy setting implies that there is no one single point of intervention for policy instruments to "push" CHP, but a range of policy instruments needs to be considered simultaneously:

> The analysis makes clear that no one point of level of intervention will be adequate – particularly and exclusive focus on the design and development phase of innovation. It opens up a wider range of points of influence, and draws attention both to tensions between different means of intervention and to opportunities for synergy and reinforcement. (Russell & Williams, 2002: 144.)

Finally, Russell recognises the importance of the timing of policy interventions. His arguments in favour of a more modest approach to technology policy do not mean that the influence of policy is insignificant, but that the effectiveness of interventions strongly depends on the right timing of a major initiative. If this is judged correctly, a regime changing impact can be achieved, as in the case of the deregulation and privatisation policy after 1989, which provided an opportunity to change course in the energy sector of the UK. This could have changed the role of CHP, but it would have required an active and sustained policy to remove obstacles and provide incentives to stimulate investment into CHP. This is reflected in Russell's assessment of an active and supportive government policy to induce change in socio-technical systems. He argues with regard to the British situation:

> At privatisation it was widely assumed that the chances of a significant introduction of CHP would improve, but the structure of the new electricity market is providing a new and perhaps more daunting set of obstacles (Russell, 1996: 1).

However, a pro-active enforcement strategy of government to overcome entrenched interests and associated path-dependencies is unlikely to be pursued if it is not in line with the prevailing political culture. It requires the willingness and ability to give multiple and sustained policy impulses, and ultimately on the political culture of a country.[7]

A Multi-Level Framework

The integration of these main building blocks of Russell's thinking about technology choices in society into a consistent framework was partly done by Russell himself. Inspired by the conviction that the structure – action dichotomy needs to be overcome, he proposed three interdependent levels of analysis (Russell, 1986a):

1. *Context* in which a specific debate about a technology is embedded;
2. *Interactions* in organisations and arenas, which are dealing with the technology in questions;
3. *Knowledge* in terms of issues, evaluations and arguments, which are constructed and used in the interactions, arenas and organisations.

Six of Russell's key arguments can be assigned to these three levels, in the sense that they provide the main lines of reasoning for explaining technology choices and socio-technical change. The interactions between these three levels, and thus the interplay between the six main lines of reasoning, are embedded in Russell's guiding argument about the emergence socio-technical change processes, which is inspired by Marxist and complexity thinking.

The two context-related lines of argumentation ensure that the specific issue of technology choices is not seen in isolation, but as embedded in a wider range of structural, institutional

Table 1. Russell's multi-level framework

Layers of analysis	**Key argument**
Context	• Structures as frames for technology choices (e.g. societal or energy system) • Organisational, institutional and cultural embedding of technology
Interactions	• Interests and power in relation to technology choices • The role of the state in the governance of technology
Knowledge	• Knowledge dynamics and the assessment of technology • Embedding in broader debates and expectations
Dynamics	**Key argument**
	Socio-technical change as complex process of creation and destruction

organisational and cultures conditions, which tend to impose major path-dependent constraints on technology choices in society. Interactions associated with interests and power are at the core of Russell's framework, and they extend to the shaping of the arguments and knowledge claims that underpin interests and power positions. In this regard, the ability to manage and negotiate the knowledge claims is seen as crucial by Russell for understanding how interests and power can actually be used to determine technology choices. The knowledge claims are nurtured by a range of wider debates from which arguments and expectations can be drawn in order to underpin the assessments in favour or against the choices under debate. Government agents, either local or national, are just some of the players in that game and, depending on their specific role, they can influence context as well as specific choices and knowledge dynamics. Government policy can, exert a major influence on the future course to be taken, if time windows of opportunity are targeted in a coherent manner at the different policy levels and in a range of policy domains of relevance to the choices in question. Overall, a government-induced process of changing course in a complex system like energy supply will require destabilizing historically grown structures, institutions and practices, together with their underlying stabilizing mechanisms, while in parallel triggering the emergence and growth of the elements of an alternative by establishing corresponding self-reinforcing mechanisms at a suitable moment in time.

Explaining the Paradox – Comparing CHP in the UK, Germany and the Netherlands

If Stewart Russell's framework for explaining technology choices in society is a powerful analytical instrument, then it should provide a basis for an explanation of the innovation diffusion paradox of CHP. This is that while CHP technology and applications do not really differ significantly across countries, the patterns of innovation diffusion diverge significantly, with diffusion rates very high in some countries and very low in others. Denmark, the Netherlands and Finland generate between one third and half of their electricity from CHP. Other countries such as the UK or Sweden, while having similar climatic conditions, are well below 10%. The low level of CHP diffusion in France is also remarkable, but among several other factors the important role of nuclear power generation needs to be taken into account here. Other countries show intermediate levels of CHP diffusion. Germany and Austria, but also some Mediterranean countries, have quite significant CHP capacities installed.[8]

The UK, Germany and the Netherlands have been selected for detailed investigation and comparison, each showing distinct patterns of innovation and uptake of CHP. In the UK, the level of diffusion of CHP and district heating has remained very low, even if some growth in industrial CHP has been observed since liberalisation of gas and electricity supply markets in the second half in the 1980s. The Netherlands are characterized by very rapid growth of small-scale and industrial CHP applications since the late 1980s and a moderate uptake of district heating schemes, which was equally enabled by liberalisation of energy markets. In Germany, both industrial CHP and district heating have played quite a significant role over a much longer period of time. This was further enhanced and complemented by small-scale applications during the 1990s, a development that was at least partly facilitated by the slowly liberalising energy sector in Germany. As major external conditions for the uptake of energy technologies, such as the climate conditions or the level of industrial development, are similar in all three countries they can be excluded as important explanatory factors for the differences in patterns of innovation and uptake.

The focus of this comparative analysis will be on the past forty years starting with the growing interest in energy efficiency after the oil crises of the 1970s, and covering, in particular, the period before and after liberalisation of energy supply markets. This period is very suitable for comparative analysis because it allows for the study of

Table 2. Phases of evolution and uptake of CHP in the UK, Netherlands and Germany

Phase	Disruptive event	Relation to interest in CHP	Change in use of CHP
1	Early industrial applications	First examples of industrial CHP and DH demonstrate feasibility and stimulated interest in efficient energy solutions	• Isolated cases of CHP development was the norm across all three European countries • Led by individual engineers
2	Post-war reconstruction following destroyed infrastructure	Rebuilding of cities and industry presented opportunities to consider CHP for heat and power supply	• In UK and the Netherlands evidence of active consideration of district heating, but limited realisation • In Germany CHP application to both housing and industry
3	Oil crisis of early 1970s	More expensive energy stimulated interest in exploring more efficient alternative technologies	• Some further development and retrofitting of CHP in Germany • Growing attention, but little change in the UK and the Netherlands
4	Liberalisation / privatisation of heat and energy supply markets	Presumed economic efficiency of open markets expected to provide opportunities for new approaches	• Rapid increase in CHP in the Netherlands • Slow, but steady further expansion of CHP in Germany • Little change in the UK
5	Support for decentralised renewable energy	Increases economic viability of alternatives to existing generation	• Expansion of CHP continues in Germany • Stagnation of CHP at low level in the UK, and at high level in the Netherlands

responses and patterns after an external shock. However, as highlighted by Russell, history matters, and a brief look at previous decades of CHP/DH history is needed. There were some 'windows of opportunity' for CHP/DH in earlier times, such as after the Second World War, and some of the structural, organizational, institutional and cultural aspects can even be traced back to developments in earlier decades of the twentieth century.

The main categories of Russell's framework, i.e. context, interactions, knowledge and overall dynamics, will then be applied to structure the discussion of the three cases in a comparative way with a view to explaining the differences in the innovation diffusion dynamics. The empirical material presented draws mainly on secondary sources from the three countries.[9]

The Historical Patterns of CHP Development

In the course of the twentieth century a number of main phases can be differentiated which were significant for the evolution of CHP. These phases provide a historical perspective on contextual developments that opened up new opportunities and/or specific challenges for CHP, but to which different countries reacted in distinct ways. In other words, these phases provide a common historical framing for the three countries under study, and, as such, may help understand the cultural and institutional contexts that are still influential.

Five phases are identified which are marked by major external (e.g. war, oil crisis) or political (i.e. policy reform) disruptive events. These phases are common to all the countries under discussion here (and were observed by Russell in relation to the UK) but, as sketched in Table 2, the outcomes for CHP development vary between them.

This longer-term historical picture shows that even if strong organisational path-dependencies exist, there are distinct moments in time when these patterns can be shifted. Disruptions, such as the Second World War, the oil crisis, or liberalisation of energy supply, seem to open up opportunities for major changes to occur. Whether these opportunities are exploited depends on the strategies pursued within national systems to overcome the full spectrum of barriers and constraints; strategies for which government policy can be the main trigger.

Context

Structures as frames for technology choices

The autonomy and competencies assigned to local authorities are important structural features framing technology choices, particularly with regard to district heating applications of CHP. Whereas in the UK local authorities have traditionally been endowed with weak competencies, the opposite is true in Germany. This British picture has not really changed, in spite of the 'devolution' policy to decentralize certain political competencies. German local authorities have in principle many different levers of change at their disposal, ranging from ownership of utility companies, special subsidies and regulations, through to planning and coordination. They are often responsible for the supply of a range of utility services, including water, transport, electricity and heat, allowing for both decentralization and horizontal integration of electricity and supply under one roof. In the Netherlands, local authorities also have a significant degree of autonomy, but are endowed with less resources for pursuing independent energy supply strategies than in Germany.

With regard to industrial applications of CHP, all three countries are home to energy-intensive sectors and thus offer

– in principle – a significant potential for CHP. In practice, only Germany has seen a significant amount of CHP installed since the 1960s, with the Netherlands catching up very quickly since the 1980s. Whether industrial CHP could flourish or not was thus a matter of regulatory conditions rather than of structural constraints on the demand side. Another industrial characteristic to consider in the context of CHP is the role of oil- or gas-extracting industries, which are still quite important in both the UK and the Netherlands. In contrast to the UK, the Netherlands have always been very concerned to exploit their natural gas resources in as efficient and sustainable way as possible.

The supply side of CHP systems is also of relevance here. With major technology supply companies in the energy sector operating increasingly at global level, their investment priorities have been slowly adapted to the standards of international financial markets. Less attention is paid to local specificities. This is an issue of particular importance for the UK (Hawkey, 2012: 20), where private investors play a more prominent role in the energy sector than in Germany or the Netherlands.

Most of these structural conditions remained in place even after the destructive shock created by the liberalisation and (partial) privatisation of the energy sectors. Against this backdrop, it is important to consider whether new CHP-friendly players outside the energy sector emerged in this transition phase or not. In Germany, there were influential supporters of CHP already active before liberalisation, and they emerged in the Netherlands quite quickly. In the UK, however, they remained marginal. Taking these changes in actor configurations into account is important to understand the evolution of CHP in the post-liberalisation phase. The arguments in favour of CHP could be made much more forcefully in the Netherlands and Germany, and this influenced the shaping of new regulatory frameworks in the broader national debates on the liberalisation of energy markets.

Organisational, institutional and cultural embedding of CHP

The organizational settings of the energy sector, in terms of the degree of centralization of the electricity supply industry (ESI), the infrastructure backbone, or the separation of heat and power supply, represent key elements of the terrain in which CHP is embedded. As described in his detailed historical account, Russell (1986a, 1993, 1994, 1996) shows that in spite of several serious attempts over the decades to establish CHP more firmly as part of the British energy system, it never really fitted the structure of vertically integrated, but horizontally separated chains of heat and of power supply, and thus fell in-between the interests of the main industrial players. And as pointed out above, local authorities were not in a sufficiently powerful position to establish CHP major district heating schemes either. Although the German ESI has also relied for several decades on large-scale regional monopoly suppliers, there has always been a lot of room for local and industrial CHP initiatives. Local energy companies and industrial power producers had sufficient resources and competencies to run their own local low-voltage grid infrastructures, pursue their own energy strategies, and thus ensure a diversity of technology solutions, including CHP.

Linked to the organisational structure of the electricity supply industry is the specific institutional and regulatory context in which the ESI is embedded. Liberalisation and privatisation of energy supply changed the rules of the game allowing the emergence of new players who could build and operate CHP plants. In both the UK and the Netherlands, this period of policy changes and liberalisation of electricity supply went hand in hand with a phase of renewed interest in CHP. With the market entry of private energy service suppliers, industrial and small-scale CHP started to diffuse more widely, but ultimately the specific rules and regulations defined by the regulating authorities imposed limits on the economic viability of many CHP projects. In the UK, CHP had fallen for decades into the gap between electricity companies and heat suppliers, which both had a marginal interest only in a technology that was bridging between the two energy systems. With liberalisation, there was at least the possibility of better connecting the two systems through the setting up of specialised energy service companies. These companies considered it their main business to provide in particular industrial heat and power users with advantageous services that were not part of the core business of the firms in question. However, in spite of these improvements, CHP still had to fit into a regulatory context that was not conducive to its uptake (Russell, 1994). The opposite was true in the Netherlands where the liberalisation process was designed in a way which enabled the fast and widespread emergence of new players on the energy supply market, with the clear and explicit intention of government to facilitate the uptake of CHP and make it a major pillar of its energy supply system. Liberalisation in Germany may have been less forcefully implemented than in the other two countries, but it built on an already existing population of CHP plants of various types. As local grid infrastructures for providing citizens with heat and energy services were in the hands of municipal energy companies, they had much better opportunities to bridge the technical boundaries between heat supply and electricity supply.

The ways of handling the change process of institutional and organizational settings for energy supply are a matter of political culture and governance, and it is instructive to look at the political cultures of managing change during liberalisation in the three countries. The British liberalisation and privatisation debate of the 1980s and 1990s was characterized by strong ideological positions over the respective pros and cons, with little room for pragmatic solutions. Differentiated arguments about the need for targeted enabling measures to support specific technologies like CHP found no more than a limited place in these debates. Concerns about institutional and organisational barriers were largely ignored, driven by a strong belief in the benefits of the operation of market forces. In the Netherlands, a much broader consensus was sought in relation to the radical reforms of the energy systems, including major support measures for CHP that were put in place from the mid-1980s onwards. The German political context left much more room for diversity, due to the federal system which allowed the emergence of differences in regulatory and support structures between States, with some pursuing more active CHP promotion policies than others. This diversity offered opportunities to experiment with novel technical and regulatory solutions to a much greater extent than in the two other countries.

An important role was played by support organizations that contribute to the promotion of CHP from energy producers and users as well as in the policy-making context. In Germany, several different organizations were already in place and active in making the case for CHP-friendly rules and regulations, including the Association of Local Authorities, the Association of Industrial Power Producers and various engineering associations.

The Dutch PWK (Projektbureau Warmte Kracht), later called COGEN Netherlands, was set up explicitly with government support in order to serve as a network node for users, suppliers and authorities with regard to all matters relating to CHP, and it played an important facilitating role for CHP during the 1990s in particular. The British CHPA (Combined Heat and Power Association) never acquired the same level of influence as its German and Dutch counterparts, due to its narrower membership and resource base.

Interactions

Interests and power in relation to technology choices

For Russell, technology choices need to be seen against the backdrop of the interests of the main actors and their power relations. In other words, organizational structures in the sector are so important because they determine whether or not there is any institutional voice with an interest in the joint production of heat and power or not. In some of the countries studied, such organizations were in place, in others, this did not exist to the extent needed to support a wider uptake of CHP.

The British situation is very telling in this regard. Given the weak position of local authorities and the separation of the electricity and heat supply, which remained largely in place even after liberalisation, the only organizations with a serious interest in CHP were industrial users, in particular in heat-intensive industries. This is reflected in the growth of industrial CHP after liberalisation, be it on the basis of small-scale applications or by adding power production to established industrial production processes. After liberalisation, private energy service companies discovered the potential of CHP, as did some subsidiaries of the Regional Electricity Companies. However overall, the role of industrial CHP remained marginal due to the regulations and financial conditions regarding power exports to the grid. Other key actors in the ESI may have shown some temporary interest in CHP, but without sustained commitment. (Russell, 1996.)

In the Netherlands, it was also primarily the industrial application domain that saw a boost in the post-liberalisation period; a boost that drove the share of CHP-generated power up to almost half of Dutch power production. The subsidies and feed-in tariffs provided strong incentives to invest in CHP plants. Even if the level of incentives remained lower than in the Netherlands, similar arguments apply to Germany, in particular after feed-in tariffs for renewables were also applied in modified form to CHP. However, as a consequence of the more limited incentives and the existence of an already significant industrial CHP capacity, the growth of the industrial CHP was more moderate.

All three countries saw the emergence of a new type of company which made the provision of useful forms of energy, i.e. both power and heat, to industrial and public sector customers their business. The extent to which these integrated energy supply companies could flourish was quite different though. Given the limited market opportunities for industrial CHP and the difficulties in creating suitable public-private arrangements in the UK for district heating, their influence remained quite limited. In Germany, both public and private integrated energy supply companies emerged, with some local utilities explicitly moving into the business of providing, or at least facilitating, integrated energy services.

Germany serves as proof that this model also works at the level of municipalities. Local grid infrastructures for providing citizens with heat and energy services are in the hands of municipal energy companies that had much better opportunities to bridge the technical boundaries between heat supply and electricity supply. In the British context, the weak role of local authorities and lack of organisational integration of different types of energy services made the realisation of this kind of approach much more difficult (Hawkey, 2012).

In contrast to both the UK and the Netherlands, German cities also continued to be strong supporters and carrier organizations of CHP for district heating purposes. However, the growing public deficits and tighter competition policy rules imposed on cities increasingly limited their room for manoeuver. Since the mid-2000s, several local authorities have sold their power supply divisions to one of the large scale power producers and with this gave up control over their joint heat and power supply activities.

The positions of the main types of actor relating to CHP are embedded in the public debates about energy supply issues, and need to respond to the political claims raised. The strong support for a CHP-friendly policy in all its facets in the Netherlands was hardly contested. Even if power supply companies in the Netherlands had initially only a limited interest in CHP, they were not in a position to oppose that development. The consensus on the expected societal benefits of CHP was strong enough to lend legitimacy to a pro-active government policy. The German situation was more diverse, but ultimately a moderately positive stance towards CHP was part of the political consensus on the principles of energy policy, even while opinions differed about the means to achieve that end, as reflected in the controversies about the electricity feed-in tariffs for CHP or about the potential impact of these tariffs on a more generalized decentralization of power supply. The British situation was again different in that no generalized consensus on the long-term societal benefits of CHP was reached. Strict economic assessment criteria continued to prevail and determined investment decisions; a policy that was in line with the interests of the main incumbents in the sector.

The role of the state

Prior to liberalisation the possibilities for autonomous power generation were very limited in strict legal terms. With liberalisation a new window of opportunity was thus opened up by public policy. The Dutch case shows that a change in the energy supply trajectory can be achieved, if complementary policies are adopted alongside a liberalised framework. It shows the importance of clear and sustained political commitments and the definition of ambitious targets to orientate policy, coupled with strong financial incentives. Various kinds of incentives were created both to stimulate investment and R&D in CHP. The success of the support measures was so overwhelming that the Dutch government had to reduce the incentives to dampen the diffusion of CHP, because it had reached a level at which the technical stability of the power grid could no longer be ensured.

In Germany, other instruments were used, but the impulse was equally strong. The strongest impact was achieved through special feed-in tariffs, which were applied not only to solar and wind power, but also to CHP. This provided a major incentive for renewable power generation as well as for CHP. Various generations of this feed-in law, including earlier voluntary agreements, gave a sustained impulse in favour of CHP. This was supported by the diversity of energy policy settings in Germany, itself a consequence of the high level of autonomy of federal states and strong local authorities. This case shows how a diversified political system can help trigger experimentation with a range of energy policy instruments and their impact on technology options.

In the UK, liberalisation opened up the possibility of autonomous power generation, and thus opportunities for CHP, because deregulation opened up the electricity market to competition and gave new power generators access to the grid. However, many structural, organisational, cultural and institutional barriers remained in place and new ones were introduced, so that the conditions were not sufficiently conducive to enable a significant uptake of CHP. Ultimately, "CHP still has to fit somehow into a (deregulated) system that has not been designed to suit it" (Russell, 1994: 31).

In line with the limited incentives, capacity targets were also far less ambitious than in the Netherlands. Much was left to individual initiative, both at local level and industrial firms. Recent efforts to initiate district heating schemes moved ahead only through the initiatives of some key individuals, and in spite of scarce technical skills and knowledge (Hawkey 2012: 20).

Liberalisation is usually regarded as a potentially powerful trigger for CHP diffusion, but it can also have unintended detrimental effects. In combination with a tighter application of competition policy principles, for instance, it obliged local authorities to maintain a more transparent separation between the different utility services in Germany. Competition at local level also obliged them to pay more attention to cost-benefit ratios of their investment. Ultimately, this development in conjunction with the budgetary problems of several local authorities led to a take-over of many local energy utilities by the large power suppliers like RWE, EON or Vattenfall, and thus to a loss of local power in defining energy solutions.[10]

Knowledge

Knowledge dynamics and assessment of technology

It is a well-known phenomenon in innovation research that the production and diffusion of knowledge can give rise to self-reinforcing mechanisms and path-dependencies. In the case of CHP, for instance, knowledge and expertise need to be available locally, because CHP systems are embedded in industrial production or urban heat and power systems. As pointed out by Hawkey et al. (2013) for the UK, the lack of local knowledge and access to local social capital continues to pose a major challenge for cities interested in district heating applications of CHP. The ability to build up this knowledge is dependent on the access to other actors' knowledge, and thus on the embedding in networks of suppliers and other users. Industrial and local authorities associations can play an important role in this regard, as does the direct mutual knowledge exchange support among cities and firms. In the UK, this kind of local social capital has never been very well developed, not least due to the very limited diffusion of CHP in general. There were simply not many cases to learn from. The situation is very different in Germany, where associations of engineers, industrial associations as well as associations of local energy producers have been in place for many years, facilitating the exchange of knowledge and the specification of standards regarding CHP. Some of these associations have either dedicated sections dealing with CHP or were even set up explicitly for that purpose. Moreover, due to the number and diversity of specific local situations for CHP, there was quite a lot of diversity and experimentation taking place in Germany, thus offering wide scope for learning. In the Netherlands, the access and distribution of knowledge and experiences was one of the key tasks of

PWK (Projektbureau Warmte-Kracht), later on renamed Cogen Netherlands, which was built up with government support during the 1980s. It effectively played the role of a knowledge hub for CHP in the Netherlands.

Knowledge of CHP is also crucial for various kinds of assessments of the technology, ranging from techno-economic assessments at the plant level to wider socio-economic considerations regarding its risks and opportunities. As shown by Russell (1986a, 1994), in the absence of more supportive structures and regulatory conditions, the economic benefits and potentials of CHP were under-rated in debates about specific plants. This was partly due to a lack of knowledge, but also the result of the separation of heat and power supply utility services, which made it more difficult to exploit the synergies within the organisational frame of a single company. This problem of finding appropriate organizational governance models for district heating continues to be relevant even today (Hawkey et al., 2013).

Similar problems can be observed at national level, where the emphasis was put on a narrowly defined economic assessment dimension only. In the UK, other arguments which might have been expected to be supportive of CHP and district heating entered the debates at various moments in time, such as those relating to energy poverty and energy efficiency. Although in part dating back to the 1950s, these lines of reasoning never acquired a sufficiently strong and sustained role in the public and policy debates, even in the post-liberalisation phase. As a consequence, liberalisation had only a comparatively limited impact in unblocking potential for CHP, and then only in the industrial sphere. Public debates about energy policy and CHP at national level were not only constrained by a lack of knowledge and experience, but also by a lack of a sufficient diversity of informed voices. In the absence of positive experiences with district heating, for instance, it was hard to make a case in favour of it. And due to the almost complete absence of informed supporters of CHP in the debates, the arguments of incumbent players, usually opposed to CHP, had a dominant influence on policy and regulatory decisions. In Germany, on the contrary, both local authorities and industrial firms were in a position to reap the economic benefits of joint production of heat and power. Their respective industrial associations could make themselves forcefully heard in energy policy debates. As a result, CHP has been recognized as a desirable option since the 1990s in a number of important pieces of regulation. Most important in this regard were the feed-in tariffs for decentralised power production, which made the economics of CHP very promising. Similarly, the regulatory framework conditions and incentives introduced in the Netherlands led to positive economic assessments of CHP plants. These supportive conditions were embedded in corresponding debates at national level about the long-term economic and non-economic benefits of CHP and other renewable or highly efficient energy technologies.

Knowledge dynamics are not only driven from the demand side, but also from the supply side. In view of the CHP-friendly developments on the demand-side of energy supply in the Netherlands and Germany, it is of little surprise that significant public and private investments were made in R&D. As it was perceived as a growing market in both countries, private firms developed new generations of remote control systems, efficiency-enhancing prime-mover technology, in particular for small-scale applications (e.g. Stirling engines and fuel cells). Few comparable developments can be observed in the UK, where instead Dutch producers of CHP systems successfully entered the market for small-scale CHP. As a consequence, the virtuous cycle resulting from the interplay of positive expectations on both the supply and demand side of the new technology has never worked effectively in the UK. This stands in contrast to the situation in the Netherlands and Germany, where conducive conditions led to positive expectations about future investments in CHP, and thus also to investments in R&D. This, in turn, helped improve the economic and other performance characteristics of the technology as compared to other alternatives.

Embedding in broader debates and expectations

CHP plants need to fulfil economic criteria, but the assessment criteria applied, the organisational and institutional framework, and specific regulatory or financial policy measures may shift the balance for or against specific plant projects. These determinants are framed and legitimized by reference to wider policy objectives, and embedded in broader debates and expectations about the future of energy supply.

In the Netherlands and Germany, proponents of CHP were very successful in generating legitimacy for CHP by embedding it in such broader debates, and could thus generate dedicated support for the technology. The British situation was different, because in spite of other broader debates about the social and environmental benefits of CHP at different moments in time (e.g. energy poverty, resource efficiency, long-term security of gas supply), there was never a sustained period of support during which, for instance, a significant number of district heating plants could be built, which subsequently could have served as positive exemplars.

It is also interesting to observe that these broader legitimacy-enhancing debates change their reference points in the course of time, for instance from energy security and efficiency gains to CO2 reduction, climate change and renewables. This is important to consider, because a technology like CHP requires sustained support over longer periods of time to become established, to build the support networks around it, and in order to reduce uncertainty for potential investors. In Germany, the policy support lent to CHP in the 1980s and 1990s was mainly driven by energy efficiency arguments and arguments about the autonomy of industry in securing its heat and power supply, but in the course of the 2000s the framing debate to provide support for CHP shifted towards climate change issues and renewables, which were then strongly supported by government. CHP-promoters managed to position the technology under that roof and thus ensured sustained support, e.g. with regard to R&D funding and the application of a new generation of feed-in tariffs. The Dutch situation is similar in many regards, but in addition concerns about the long-term security of national gas reserves played an important role. They were used initially to justify support to a highly energy efficient technology, and later on to limit the support to CHP in favour of 'real' renewables.

Socio-Technical Change as Complex Process of Creation and Destruction

Interpreting the dynamics of socio-technical change

This section brings us back to the initial research question, namely whether Russell's conceptual thinking provides an adequate explanation of the paradox of significant differences in the patterns of socio-technical change associated with CHP innovation and diffusion in different countries. For Russell socio-technical change needs to be understood as a complex process of creation and destruction, resulting from the interplay of organisational and institutional conditions with social behaviour.

From a very simple comparative perspective, it could be argued that after liberalisation, the majority of the building blocks discussed remained hostile to CHP in the UK, while many of them became supportive in the Netherlands. The rapid shift in the structure of heat and power supply towards CHP-based systems observed in the Netherlands and the conservation of its rather marginal role in the UK can in principle be related to this generic observation. The German case also fits this picture. CHP had already been much more established a technology, be it for industrial or district heating purposes. Therefore the influence of liberalisation on the further uptake of CHP was more limited.

However, such a static interpretation is too superficial. In line with Russell, a historical view on socio-technical change needs to be adopted that is characterized by the operation of complex mechanisms leading to path-dependent developments (Weber, 2002; Russell, 1993); mechanisms that stem from the interplay between the six building blocks considered to be his framework.

Historically grown structures and cultural pre-dispositions (e.g. in terms of the role and influence of incumbent players, the degree of centralisation of political competencies and of energy supply, or the strict separation of heat and power supply) constrain the opportunities to break with past trajectories and realize organisational and institutional changes, but they should nevertheless not be regarded as fixed. Even within the confines of these structural constraints, there is still some, albeit limited, room for manoeuver, to change the self-reinforcing mechanisms at play that stabilise the prevailing path. Structures and institutions shape and influence the interests, options and power positions of the actors involved in decision-making about heat and power supply options, but at the same time the decisions and strategies of key players tend to shape the structures and institutions that are supportive for their interests and power positions. The degree of flexibility and dynamism of the system then depends on the balance between the stabilising influence of incumbent players and the opportunities for alternative voices to be heard.

While this interpretation of the relationship between path-dependencies and flexibility may be appropriate at times of incremental change, the situation is different at times of disruptive change such as in the post-liberalisation period, or after the Second World War. Major changes are only likely to happen once inherent contradictions and tensions become so strong that alternative structural and institutional settings need to be established. This kind of development can be observed in all three countries prior to liberalisation, but there were major differences in what was actually done to shape the subsequent process of change. Germany and, in particular the Netherlands, used these 'windows of opportunity' for CHP in a very different way than the UK. Liberalisation, as a policy-induced change process, opened up new opportunities that could trigger very different pathways of structural and institutional change in the energy system. The choice of specific mechanisms and incentives affected the extent to which a departure from the established structures and institutions was realised or not.

This interpretation suggests a co-evolutionary understanding of change processes in energy systems, where phases of incremental change can be interrupted by periods of transformative change. To unleash the potential of CHP in a context that is not conducive to its application requires a break with historically grown path-dependencies and associated blocking mechanisms, while creating new self-reinforcing mechanisms that stabilise a process of structural change which supports CHP. Such a change process cannot be steered in a top-down manner by government, but it requires mechanisms to be put in place to guide the self-organisation of the actors in a CHP-friendly direction. This is in fact what happened in the Netherlands, but never took place in the UK.

The success story of Dutch CHP

The Dutch case shows what can be achieved with substantive and sustained changes to institutional framework conditions and targeted support measures. Regulatory changes facilitated the emergence of new players at the interface between heat and power supply, and major subsidies over a longer period of time provided sufficient incentives to make CHP economically viable. The establishment of a carrier organisation that served as knowledge hub and support organisations for both suppliers and users of CHP fulfilled an important caretaker function, and R&D funding helped foster the development of next-generation CHP technology.

While liberalisation as the main institutional trigger of the change process opened up the legal possibilities for self-generation of power, it was accompanied by a clear political commitment in favour of CHP, reflected in the well-timed introduction of a range of sustained support initiatives.

Reliable and supportive planning conditions for investing in CHP were thus offered to industry as well as to cities. These initiatives set positive self-reinforcing mechanisms in motion, which were particularly effective in industry. Cities did not have the same level of autonomy and competence in public utility services as their German counterparts, but they were able to make use of the fast growing energy service industry. This offered integrated solutions that allowed a bridge between heat and power supply, or between the gas regime and the electricity regime.

The strong incentives for CHP were maintained in spite of criticism raised by incumbent power generators. By embedding CHP in the long-term gas policy and later on in climate policy objectives, public and political debates remained supportive of the pro-active CHP policy. Other criteria than just narrowly defined economic ones were taken seriously in the decision-making processes.

Apart from the financial drivers, the creation of a carrier organisation for CHP must be regarded as giving rise to several self-reinforcing mechanisms. PWK not only served as an information and knowledge hub for suppliers and potential users of CHP, it also fuelled the public and policy debates with arguments and experiences that lent support to the pro-CHP policy of the Netherlands. It facilitated the fast replication of CHP experiences in different industrial areas in particular, and also helped to counteract efforts to discredit CHP.

Due to the fast growing market expectations, serious R&D efforts were made in the Netherlands as well. After a few years, Dutch CHP companies were among the leading players in small-scale CHP technology, with great success not only on the Dutch, but also on foreign markets (including the UK). Arguments regarding the creation of a competitive industrial activity thus contributed to enhancing the political support lent to CHP.

In other words, the time window of opportunity offered by liberalisation was actively seized and supported by targeted government action. The fast diffusion of CHP marked the beginning of a process of structural change in the energy system, which affected the actor constellations, the degree of decentralization of energy supply, the integration between heat and electricity supply, and the specialisation patterns of the energy industries.

Structural continuity and the neglect of CHP in the UK

The British case is an example of a quite radical liberalisation and privatisation effort that nevertheless preserved several structural path-dependencies. These path-dependencies continued to exclude systematically several technological options like CHP. Even despite incentives for individual energy end-users, structural features of the sector may thus act systematically against energy saving investments (Russell, 1994: 50).

The institutional and regulatory framework in the UK never offered effective enabling conditions for CHP, with the consequence that the kinds of self-reinforcing mechanisms observed in the Netherlands never acquired the same level of significance. The unleashing of the dormant CHP potential which could be observed so forcefully in the Netherlands, was only present in the UK for a small fraction of industrial plants and some larger public buildings. Even today cities do not have the power, the resources and the competencies to engage effectively in a local energy policy, and continue to struggle with a framework that requires difficult PPP models for CHP to be realized to bridge between separate systems of heat and electricity supply (Hawkey et al., 2013). Under these circumstances, CHP-based district heating has little likelihood of being realized, even in new residential areas.

Due to the absence of a clear commitment in British energy policy to CHP as a serious option, linked to a lack of dedicated support measures for CHP, investment in the advancement of CHP technology remained limited, even while some companies specialized in the provision of standardized small-scale CHP systems.

The role of the Combined Heat and Power Association (CHPA) as a caretaker and carrier organisation was also less influential than that of its Dutch and German counterparts. In fact, given the comparatively small number of CHP plants in the UK, the number of members and thus the scope for learning and knowledge exchange remained limited. In the absence of other influential proponents of CHP, the influence of CHPA on public and policy debates remained very limited, their arguments often overridden by other players. Without influential support, it is no surprise that hardly any dedicated incentives and regulatory provisions for CHP were taken up, apart from a rather modest CHP capacity target.

In spite of these detrimental conditions, some efforts were made in recent years to realise CHP at city level. However it required engaged individuals to push such new initiatives. Both in the private sector and in the public sector examples of this kind of entrepreneurship can be found. As shown by Hawkey et al. (2013) the situation in the UK is still characterized by major difficulties for local authorities to come up with workable solutions for district heating in a context of limited competencies, resources and networks.

Overall, one can argue that the UK missed the opportunity to change course towards a more decentralised, horizontally integrated energy system based on a significant share of CHP. In the meantime, new path-dependencies have been created and, as a latecomer technology, CHP continues to struggle with an institutional and regulatory framework that is not made to suit this technology (Russell 1994).

Strengthening the existing pathway of CHP in Germany

The German case is different from the UK and the Netherlands because at the same time as introducing a liberalised framework for electricity supply in the 1990s, Germany was able to build on an already significant capacity of, and experiences with, both industrial CHP and district heating. There were already several decentralised and autonomous power production units in place. With the introduction of a system of feed-in tariffs the economic and legal conditions for CHP became more reliable and attractive. This was achieved in part due to the influence of some strong supporters of self-generation in general and of CHP in particular, in both industrial and municipalities associations.

This policy was not uncontested. Critical positions were expressed on the side of the large incumbents in the electricity sector, but political support for CHP was maintained by linking to energy efficiency, security of supply and, later on, climate change debates.

Given the comparative large number of existing CHP plants in cities and in industry, a large body of knowledge and experiences was available on which the newcomers to CHP could draw though various professional and industrial associations that were active in knowledge diffusion and standardisation. Due to the diversity of the specificities of regulation and support measures across Federal States, there was also room for experimentation with and learning from novel approaches.

Apart from the possibility to draw on an existing path and on strong and competent local utility companies, the willingness of national policy to provide active and targeted support to CHP applications in industry and public sector turned out to be decisive for strengthening the role of CHP in the liberalised German framework. Overall, the impact of liberalisation in Germany may have been less radical and influential from a CHP perspective, but it shows that it was possible to sustain the continuation of a growth path of decentralised and combined heat and power supply within a liberalised framework.

Lessons learned

Several lessons can be learned from this comparison of the evolution of CHP in the three countries, interpreted on the basis of Stewart Russell's reconstructed conceptual framework. In a nutshell, the three country cases show that in order to overcome the path-dependencies and trigger a process of 'creative destruction' after liberalisation, three strategic ingredients were of major importance, namely a) sustained effort to break structural and institutional settings and withdraw support for their stabilizing mechanisms, b) establishment of self-reinforcing mechanisms that help experiment with and promote the uptake of new options like CHP, and c) responding to a window of opportunity to trigger the change process in the desired direction.

Firstly, after a major shock like liberalisation, sustained efforts are needed to break with prevailing path-dependencies and create new self-reinforcing mechanisms that allow change in historically grown structures and institutions of energy supply. Although different tools and instruments were used, the German and in particular the Dutch experiences show that a sustained political commitment in combination with strong financial incentives and regulatory provisions can be effective in establishing an alternative trajectory. This is in line with the argument by Hard and Olsson (1995: 201) who call for a stable and persistent energy policy and "for governments that are not afraid of taking on the roles of a 'guiding actor' and a 'creative regulator' ". In their view, deregulation and privatisation are enabling factors for the uptake of CHP, but should not be driven too far in order to avoid negative side effects. Instead complementary support measures need to be installed to overcome path-dependencies. In the UK there have been several historic moments when CHP received quite a lot of rhetoric support but, in view of the long lead times of energy investments, the efforts to support CHP were not sustained long enough to lead to the implementation of major CHP plants and of DH plants in particular.

Secondly, efforts to break with the past need to be complemented by efforts to create, reinforce and stabilise an alternative path. Government cannot control this change process in a top-down manner, but in the course of the turbulent phase following a major shock such as the liberalisation and part privatisation of energy supply, there is an opportunity to trigger and nurture new self-reinforcing mechanisms that help establishing an alternative pathway. Obviously it is not possible to fully anticipate how these new mechanisms will work, or whether they will be sufficiently effective and lead to desired outcomes and impact. Experimentation, monitoring and learning are thus required to accompany the change process. It is not easy to establish the financial support and regulatory changes necessary for such a major change, in particular if some incumbent actors' economic interests could be negatively affected. To pave the way towards a significant change, it is necessary to embed the rationales for the change process in wider political and public debates, i.e. to connect them to higher-order and longer-term goals (Budde & Konrad, forthcoming). In the UK, contrary to the Netherlands and Germany, neither of these mechanisms could be observed. A structural change of a different sort took place, based on a 'dash for gas', still reliant on a separation of heat and power supply.

Thirdly, even a powerful and intelligent change strategy can easily fail, if the initiatives and measures do not fit the right windows of opportunity. Liberalisation and privatisation offered such a window of opportunity to change the rules of the game and trigger a transformative change towards a new pathway of energy supply. That window of opportunity was clearly seized in the Netherlands, it was used to strengthen a pre-existing path in the Germany, but it was missed in the UK. As a consequence, a different direction was taken in the UK. This is not the place to judge the merits and problems of the British choice, but it is clear that CHP is still struggling today to find an appropriate place in a system that still does not suit it.

Overall, the paradox thus results not only from historically grown structural path-dependencies, but also from the willingness, or failure, to take the opportunities offered at certain moments in time in order to change course. Whether the changes in framework conditions turned out to trigger change or not was then determined by the emergence (or not) of self-reinforcing mechanisms of various sorts: good examples, structural changes conducive to CHP that met with the local initiatives taken by various entrepreneurs, the empowerment of local players, either private or public, conducive regulation, financial incentives. And this alone would not be enough, if efforts are not sustained for long enough or sufficiently broadly. Bringing these changes about is a matter of supportive influences and interests in the debates about the pros and cons of different approaches, and thus also of the ability to connect with wider debates in order to ensure sustained support for CHP.

Conclusions

Stewart Russell's work on CHP/DH in the UK is recognised as a pioneering empirical contribution to the shaping of the emerging field of science and technology studies, but his conceptual thinking has thus far been under-exploited. This paper has made an attempt to revive this part of his legacy by re-constructing his main lines of reasoning about how technology choices in society come about and give rise (or not!) to processes of socio-technical change. The ambition was also to assess whether his framework provides an useful approach for explaining the significant differences in socio-technical patterns between countries.

Russell rejects any notion of technological determinism and stresses the socially and politically shaped character of technology choices in society, but he also acknowledges that social behaviour and choice must be seen as embedded in structural and institutional contexts. Innovative social behaviour can only exert its shaping power to the extent that it is enabled by structural and institutional conditions. Historically grown structural arrangements support and strengthen certain economic and political interests to the detriment of others, and thus affect the choices made and the decisions taken. In this way, some technological options may be more or less systematically excluded or even actively resisted. Similarly, knowledge about prevailing and novel options is neither objective nor neutral but constructed and deployed in line with the interests of the different players involved, for instance with regard to the economic assessment of energy technology choices and the criteria underpinning these choices.

Russell recognizes that structural and institutional conditions should not be taken as given. They are equally open to change but, being the result of historically and culturally framed processes, they tend to change rather slowly. However, as evidenced by liberalisation, if inherent contradictions have become so strong that alternative structural and institutional settings need to be established, the corresponding changes can happen at an accelerated pace. If appropriately guided by policy, these windows of opportunity allow a break with established path-dependencies and a change in course to a qualitatively different direction. It is this kind of theoretical principles (rather than any grand single theory) that need to be used as building blocks to explain specific arrangements (Russell, 1986a). Government policy has a key role to play in guiding and framing these long-term processes of socio-technical change in response to emerging tensions. With the help of these lines of reasoning, Russell demonstrates that it is possible to reconcile the macro and the micro to explain technology choices in society, without collapsing one into the other (Russell, 1994: 51).

With his focus on the (non-)occurrence of transformative change and on the interplay between three levels of analysis – context, interactions and knowledge – Russell's conceptual perspective is a pre-cursor of other more recent multi-level and systemic perspective on technology choice and socio-technical transitions (Geels, 2002; Hekkert et al., 2007). His emphasis on tensions as the origins of the destruction of the old and the creation of the new is still topical today, because it is increasingly recognized that transitions are not necessarily consensual processes, but involve conflict and power (Smith et al., 2005).

With the reconstruction of Russell's conceptual framework, his guiding ideas have been given a clearer shape and can now be used systematically to guide empirical analysis. As shown by the comparative analysis of CHP in the UK, Germany and the Netherlands, his framework delivers a plausible explanation of the innovation diffusion paradox of CHP. It is sufficiently comprehensive to deal not only with the British CHP case, which represented Russell's main empirical basis, but also to handle the peculiarities of the two other countries. With the help of his framework, what seems to be a paradox at first glance, turns out to be a coherent story of social choices in times of major external shocks. The case of CHP has thus been productive in demonstrating the explanatory power of Russell's perspectives on socio-technical change.

The potential of Russell's ideas still remains to be further exploited, both in terms of conceptual refinements and empirical applications. His framework could be further developed, for instance with regard to the rationales suggested for explaining transformative change, which stress the importance of tensions, conflicts of interest and power struggles. In this regard, it represents a promising addition to prevailing transition theories.

In empirical terms, many of the insights generated in the context of the CHP case could be transferred to other technologies with similar characteristics. Given the high political interest in future energy transitions towards a more decentralised and renewables-based regime, applying Russell's framework could be helpful in informing technology choices ahead of us. In fact, there are several other emerging technology developments in the energy field that could be faced with similar blocking and reinforcing mechanisms as the ones at work in the case of CHP.

Stewart Russell's work is still highly topical in several regards. His pioneering research on the social and political shaping of CHP can be interpreted as a pilot case for later debates about decentralised and renewable energy technologies. His conceptual insights point to lines of reasoning that are under-represented in today's debates about energy transitions and should be brought more prominently to the fore. It remains to be seen whether we have learnt something from past insights as those so thoroughly elaborated by Russell.

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Notes

1 There are several seemingly separate strands within the STS literature such as the Social Shaping of Technology (SST), Social Construction of Technology (SCOT), Actor-Network Theory (ANT), Large Technical Systems (LTS) and others, which nevertheless share the criticism of technological determinism. For a thorough review see Russell and Williams (2002).

2 The Dutch company Nedalo BV, for instance, had a quite successful subsidiary operating in the UK since the early 1990s.

3 Understanding innovation and socio-technical change as "creative destruction", to use Schumpeter's words (Schumpeter, 1942), has gained ground in other disciplines as well, in particular in economics, where evolutionary and Neo-Schumpeterian innovation economics revived the interest in Schumpeter's arguments.

4 This is not the place to enter into the details of the debates between the different schools of thought addressing the social shaping of technology in the late 1980s and early 1990s. There is an extensive literature on these differences, which, in the meantime, have given way to a more pluralist stance on the appropriate frameworks to be used.

5 The use of the term 'terrain' by Russell reflects the difficulties of delimiting the range of actors to be considered in an analysis of socio-technical change, and thus of 'cutting' the appropriate terrain. Russell has broadened the range of actors considered 'relevant' for a terrain beyond what is usually considered in a sectoral analysis. (Russell & Williams, 2002: 43, 77.)

6 David Collingridge's influence on Stewart Russell's thinking is not a coincidence because he was one of Russell's doctoral supervisors.

7 Russell thus draws similar conclusions on the role of the state as Hard and Olsson (1995), who also looked at the fate of CHP/DH in the context of debates about liberalisation and sustainability, and the political strategies for dealing with the tension between these two guiding principles. In their analysis, they draw on experiences made in Sweden, Austria, Denmark, the Netherlands, Germany and the UK.

8 Geographical and climatic conditions have always played an important role in defining the potential for district heating, but in recent years, CHP has also been expanded to district heating *and* cooling applications, which now makes the Southern European countries more attractive markets for CHP.

9 In addition to the comprehensive empirical material published by Stewart Russell, the British case draws on other studies and scientific articles published over the past three decades, including Weber (1999, 2002), Weber et al. (2000), Alcock and Marvin (1988), Marvin (1991) and for the more recent developments Bolton (2011), Hawkey (2012), and Hawkey et al. (2013). The German case was investigated in depth by Weber (1999, 2002) and Walz (1994). The situation in the Netherlands was studied among others by Blok (1993), Weber et al. (2000), Raven (2007), Raven and Verbong (2007), Meijer et al. (2007).

10 Interestingly enough, a shift to re-localisation of energy supply can be observed, with local authorities buying back their local grids and power generation units from the large operators. The most prominent of these cases is the City of Hamburg which decided in referendum in 2014 to buy back its grid from Vattenfall.

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