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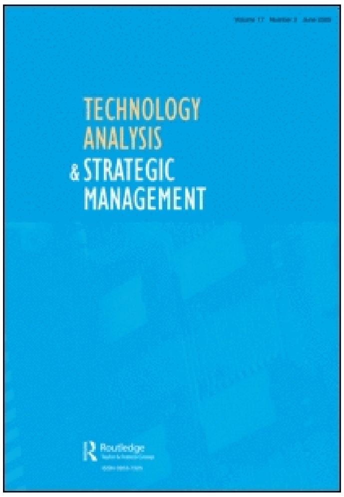

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The hesitant emergence of low carbon technologies in the UK: the micro-CHP innovation system

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Micro combined-heat-and-power (micro-CHP) technology has potential to contribute significantly to the UK's climate change strategy. This study applies a technological innovation systems (TIS) analysis to the UK domestic micro-CHP sector to better understand the dynamics of this emerging technology, identify policy options for enhanced system development, while also assessing the effectiveness of the TIS framework as an analytical tool. Interviews with key system actors are used to understand system functions, enabling an analysis of system development over time in terms of inter-functional relations, and a brief comparison with the Dutch micro-CHP system. Specific policy recommendations are made, including clarification of government 'renewable' vs 'low-carbon' climate change mitigation objectives, establishing dedicated targets, incentives and supports for adoption, installation and industry representation. A critique of the TIS framework highlights the dangers of selectivity with regard to key functional patterns, underdevelopment of consumer influences, and insularity with respect to wider influences on innovation.

Keywords: technology and innovation studies; energy industry; innovation studies; technology diffusion; renewables; low carbon; technological innovation systems; micro-CHP; innovation; policy; microgen

1. Introduction

1.1. *Background*

Growing concerns about the scale and impacts of climate change have prompted policy makers to develop new policy initiatives to cut production of CO_2 and other greenhouse gases. The UK government has made a number of ambitious commitments to reduce CO_2 emissions, and, within this, has acknowledged the potential role of microgeneration technologies (Department of Trade and Industry (DTI) 2006, 2007). It has been estimated that widespread microgeneration adoption could account for greater than 12 mega-tonnes of annual CO_2 savings by 2030, and micro-combined heat

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and power (micro-CHP) has been identified by government and industry as a leading technology in the domestic microgeneration sector (DTI 2006; Element Energy Ltd (EE) 2008). Nevertheless, this promising technology must compete in a UK energy system still dominated by established, centralised large scale 'lock(ed)-in' energy suppliers (Foxon et al. 2005, 2135). An analysis of technological innovation and diffusion which is able to address both micro-level technology-specific processes, and also wider system-level enablers and barriers at the level of the energy system, is therefore necessary. By applying the technological innovation systems framework (Jacobsson and Johnson 2000; Bergek and Jacobsson 2002; Hekkert, Suurs, et al. 2007; Bergek et al. 2008), this paper seeks to generate insight into barriers and opportunities to further develop domestic micro-CHP in the UK.[1] Micro-CHP presents an interesting case study for Technological Innovation Systems (TIS) analysis. By 2008, the TIS framework had been applied in several energy systems analyses (e.g. Hekkert, Harmsen, and de Jong 2007; Hekkert, Suurs, et al. 2007; Meijer, Hekkert, and Koppenjan 2007; Bergek, Jacobsson, and Sandén 2008; Negro, Hekkert, and Smits 2008; Hillman et al. 2008), but there have been relatively few studies of microgeneration technologies, where the energy consumer often has an important influence on technology development and deployment. The TIS framework is still undergoing conceptual development, particularly in terms of the understanding of specific system functions, and the relationship between functions. This study applies a TIS framework analysis to UK domestic micro-CHP, based on interviews conducted with a variety of industrial and other-organisational system actors. The analysis aims to provide insight into the dynamics of the UK micro-CHP system, and identify policy options to stimulate enhanced system development; in addition, the research seeks to contribute insight into the effectiveness of the TIS framework as an analytical tool.

The paper proceeds as follows: Section 2 outlines the evolution of the TIS approach and how it was adapted for use in this case study. Section 3 provides an analysis of the micro-CHP case study by presenting a TIS analysis in a number of ways: a function-by-function system analysis, a mapping of inter-functional relationships and patterns, an identification of the barriers and inducements affecting the system, and finally a brief comparison with the Dutch micro-CHP system. Section 4 identifies policy recommendations emerging from this research, offers a commentary of the effectiveness of the TIS framework, and highlights issues for further research. Section 5 concludes the article.

1.2. *Micro-CHP technology*

Micro-CHP replaces conventional domestic central heating boilers to supply both electricity and heat for individual homes or small buildings (Hekkert, Harmsen, and de Jong 2007). Domestic CHP models typically produce up to 1 kW of electricity and provide heat for the dwelling, virtually eliminating transmission losses and enabling fuel efficiency upward of 80% (DTI 2006; Hawkes and Leach 2007). Micro-CHP units connect to the grid upon installation, allowing any surplus electricity to be sold back to the grid (Peacock and Newborough 2006). Today, micro-CHP units are fuelled predominately by natural gas, but in the longer term there is potential for other low-carbon fuels, especially hydrogen-powered fuel cell units (Foxon 2003).

A variety of technologies are in development, based on the Stirling engine, Organic Rankine Cycle (ORC) engines, and fuel cells. Each design offers different advantages in terms of cost, efficiency and ratio of electricity to thermal output. For example, Stirling engines are appropriate for large homes with high heat and low electricity demands (Carbon Trust (CT) 2007), while ORC units are less efficient but can be built at a much lower cost and with greater electrical output.[2] Fuel cell units can produce a higher electrical output and are expected to perform in a broader range of homes. Reducing unit costs and increasing lifetimes are the primary challenges to micro-CHP deployment.

2. Technological innovation systems

2.1. *Innovation systems*

Innovation systems (IS) can be broadly defined as ‘the elements and relationships which interact in the production, diffusion and use of new, and economically useful knowledge’ (Lundvall in Foxon et al. 2005, 2124). The actions of innovators, the relationships between innovating organisations and the surrounding socio-economic environment are all taken into account (Carlsson and Stankiewicz 1991; Hekkert, Suurs, et al. 2007). In this way, innovation systems analysis offers a means of enabling a greater understanding of innovation dynamics and performance (Bergek et al. 2008, 408).

IS theory evolved in response to the so-called ‘linear’ model of innovation, to provide greater recognition of the institutional environment within which innovation occurs, and the complex interdependencies between multiple agents (Carlsson and Stankiewicz 1991; Foxon 2003; Jacobsson and Bergek 2004; Geels, Hekkert, and Jacobsson 2008). In the context of sustainable development, innovation systems analysis combines economic, sociological and political disciplines to more effectively capture the ‘intrinsic inter-relatedness’ of environmental problems, and their potential solutions (Geels, Hekkert, and Jacobsson 2008, 523, 534).

The variety of contexts and purposes for which innovation occurs challenges the concept of a universally applicable IS model of analysis (Foxon et al. 2005), and has led to the evolution of specific frameworks to facilitate more thorough examination in terms of *sectoral innovation systems* (focused on an industrial sector), *national systems of innovation* (addressing a specific nation), and *technological innovation systems* (regarding a specific technology) (Carlsson 1997; Carlsson and Stankiewicz 1991; Jacobsson and Johnson 2000; Jacobsson and Bergek 2004).

2.2. *Technological innovation systems*

The technological innovation system (TIS) framework examines the generation, diffusion and utilisation of a particular technology by observing the interactions between actors, networks and institutions (Meijer, Hekkert, and Koppenjan 2007; Bergek et al. 2008; Markard and Truffer 2008). TIS analyses are focused around *functions* as ‘emergent properties of the interplay between actors and institutions’ (Markard and Truffer 2008, 597). TIS case studies interpret this interplay to derive key insights into how innovation processes can be influenced (Meijer, Hekkert, and Koppenjan 2007). Functional analysis in TIS facilitates the comparison of different case studies, so as to enable ‘a more systematic method of mapping determinants of innovation’, and ultimately more effective policy recommendations (Hekkert, Suurs, et al. 2007, 420).[3]

TIS studies have recently been applied in several energy systems analyses: cogeneration in the Netherlands, renewable energy technologies in the UK, biomass in the Netherlands, biofuels in the Netherlands and Sweden (Foxon et al. 2005; Hekkert, Harmsen, and de Jong 2007; Negro, Hekkert, and Smits 2008; Hillman et al. 2008). The TIS framework continues to evolve. No one framework has been universally established as the accepted model for analysis and a synthesis of two leading approaches was developed and applied for the present case, as described below.

2.3. *TIS framework applied in this case study*

The present study combined elements of Hekkert, Suurs, et al.'s (2007) 'Functions of innovation systems' and Bergek et al.'s (2008) 'Functional dynamics of technological innovation systems'. The process of conducting a TIS case study – scoping, stakeholder identification and specific functional analysis guidelines – were based on the Bergek et al. (2008) framework, while the development of guidelines on function fulfilment and analysis of inter-functional relationships were based on Hekkert, Suurs, et al. (2007). Although measurement and mapping techniques differ between these two frameworks, similar typologies of functions are used in both frameworks and elements of each have been used here (Hekkert, Suurs, et al. 2007; Bergek et al. 2008).

Case research consisted of a review of published and 'grey' academic and industry literature, and semi-structured interviews with key actors in the UK micro-CHP system. The literature review provided a wealth of information regarding relevant policy and stakeholder comment on micro-CHP. However, where published material was less available, original research interviews were undertaken to enable 'a better understanding of social realities and … processes' (Flick, von Kardoff, and Steinke 2004, 3) and the capturing of the perception of experience of other stakeholders, particularly from industry (Hekkert, Suurs, et al. 2007; Bergek et al. 2008). Ten semi-structured in-depth interviews were conducted with representatives from micro-CHP system manufacturers, trade associations, consultancies and government agencies, all of whom were identified through the structural components stage of the framework (Bergek et al. 2008). Interview questions were designed to address the different system functions (see Table 1). Interviews were conducted in June and July 2008. Interviewees are not identified by name, but their position in the innovation system is described.

Seven system functions have commonly been applied in recent TIS studies (Hekkert, Harmsen, and De Jong 2007; Hekkert, Suurs, et al. 2007; Hillman et al. 2008; Meijer, Hekkert, and Koppenjan

Table 1. System functions and fulfillment criteria (adapted from Hekkert, Suurs, et al. 2007; Bergek et al. 2008).

System function	Performance criteria
F1: Entrepreneurial activities	Intensity of new entrepreneurial activity, diversification and exploration of new applications, variety of technological experimentation
F2: Knowledge development	Research and testing performed, the number of patents held, the evolution of the knowledge base
F3: Knowledge diffusion	Number of learning/educational seminars and summits, size of the network system and industry associations
F4: Guidance of the search	Expectations of actors, incentives created for uptake, established government targets or objectives, articulated consumer demand
F5: Market formation	Phase of the market, niche markets, uptake projections and policy uptake inducements
F6: Resources mobilisation	Availability and accessibility of materials, skills and labour, volume and quality of education and training, deployment capacity
F7: Creation of legitimacy/counteract resistance to change	Presence of lobby organisations and activities, consumer and institutional expectations, establishment of technological legitimacy

2007; Bergek, Jacobsson, and Sandén 2008). The set of functions applied in this case (Table 1) was derived from Hekkert, Suurs, et al. (2007) and Bergek et al. (2008).

Although there is no objective standard against which the success of the ‘functional pattern’ can be measured, this typology enables a comprehensive account of the multiple factors shaping innovation, and the various inducement and blocking mechanisms involved. Further, the analysis of inter-functional patterns helps identify ‘virtuous’ or ‘vicious’ cycles which explain system growth or decline (Bergek et al. 2008, 420; Hekkert, Suurs, et al. 2007, 426). A comparison with systems of other countries is suggested by Bergek et al. (2008) to provide greater insight into the specific processes under analysis. Although a comprehensive comparison was not possible here, a brief comparison with system elements of micro-CHP in the Netherlands (a country with greater uptake of micro-CHP technology than the UK) was carried out. Policy recommendations can then be deduced from the analysis, identifying areas for market support or other actions (Bergek et al. 2008; Hekkert, Suurs, et al. 2007).

3. TIS analysis of domestic UK micro-CHP

3.1. *Functional analysis*

Data from interviews with different system actors was organised so as to assess performance of each function against the criteria described in Table 1. The relevance of the data for each function depended on the interviewees’ role within the micro-CHP system.

3.1.1. *Function 1: entrepreneurial activities*

The UK domestic micro-CHP industry emerged in the late 1990s, and by the early 2000s expectations had developed around the impending commercial launches of two Stirling engine designs (Harrison 2003). Developers lobbied for government-sponsored trials which were expected to validate the technology and many stakeholders believed that this activity led the Carbon Trust (CT) to establish its Micro-CHP Accelerator Programme. The CT field trials commenced in 2003, but few models proved ready to participate, resulting in the trials progressing with just one participating domestic micro-CHP company (CT 2007). The technology was revealed to be earlier in its development than perhaps assumed and the commercial launches were postponed. Early expectations were left unfulfilled and investment was withdrawn from the industry, subsequently reducing its size, producing a significant set-back or ‘false dawn’.

Entrepreneurship activities intensified again after 2005, as a resurgence of interest in micro-CHP in the UK followed successful uptake in other countries, such as Japan and Germany, and as the climate change agenda shifted increasingly onto low-carbon energy technology and microgeneration (DTI 2006). By 2008, 10 companies were commercially developing domestic micro-CHP products for the UK market, six having entered the industry since 2006. With reduced costs and improved mass-production capacities, a number of micro-CHP designs were expected to be commercially launched in the UK in 2009, including Whispergen’s Stirling engine units, EcoGen’s free-piston Stirling engine (made by Microgen Engine Corporation (MEC) and Baxi Heating UK Ltd (BHUL)), and the Genlec ORC design by Energetix (CT 2007; BHUL 2008; DTI 2006).[4] Fuel cell micro-CHP units are at an earlier stage of development, but Ceres Power is developing low-temperature solid oxide fuel cell (SOFC) designs (Energy Saving Trust (EST) 2007, 46; CeresPower (CP) 2008; CT 2007, 15).

This degree of development indicates that a variety of micro-CHP models have been launched, or are likely to become available in the UK market between 2008 and 2012, generating market competition. Despite this competition, an engine manufacturer (interviewee, 2008) identified the common interest across the developer community:

> Even though we're competitors there's room for all of us . . .. It's better that [each company] launch . . . it gives more credibility to the industry.

New corporate partnerships and investments are also supporting a greater range of products. For example, British Gas (BG) signed a major contract with Ceres Power in January 2008, securing exclusive rights for marketing and servicing (CP 2008). European utilities company E.on is developing marketing, installation and servicing capabilities for a range of technologies, including Whisper Tech and Energetix units. This expansion of the network reflects significant advancement of the technology and mass manufacturing, with marketing and sales agreements forged, and utility and supply companies engaged.

3.1.2. *Function 2: knowledge development*

The establishment of the current technological knowledge base is indicated by the retention of patents. Of the leading developers, Whispergen currently holds hundreds of patents, internationally, for the integration and core design of the 'wobble yoke' engine. MEC holds 45 patents for the free-piston Stirling engine, while Energetix has patented the Genlec unit as a core patent and is awaiting the grant of several more pertaining to the assembly of the unit. Ceres Power and Disenco Energy also hold patents for their specific models, ensuring that their intellectual property is protected in an increasingly competitive industry.

Lengthy trials of Stirling engine units have resulted in significantly increased efficiency. In the UK, several industry interviewees highlighted the importance of data generated from the Carbon Trust's field trials regarding equipment, installation requirements and the capacity for CO_2 and fuel cost savings. At the same time, industry interviewees identified a need for additional trials, conducted on a 'larger scale' or with newer technology; for all developers, field trials play an essential part in the micro-CHP innovation system.

3.1.3. *Function 3: knowledge diffusion through networks*

Trade associations and organisations interface between micro-CHP manufacturers, equipment providers and utility companies,[5] while also facilitating dialogue with policy and regulatory bodies. The Combined Heating and Power Association (CHPA) represents the CHP industry in the UK. The Micropower Council (MC) represents the microgeneration sector in general, while the Heating and Hot water Industry Council (HHIC), a division of the Society of British Gas Installers (SBGI), specialises in the 'domestic heating and hot water industry' of which micro-CHP is included (SBGI 2006).

Trade associations facilitate information sharing through conferences, workshops, research and publications. Domestically, trade associations enable the dissemination of technical, market and policy information between manufacturers and developers, government and research organisations. The Carbon Trust's trials have also enhanced communication between the industry and government.

At least eight European conferences or summits held in 2008 featured micro-CHP as either a primary or key topic, enabling exchange of information regarding technological developments and influencing the development of the approach to market and political initiatives. Three UK trade associations, the CHPA, MC and HHIC, all host annual conferences that include micro-CHP. Collaboration with countries that have more established industries, such as Japan and Germany, is also facilitated. The development of the UK system is thereby being enhanced by 'learning by interacting' internationally (Hekkert, Suurs, et al. 2007). However, the case research indicated that other potential fora for knowledge sharing, such as industry–university or user–supplier networks, are not playing an important role in the emerging micro-CHP system. As is discussed in Section 4, the under-developed role of the (domestic) user is a wider concern in TIS analysis.

3.1.4. *Function 4: guidance of the search*

Rising levels of interest in the UK micro-CHP industry since 2000 have reflected a wider energy policy shift toward non-market imperatives, especially decarbonisation and enhanced security of supplies; energy had previously been perceived as a 'commodity good, competing on price' (Winskel et al. 2006). Energy White Papers in 2003 and 2007 outlined the UK government's aims to achieve carbon reduction targets, including a 60% reduction of CO_2 in the UK from 1990 levels by 2050, revised in 2008 to 80% (DTI 2003, 2007; UK Government 2008a). The UK Microgeneration Strategy addresses the role of microgeneration in achieving the emissions targets, within which micro-CHP is recognised as potentially playing a pivotal role (DTI 2006; Allen, Hammond, and McManus 2008; DTI 2006).

However, many UK policy initiatives only apply to 'renewable' microgeneration, and exclude other low-carbon technologies such as micro-CHP. This means that domestic micro-CHP does not qualify for important UK support programmes, despite its acknowledged potential as a means for relatively affordable CO_2 emission reductions. All interviewees expressed a need for government strategies to adopt a more consistent matching of overall policy objectives with technology-specific support measures. At the same time, most interviewees recognised a need for the technology to 'prove' its potential in the market before greater support comes forward. When interviewed in 2008, one manufacturer commented that:

> The micro-CHP industry over the last five years has over-promised and under-delivered; for the last 10 years it's always been two years away. So the Government have been annoyed with that … there's a lot of groundwork that needs to be done to improve the reputation.

There is also a perception that the UK government is proceeding with caution given the 'false dawn' that occurred in 2003. The UK government has yet to set specific targets for micro-CHP adoption, and as a result there are only weak incentives for uptake. Institutional frameworks are administered by many different actors with overlapping responsibilities and distinctive agendas, making the harmonisation of initiatives and the achievement of overarching policy objectives a complex and difficult process. Each body affects micro-CHP development in particular ways. The Department for Energy and Climate Change (DECC) is responsible for energy policy including microgeneration and energy efficiency, while the Office of Gas and Electricity Markets (Ofgem) has statutory responsibilities for regulating the energy market (Ofgem 2007). The UK government is also developing a strategy to achieve 'zero carbon' status by 2016 for all new-build homes (DTI 2007). Independent government-funded agencies such as the Carbon Trust (CT) and Energy Saving Trust contribute significantly to policy, as the CT informs policy development by conducting research programmes, while the EST provides policy analysis and informs the public on renewable energy and efficiency (EST 2008).

Boiler purchases are predominately 'distress' in nature, resulting in a market where consumers purchase their units based mostly on necessity, and little demand has been articulated by consumers outside of the early adopters. There are a number of more specific incentives and mechanisms for micro-CHP unit uptake. Value Added Tax (VAT) on microgeneration, including micro-CHP, was reduced from 17.5% to 5% (DTI 2007). Ofgem is managing the Carbon Emissions Reduction Target (CERT) which obliges energy suppliers to reduce the CO_2 emissions produced by homes and dwellings (DTI 2007). CERT is expected to be a prime stimulator of microgeneration, particularly micro-CHP, as suppliers strive to meet the established targets by offering to install microgeneration systems (Ofgem 2007). The Low Carbon Buildings Programme (LCBP) provided capital grants to the general public for domestic installation of microgeneration, including, micro-CHP (Department of Business Enterprise and Regulatory Reform 2008). The LCBP however, was heavily criticised by interviewees as favouring certain technologies over others, and lacking sufficient funds to support significant levels of micro-CHP adoption.

This discussion reveals a complex institutional and political landscape shaping the 'guidance of search' function in the UK micro-CHP system. While not contradictory, the measures described here are not all fully complementary, and the ability to realise wider energy system objectives may be enhanced by more consistent alignment across this landscape, in terms of communication, planning and execution of different initiatives.

3.1.5. *Function 5: market formation*

The UK micro-CHP market is in a *nursing phase*, in which a protected 'learning space' has been established (Andersson and Jacobsson 2000, 1039), and is beginning to move toward a *bridging phase*, where the quantity of units is rising and the network is expanding and shifting towards production rather than research (Bergek et al. 2008, 416).

A niche market of early adopters who are willing and able to pay the high costs of the technology currently exists. In addition, a significant amount of market analysis has been undertaken regarding domestic micro-CHP potential in the UK, providing market projections and analysis of the impact of different policy mechanisms (although more detailed understanding of consumer motivations and behaviour is absent from these studies). For example, it is estimated that with support, numbers of installed units could increase to 1 million by 2020 and 3.3 million units by 2030 (representing 10% of UK dwellings), while others claim that 'micro-CHP can realistically take a 30% share of the boiler replacement market by 2015' (SBGI 2006, 3; EE 2008, 11). The Stirling engine is projected to be the fastest growing micro-CHP unit over the short term, with fuel cell units taking a growing market share by 2020 (EST 2007; EE 2008).

Significant penetration of the UK boiler market, with an annual replacement volume of 1.5 million units, would more fully enable micro-CHP to break out of this niche, but there is a risk the market will remain small unless stronger support measures are provided. For example, the current price of domestically produced electricity in 2008, as typically paid by energy companies, is too low to sufficiently compensate the producer, so arguably does not reflect the added value of low-carbon energy (DTI 2006). Feed-in tariffs (guaranteed above-market prices paid by utility companies to producers of microgenerated energy for energy sold back to the grid) were identified by the majority of interviewees as the most effective incentive for micro-CHP uptake. However, a utility company interviewee expressed concerns about market interference issues:

> Government keep distorting the market with things like grant funding for specific technologies and not for others, which is particularly unhelpful to the technologies which are not included on the list.

The government's intention to establish feed-in tariffs (FITs) was stated in the 2008 Energy Act (UK Government 2008b). In 2010, FITs were introduced for a number of microgeneration technologies, including, on a pilot basis, domestic micro-CHP (DECC, 2010).

3.1.6. *Function 6: resources mobilisation*

Technological and material resources in the micro-CHP industry are generally available, in that micro-CHP combustion engines are assembled predominately using available parts (with the exception of magnets in the MEC free-piston design, and special tooling required for Whispergen designs). Fuel cell unit components, sourced from the aerospace industry, are much more costly, although Ceres Power is developing a lower temperature unit enabling the use of mass-produced components. The resurgence in the industry since 2006 has attracted large volumes of new investments, both from inside and outside the UK, increasing the number of participating companies and associated resources.

This said, a key resource that is undersupplied is a sufficient number of trained installers to service commercial units. The majority of failures that occurred in early micro-CHP trials were due to faulty installation and there remains little incentive for the nearly 60,000 boiler installation companies operating in the UK to train for micro-CHP installation at their own expense. Utility companies such as E.on are creating their own solution here by establishing installation teams to service their own micro-CHP products. Nevertheless, extensive training support will be necessary for effective installation if market penetration targets are to be achieved. The circumstances of the micro-CHP industry were likened by interviewees to the installation problems of condensing boilers, which required compliance regulation and government-supported installation training before widespread uptake was realised.

3.1.7. *Function 7: creation of legitimacy/counteract resistance to change*

As described in sub-section 3.1.3 above, there is no single advocacy group dedicated to representing the interests of the micro-CHP sector in the UK: industry actors tend to subscribe to different organisations and associations, none of which are working exclusively in their interests. A major task for these groups, according to a trade association representative, has been to overcome legacy issues associated with the ‘false dawn’ of the early 2000s. Each association is contributing to micro-CHP development through their own projects, such as the CHPA’s MicroCHP R^3 study, which aims to enhance support and organisation within the industry, the MC’s report on the Standard Assessment Procedure (SAP) rating, and the performance assessment and accreditation scheme currently being developed by the SBGI with government agencies.

Because the industry representation is fragmented, communication with government occurs through multiple channels. A view echoed by many interviewees was the ‘need for consistent forms of representation to government’. In addition, as discussed in sub-section 3.1.4 above, the legitimacy and advocacy of micro-CHP relative to other low carbon options is weakened because of its exclusion from renewable technology organisations and networks.

3.2. ***Analysis of functional patterns***

A primary focus of TIS analysis is to identify patterns and sequences of inter-functional relationships. In some cases these relationships can be characterised as ‘virtuous cycles’, or periods where positive stimulation between functions stimulates growth and penetration into an established sector, or ‘vicious cycles’, or periods where negative relationships between system functions hinder or dampen system development (Hekkert, Suurs, et al. 2007, 426–7). Analysing the inter-functional relationships in the micro-CHP system reveals a fluctuation from virtuous to vicious cycles in its development and a return to a positive state in its current phase.

The system has been operating in a positive pattern, as shown in Figure 1, since 2006. Hekkert, Suurs, et al. (2007, 426) suggest that entrepreneurs who lobby for R&D funding or market support

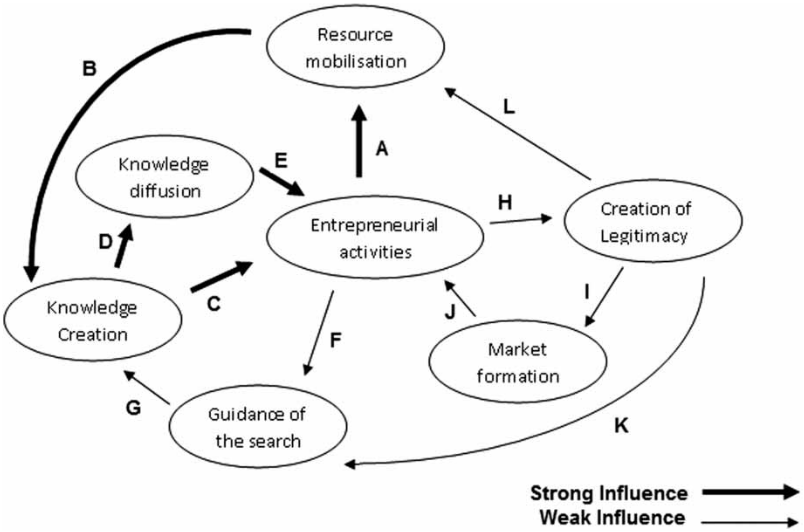

Figure 1. Functional pattern dynamics of the UK micro-CHP system in 2008. (The arrows point in the direction of positive influence while the thickness of the arrows indicates the strength of positive influence). Adapted from Hekkert, Suurs, et al. (2007).

resources can trigger a virtuous cycle, and this sequence, along with a heightened political emphasis on climate change mitigation, reflects the development of the strong functional links in the current system (Figure 1, cycles ABC and ABDE). Entrepreneurial activity has generated technical and financial resources to assemble and trial the technology, thereby helping to build a solid body of knowledge. This knowledge stimulates further development by entrepreneurs, while also being diffused through system-related networks at conferences, association meetings and publications. This cycle is enhanced by other functions acting as secondary influences.

Knowledge creation is further stimulated through extensive testing of the technological integrity of the units, via the CT trials (Figure 1, arrow G). Functioning of the units is observed to identify technological inefficiencies, thereby generating the knowledge to further improve upon unit design. However, the CT is currently the only major institutional support for micro-CHP research in the UK, suggesting a relatively weakly developed guidance of the search, a critical function in growing systems (Hekkert, Suurs, et al. 2007). This hinders the potential of the technology from being fully realised. Lobby groups have increased their activities, but have yet to unify under a single organisation while confidence in the technology from policy-makers remains fragile given earlier disappointments, weakening the extent to which government-led legitimisation is able to guide the search (K). This rather weak legitimacy also provides limited support for market formation and resource mobilisation (I, L). Stronger industry lobbying activity may increase private and public support for further development, particularly regarding the training of installers (L).

The initial development of the micro-CHP network in the early 2000s was positive and closely resembled the more recent pattern shown in Figure 1. The technology evolved in response to its early market potential identified by entrepreneurs. While a strong lobby had not yet been formed, the industry successfully campaigned for government-supported CT trials (portrayed as FGC in Figure 1). However, the technology largely failed to meet expectations at this time and an over-optimistic assertion of the maturity of the technology by several industry actors damaged the relationship between the industry and government (F). The trials continued, but under reduced government and investor confidence, leading the system into a negative period.

This stalling of system progress damaged other functional relationships. Erosion of policymaker and investor confidence reduced the intensity and size of the emerging network, and lobby groups now had virtually no influence (L and K). During this period, however, knowledge development continued and was to fuel entrepreneurial activities that would revitalise the system after 2006. The industry managed to bypass government to access resources from private investment (A) for continual product development (ABC) (Hekkert, Suurs, et al. 2007). Positive relations between functions were subsequently re-established. Nevertheless, the loss of legitimacy has had a lasting effect, in terms of continuing weaknesses in government–industry relations.

3.3. *Comparison with the Netherlands*

Micro-CHP system development in the Netherlands provides a compelling comparison with UK experiences. There are high expectations for micro-CHP growth in the Netherlands; projections for uptake estimate 1.3 million installations by 2020 (Meijer, Hekkert, and Koppenjan 2007, 531; Micro-WKK 2008). A significantly larger number of companies are involved in micro-CHP technology in the Netherlands than in the UK, however the industry also faces a lack of skilled installers (Meijer, Hekkert, and Koppenjan 2007). The Dutch Smart Power Foundation provides a strong coalition of micro-CHP industry members, establishing legitimacy and actively engaging with government, instilling confidence in the technology to enhance the guidance of the search (Energy Transition Task Force (ETTF) 2006; Smart Power Foundation 2008).

The Dutch government also actively directs search activities more strongly than the UK by providing financial incentives and installation targets (Meijer, Hekkert, and Koppenjan 2007).[6] The Netherlands has historically supported innovative energy technology to a greater extent than seen in the UK and is now cultivating a micro-CHP industry on a foundation of experience with decentralised energy systems (ETTF 2006). The Dutch government is also explicitly stimulating the development of micro-CHP through a collaborative approach to energy transitions (SenterNovem 2005; Meijer, Hekkert, and Koppenjan 2007). The Energy Transition Strategy coordinates six government agencies and wider organisations through the platform for sustainable electricity supply. As part of the elaboration of a number of ‘transition paths‘, micro-CHP features as part of the development of efficient building options (ETTF 2006, 9).

A brief comparison therefore suggests that some of the strongest functions in the Netherlands system are among the weakest in the UK. The more strongly collaborative approach in the Netherlands (and a stronger industry lobby) creates an environment potentially supportive of innovative technology.[7] The Dutch government demonstrates the importance of the process of change in achieving climate change mitigation through its ‘transition path’ approach, whereas the UK government has yet to move beyond the setting of more general carbon emission reductions targets. While the Dutch approach may not be the most effective in supporting renewable technology, nor be fully transferable to the more market-based UK energy context with its less thoroughly engaged networks between the government and industry, the Netherlands provides important insights into how the UK approach to supporting decentralised and low-carbon energy technology may be improved.

4. Discussion

4.1. *Recommendations for stimulation of UK micro-CHP system*

The application of the TIS framework has enabled a comprehensive analysis of the UK domestic micro-CHP system, from which a number of recommendations for improving system functioning are derived, below:

- Clarification of UK climate change mitigation policy instruments regarding ‘renewable’ and ‘low-carbon’ technology would increase policy effectiveness and the likelihood of reaching emissions targets in the most cost-effective manner. The terms ‘renewable’ and ‘low-carbon’ are often used interchangeably regarding broad policy objectives, but micro-CHP is excluded from many specific support measures because of its non-renewable status, hindering market development. Policy approaches towards micro-CHP are arguably still conditioned by the false dawn of the early 2000s. Effective policy and market mechanisms are necessary to enable greater uptake and propel the technology beyond a niche market.
- Setting specific targets for micro-CHP installation, as has been done in the Netherlands, would stimulate both the industry and the market while supporting the overall emission-reduction targets and contributing to the greater legitimacy of the technology. The feed-in tariff introduced in 2010, if sufficiently strong and durable, may offer appropriate market stimulation.
- Support for installation training is an important part of system-building. Micro-CHP installation requires specific training and the current number of skilled installers is inadequate for widespread adoption. The efficient functioning of the technology that results from proper installation would further increase consumer and policymaker confidence in the technology.
- The formation of a micro-CHP specific trade organisation would focus and unite interests. The industry has proven to be resilient, having maintained a diverse foundation of knowledge and technology throughout fluctuating fortunes. Yet this strength is not effectively represented given the multiplicity of representative bodies.

4.2. *Analysis of the TIS framework*

The technology innovation systems (TIS) framework used here has enabled a comprehensive analysis of the multiple influences shaping the emergence of new technologies, the range of actors, networks and institutions involved, and the complex inter-dependencies between different parts of the system. The functional analysis typology has proven particularly useful in its ability to interrogate patterns of system growth, decline and resurgence since 1998. At the same time, the case provides insight on aspects of functional analysis which are problematic, or in need of further development. These are now briefly discussed.

Hekkert, Suurs, et al. (2007, 426) highlight the importance of particular ‘motors’ of system change and place particular emphasis on entrepreneurial activities in this regard.[8] In the present case, while entrepreneurial activities proved essential to sustaining the micro-CHP system, it alone proved insufficient for moving beyond a niche market to broader uptake. The case suggests that the impact of entrepreneurship on system development is heavily conditioned by other system functions and without wider system supports, may even cause setbacks to the overall development of the system. In the case of micro-CHP in the UK, entrepreneurship was associated with exaggerated statements of technological capabilities which ultimately led to a ‘hype–disappointment’ cycle (Borup et al. 2006; Verbong, Geels, and Raven 2008).

Another function whose role has been highlighted in TIS research literature is the creation of legitimacy (see especially Bergek, Jacobsson and Sandén 2008). The importance of legitimation processes in early system development was borne out in the present case. During the early 2000s, micro-CHP technology lost credibility among policymakers by failing to meet government and wider expectations raised by advocacy groups. The subsequent weakening of the legitimation function under conditions of reduced policymaker commitment can be linked to system weaknesses (e.g. lack of specific deployment targets) that had longlasting effects on development.

The overall point here is that while particular functions may assume greater importance in specific cases at certain times, emphasising the primacy of some functions (and inter-functional relationships) over others may detract from less obvious, but important functions and relationships. In the present case, the ability of the micro-CHP system to withstand the disappointments of the mid 2000s reflected important resilient system properties: an ability to draw on diverse resources for continued product development that allowed for a later re-emergence of system growth. Although less obvious and less observable engines of system development, knowledge development and resource mobilisation proved key sources of system resilience and regrowth.

The present case also informs two other wider themes in TIS analysis: the (under-developed) roles of the technology user, and the wider environment for system development. The role of the user (or consumer) tends to be under-articulated in TIS functional analysis. As Table 1 suggests, it is captured via legitimacy and market demand functions, but this role may go much wider for domestic technologies such as micro-CHP. Most TIS case studies of the energy sector reflect a longstanding bias toward supply-side interests in energy industries, with the end-user an essentially passive recipient of power or heating. (For example, consumer responses to micro-CHP are typically underplayed in market forecasts produced by the supply-side interests.) Reflecting this, the TIS functional typology can be also be seen as supply-side oriented: overall the functions emphasise a process of system growth stemming from producer interests, skills and resources. As radical energy system change in the future may well feature a more active end-user of energy (involving, for example, microgeneration and smart metering) there is a corresponding need to redesign analytical frameworks to allow for a rebalancing of production and consumption influences.

The underdeveloped role of consumption may be seen to reflect a broader problem of ‘myopia’ in TIS analysis, in terms of poor appreciation of system context and wider socio-economic conditions (Markard and Truffer 2008). A number of recent studies implicitly recognise this, in terms of an orientation to ‘endogenous’ above ‘exogenous’ dynamics (Hillman et al. 2008; Hekkert and Negro 2009), and a relatively underdeveloped appreciation of the interaction between internal and external processes (Geels, Hekkert, and Jacobsson 2008). Markard and Truffer offer a promising way forwards here, by suggesting an integration of the TIS framework with the multi-level transitions perspective (Markard and Truffer 2008).

Despite these suggested weaknesses – essentially areas for further conceptual and empirical development – the TIS framework provides a valuable tool for understanding the emergence of new technologies, especially in a context of system change and sustainable innovation in order to meet societal needs for climate change mitigation. There are many opportunities for further research here, such as comparative analysis of different microgeneration technologies, or cross national comparisons between systems with relatively low (such as the UK) and relatively high (such as Germany and Japan) performance characteristics.

5. Conclusions

Micro-CHP technology has an acknowledged potential to contribute significantly to the UK government’s Climate Change Strategy by reducing CO_2 emissions and improving energy security. The application of the TIS functional framework to the micro-CHP system in the UK revealed strengths and weakness within the emerging system and a study of inter-function relations enabled greater understanding of the dynamics of growth, decline and recovery in the development of the system over time.

The micro-CHP system has proven to be reasonably strong and resilient, having developed and maintained a diverse foundation of knowledge and technology despite fluctuations of growth and decline related to market formation and political legitimacy. At the same time, these strengths will not be able to move the technology beyond a niche market. The influence of micro-CHP advocacy groups arguably remains insufficient to overcome the low level of confidence among key policy and investment groups. A number of recommendations are presented here to overcome challenges, and to stimulate further micro-CHP development.

The TIS framework is an invaluable tool for assessing the development of emerging sustainable technologies, enabling the achievement of aggressive overall policy targets for the mitigation of climate change. The application of the framework here has provided useful insights into patterns of technology development and the wider processes of sustainable development.

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Notes

1. For a more extensive review, see Winskel et al. (2006).
2. Disenco is developing a unit that will provide up to 3 kW/h (kilowatt/hour) of electricity, diverging from the standard 1 kW/h design (Disenco 2007).
3. While system functions have been a core theme in the development of IS, the limitations of 'functionalism' have been recognised, in terms of assumptions of objectivity and separating the object of study from the social environment (Hekkert et al. 2007b, 428).
4. Although there have already been a significant number of micro-CHP units produced, particularly by Whispergen, these have been manufactured on a relatively small-scale basis. Manufacturers have now secured the means to mass-produce, which has been a condition of investment from companies such as E.on and British Gas that will market, service and sell the units. The ability to mass produce has therefore been a necessary precondition for wider market access. At least four different models are due to begin mass-production in 2009.
5. In the micro-CHP system, equipment suppliers (companies selling, supplying or leasing out micro-CHP units) are distinct from technology manufacturers.
6. An installation target of 10,000 micro-CHP units by 2009 has been established, with capital grants of €1000 per unit provided to help achieve this objective (Ministerie van Economische Zaken 2008).
7. This is not to suggest that patterns of 'hype-disappointment' have not also been experienced in efforts to promote low carbon technology innovation in the Netherlands (see Verbong, Geels and Raven 2008).
8. Other TIS case studies also emphasise the role of entrepreneurship as a primary motor of system development. For example, Hillman et al. (2008, 609) refer to entrepreneurial activities as 'crucial . . . prime mover'.

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