The story of a "Cinderella" technology: barriers to and lessons learned from the history and present state of CHP in the UK

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1 Introduction

Combined heat and power technologies, defined by their dual output of electrical energy and usable heat in the same process (Weber, 2014), have been available in the UK energy system for more than a century (Russell, 1993). Despite their potential advantages, particularly promises of improved energy generation efficiency, reduced costs of energy to both producers and end users and, in more current visions, improved sustainability (Foxon, 2013), the diffusion of CHP technologies remained relatively low observed at the level of the entire energy sector, even though high market shares were reached in specific niche markets. Multiple reasons have been identified by researchers for this somewhat subdued development: from political and policy processes tied to wavering interest by decision- and policymakers (Russell, 1986) over lacking capacities of key actors (Hawkey, 2014) to incompatibility with existing market structures (Toke and Fragaki, 2008). Through a combination of all these factors, a promising, "reasonable" technology was never implemented to its full potential, even though increased implementation did take place in other European countries with somewhat comparable geographical and socio-political characteristics (Raven and Verbong, 2007; Toke and Fragaki, 2008; Weber, 2014). Even though, at present, CHP is still considered to be a useful technological concept (RTP Engine Room, 2015), concerns are increasingly raised over its long-term viability in the face of tighter regulation and the rapid development of new energy technologies with even better efficiency and sustainability performance.

In this paper, the author draws on concepts from Transitions Studies research in order to provide an account of the development of cogeneration technologies in the UK context. Reviewing both the historical development of CHP and the current situation, the analytical constructs of niche, regime and (technological) innovation system are used to illustrate the actor networks and institutions related to the technology, and the functions and dynamics generated by and between them. The niche, regime and system concepts are brought together following a joint framework developed in previous research (Markard and Truffer, 2008) and conceptual and functional linkages recognised in later studies (Smith and Raven, 2012). By combining a historical study with a state-of-the-moment analysis, the author draws on multiple established traditions from Transitions Studies (Markard et al., 2012). The long-term historical observation of an ongoing transition process (Geels, 2002, 2006, 2007) connected with the application of a *multi-level perspective* is combined with a structural and functional analysis of a system in its current state, utilised in innovation systems approaches, particularly in the *technological innovation systems* approach (Negro et al., 2008; Praetorius et al., 2010; Hudson et al., 2011; Wirth and Markard, 2011).

The main aim of the author is to tell the story of UK CHP, combining historical lessons with insights into the current situation. Drawing on the history of Transitions Studies approaches being utilised as supporting instruments for policy-makers (Kemp et al., 2007; Bergek et al., 2008; Loorbach and Rotmans, 2010), a number for recommendations supportive for the future development and diffusion will be made. These recommendations will primarily be related to the different identified blocking mechanisms, ranging from internal, structural issues related to the CHP innovation system to external barriers generated by incumbent regimes i.e. their selection environment (Kemp et al., 1998). The rest of this paper is structured as follows: in Sections 2 and 3, the author will review the theoretical background of the joint framework utilised in this study, and present the framework itself. Section 4 introduces CHP in the UK as an empirical case. In Section 5 the identified internal structural issues and external barriers will be presented, and subsequently discussed in more depth in Section 6, combined with a number of recommendations to key actors and policymakers connected to CHP. Finally, Section 7 will include a summary of the key points of this paper, as well as a general conclusion.

2 Innovation *niches*, innovation *systems* and the role of barriers – a theoretical review

Drawing on insights from Transitions Studies (Markard et al., 2012) two related (Markard and Truffer, 2008) concepts were operationalised: the niche-regime relationship investigated in the multi-level perspective (Geels, 2002, 2005) and in the strategic niche management (SNM) approach (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012), and the technological innovation system concept (Hekkert et al., 2007; Bergek et al., 2008).

Both niche and system are defined as socio-technical constructs consisting of actors, networks and institutions, while regimes are the “deep structure” accounting for the stability of a socio-technical system. Consisting of sets of regulative, cognitive and normative rules related to a particular technological artefact or a set of technologies (Geels, 2004), regimes are continuously re-created by incumbent actor networks and supported by financial and infrastructural resources. Locked into a state of dynamic, self-replicating stability, they tend to facilitate incremental change at the expense of more radical transformations. Trajectories of incremental change in regimes extend beyond technologies, including cultural, political, industrial, scientific and market dimensions (Geels, 2011).

Existing on a lower level of aggregation compared to innovation systems and regimes (Markard and Truffer, 2008), niches act as “protective spaces” (Smith and Raven, 2012) in which radical innovations can develop outside of the selection environment generated by regime incumbents. In both the multi-level perspective and strategic niche management niches have the function of innovation incubators, once sufficiently developed, niche innovations and their supporting structures “break out” towards the incumbent regime, engaging in various strategies (Raven, 2007; Smith and Raven, 2012). Niche break-outs can lead to multiple potential transition pathways (Geels et al., 2016) depending on niche and regime stability as well as the influence of external factors, conceptualised in the form of the *landscape* (Markard and Truffer, 2008).

Niches fulfil a number of functions supporting the development of the focal innovation. On one hand, and in line with their original conceptualisation in SNM (Kemp et al., 1998), they act as protective spaces, providing both active and passive protection from the regime selection environment (Smith and Raven, 2012). With regard to the niche`s internal structure – actors, networks and supportive institutions – several types of nurturing functions are provided: assisting learning processes, in particular second-order learning (Schot and Rip, 1996), articulating expectations and supporting networking processes and the development of actor networks (Smith and Raven, 2012). Finally, a niche also empowers the focal innovation – depending on the nature of the innovation, and the strategy chosen by niche actors (Raven, 2007). Empowerment can be *fit and conform* empowerment, aiming to ensure the competitiveness of the innovation in the existing selection environment, or *stretch and transform* empowerment, where the aim is to partially or wholly change the regime itself (Smith and Raven, 2012; Verhees et al., 2013).

Technological innovation systems can be seen as somewhat related concepts, being defined as a set of actor networks and institutions interacting in a specific technological field, contributing to the generation, diffusion and utilization of the focal (technological) innovation (Markard and Truffer, 2008). From the analyst`s point of view, technological innovation systems can be evaluated through their structure and the functions they provide, the latter being related but not limited to the nurturing functions fulfilled by niches (Smith and Raven, 2012). Therefore, the results of a technological innovation system (TIS) evaluation are both a structural and a functional analysis (Hekkert et al., 2007; Bergek et al., 2008), providing the analyst with a good starting point for establishing the structural soundness and internal functionality of the observed system.

Both Strategic Niche Management and the TIS approach can be utilized to identify and describe barriers for the development of innovative technologies – while in the former barriers are defined as regime-generated selection pressures (Smith and Raven, 2012), in the latter barriers can be both system-internal and system-external, and can relate to structural shortcomings (Bergek et al., 2008; Hekkert et al., 2011), “system failures” (Klein Woolthuis et al., 2005) and internal and external obstacles to policy goals (Hekkert et al., 2011). In Strategic Niche Management, barriers are observed from a (mainly) bottom-up perspective (Schot and Geels, 2008), with niche functions providing protection (Smith and Raven, 2012) against barrier-related pressures as well as ways to engage or circumvent them (Raven, 2007; Smith and Raven, 2012). In TIS, on the other hand, barriers are considered from a policy point of view, their presence and influence shaping a challenge for policymakers that needs to be addressed at the meso-level (Hekkert et al., 2011).

3 Shaping the research framework – design and methodology

Drawing on the research strands discussed in the previous chapter, a number of analytical constructs were operationalised in order to reflect the empirical case investigated in this study. The authors used a joint framework approach (Markard and Truffer, 2008), combining a review of the CHP industry as a technological innovation system with a SNM-based observation of the case. In the latter, the focus shifted to a number of CHP niches existing within the innovation system and interacting with two incumbent regimes: the electricity regime and the heat regime, which in the UK context is mainly replaced by the gas regime. This joint framework approach was primarily utilized in order to provide to separate viewpoints for the analysis, which are also reflected in the data collection: a “high”, meso-level view of the entire CHP industry as a technological innovation system and a “low”, micro-level, bottom-up view from the perspective of individual CHP schemes respectively actors involved in them. It needs to be noted that “high” and “low”, in this context, are not used to designate any sort of order of observation, they are merely used to illustrate the two perspectives. Drawing on Smith and Raven (2012), this also enabled the actor to combine perceived strengths of the two combined research strands: the environment- and regime-oriented analytical approach of SNM/MLP with the focus on system-internal functions, or the “nurturing” function of niches, inherent to a TIS analysis (Bergek et al., 2008). This was followed by taking an SNM/MLP approach in order to review external, regime-generated barriers to CHP development and investigate inter-regime relationships, while drawing on TIS analytical steps in order to assess the internal structure and performance of the industry.

A qualitative-dominant case study approach has been adopted by the author for the purposes of this study, keeping in line with established research designs in Transitions Studies (Smith et al., 2014; Verhees et al., 2015). Qualitative data gathered from secondary data analysis as well as semi-structured case studies and interviews is utilised to describe and evaluate complex phenomena, while quantitative data such as energy statistics or industry databases is used to cross-check and validate initial conclusions. While the selection of the empirical case, e.g. CHP in the UK was to an extent mandated by the requirements of the broader research project within which this study was undertaken, the research was subsequently designed as a multiple-case embedded design case study (Yin, 2014), with the individual cases selected using an information-oriented maximum-variation approach (Flyvbjerg, 2006).

The two main data collection methods used in this study are semi-structured interviews (Kvale, 2007; Yin, 2014) and secondary data analysis including academic studies, industry publications, policy documents and thematically relevant “grey” literature (Bryman and Bell, 2015). A series of ten in-depth interviews with key actors from the CHP sector, representing industry, academia and the public sector was combined with 10 case studies representing various application settings for CHP technologies. While the key actor interviews were executed as qualitative in-depth interviews following a pre-defined guideline, data for the case studies was gathered from a combination of qualitative, guideline-based in-depth interviews, observational data gathered during site visits and secondary information provided by the case study partners. The gathered data was analysed through a thematic coding approach (Braun and Clarke, 2006), the codes being informed by previous Transitions Studies research and information gathered through secondary data. Wherever possible, triangulation using different data sources was used in order to ensure the veracity and robustness of findings.

4 Short overview of CHP technologies in the UK

Combined heat and power generation (CHP) can be defined as the simultaneous generation (co-generation) of heat, most often in the form of high-temperature steam, and electrical energy. CHP is regarded as a proven and mature technology, with the first applications being recorded around the turn of the 20th century, which might lead to significant decreases in emissions and fossil fuel use due to efficiency increases (Kelly and Pollitt, 2010).

Within this study, the term CHP is used to describe a concept, or a group of technologies rather than a single specific technology, following (Bergek et al., 2008) the term "knowledge field" will be used. The knowledge field in question is centred on the principle of simultaneous generation of electricity and usable heat (Weber, 2014) and includes multiple technologies whose main mode of operation follows that principle. In the UK, the majority of deployed CHP prime movers are either turbines or reciprocating engines using fossil-/carbon-based fuels (90% in 2015, 71% of which is natural gas), with only 10% of the total number of CHP schemes using renewable fuels. Policymakers distinguish between four main types of prime movers: steam turbines (back pressure and condensing), combined cycle systems, gas turbines and reciprocating engines (Department for Business, Energy and Industrial Strategy, 2016). Most future scenarios, as well as beliefs held by current actors place a stronger emphasis on the role of renewables for future developments (RTP Engine Room, 2015). Also, different, more radical prime mover units are considered: solar-thermal CHP fuel cells (Brown et al., 2007), Stirling and Rankine cycle engines (Cockroft and Kelly, 2006), bio-liquid engines (Ricardo-AEA, 2013) and even nuclear reactors (Carlsson et al., 2012).

The application areas for cogeneration technologies are equally varied and range from domestic, single-household schemes to large-scale industrial applications and schemes including settlement-wide heating networks (Russell, 1993; Hawkey, 2014). In practice, while CHP schemes can be found in many different settings, there is a number of key application areas in which energy systems based on cogeneration can be deployed. For the purpose of the research project on which this paper is based, and for an adequate reflection of the current situation, the following four main application areas were identified:

1) CHP in district heating networks
2) CHP in private single-site applications (ranging from large industrial to small commercial schemes)
3) CHP in public single-site applications
4) Domestic micro-generation CHP

Throughout the history of CHP development and deployment, the importance of these application areas for CHP proponents has varied. While CHP in district heating has a long history of research and application, and cogeneration as a principle was tied to the idea of heating networks for a long time (Russell, 1986, 1993; Hawkey, 2014), utilisation of CHP in small commercial and public schemes, as well as microgeneration CHP has a shorter history, being implemented only recently in larger number, although at high implementation rates (Department for Business, Energy and Industrial Strategy, 2016). The use of CHP in large-scale industrial schemes is another "traditional" application area, although one that has currently entered a state of stagnation due to both the general downturn of traditional manufacturing industries in the UK over the last several decades, and negative experiences by operators of large schemes following the implementation of the BETTA trading agreements (Pearson and Watson, 2012).

Actor visions and expectations related to the implementation of CHP technologies have also been varied, but usually reflected the dominant discourse at the landscape level. Over time this changed from a promise of affordable energy, and nationalisation of the energy sector, which were drivers in the interwar period and during the reconstruction efforts of the late 1940s and early 1950s (Russell, 1986), to a promise of fuel efficiency and cost reduction during the oil crises of the 1970s (Hawkey, 2014). In more recent times, following the increased importance of the environmental/sustainability discourse, the visions and expectations shifted from fuel efficiency for the sake of cost reduction and fuel safety to sustainability gains through efficiency. At the same time, regime-level changes in form of stricter emissions and building regulations allowed CHP to be utilised as a technological solution by developers.

Another important arena for the development of CHP, particularly CHP in district heating schemes, was the broader discussion about the role of the state in energy generation, as well as the allocation of powers between central government and local authorities (LA`s). For CHP district heating networks, LA`s have often taken the role of lead actors in development projects (Hawkey, 2012, 2014), however, in the earlier stages this role was often compromised by a lack of decision-making powers regarding the generation of energy, which was seen as part of the remit of central government. Over time, increased planning powers were granted to local authorities (Russell, 1993; Hawkey, 2014), however lack of control over finances and, in the current age of austerity, reduced public sector funding are still often inhibiting the development of CHP-DH schemes. One part of this arena also concerned the leading paradigm for the energy system: while the UK energy system operated as a decentralised system in its early days, a strong lock-in into a centralised system exists since the development of the National Grid and particularly since the nationalisation of the energy industry after the Second World War. While the energy system was privatised again in the late 1980s and early 1990s, this did not cause a further paradigm change: most of the energy system remained in the hand of a small number of large utility providers, the "Big Six".

The privatisation of the energy system and development of the capacity market did temporarily make large-scale industrial CHP schemes attractive for developers, however, the introduction of energy market regulation[1] (Pearson and Watson, 2012) quickly made these schemes unattractive, disrupting the return on investment periods and business models of the affected actors. These developments led to large industry actors shifting to more defensive strategies and asset protection, leading to the state of stagnation mentioned above. On the other side of the scheme size scale, smaller CHP schemes are utilised by actors aiming to fulfil planning and emission requirements, fulfil aims of sustainability strategies or benefit from resource efficiency improvements. For some schemes, public sector support such as for example the Renewable Heat Incentive (RHI) could be used, although proposed changes to subvention programs and a possibility of abrupt policy changes (Geels, 2014) led a number of actors to develop their schemes outside of the subvention programmes, attempting to make them viable in normal market conditions. Compared to other European countries, most smaller scale schemes were developed for on-site use of the generated energy, due to high entry barriers for smaller producers entering the capacity market (Toke and Fragaki, 2008).

[1] New Electricity Trading Arrangements (NETA), later changed name to British Electricity Trading Transmission Arrangements (BETTA)

5 Limiting factors for the development and diffusion of CHP in the UK: structural issues and external barriers

Following the presentation of the empirical case in the previous chapter, the authors will summarize the structural issues and external barriers influencing the development of CHP in the UK that were identified in the SNM evaluation and technological innovation system analysis. In line with (Bergek et al., 2008) the first set of limiting factors observed by the author will be the (internal) structural issues. They are directly related to weaknesses in the structure of the system (actors, networks, institutions) and have a negative effect on the fulfilment of the system`s functions (Hekkert et al., 2007).

The first major identified structural issue is the lack of a *shared vision* for the future of combined heat and power, together with articulated *expectations*. While, at times, there was a dominant vision (access to affordable energy, resource efficiency in times of resource shortage) the life-span of these visions, and their support by powerful actors was relatively short (Russell, 1993; Hawkey, 2014). It needs to be noted that the periods in which there was a shared vision coincided with upswings for CHP proponents, for example through the National Programmes for district heating (Hawkey, 2014). At the same time, during less successful periods the fragmentation of visions was also connected to a downturn in the availability of resources, and potential fragmentation of development trajectories. A fragmentation of visions is also visible in the present situation of CHP, with both interviewed experts and actors connected to case studies expressing several different, and sometimes conflicting, sets of expectations and visions regarding the future of CHP. These visions range from CHP taking a permanent role in a future energy system, over the use of CHP as a bridging technology to the phasing out of CHP in favour of zero-carbon energy generation, or in a less drastic scenario the phase-out of "conventional CHP" and retention/introduction of biofuel and fuel cell CHP. The current, fragmented situation is summarized in the following quote from one of the expert interviews:

"There are different visions and expectations – there is no single vision shared by a lot of actors, partly that's because CHP is quite unusual in the UK – there are different ways of analysing its impact on the energy system now and in the future; different assumptions could be made (…) Different actors therefore think about CHP in different ways, and draw different conclusions." (CHP researcher, UK University)

A second key issue, also relating both to the history of CHP and to its current state is the relative weakness of *actor networks* supporting the technology. While supporting networks have existed in the past, and several successful networks are operating presently, they are limited by both resource limitations and their spatial reach. For example, while there are successful local networks operating throughout the UK, the reach of these networks and the ability to transfer knowledge and support individual actors is mainly limited to their local areas. The national umbrella organisation for CHP, the Association for Decentralised Energy (ADE)[2], provides a high level of support for CHP actors within its own remits, but its impact is ultimately somewhat limited due to human and financial resource constraints. The relative weakness of networks is also connected to the lack of "champions" of CHP, as powerful actors (Avelino and Rotmans, 2009) could act as network coordinators, as well as providers of resources and knowledge, particularly tacit knowledge. CHP "champions" could also contribute to the shaping of shared visions, the lack of which is negatively affecting CHP development by acting as figureheads for these visions as well as using their political and social influence to support vision narratives.

The third identified internal issue are the effects of the dual institutional framework for electricity and heating (gas), with the CHP system structure partially aligned to both, reducing the possibilities for holistic developments. Both electricity and heating can be operationalised as regimes which are connected through the liberalised UK energy market (Toke and Fragaki, 2008; Pearson and Watson,

[2] Formerly known as the Combined Heat and Power Association (CHPA)

2012) and applicable EU regulations such as the Directive 2012/27/EU on energy efficiency or the Regulation on Energy Market Integrity and Transparency (REMIT). However, the lower-level regulatory frameworks (BETTA and the Unified Network Code for electricity and gas, respectively) are separate, as is the required infrastructure and the Distribution Network Operators (DNOs) managing the infrastructure. At this level, the internal issues start to manifest as lack of regulations and lack of infrastructure, both tied to the virtual absence of a dedicated heating regime. In the UK, more than 80% of heat users utilise gas from the national grid as the main fuel and heating source, leading to a virtual replacement of the heating regime with a gas regime. This consequently means there is a lack of regulations governing the trade of heat as a commodity, as well as a lack of infrastructure in the form of heat pipes. These two characteristics have a paralysing effect on heat developers – on one hand, there is not sufficient heating infrastructure available, even in urban areas, to utilise existing networks for the development of CHP-based heating schemes. On the other hand, the lack of regulations means that heat developers cannot use statutory powers to develop the needed infrastructure, having to rely on negotiations with various landowners instead. The following quote highlights the lack of a heat market, also reflecting on the effects of a lack of "champion" actors:

"There isn't really an institution or actor for the creation of local heat markets in the UK – this is important. Even though CHP is considered to be a transitions technology for DH, balancing the grid. A lot of these visions consider having widespread heat networks in cities, but the UK lacks institutional means to develop those networks as there are no actors with the capacity to assemble a large number of heat users." (CHP researcher, UK University)

This last internal issue is also connected with the existence of external barriers for the development of CHP technologies, which have been reviewed from a Strategic Niche Management point of view (Kemp et al., 1998; Smith and Raven, 2012). The barriers are part of a broader selection environment created by the dominant regimes, which themselves are partially integrated (Raven and Verbong, 2009), connected at the macro-level of policies as well as through the shared use of gas as a fuel source for electricity generation and the main fuel for heating while separate at lower level of organisation and regarding the utilised infrastructure. In the following paragraphs, the different barriers are discussed using a barrier typology proposed by (Smith and Raven, 2012).

The main external barrier to further development can be related to both *established industry structures* and *existing markets and dominant user practices* and is also closely tied to the dual regime framework discussed above. Across both regimes, powerful actors and policy-makers are committed to a centralised energy generation system, preferring development trajectories towards nuclear/all-electric or a biogas/hydrogen future. This is at odds with the decentralised nature of CHP, particularly when utilised in district heating networks, leading to decreased interest in cogeneration as a future technology despite the existence of scenarios proposing it as a possible solution (RTP Engine Room, 2015). Further, heat users in the UK are mainly focused on heat provision through the combination of household-level boilers connected to the national gas grid; this, together with increased maintenance demands of domestic CHP compared to conventional boilers serves as a significant limiting factor for the uptake of domestic CHP, illustrated in the following quote:

"I don't think domestic consumers will accept the level of... they won't accept high levels of maintenance, that's not what they want. They expect to get their boiler a quick once-over once a year and they have to run perfectly the rest of the time. Until there's a technology out there that can do the same for domestic CHP consistently and deliver the reliability, maintenance-free benefits of what the current boiler will, it will never ever trump the boiler." (CHP expert, industry)

Another barrier manifested from the dual regime framework is the lack of holistic energy policies including both energy and heat generation. Current policies are aimed either primarily towards energy generation or towards heat generation, effectively negating the efficiency increases that are the core advantage of CHP. CHP actors are therefore forced to choose one type of output as their primary focus

– either low-carbon or capacity agreements – where cogeneration technologies may be at a disadvantage compared to sustainable, single-output energy generation technologies. Further, there have been multiple instances of abrupt changes to policies in the energy sector (Russell, 1986; Geels, 2014; Smith et al., 2014), creating uncertainty for developers of large schemes whose return on investment periods can be prolonged and business models made unviable on relatively short notice. An example for the effects of abrupt policy change on a sub-sector of CHP can be seen in the following quote from an industry expert working for a specialized CHP company:

"And that's very much what happened in the biogas market this year, with CHP. Last year, we did loads of anaerobic digestion projects, absolutely lots of people were getting them in, left right and centre, set them up, alright, (…) tariffs. This year, not a single one. The whole market went from being just chaos to… boom, just literally boom the (…) out. I believe it was the RHI, I think they capped off or ROX, one of the others they capped off, and all the financial cases just immediately fell apart." (CHP expert, industry)

The disruptive effect of policy changes in the UK energy system is also caused by the centralized, top-down style of policymaking and policy implementation (Geels et al., 2016), leaving local actors with little ability or influence on centrally developed and implemented policies that might be damaging to local projects. This also means that changes in energy policy might be influenced by external contextual factors from the broader political process, which may not always be directly connected to the energy sector (Geels, 2014).

A strong barrier for CHP actors attempting to export generated electricity is created by the high entry barriers for small electricity producers joining the capacity market, further exacerbated by increasing resistance by regional Distribution Network Operators (DNOs) in the form of stringent licensing requirements and generation caps. While some of these issues have been partially of fully solved in other European countries (Toke and Fragaki, 2008), there is currently little activity in the CHP system or by regime actors to remove these barriers. The current *modus operandi* of CHP developers is to address the barriers on a case-by-case basis, which does create localised solutions but further increases exchange of knowledge issues as well as reduces network strength.

It is worth noting that most observed barriers are created at regime level through the action (or inaction) of regime actors, and that not all barriers are generated and upheld in order to create resistance towards CHP – rather, CHP technologies are very often neglected in policy-making processes, with negative effects a collateral of policy change rather than a result of deliberate action. However, at times direct resistance is also observable, either as overt action (as, for example, the increasing resistance of DNOs against CHP developers) or as covert, systematic neglect (Russell, 2010). At the level of end-users, little *cultural significance* is assigned to specific technologies, with the end users behaving in a stability-seeking, cost-optimizing way, preferring energy generation with as-low-as-possible, predictable costs and low procurement and maintenance costs. This is also reflected in the previously-discussed user practices, where ease of operation and low costs are seen as key factors in the slow uptake of domestic CHP. Further, negative experience with cogeneration might lead to instances of "negative learning" where users take a more negative stance towards CHP following bad experiences with the technology, even in cases when the cause of the bad experience was not directly the technology`s fault (Russell, 1993; Hawkey, 2014).

6 Discussion and recommendations to policy-makers

Throughout the history of CHP in the UK, various internal issues and external barriers had a significant impact on the development and diffusion of the technology, leading to CHP, particularly in application niches such as district heating networks or domestic micro-generation, being under-developed compared to other European countries (Weber, 2014). In the previous chapter, some of the key internal issues and external barriers were presented; in the following paragraphs, the authors will discuss them in more depth, drawing on theoretical insights from Transitions Studies.

Regarding the internal, structural issues it can be noted that a majority of these issues relate to the actors and actor networks supporting the technology: a lack of strong, powerful actors "champions", the relative weakness of networks, and a lack of shared visions and expectations. These structural issues have a direct negative impact on the fulfilment of several functions of the CHP system: effective *guidance of the search* is made less likely, having a negative effect on *knowledge development* and *knowledge exchange* in the sense that multiple different pathways are advocated for and explored rather than focusing in-depth on specific visions and outcomes. All three issues are interconnected and, to a degree, self-reinforcing – powerful actors supporting a technology often play a key role in developing and communicating visions (Raven, 2006), and can also act as coordinators and centrepieces of networks (Caniëls and Romijn, 2008), supporting network development. Networks can also be stabilised through shared expectations, which can create common arenas for actors to cooperate and exchange knowledge and resources – an example would be an international research project on CHP which was used as a case study, where multiple actors from different backgrounds were connected into a (temporary) network based on the expectation of development of specific technological solutions.

Another interesting perspective on the role of shared visions and expectations can be drawn from the history of CHP: while the technology can be considered fairly successful in specific application areas, most major visions for CHP were centred on its role in a decentralised system and/or district heating schemes, which was a particularly contested area with high regime resistance (Russell, 2010; Hawkey, 2014).

The structural issues connected to the dual institutional framework are somewhat more complex, concerning both internal system failures and manifestations of external barrier. For the former, a major issue is the non-existence of a heating regime, together with the partial integration of the gas regime taking its role and the electricity regime. From a niche actor perspective, the partial integration has a negative effect on niche development strategies of the *hybridisation* type, as well as on *fit-and-conform* empowerment, as increased alignment with one of the regime may result in de-alignment from the other regime, whose selection barriers may become more pronounced as a consequence. Further, on, the partially overlapping institutional frameworks force CHP actors to, effectively, choose one-half of their potential output, competing against technologies that may offer better performance in single-output mode. This is compounded by a lack of holistic policies, also resulting in a lack of resources available for both types of energy generation – both financial resources in the form of subventions and financing schemes, and infrastructure, particularly pipework required for heat provision in DH systems.

The dual framework and the presence of two regimes is also manifested in the external barriers: a strong incumbent lock-in into a centralised system means regime actors are slow in taking up CHP as a technological solution for a future energy system, or might even directly oppose its development (Russell, 1986, 1993). While resistance is not always directed specifically against cogeneration technology, the connections of CHP to decentralised energy systems make it hard, if not impossible for CHP supporters to remain neutral in the competition between the centralised and decentralised energy network paradigms. Policy and institutional changes in one of the regimes can have negative effects on the other regime, which might create additional barriers for CHP actors, who usually lack the representation and power necessary for successful lobbying activities (Avelino and Rotmans, 2009).

While most of the above could lead to a conclusion that the presence of two (or more) regimes is generally negative for a niche innovation, this doesn`t always have to be the case. The cases of CHP in the Netherlands (Raven and Verbong, 2007) and bioenergy in the Netherlands (Raven and Verbong,

2009) that multi-regime environments can create both barriers and opportunities, however, concerted, targeted action by government actors is important in solving the former. For CHP in the UK, supportive government action happened only rarely (Hawkey, 2014), consequently, existing barriers were not addressed while at the same time the lack of shared visions and powerful actors reduced the chance of successfully using existing opportunities.

Further, in the external barriers instances of direct resistance by regime actors can be noticed, most openly in the increasing resistance of DNOs to small generators as well as the rest of the entry barriers for small generators entering the capacity market. This can be characterised as "classic" barriers to innovations (Kemp et al., 1998) although the direct resistance by regime actors can also be attributed to the effects of political agency (Geels, 2014).

One final barrier/structural issue relevant for the current state of CHP is generated not by a strong, stable regime but due to a lack of it. While stable regimes are seen as potential issues for successful transitions, a weak or missing regime can have a similarly negative effect (Verbong et al., 2010). In the case of CHP, the lack of a heating regime where (usable) heat is traded as a commodity, respectively its replacement by the gas regime, results in the lack of an institutional framework within which heat-focused CHP actors could operate. One of the most important consequences of this is the lack of statutory powers for heat developers, who are thereby at a significant disadvantage compared to other utility providers. This can be seen as both an internal structural issue, as heat developers normally take the role of niche actors, and as an external barrier generated by the lack of a clearly defined regime framework.

While a number of recommendations for CHP proponents and policy-makers were developed in the course of the study, in the following the authors would like to focus on the key recommendations directly related to the above-mentioned structural issues and barriers:

1) Develop more holistic energy policies addressing and regulating multiple types of energy generation and provision instead of having a narrow focus on one specific type of energy. Considering the current state of UK energy policymaking (Geels et al., 2016), such policies need to be done at national level and subsequently translated "downwards" through the public government structure
2) Provide statutory powers to heat network developers based on the statutory powers available to energy and telecommunications developers. The main aim of these provisions should be to simplify and streamline the process of infrastructural development in the form of heat piping network and supporting structures.
3) Simplified access to the capacity market for small electricity generators (potential solutions have been tested in practice in the form of the "Licence lite" but would need a broader roll-out to be effective) and a simplified trading system allowing for greater flexibility in production outputs for small generators.
4) CHP actors should increase internal communication within the frame allowed by the available resources, and focus on shared messages and visions, strategically nominating lead actors "promise champions" (Van Lente and Rip, 1998) to carry these visions. These visions could draw on existing future scenarios (Foxon, 2013; RTP Engine Room, 2015) and should take the form of "future bids" (Geels and Smit, 2000) aligned with societally accepted broader energy visions, for example, the energy future of the UK

7 Conclusion

Combined heat and power technologies in the United Kingdom have had a long and sometimes turbulent history, never quite reaching the full potential of its promises (Russell, 1993; Weber, 2014) despite becoming a standard application in a number of sectors such as, for example, the chemical industry, the paper industry, hospitals or leisure centres. Over the last century, periods of strong expectations for CHP interchanged with periods of decline and lack of interest by government actors, with the latter often undoing any effects of the former. In order to highlight and discuss some of the main factors contributing to these developments, the authors drew of the Technological Innovation System (TIS) and Strategic Niche Management (SNM) approach from the broader field of Transitions Studies, operationalising the system, regime and niche concepts to represent the CHP industry, specific application areas for CHP and the electricity and gas (heating) regimes.

The results of the review show that even though multiple internal issues and external barriers have influenced CHP development and diffusion, the two main factors were an (internal) lack of strong actors, networks and shared, dominant visions and the connection of CHP to both the electricity regime and the gas (heating) regime. While the former limited the ability of CHP proponents to engage in lobbying activities, to develop momentum through clear, concise visions and expectations and to develop public legitimacy, the latter forced niche actors to engage in a continuous process of "boundary crossing" between regimes. As part of this process, actors had to reorient niche development strategies and empowerment activities towards one regime or the other depending on current regime dynamics and broader landscape pressures. Finally, the relative weakness of the heating regime, in particular related to the trading of usable heat as a commodity, meant that CHP proponents were lacking a functional institutional framework within which the heat-generating side of CHP could be developed.

Drawing on the review and the identified barriers, the authors have put forward a list of recommendations for CHP actors and policy-makers operating in the UK context. While these recommendations are case-specific, and might not be directly applicable elsewhere, the general insights provided by the analysis can be used to inform actors on transition pathways and policy-makers in other spatial and political settings.

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