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Low-carbon district heating in Sweden - Examining a successful energy transition

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Abstract

District heating (DH) systems may contribute to reducing the use of fossil fuels for heating purposes since they enable the use of waste heat and facilitate the use of renewable energy sources. This paper focuses on the transformation of the Swedish DH systems with regard to energy supply in 1960-2011. Swedish DH production was completely dependent on oil until the late 1970s, while today it is dominated by biomass and other renewable energy sources. The objectives of this paper are to describe and explain the fuel transition in the context of the main events that have characterised the development of the Swedish DH sector. For this purpose, we employ theories and approaches grounded in the literature on systems of innovations, especially the Multi-Level Perspective. The study shows that the transition involved a series of steps. Initiated by the oil crises in the 1970s the oil-based regime collapsed rapidly, while the growth of the biomass-based regime was a steered process governed by actors and supported only by external events. The lessons learned from the transition towards low-carbon and more sustainable DH systems in Sweden could be useful in the challenging task of steering future energy transitions in other countries and sectors.

Keywords: district heating, Sweden, energy transition, multi-level perspective, systems of innovations

1 Introduction

Fossil fuels such as oil and natural gas are the dominating energy sources for heating purposes in much of the world (IEA, 2011). This reliance on fossil fuels is not sustainable from the climate perspective, or with regard to security of supply. District heating (DH) systems may contribute to reducing the use of fossil fuels for heating purposes since they enable the use of waste heat, and may facilitate the use of renewable energy sources. DH involves the distribution of heat from one or several heat production plants to a number of consumers in a city or town through a network of pipes. Due to the scale involved in DH, these systems provide the opportunity to use unrefined biomass, deep geothermal heat, industrial waste heat and heat recovered from waste incineration. These systems also enable combined heat and power (CHP) production. DH systems may thus reduce the use of fossil fuels for heating purposes and contribute to energy efficiency of the energy systems. In future energy systems with large proportions of intermittent power, such as wind and solar power, the DH systems could also have the important task of balancing the power grid by accommodating excess power production (Lund et al., 2014).

DH systems are very common in European countries such as Finland, Germany, Denmark, the Baltic countries and Eastern Europe (Euroheat & Power, 2007), as well as in Russia and China (Werner, 2004). This paper focuses on Sweden, where DH systems can be found in essentially all municipalities, accounting for 57% of the energy supply for space heating and hot tap water in the residential and service sectors (SEA, 2013). Apart from the high penetration rate, the Swedish DH sector is an interesting case due the profound transformation it has gone through with regard to the sources of energy employed. Until the late 1970s, the sector was completely dependent on oil, while today biomass is the dominant energy source, accounting for 45% of the energy supply (SEA, 2013). This paper focuses on the transformation of the Swedish DH sector with regard to energy supply, a development that can be described as a low-carbon, sustainable energy transition, due to the societal benefits of breaking the dependence on fossil fuels in the heating sector.

The historic development of the Swedish DH sector has been addressed in previous research. The literature in this area mainly focuses on the introduction and expansion of DH networks, although changes in energy supply are also touched upon (see, for example, Werner, 1991 and 2007). These studies show that development has been shaped by a number of institutional factors, including strong municipalities and various national policies and regulations, but also other circumstances, such as the lack of alternatives such as natural

gas, which was not available in Sweden until 1985. Magnusson (2012) takes more recent developments as his starting point to argue that the Swedish DH sector is heading towards a stagnation phase due to decreasing heat loads and saturated markets. There are also a number of studies focusing on the local (political) processes behind the decision to build or expand DH systems in a particular municipality (e.g. Bohlin, 2004; Summerton, 1992; Palm, 2006).

In this paper we examine the development of the Swedish DH system at national level in the period from 1960 to 2011, with particular emphasis on the source of energy. The aim of this paper is twofold. The first is to describe the transition from oil to biomass and other renewable energy sources in the context of the main events that have characterised the development of the Swedish DH sector. The second is to explain this transition of energy supply. For this purpose we employ theories and approaches grounded in the literature on systems of innovations (Elzen et al., 2004) and, in particular, the Multi-Level Perspective (MLP), upon which much of the systems innovations literature is based (Geels, 2002, Rip and Kemp, 1998). The MLP is a flexible framework that can be applied to analyse transitions interpreted as encompassing economic, technological, institutional and socio-cultural domains (Wieczorek and Berkhout, 2006). Our study is based primarily on empirical material drawing upon scientific literature, government official reports and bills, reports from relevant Swedish government agencies, official statistics and five interviews with actors currently or previously involved in the Swedish DH systems. The interviews focused mainly on the early period of this study (1960-1980), for which less documentation was available. The interviewees included two CEOs (one retired) of two fuel procurement companies, one retired employee at Sydkraft (now E.ON), one professor emeritus at Lund University and a communicator at the Swedish Bioenergy Association (SVEBIO).

The case of DH in Sweden is a rare example of a successful transition from fossil fuels to renewable energy sources. In many countries this type of transition is viewed as a societal goal in sectors as diverse as transport, electricity generation, heating and cooling, and agriculture. However, experiences associated with this type of transition are often characterized by barriers, problems and failure. This study originates from the assumption that previous transitions may provide knowledge on the processes and dynamics involved in system transitions (Fouquet and Pearson, 2012) that may be relevant in initiating or steering future transitions (Wieczorek and Berkhout, 2009). Understanding how a transition pathway may unfold is vital in the challenging task of steering future transitions, and studies of

successful cases of innovation and transition can contribute to the field of energy studies (Sovacool, 2014).

In Section 2 we illustrate the analytical framework employed in this study and the theoretical basis upon which it was developed, i.e. the MLP of transitions. Section 3 describes major developments in the DH system in Sweden between 1960 and 2011, identifying three key periods: (i) expansion of DH systems fuelled by oil (1960-1972); (ii) the oil crises and fuel diversification (1973-1989); and (iii) the increasing dominance of biomass (1990-2011). In Section 4, we analyse the process and dynamics of the transition focusing on two periods of substantial/extensive change: regime collapse and regime formation. The results of the analysis are discussed in Section 5, where the main conclusions of the study are also presented.

2 Systems of innovations and transition pathways

Academics have shown increasing interest in the dynamics of system transitions and innovations. An important approach in this respect is the MLP in which transitions are regarded as systems of innovations, i.e. as changes from one socio-technical system to another (Geels, 2005a). The concept of socio-technical systems emphasizes the interdependence and co-evolution of material and social structures (e.g. policies, technologies, markets) which over time evolve into a stable configuration that fulfils a societal function such as providing indoor heating, electricity or water (Fuenfschilling and Truffer, 2014). The structural components of socio-technical systems are: (i) material and technical artefacts, (ii) networks of actors and social groups, and (iii) institutions, or the formal, normative and cognitive rules that guide the activities of the actors (Geels, 2002). A key feature of the MLP is that transitions result from the interplay between dynamics at three levels: micro-, meso-, and macro-. At the meso-level, socio-technical *regimes* represent the dominant ways of fulfilling a societal function (Geels, 2004), including "engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures" (Geels, 2002). Socio-technical regimes are stable and their development is path-dependent due to mechanisms such as vested interests, organizational capital, sunk investments (in infrastructure, production lines, skills), stable beliefs, etc. (Geels, 2005a). At the micro-level, *niches* form the socio-technical environment where novelties emerge (Kemp et al., 2001, Schot, 1998). Finally, at the

macro-level the *landscape* includes all exogenous elements that affect the development of niches and regimes, but which are largely outside the influence of niche and regime actors (Geels, 2002, Geels and Schot, 2010). Landscape elements may not change, or change only slowly over time (e.g. change in climate), or may change very rapidly (e.g. oil price hikes) (Van Driel and Schot, 2005).

To analyse the transition from oil to renewable energy sources in the Swedish DH system, we employ an analytical approach based on the MLP. We consider oil-based DH as the socio-technical regime at the beginning of our analysis since oil combustion was the main (only) way of producing DH in Sweden throughout the 1960s and early 1970s (Fig. 1). To delineate the boundaries of the regime, we distinguish three dimensions: (i) the technological system composed of material and technical artefacts which enable the supply of energy feedstock and its transformation into district heat; (ii) the social system formed by networks of actors and social groups that carry out, or influence the process of feedstock supply and transformation into heat; and (iii) the institutional framework, which includes the formal, normative and cognitive rules that guide the activities of those actors. In this study only technologies and artefacts relevant for the supply of energy and its transformation into heat (shown in the dashed box in Fig. 1) are considered part of the technological system, while the distribution and consumption of DH is excluded. Consequently, only actors using or influencing the use of these technologies are considered part of the socio-technical regime. This approach is also used to define the boundaries of the socio-technical niches. In this paper niches are interpreted as socio-technical configurations which compete to diffuse in the DH system, even though some level of technical, social and/or institutional symbiosis should be expected in some instances.

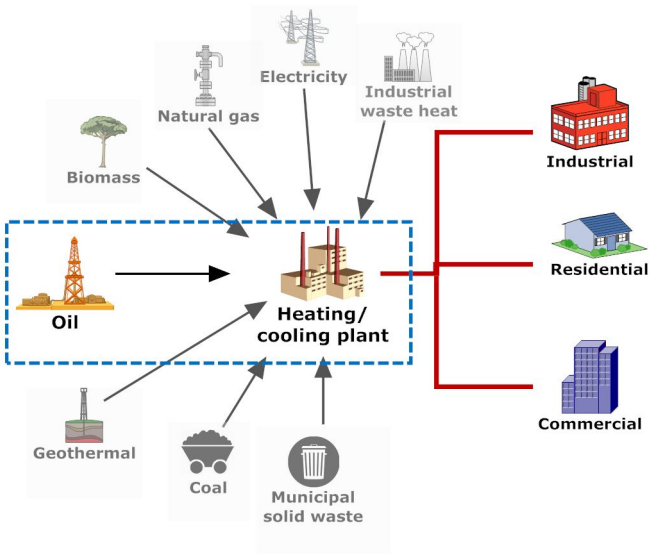

Figure 1. Technical components of the oil-based DH regime.

MLP studies have shown that socio-technical transitions come about when developments at all three levels link up and reinforce each other[1]. A typology of transition pathways based on the type and timing of multi-level interactions has been suggested by Geels and Schot (2007). The classical case is that of *substitution*, which occurs when landscape pressures create 'windows of opportunity' for niches that are sufficiently developed to exploit the opportunity, which then diffuse and eventually replace incumbent regimes (Berkhout et al., 2010, Geels, 2002). An alternative transition pathway is the *de-alignment/re-alignment* pathway, in which major landscape changes lead to critical and insurmountable problems in the regime. As a result, core actors abandon the regime, i.e. system de-alignment. This is followed by a period of uncertainty characterised by the co-existence of multiple niches, hybridization and widespread experimentation. Eventually, a dominant alternative emerges, which leads to the re-alignment of the system (Berkhout et al., 2010)[2]. The remaining two pathways, transformation and reconfiguration, are cases of failed or

[1] The MLP has been used to explain past (Geels, 2002, Geels, 2005b, Geels, 2006a, Geels, 2007) and contemporary transitions (Kern, 2012, Nakamura et al., 2013).

[2] The processes of de-alignment and re-alignment have received little attention in the MLP literature. Geels' (2005b) study of the transition from horse-drawn carriages to automobiles in the US is the reference case in the literature.

partial transition. *Transformations* are characterized by niches that are insufficiently developed to emerge (Berkhout et al., 2010, Geels, 2006a). In the *reconfiguration* pathway, although niches are more developed when the regime faces pressures, they are symbiotic and can be adopted by the regime as add-ons, leading to only a gradual reconfiguration of the system (Verbong and Geels, 2008, Geels, 2006b).

A key component of all four transition pathways is system destabilization caused by pressure on the incumbent regime. Pressure from the macro-level (the landscape) is often portrayed as the primary cause of destabilization. However, destabilization can be the product of different types of pressure originating, for example, from social or technical problems intrinsic to the regime, or from competition with emerging (niche) alternatives. Furthermore, pressure can be of economic nature (e.g. shrinking markets, changing markets, supply problems, competition from new entrants or new technologies, etc.), resulting in performance problems and decreasing financial resources, or of socio-political nature (e.g. changes in policy, public opinion, cultural discourse, social movement protests, etc.) affecting the legitimacy of the regime (Turnheim and Geels, 2013).

MLP scholars have interpreted the process of regime formation as a multi-level, multi-factor, multi-actor process. Kemp et al. (2001) suggest that regime formation is the result of dynamics within the system under analysis, i.e. within the emerging niche, and among the niches, the regime and the landscape. Niche internal processes have received attention in the literature of Strategic Niche Management (SNM) (Kemp et al., 2001, Kemp et al., 1998, Schot et al., 1994). SNM scholars have shown that experimental, pilot and demonstration projects are an important phase between RD&D and market diffusion for building social networks, learning about user preferences, technical design and infrastructure requirements, and for the articulation of expectations. Based on these lessons, SNM scholars suggest that only when niche development results in robust technologies, including improved price/performance ratios (Geels, 2005b), can niches enter mainstream markets and diffusion can occur (Geels and Raven, 2006). In recent years, systems interactions, i.e. interactions between the emerging niche and actors, resources, processes and events within other systems, have also attracted the attention of MLP scholars (see Papachristos et al., 2013; Raven, 2007; Konrad at al., 2008). However, these interactions are less understood and conceptualized.

In this study we seek to understand the process of regime formation in the Swedish DH sector by considering three types of dynamics: niche internal processes, interactions within the system under analysis, and interactions between the emerging niche and other systems.

3 Development of the Swedish district heating sector, 1960 - 2011

This section illustrates the development of the Swedish DH sector from 1960 to 2011, broken down into three time periods. For each period we illustrate landscape, regime and niche elements with particular attention on technologies and artefacts, actors and networks, and institutions (including official policies, values and beliefs). Although our key interest is the transition between energy supply systems (Fig. 2), we cover a wide range of events that affected the development of the Swedish DH sector in the period under analysis.

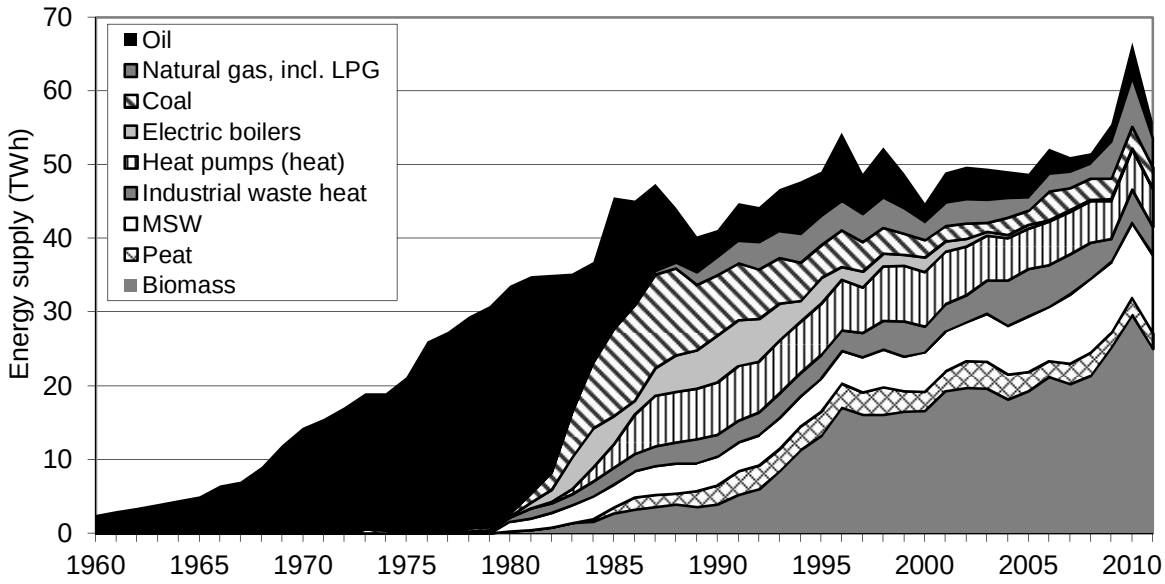

Figure 2: Energy supply in Swedish DH production, 1960-2011. The energy supply that can be attributed to electricity production in CHP plants is not included. 1960-1969: approximations from SDHA (2001); 1970-2010 from SEA (2012); 2011 from SEA (2013). Sharp annual variations are caused by variations in the outdoor temperature between years. For example, the winter of 2010 was unusually cold in Sweden.

3.1 Expanding district heating systems fuelled by oil (1960 - 1972)

In the 1950s, all the major Swedish towns started to build DH systems, for example, Malmö (1951), Gothenburg and Stockholm (1953) (Werner, 1991), following the example of Karlstad, where the first publicly owned DH system was taken into operation in 1948

(Werner, 1991)[3]. The initiative to build DH systems came from the municipalities, i.e. the local authorities, who were also responsible for DH utilities. The main reason for municipalities to build DH systems in the 1950s and 60s was to enable efficient electricity production in CHP plants (Werner, 1991). With the steady increase in electricity consumption, additional thermal electricity production was considered a necessary and competitive complement to hydropower. Until the mid-1960s, Swedish electricity production consisted almost entirely of hydropower, which was believed could not be expanded sufficiently to meet future increases in electricity demand. The first DH systems were thus built in towns with steam power stations that served as reserve resources and during peak loading, which were retrofitted for the cogeneration of electricity and district heat (Werner, 1991). These municipal initiatives were supported by The Heat Utility Association (*Värmeverksföreningen*), which was established in 1949 by 16 municipal energy utilities. The Association, which later changed its name to the Swedish District Heating Association (*Svensk fjärrvärme*), provided a forum for members to exchange information and discuss technical issues, becoming a key actor in the promotion of DH in Sweden (Borglund et al., 1999). The DH utilities continued to be managed by the local authorities until the 1970s, when many were transformed into municipally owned companies that could act more freely and with less political control (Andersson and Werner, 2005).

The growing interest among municipalities to build DH systems, and CHP plants in particular, raised opposition from Vattenfall, the state-owned power company, who saw this development as a potential threat to future nuclear power. During the 1960s, Vattenfall thus offered several large municipal energy utilities long-term power purchase contracts with substantially lowered electricity prices in order to discourage the building of CHP plants (Werner, 1991).

Nevertheless, Swedish DH systems expanded rapidly in the 1960s and 70s, coinciding with a period with a high rate of housing construction following the adoption of the Million Homes Programme (*Miljonprogrammet*). The Million Homes Programme was launched in order to address a severe shortage of housing in Sweden, and the goal was to build 1 million dwellings between 1965 and 1974 (Hall and Vidén, 2005). This was an impressive goal

[3] Before 1948, only a few small, non-public systems that distributed heat to a hospital or a small group of multi-dwelling buildings were in operation.

considering that the Swedish housing stock at the time was barely three million dwellings. The Programme provided the municipalities an opportunity to coordinate the building of these new residential areas with that of the DH networks. As a result of the building and expansion of the DH systems that replaced local heat boilers, urban air quality improved in many Swedish towns during the 1960s and 70s (Werner, 1991).

Although some of the first DH plants used coal during the 1950s (Werner, 1991), oil rapidly emerged as the dominant energy source during the 1960s, and was thus established as the new regime within the DH system. Oil was economically attractive since real oil prices in Sweden had been falling steadily since the Second World War (Wickman, 1988). After the Second World War, Sweden experienced rapid economic development, and the use of energy increased, especially oil and electricity. By 1970, oil accounted for 77% of the national energy supply, nearly all of which was imported from the Middle East (SEA, 2013). In spite of sporadic concerns in political circles about the effects of the increasing dependence on Middle Eastern oil on energy security, the basic trend of increasing electricity and oil consumption was not affected (Bergman, 2001). An important landscape element during this period was the rapid development of the international oil market, which made oil and oil products widely available at low prices also in Sweden (Bergman, 2001). The trend of falling oil prices continued until 1973 (Wickman, 1988).

3.2 The oil crises and fuel diversification (1973 - 1989)

The belief in a sustained supply of cheap imported oil was abruptly crushed as a result of the shocking increases in the price of oil in the 1970s, which constituted important landscape elements during this period. Following political events in the Middle East, international oil prices increased sharply in 1973-74, with the real price of heavy fuel oil in Sweden tripling between 1972 and 1977 (Wickman, 1988). The first oil crisis highlighted Sweden's heavy dependence on imported oil, and brought energy into the national political arena (Kaijser, 2001). In response to the crisis, Sweden adopted its first energy policy in 1975, and energy security became the overall policy objective (Government, 1975). The two main policy strategies adopted to achieve energy security were energy conservation and the replacement of oil with indigenous energy resources[4], imported coal and nuclear power. The urgency of

[4] Sweden has considerable biomass and peat resources. Sweden also has large reserves of low-grade uranium, which have not been exploited, and very limited coal deposits (Hambraeus and Stillesjö, 1977).

reducing Sweden's oil consumption was confirmed by the second oil crisis in 1978-79, which led to a doubling of the real prices of light and heavy fuel oil from an already high level (Wickman, 1988).

One of the reactions of the Swedish Government to the oil crises was the increased funding of energy research, development and demonstration (RD&D) (Haegermark, 2001). The first three-year Energy Research Programme was launched in 1975, covering both energy conservation and a number of alternatives to oil, including coal, as well as renewable energy sources. In the aftermath of the second oil crisis more emphasis was placed on sustainable and renewable energy sources, especially solar heat, wind power and biomass (Haegermark, 2001). Key areas within bioenergy RD&D included fuels from forestry residues, short-rotation forestry, fuel refinement and conversion technology (SOU 2007:36). The increased funding of bioenergy RD&D indicates that bioenergy was now viewed as a viable source of energy, in spite of previous concerns regarding limited resources and competing uses in the forest industry (SOU 2007:36).

After the oil crises, DH was no longer just a local concern, but also a prioritized area in national energy policy. An example of this is the introduction of government subsidies for the replacement of oil boilers with DH (Wickman, 1988). The government also emphasized the role of the municipalities as implementers of national energy policy when it adopted a law in 1977 that required them to develop energy plans to address energy efficiency and energy security at local level (SFS 1977:437). The law was supplemented in 1980 with the requirement to formulate specific oil reduction plans. DH systems continued to expand rapidly in the 1970s and 80s, partly as a result of these subsidies and policies (Carlsson, 1992; SEA, 2008).

As a result of the insecurity of supply and price volatility generated by the oil crises, a number of DH companies started to coordinate their purchase of imported oil. In 1973, five municipal energy utilities in the Stockholm area created EFO (*Ekonomisk föreningen för oljeanskaffning*), a joint non-profit fuel procurement company. According to Ryk[5] the purpose of EFO was to reduce costs and secure the supply of low-sulphur oil, of which EFO became the largest purchaser in Europe. In Southern Sweden the purchase of fuel was

[5] CEO at EFO AB, Stockholm, personal communication, 2013-11-21.

coordinated (although less formally), according to Lenander [6], through *Sydsvenska Bränslegruppen* (the fuel group of southern Sweden).

The oil crises spurred municipal energy companies to look for, and gradually switch to, alternatives to oil in DH production. The alternatives developed in niches, and included traditional fuels such as coal, wood fuels and peat, but also new energy sources such as municipal solid waste (MSW), heat pumps, electric boilers and industrial waste heat (Fig. 2). The town of Helsingborg became a pioneer in the use of industrial waste heat when it signed a contract in 1974 with the chemical company Boliden, for the purchase of industrial waste heat (Bohlin, 2004). Similar arrangements were soon initiated in several municipalities hosting process industries.

MSW was introduced into DH production during the 1970s as a growing number of municipalities built waste incineration plants with heat recovery[7]. Initially, investments in such plants were mainly driven by constraints on space for landfilling, but eventually the opportunity to reduce oil consumption became another strong motive (RVF, 2005). The incineration of MSW with heat recovery in a DH system provided a solution to two municipal functions: DH and waste management.

Biomass and peat were also introduced in DH production during this period. Among the first DH plants built for wood chips were the plants in Mora in 1978 and Enköping in 1979 (Andersson, 2012). The first large conversion of a CHP plant to biomass took place in Växjö in 1980. Another pioneer was Borås, which started to co-fire coal and biomass in 1984 (Jacobsson, 2008). The introduction of biomass was facilitated by investment subsidies and soft loans, which were available from 1975 and during much of the 1980s, for the construction of demonstration plants burning solid fuels (SOU 2007:36, pp. 218-19). The use of solid fuels, or rather fuel flexibility, was further promoted through the Solid Fuel Act (SFS 1981:599), which required new boilers over a certain size to be able to burn solid fuels, and smaller boilers to be easily adapted to solid fuels. The foundation of the Swedish Bioenergy Association (SVEBIO) in 1980 promoted the commercialisation of biomass.

[6] Former CEO of United Fuels, the fuel procurement agency that replaced Sydsvenska bränslegruppen, personal communication, 2014-01-17.

[7] The first large waste incineration plants with heat recovery for DH systems were built in 1970 in Stockholm and Umeå (RVF, 2005).

According to Andersson[8], SVEBIO was initiated by a group of students and researchers at the Royal Institute of Technology in Stockholm, and immediately became a broad network of equipment suppliers, as well as actors within biomass production, refinement and end-use, for example, municipal energy companies. The use of biomass slowly increased in the 1980s, and in 1989 accounted for 9% of the DH production (SEA, 2013).

During the 1980s a number of municipalities built coal-fired DH or CHP plants. Although many planned coal-fired plants were never realized due, for example, to concerns over air quality and expensive emission control equipment, imported coal became the primary substitute for oil (Bardouille, 2001). The use of coal peaked in 1986-87, when it accounted for about 30% of the energy supply in DH production (SEA, 2013). However, interest in CHP production decreased in the 1980s due to low electricity prices. These low prices were the result of the rapid expansion of nuclear power that took place during 1973-1985, when 12 reactors were taken into operation. The DH sector became instead a net consumer of electricity through the installation of electric boilers and large-scale heat pumps utilising surface water or wastewater. In 1989, electric boilers and heat pumps accounted for 30% of the DH production (SEA, 2013).

Natural gas was not introduced in Sweden until 1985, when a natural gas grid was opened in the south-west coast of the country. Some DH companies in this area started to use natural gas, but its contribution to total DH production remained fairly modest. Towards the end of the 1980s, oil also constituted a fairly modest contribution to DH production. The reliance on oil in DH production gradually declined after the first oil crisis, and continued to do so during the 1980s, in spite of decreasing oil prices. The share of oil decreased from 100% in 1973 to 12% in 1989, when it was mainly used for peak load production (SEA, 2013).

3.3 Growing dominance of biomass (1990 - 2011)

Up until the late 1980s, environmental concerns related to energy mainly involved local and regional air pollutants, nuclear safety and local impacts associated with the exploitation of rivers for hydropower. Climate change did not emerged on the political agenda in Sweden, or internationally, until the late 1980s, and since then has been an important landscape element. Sweden adopted its first climate target in 1988, which aimed at the immediate

[8] Communicator at the Swedish Bioenergy Association (SVEBIO), personal communication, 2013-11-29.

stabilisation of carbon dioxide emissions (Government, 1987). Growing awareness of climate change made the issue a new important factor in Swedish energy policy. With the adoption of a major energy bill in 1991 (Government, 1990), the development of sustainable energy systems became an overall objective of Swedish energy policy, in addition to a secure and competitive energy supply. Furthermore, in 1988 a parliamentary decision was made to start phasing out nuclear power in 1995[9]. This decision was reviewed in 1991 when the phase-out was made contingent upon the availability of electricity from other sources. As a result, the development of electricity from renewable sources, including biomass, became a political priority.

A carbon tax was introduced as part of a major energy tax reform in 1991 to reduce the emission of greenhouse gases. The tax was first set at 25 EUR/tonne CO_2, and was increased in 1994 to 36.5 EUR/tonne CO_2[10]. Biomass and peat were exempt from this tax[11]. The energy tax reform immediately almost doubled the price of coal and made biomass the most competitive fuel for heat production (Fig. 3). The use of biomass in DH production quadrupled between 1990 and 1996 when it reached 17 TWh (Fig. 2) (SEA, 2013). Despite less favourable taxation within the electricity sector, the use of biomass also increased for electricity production in the DH systems (Fig. 4). This development was promoted through two governmental investment schemes (1991-1996 and 1997-2002) supporting the construction of new biomass-fired CHP plants, and initially also the retrofitting of fossil-fired CHP plants for the use of biomass (Ministry of Trade and Industry, 2000).

[9] The parliamentary decision was made shortly after the Chernobyl accident in 1988, but was also motivated by the 1980 referendum in which the Swedish electorate voted for the long-term phasing out of nuclear power.
[10] This amount is based on an exchange rate of 1 EUR=10 SEK.
[11] Fossil fuels used in heat production were subject to taxes on carbon, sulphur and energy, while biomass was exempt from these taxes and only sulphur tax was levied on peat. Fuels used in electricity production, including the fuel fraction used for electricity production in CHP plants, were not taxed, but the consumption of electricity was taxed instead.

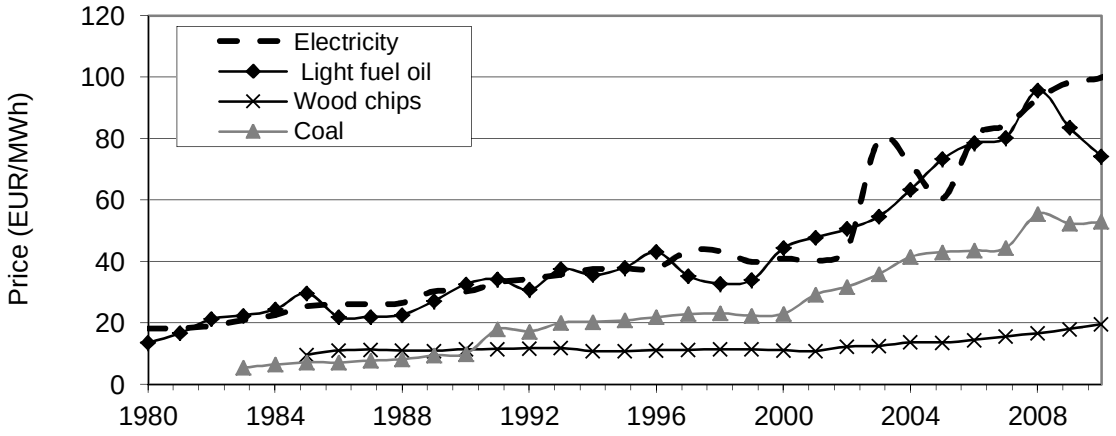

Figure 3: Nominal fuel and electricity prices, including taxes, paid by Swedish DH producers in 1980-2010. The fuel prices after 2004 refer to fuels used in heat production only, since fuels used in CHP production were taxed differently after 2004 (SEA, 2009; SEA, 2013).

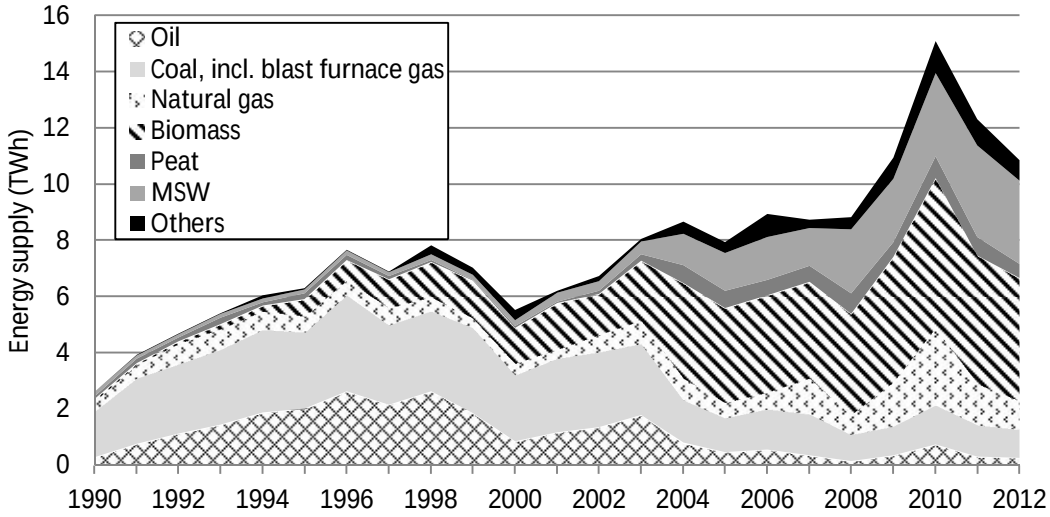

Figure 4: Energy supply for electricity production in CHP plants in Swedish DH systems in 1990-2012 (SCB, 2014).

Biomass expanded largely at the expense of coal, the use of which in DH production decreased considerably during the 1990s. The biomass consisted mainly of wood fuels such as wood chips, wood pellets and waste wood, but tall oil, a by-product of pulp production, was also used. Many DH utilities were able to switch to wood fuels with only minor adjustments to their existing infrastructure for burning coal. The switch to wood fuels was either complete or involved coal co-firing, depending on the coal burner technology installed and the plant's ability to receive and store wood fuels. Co-firing of wood pellets became an attractive initial strategy for large CHP plants with powder burners (Mahapatra et al., 2007).

However, although some DH companies became involved in wood fuel production (for example Stockholm Energi[12]), most of them procured wood fuels through external wood fuel companies. These were, and many still are, subsidiaries of forest industry companies, which have traditionally been key actors on the Swedish wood fuel market since they control much of the biomass flow as users and producers of wood and wood by-products. Several DH companies also started to import wood fuels during the early 1990s. Large DH plants along the coast, in particular, were able to diversify their wood fuel supply through imports. Imports primarily comprised various wood fuels from the Baltic countries, wood pellets from Canada, and waste wood from Germany and the Netherlands. The import of wood fuel in the DH sector was estimated to be equivalent to 3-4 TWh/y in 1995 (Vinterbäck and Hillring, 2000) and 5 TWh/y in 2000 (Ericsson and Nilsson, 2004).

The Swedish electricity market was reformed in 1996. As a consequence of this, the principle of cost-based pricing that had previously governed municipal energy companies was removed in order not to distort competition with private electricity companies. Municipal energy companies were instead required to operate in a business-like fashion (Westin and Lagergren, 2002). Partly due to these new circumstances and partly due to financial problems, a considerable number of municipalities decided to sell their energy companies (including their DH systems) during the 1990s and early 2000s. The buyers were large national (and international) energy companies such as Vattenfall, E.ON and Fortum, which in 2004 together accounted for 39% of the DH supplied in terms of energy (Andersson and Werner, 2005).

DH networks and the supply of district heat continued to expand during the 1990s and 2000s, although at a declining growth rate. With much of the primary market for DH already covered, the expansion during this period involved the building of small-scale DH systems and the expansion of existing systems into areas with lower heating density, a development that, to some extent, was promoted by investment grants. Between 1998 and 2002 municipalities could receive financial support for DH expansion from the Local Investment Programmes, a government-funded subsidy scheme (SEPA, 2004). DH was also promoted through investment grants that were available to households in 2006-2010, and targeted the

[12] When Stockholm Energi started to use wood pellets in its CHP plant in Hässelby in 1992, it also engaged in a joint venture with two sawmills that involved the building of a production plant for wood pellets in Härnösand (Olerup, 2000).

replacement of individual oil boilers in the residential sector with DH, heat pumps or biofuels (Boverket, 2008). In 2011, DH supplied 57% of heating to residential and commercial buildings (SEA, 2013).

The late 1990s and early 2000s witnessed an intensified phase of climate policy development. Central to this development was the adoption of Sweden's climate strategy, which included ambitious short- and long-term climate targets (Government, 2001). In line with these stringent climate ambitions, the general carbon tax was sharply increased during the early 2000s, reaching 91 EUR/tonne CO_2 in 2004. However, at the same time separate treatment was introduced for CHP plants, which became subject to a lower carbon tax. After 2008, the carbon tax was gradually phased out for CHP plants that were part of the EU emission trading system (ETS), which was launched in 2005. In spite of the reduction and phasing out of the carbon tax for CHP plants, biomass remained the preferred fuel in these plants, i.e. the use of coal did not increase. However, the use of natural gas increased in CHP production, mainly through the building of two natural-gas-fired CHP plants in Malmö and Gothenburg. An important factor for the maintained viability of biomass-based CHP was the introduction of a scheme for Tradable Renewable Electricity Certificates (TRECs) in 2003. The scheme requires electricity suppliers to purchase TRECs corresponding to a certain proportion (legislated quota) of their supply, while producers of electricity from renewable energy sources (including biomass) are eligible for TRECs on the basis of their production volumes. On the whole, the use of biomass in DH production increased from 17 TWh in 2000 to 25 TWh in 2011, when biomass accounted for 45% of the energy supply (SEA, 2013).

In spite of the growing dominance of biomass, the DH energy supply remained highly diversified in this period. Peat, industrial waste heat, natural gas and heat pumps continued to make fairly stable contributions to DH production, although their shares decreased[13]. In contrast, the use of oil decreased considerably throughout the 2000s, accounting for only 4% of DH production in 2011, while electric boilers were largely phased out by the end of the 1990s (SEA, 2013). Another important development was the considerable increase in the contribution from incineration of MSW in DH production after 2000. Motivated by waste

[13] Peat was often co-fired with wood fuels since it could reduce problems associated with ash sintering and corrosion in the boiler caused by alkali metals in the wood fuels (Steenari and Lindqvist, 1999).

management legislation, in combination with the energy and carbon taxes, several municipalities invested in incineration plants with heat recovery. In 2011 MSW accounted for 11 TWh (19%) of the energy supply in DH production (SEA, 2013).

4 Analysis of the transition and its pathways

During the past six decades the Swedish DH system has experienced significant changes regarding the source of energy supply. The transition from oil to renewable energy sources was characterized by two periods of intense change (Fig. 5). The first period corresponds roughly to the years from 1973 to 1989 when oil went from being the uncontested source of DH (with nearly 100% of the market) to being one of several sources (its share falling to only 12%). Within this short period of time, a number of niches expanded in the DH market, but none achieved a dominant position. The second period of significant change began in the early 1990s; within a period of roughly two decades, one energy source, biomass, acquired a dominant position, while all the other niches apart from MSW lost market shares.

Based on the development described above, the case of DH in Sweden is an instance of an energy transition from fossil fuels to renewable energy sources and, in particular, an example of the de/re-alignment transition pathway suggested by Geels and Schot (2007). In the MLP literature, the de/re-alignment pathway is described as being composed of two periods. In the first period (system de-alignment or opening up), external landscape elements generate high pressure on the system, which results in the collapse of the incumbent regime. In the second period (re-alignment or narrowing down), one niche becomes dominant in a system characterized by a large variety of alternatives, which leads to major restructuring of the whole socio-technical system. In the following subsections, we illustrate the development of these two sub-processes in the case of DH in Sweden, and seek to understand their development using knowledge from the literature on systems of innovations.

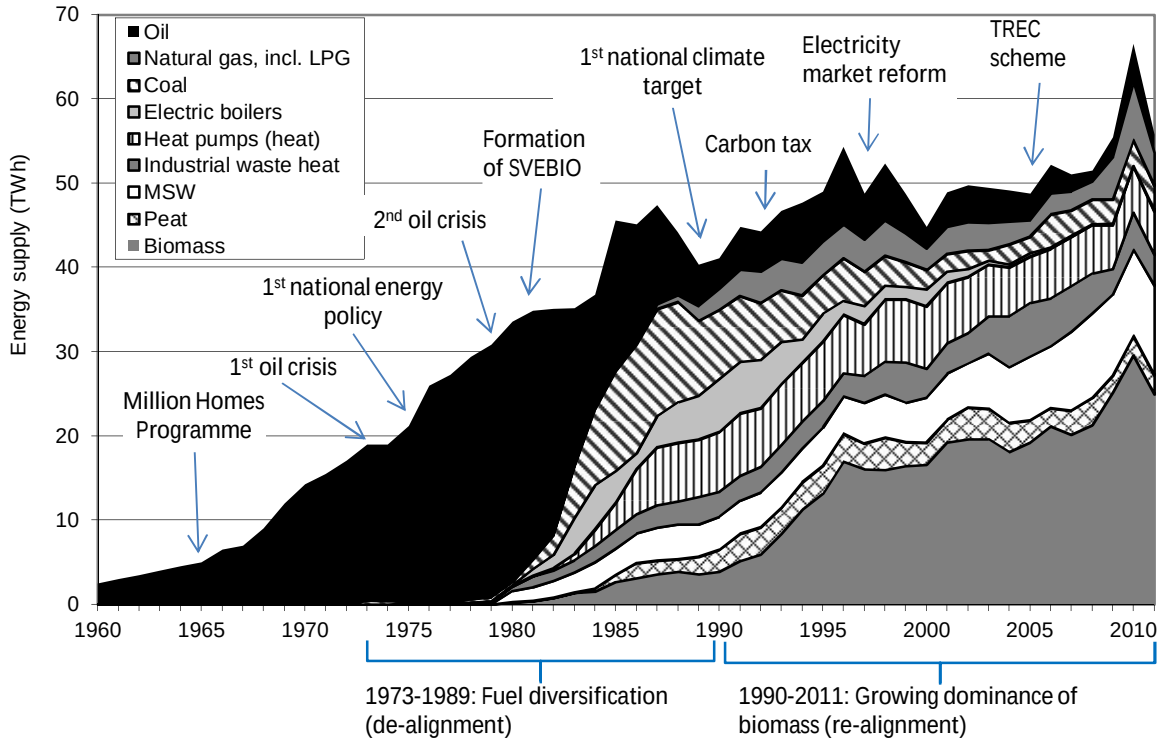

Figure 5: Energy supply in Swedish DH production from 1960 to 2011 (see also Fig. 1) and major events affecting the DH sector during this period.

4.1 Regime collapse

Starting from the first oil crisis in 1973-74, the oil-based DH regime collapsed within a period of slightly more than one decade. When observed in relation to the literature on transition pathways, this process appears to be an empirical case of system de-alignment (Geels and Schot, 2007). De-alignment can be seen as an instance of the more general process of regime destabilization, which has recently been suggested to involve a three-step process (Turnheim and Geels, 2013).

(i) *Accumulation of pressures on the regime* – In the present case, the oil-based DH regime was subject to high external pressure originating at macro-level (landscape). The first oil crisis was sudden and powerful enough to create both economic and socio-political pressure on municipal energy companies and utilities responsible for (oil-based) DH systems. Socio-political pressure created changes in public opinion and policy discourse which translated into policy support for alternative energy sources through subsidies and RD&D programmes. Economic pressure grew in terms of (in)security of oil supplies and high market prices. Both these types of pressure led to performance problems for DH utilities.

(ii) *The response of regime actors to performance problems* – DH utilities started experiencing performance problems already in 1973-74, during the first oil crisis. The first response of DH utilities to performance problems was to initiate a search for alternative heat sources (among old and new fuels) in order to reduce their reliance on oil. However, very small quantities of oil (1-2%) were replaced during the first oil crisis. Simultaneously, DH utilities began to coordinate their purchase of oil to obtain more favourable market prices and to improve the security of supply. The creation of EFO (a joint non-profit oil procurement company) is an example of such collaboration.

(iii) *Gradual weakening of the commitment of core actors to the established regime due to further pressure and performance problems* [14] – The second oil crisis in 1978-79 significantly increased external pressures on the oil regime, creating growing economic and socio-political performance problems. As a result, DH utilities intensified their search for alternative sources of heat, and the rate of replacement of oil in DH production increased considerably. The oil regime lost its dominant position in the DH system within a period of 10 years, falling from nearly 100% to 12% of the market. Technological, social and institutional features of the DH system account for the rapidity of this process. Firstly, several alternatives to oil that did not require major technical breakthroughs were available, e.g., coal, industrial waste heat and MSW. Secondly, core actors such as DH utilities did not suffer major losses associated with sunk investments by abandoning oil, since the existing oil-fired boilers could often be kept in use for peak load production in the expanding DH systems. Furthermore, since the DH utilities were managed or under the control of local authorities, their business decisions were highly influenced by political concerns about the affordability of the heating service[15]. Thirdly, between 1975 and 1980 the national government strongly supported a reduction in oil consumption by introducing public subsidies to promote the use of solid fuels such as coal, biomass and peat in demonstration plants, and by

[14] Because of lock-in mechanisms, actors will initially defend existing regime elements. However, if the pressure becomes overwhelming a destabilization process will take place, resulting in full destabilization, which may lead to a shift to a new regime (Turnheim and Geels, 2013).

[15] Municipal DH utilities/companies operated by law on a cost-recovery basis until 1996 (Westin and Lagergren, 2002).

requiring local authorities to adopt local energy plans with strategies for reducing oil consumption.

The collapse of the oil regime was a rapid and incremental process initiated and largely driven by external (landscape) elements. Core actors such as DH utilities, municipalities, the Swedish District Heating Association and the Swedish Government acted as facilitators during the process. The specific features of the regime collapse, or system de-alignment, appear to be largely determined by the socio-technical and economic features of the oil-based DH regime.

4.2 Regime formation

As discussed in Section 3.3, the biomass niche expanded considerably from the beginning of the 1990s, and can be interpreted as a socio-technical regime in the making due to its dominant and rising position in the DH system. Based on the literature on transition pathways, this process is a clear example of system re-alignment (Geels and Schot, 2007). The process of re-alignment can be interpreted as an instance of regime formation. As discussed in Section 2, MLP scholars have suggested that the process of regime formation is affected by dynamics internal to the emerging niche and dynamics that develop in connection with the external environment. In the case of DH, both internal and external processes have been at play in the development of the biomass regime.

Internal dynamics of the emerging niche – The development of a biomass regime in the DH sector started with the formation of the biomass niche in the years around 1980, when biomass was first used in DH production. In the aftermath of the oil crises, the Swedish Government began funding large RD&D programmes on bioenergy, which indicates a change in the perception of biomass as a potentially important source of energy. The programmes provided opportunities for learning with regard to technical design and infrastructure requirements, and facilitated the creation of visions and expectations. Moreover, learning and knowledge dissemination were facilitated by the networks around SVEBIO, the Swedish bioenergy association that was founded in 1980. Furthermore, in this very early stage, a number of municipalities (e.g. Växjö and Enköping) took an important step by investing in a biomass-fired CHP plant, a strategy that was consistent with local ideas concerning sustainable development and a long-term economic perspective. In this way, these experiences generated early knowledge about commercial applications, and contributed to the articulation of visions for the future of biomass in DH. The more rapid

development towards a biomass regime was initiated by the introduction of the carbon tax, a major institutional change, in 1991. Drawing on the experience and knowledge on bioenergy that was generated during the 1980s, the DH sector was able to carry out a massive fuel shift towards biomass in response to the changes in relative fuel prices.

DH internal dynamics – The development of the biomass niche was also influenced by interactions with other energy niches within the DH system. Evidence of positive interactions can be seen in the cases of coal, oil and peat. The use of coal supported biomass diffusion since coal was perceived as environmentally damaging and technically replaceable simply by co-firing biomass in coal-fired plants. Similarly, small oil-fired plants could switch to biomass fuels in the form of tall oil. In the case of peat, the biomass niche benefitted from the possibility of co-firing with peat to reduce problems associated with corrosion of the boiler caused by the wood fuels. However, there is also evidence of negative interactions with other niches, primarily due to competition for market space. In particular, incineration became a mainstream way of handling MSW in the 1990s and 2000s, thus, offering DH companies a secure and cost competitive source of heat supply. Similarly, in municipalities with large process industries, industrial waste heat offered a secure and cost competitive form of heat supply for DH. However, the size of these niches is constrained by the limited availability of local resources.

Landscape dynamics – External processes at landscape level were characterized by pressure from two major elements, the oil crises and the imperative of climate change mitigation. Although the oil crises occurred in the 1970s, their effects were still evident in this period. In addition to the legacy of the oil crises, the climate issue emerged as an influential landscape element in Sweden towards the end of the 1980s, and has remained so. Climate change and the need to reduce the emission of greenhouse gases became key considerations in national energy policy and local sustainability initiatives. Both these landscape elements supported the diffusion of biomass-based DH since biomass was largely perceived as a secure and carbon-neutral source of energy.

System dynamics – Dynamics between the emerging niche and other socio-technical systems consisted primarily of intense interactions with the forestry sector and the electricity sector. Interactions with the forest sector gave significant support to the expansion of the niche in two major ways. Before biomass was introduced in the DH sector, forestry companies already used their wood by-products to meet their own energy demand, thus providing knowledge and improving the performance of biomass combustion processes and

technologies. At a later stage, forestry companies contributed to the expansion of the biomass niche by supplying large amounts of wood fuels to the DH sector at competitive prices. In contrast, interactions with the electricity sector did not affect the biomass niche in a straightforward way. The low electricity prices that characterized the Swedish market until the early 2000s constrained CHP production from biomass and other fuels, and promoted the use of electricity in DH production (e.g. through heat pumps and electric boilers). However, the higher electricity prices since the early 2000s and, more importantly, the policy instruments promoting electricity production from renewable sources, especially the TREC scheme, stimulated the expansion of biomass-based CHP production in DH.

The (ongoing) process of regime formation, which has led to the emergence of the current biomass-based DH regime, spans a period of more than 30 years. The process was initiated and primarily driven by core actors, both at local and national level, while landscape elements have played a more limited role compared to the process of regime collapse. Finally, interactions among niches within the DH system and with other socio-technical systems, such as the forestry and electricity sectors, have also played an important role influencing the dynamics of regime formation.

5 Discussion and conclusions

This study has shown that the transition process from an oil-based DH system to a system based primarily on biomass and other renewable energy sources involved a series of steps. The destabilization of the oil-based system started as early as 1973 with the first oil crisis, and accelerated as a result of the second oil crisis. The process of energy diversification lasted over a decade, and by 1989 the share of oil had fallen by 90%. The rapid unlocking of the oil-based system was facilitated by the technical, social and institutional features of the system. However, after the collapse of the oil-based regime, the DH system was characterized by widespread experimentation and the co-existence of multiple niches, among which coal was the largest, accounting for 22% of the energy supply by DH in 1989. In the following decades the biomass niche expanded steadily due to improvements in the price/performance ratio compared with electricity, gas, coal and oil. Improvements were a consequence of technical advances (concerning the harvesting and supply of wood fuels, combustion technology, etc.) and, most importantly, favourable public policies such as the introduction of a carbon tax in 1991 and the TREC scheme in 2003.

Interpreted as a series of steps, the energy transition in the Swedish DH system is a clear example of the de-alignment/re-alignment transition pathway introduced by the MLP. In the present case, the rapid process of system *de-alignment* was initiated by external (landscape) elements. Although the oil-based DH system appeared stable and locked-in, our analysis shows that stabilizing mechanisms (technical, social and institutional) were not sufficient to contain the impacts of the oil crises. System actors such as DH utilities, local authorities and the Swedish Government became engaged in the destabilization process only in reaction to the oil crises. Three key sets of factors characterize the de-alignment process: landscape elements, the governance of public and private actors, and the specific socio-technical features of the oil regime. The process of *re-alignment* was of a different nature since it was not initiated by landscape elements, but by the initiatives of private and public actors. The active engagement of actors such as local authorities, DH utilities, SVEBIO, the Swedish District Heating Association and the national government, started and steered the re-alignment process. In agreement with the most recent MLP literature, our analysis suggests that both niche internal processes and interactions between the emerging niche and external elements were important factors in the formation of a low-carbon, sustainable DH system in Sweden.

The application of the MLP, with its central concepts (regimes, niches and landscape) and focus on multi-level dynamics, provided a comprehensive view of the energy transition that occurred in the Swedish DH system over the past six decades. The MLP approach has thus contributed to fulfilling the aim of this study. However, the MLP also presented some challenges, in particular, with regard to the operationalisation and specification of the concept of socio-technical regimes, which can be defined at different empirical levels. For example, within the area of DH, the regime could be studied at the level of primary fuel (coal, oil, gas), or at the level of the entire system (production, distribution and consumption of heat) (see Berkhout et al., 2004). Consequently, what appears to be a regime shift, i.e. a transition, at one level, may be viewed merely as an incremental change in inputs for a wider regime at another level (Geels, 2011). In this study we operationalised the concept of socio-technical regimes in accordance with the aim of the study and the specific features of DH systems (see Fig. 1). Another challenge emerging from the application of the MLP is the definition and delimitation of landscape elements, which risk becoming a “garbage can”, or residual analytical category (Geels, 2011). One approach employed in this study was

to identify landscape elements in agreement with the classifications of van Drier and Schot (2005), but to consider only elements that show substantially unidirectional interaction with the system under analysis. Therefore, the oil crises and climate change are, for example, classified as landscape elements (unidirectional influence), while the forestry and electricity sectors are interpreted as other socio-technical systems (bidirectional influence).

In conclusion, this study demonstrates that DH systems can be facilitators of socio-technical energy transitions. In the heating sector they offer technical opportunities for actors to steer the system along a more sustainable path, as was done in Sweden. There are several countries where DH could play a similar role, and where the opportunities offered by DH systems in terms of primary energy savings and integration of renewable and low-grade energy sources have not been fully exploited. For example, modelling studies of Europe suggest that there is an opportunity to expand DH in many European cities and thus replace individual fossil fuel fired boilers in urban areas (Persson and Werner, 2011; Connolly et al., 2014). Another example is China, which on the other hand, has large DH systems in the north of the country (several times the size of the Swedish systems). These systems are, however, completely dependent on coal (Draugelis & Li 2012), and contribute to the alarming levels of air pollution in urban areas throughout the region. An energy transition in these systems would bring substantial benefits to both human health and the environment.

The Swedish DH systems have experienced a major transformation towards greater sustainability during the past decades. This transformation is likely to continue and become integrated in the overall transition of the energy system. Energy transitions in other sectors are, for example, likely to increase competition for biomass. With a growing demand for renewable transportation fuels in the future, it can be envisaged that increasing volumes of biomass will be used in biorefineries that co-produce transportation fuels and, for example chemicals, electricity and heat. The growing competition for biomass may lead to lower direct use of biomass in DH production. On the other hand, DH systems could accommodate waste heat from these biorefineries. Another possible future development of the DH sector is integration with the power sector. In a future energy system with large volumes of intermittent power sources, the DH systems could provide flexible electricity demand through the use of large-scale heat pumps and electric boilers, whereby accommodating excess electricity.

The transition of the Swedish DH sector has involved a growing use of biomass, a limited resource that is less available in many other countries. Other countries may, on the other hand, have better access to low-grade heat sources and other renewable sources such as geothermal and solar energy. Hence, despite various national differences the lessons learned from the transition towards a low-carbon and more sustainable DH system in Sweden could be useful in the challenging task of steering future energy transitions.

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List of references

Andersson, K., 2012. Bioenergy - The Swedish Experience. How bioenergy became the largest energy source in Sweden. Svebio, Stockholm.

Andersson, S., Werner, S., 2005. Fjärrvärme i Sverige 2003 - en analys av att råvarukostnader, ägande, jämställdhet, priser och lönsamhet i svenska fjärrvärmeföretag, Fjärrvärmebyrån, Västerås.

Bardouille, P., 2001. A Framework for Sustainable Strategic Energy Company Investment Analysis & Decision-Support: Towards the Operationalisation of Sustainable Energy Systems, Environmental and Energy System Studies, Lund University, Lund.

Bergman, L., 2001. The economics of Swedish energy policy, in: Silveira, S. (Ed.), Building sustainable energy systems - Swedish experiences. Bulls Tryckeriaktiebolag, Halmstad, pp. 131-159.

Berkhout, F., Smith, A., Stirling, A., 2004. Socio-technological Regimes and Transition Contexts, in: Elzen, B., Geels, F.W., Green, K. (Eds.), System Innovation and the Transition to Sustainability - Theory, Evidence and Policy. Elgar, Cheltenham.

Berkhout, F., Verbong, G., Wieczorek, A.J., Raven, R., Lebel, L., Bai, X., 2010. Sustainability experiments in Asia: innovations shaping alternative development pathways? Environmental Science & Policy, 13, 261-271.

Bohlin, H., 2004. Att välja energisystem - Processer, aktörer och samverkan i Helsingborg och Gävle 1945-1983 [Choosing Energy System - Processes, Actors and Collaboration in Helsingborg and Gävle 1945-1983], Department of Technology and Social Change, Linköping University, Linköping.

Borglund, A.S., Näslund, A., Sabel, H., 1999. En sprakande historia. Svenska fjärrvärmeföreningens service AB.

Boverket, 2008. Mindre olja, bättre miljö - men till vilket pris [Less oil, better environment - but at what price], Dnr: 1399-2235/ 2008, The National Board of Housing, Building and Planning, Karlskrona.

Carlsson, L.-G., 1992. Energianvändning i bostäder och servicelokaler 1970-1990 - en jämförelse av verklig utveckling, energiprognos och energisparmål under 1980-talet [Energy use in dwellings and non-residential premises 1997-1998], R30:1992, Byggforskningsrådet [Building Research Council], Stockholm.

Connolly, D., Lund, H., Mathiesen, B.V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P.A., Nielsen, S., 2014. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy, 65, 475-489.

Draugelis, G., Li, S.F., 2012. District Heating Reform. World Bank, Washington DC.

Elzen, B., Geels, F.W., Green, K., 2004. System innovation and the transition to sustainability : theory, evidence and policy. Edward Elgar, Cheltenham.

Ericsson, K., Nilsson, L.J., 2004. International biofuel trade-A study of the Swedish import. Biomass and Bioenergy, 26, 205-220.

Euroheat & Power, 2007. District heating and cooling - Country by country 2007 survey, Brussels, Belgium.

Fouquet, R., Pearson, P.J., 2012. Past and prospective energy transitions: insights from history. Energy Policy, 50, 1-7.

Fuenfschilling, L., Truffer, B., 2014. The structuration of socio-technical regimes—Conceptual foundations from institutional theory. Research Policy, 43, 772-791.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy, 31, 1257-1274.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy, 33, 897-920.

Geels, F.W., 2005a. Technological transitions and system innovations: a co-evolutionary and socio-technical analysis. Edward Elgar, Cheltenham.

Geels, F.W., 2005b. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). Technology Analysis & Strategic Management, 17, 445-476.

Geels, F.W., 2006a. The hygienic transition from cesspools to sewer systems (1840–1930): the dynamics of regime transformation. Research Policy, 35, 1069-1082.

Geels, F.W., 2006b. Major system change through stepwise reconfiguration: a multi-level analysis of the transformation of American factory production (1850–1930). Technology in Society, 28, 445-476.

Geels, F.W., 2007. Analysing the breakthrough of rock ‘n’roll (1930–1970) Multi-regime interaction and reconfiguration in the multi-level perspective. Technological Forecasting and Social Change, 74, 1411-1431.

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions, 1, 24-40.

Geels, F.W., Raven, R., 2006. Non-linearity and expectations in niche-development trajectories: ups and downs in Dutch biogas development (1973–2003). Technology Analysis & Strategic Management, 18, 375-392.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy, 36, 399-417.

Geels, F.W., Schot, J.W., 2010. A multi-level perspective on transitions, in: Grin, J., Rotmans, J., Schot, J.W. (Eds.), Transitions to sustainable development: new directions in the study of long term transformative change. Routledge, New York.

Government, 1975. Regeringens proposition om energihushållning m.m (1975:30), Stockholm.

Government, 1987. Regeringens proposition 1987/88: 85 om miljöpolitiken inför 1990-talet, Stockholm.

Government, 1990. Regeringens proposition 1990/91:88 om energipolitiken, Stockholm.

Government, 2001. Sveriges klimatstrategi (Regeringens proposition 2001/02:55), Stockholm.

Haegermark, H., 2001. Priorities of energy research in Sweden, in: Silveira, S. (Ed.), Building sustainable energy systems - Swedish experiences. Bulls Tryckeriaktiebolag, Halmstad, pp. 163-195.

Hall, T., Vidén, S., 2005. The Million Homes Programme: a review of the great Swedish planning project. Planning Perspectives, 20, 301-328.

Hambraeus, G., Stillesjö, S., 1977. Perspectives on Energy in Sweden. Annual Review of Energy, 2, 417-451.

IEA, 2011. Cogeneration and Renewables - Solutions for a Low Carbon Energy Future, OECD/IEA, Paris.

Jacobsson, S., 2008. The emergence and troubled growth of a 'biopower' innovation system in Sweden. Energy Policy, 36, 1491-1491.

Kaijser, A., 2001. From the stoves to nuclear plants - the history of Swedish energy systems, in: Silveira, S. (Ed.), Building sustainable energy systems, Stockholm, pp. 57-93.

Kemp, R., Rip, A., Schot, J., 2001. Constructing transition paths through the management of niches, in: Garud, R., Karnoe, P. (Eds.), R. Garud, P. Karnoe. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 269–299.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. Technology Analysis & Strategic Management, 10, 175-198.

Kern, F., 2012. The discursive politics of governing transitions towards sustainability: the UK Carbon Trust. International Journal of Sustainable Development, 15, 90.

Konrad, K., Truffer, B., Voß, J.-P., 2008. Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors. Journal of Cleaner Production, 16, 1190-1202.

Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al., 2014. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy, 68, 1-11.

Magnusson, D., 2012. Swedish district heating—A system in stagnation: Current and future trends in the district heating sector. Energy Policy, 48, 449-459.

Mahapatra, K., Gustavsson, L., Madlener, R., 2007. Bioenergy Innovations: The Case of Wood Pellet Systems in Sweden. Technology Analysis & Strategic Management, 19, 99-125.

Ministry of Trade and Industry, 2000. Electricity production from renewable energy sources - economic conditions and market mechanisms (In Swedish) Ds 2000:20, Stockholm.

Nakamura, H., Kajikawa, Y., Suzuki, S., 2013. Multi-level perspectives with technology readiness measures for aviation innovation. Sustainability Science, 8, 87-101.

Olerup, B., 2000. Scale and Scope in Municipal Energy Planning in Sweden. Journal of Environmental Planning and Management, 43, 205-220.

Palm, J., 2006. Development of sustainable energy systems in Swedish municipalities: A matter of path dependency and power relations. Local Environment, 11, 445-457.

Papachristos, G., Sofianos, A., Adamides, E., 2013. System Interactions in Sociotechnical Transitions: Extending the Multi-Level Perspective. Environmental Innovation and Societal Transitions, 7, 53– 69.

Persson U, Werner S., 2011. Heat distribution and the future competitiveness of district heating. Applied Energy, 88, 568-76.

Raven, R., 2007. Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls. Energy Policy, 35, 2390-2400.

Rip, A., Kemp, R.P.M., 1998. Technological Change, in: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change. Battelle Press, Columbus, pp. 327-399.

RVF, 2005. Avfall blir värme och el - en rapport om avfallsförbränning, RVF 2005:02, Svenska Renhållningsverksföreningen, Malmö.

SCB, 2014. Statistikdatabasen, Årlig energistatistik (el, gas och fjärrvärme), Bränsleförbrukning för produktion av ånga och hetvatten i Sverige efter produktionsslag och bränsletyp. År 1990 - 2012.

Schot, J., 1998. The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century. History and Technology, an International Journal, 14, 173-200.

Schot, J., Hoogma, R., Elzen, B., 1994. Strategies for shifting technological systems: the case of the automobile system. Futures, 26, 1060-1076.

SDHA, 2001. Fjärrvärme 2000; fakta och statistik, Swedish District Heating Association, Stockholm.

SEA, 2008. Heating statistics (unpublished), Received from Linn Stengård (Swedish Energy Agency) in November 2008.

SEA, 2009. Facts and figures - Energy in Sweden 2009 ET2009:29, Swedish Energy Agency, Eskilstuna.

SEA, 2012. Energy in Sweden - Facts and figures 2012 ET 2012: 34, The Swedish Energy Agency, Eskilstuna.

SEA, 2013. Facts and figures - Energy in Sweden 2013, ET 2013:22, Swedish Energy Agency, Eskilstuna.

SEPA, 2004. A better environment with district heating and small-scale district heating - An evaluation of LIP financed district heating and small-scale district heating projects (in Swedish), Report no. 5372, Environmental Protection Agency, Stockholm.

SFS 1977:437, Lagen om kommunal energiplanering [Law on Municipal Energy Planning], Swedish Parliament, Stockholm.

SFS 1981:599, Lag om utförande av eldningsanläggningar för fastbränsle (avslutad i SFS 1994:793) [Act for design of heating plants for solid fuels (terminated in SFS 1994:793)], Swedish Parliament, Stockholm.

SOU 2007:36, 2007. Bioenergi från jordbruket - en växande resurs, Statens offentliga utredningar, betänkande av Utredningen om jordbruket som bioenergiproducent, Stockholm.

Sovacool B. K., 2014. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda, Energy Research & Social Science, 1, 1-29.

Steenari, B.M., Lindqvist, O., 1999. Fly ash characteristics in co-combustion of wood with coal, oil or peat. Fuel, 78, 479-488.

Summerton, J., 1992. District Heating Comes to Town - the Social Shaping of an Energy System, Doctoral thesis, Department of Technology and Social Change, Linköping University, Linköping.

Turnheim, B., Geels, F.W., 2013. The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). Research Policy, 42, 10, 1749–1767.

Van Driel, H., Schot, J., 2005. Radical innovation as a multilevel process: introducing floating grain elevators in the port of Rotterdam. Technology and Culture, 46, 51-76.

Verbong, G., Geels, F., 2008. Pathways for sustainability transitions in the electricity sector: multi-level analysis and empirical illustration. IEEE Xplore, Rotterdam.

Vinterbäck, J., Hillring, B., 2000. Development of European Wood-fuel trade. Holzforschung & Holzverwertung. Vienna.

Werner, S., 1991. District heating in Sweden 1948-1990. Fernwärme International, 20, 603-616.

Werner, S., 2004. District Heating and Cooling, in: Cleveland, C.J. (Ed.), Encyclopaedia of Energy. Elsevier, pp. 841-848.

Werner, S., 2007. Low carbon district heat in Sweden. Euroheat & Power - English edition 4, 20-25.

Westin, P., Lagergren, F., 2002. Re-regulating district heating in Sweden. Energy Policy, 30, 583-596.

Wickman, K., 1988. The energy market and energy policy in Sweden 1965–1984. Energy, 13, 83-96.

Wieczorek, A.J., Berkhout, F., 2006. Progress in industrial transformation, IHDP Newsletter, vol. 1.

Wieczorek, A.J., Berkhout, F., 2009. Transitions to Sustainability as Societal Innovations, in: Boersema, J.J., Reijnders, L. (Eds.), Principles of Environmental Sciences. Springer Netherlands, pp. 503-512.