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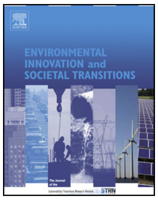

The role of lock-in mechanisms in transition processes: The case of energy for road transport

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ABSTRACT

This paper revisits the theoretical concepts of lock-in mechanisms to analyse transition processes in energy production and road transportation in the Nordic countries, focussing on three technology platforms: advanced biofuels, e-mobility and hydrogen and fuel cell electrical vehicles. The paper is based on a comparative analysis of case studies.

The main lock-in mechanisms analysed are learning effects, economies of scale, economies of scope, network externalities, informational increasing returns, technological interrelatedness, collective action, institutional learning effects and the differentiation of power.

We show that very different path dependencies have been reinforced by the lock-in mechanisms. Hence, the characteristics of existing regimes set the preconditions for the development of new transition pathways. The incumbent socio-technical regime is not just fossil-based, but may also include mature niches specialised in the exploitation of renewable sources. This implies a need to distinguish between lock-in mechanisms favouring the old fossil-based regime, well-established (mature) renewable energy niches, or new pathways.

1. Introduction

The concept of lock-in has been extensively used to explain the persistence of fossil fuel-based technological systems despite the fact that their well-known environmental externalities contribute to climate change. Moreover, this ‘carbon lock-in’ inhibits the diffusion and adoption of carbon-saving technologies (Frantzeskaki and Loorbach, 2010; Unruh, 2000).

Lock-in can be defined as positive feedbacks or increasing returns to the adoption of a selected technology (Arthur, 1994b; Unruh, 2000, 2002). As a result, incumbent technologies have a distinct advantage over new entrants, not because they are necessarily better, but because they are more widely used and diffused. Positive feedback mechanisms decrease production costs and create additional benefits for users. A stable incumbent regime is the outcome of various lock-in processes and it favours incremental as opposed to radical innovation. The cost and performance of a new technology are more uncertain compared to incumbent technologies (Sandén and Azar, 2005).

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The discussion of lock-in mechanisms in this paper is motivated by our interest in transition processes, especially transitions towards more sustainable energy and road transportation systems. In this regard, initially "minor changes and marginal developments may evolve into massive structural configurations that then restrict the variety of directions to future changes" (Voß and Kemp, 2006:13). Such transition processes are, therefore, path-dependent. In this paper, we do not focus on processes of path-creation, but rather on the lock-in mechanisms that set the preconditions for these new paths.[1] Lock-in mechanisms are conceptualised as mechanisms, which reinforce a certain pathway of economic, technological, industrial and institutional development and can lead to path-dependency.

A core argument of our paper is that the persistence of existing socio-technical systems can be explained by using more specific concepts than niche, socio-technical regime and landscape as provided by the multi-level perspective (MLP) (i.e., Geels, 2004; Kemp et al., 1998). In the MLP framework, the concept of a regime is defined as:

> "the rule-set or grammar embedded in a complex of 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" (Rip and Kemp, 1998:338).

It is argued that the different elements of such a complex system – the material, organisational and conceptual dimensions of the system (Sandén and Hillman, 2011) – are aligned with each other. Thus, the existing socio-technical system has a stabilising influence on innovation dynamics and technological change and prevents the introduction of radically new technological trajectories.

However, a key critique of the MLP framework is that it describes lock-in in a rather totalising way, with few specifications of the specific mechanisms through which lock-ins become manifested. We argue that distinguishing between various technological and institutional lock-in mechanisms improves our understanding of the persistence of the dominant socio-technical regimes and the difficulties for emerging niches to upscale. Thus, this specifies the ways in which existing regimes set the preconditions for the development of new transition pathways. As different regimes are characterised by different lock-in mechanisms, the opportunities for upscaling a given niche depends on the specific characteristics of the relevant regime.

A comparative perspective on lock-in mechanisms in ongoing transition processes helps develop a clearer understanding of transition processes as being the result of an "interplay of path dependence, path creation and path destruction" (Martin and Sunley, 2006:408). In this paper, we analyse the transition from fossil energy to renewable energy-based road transport systems in the Nordic countries and we specify the role of various lock-in mechanisms in this transition process. We focus on possible transition pathways towards more sustainable energy and transportation systems in four Nordic countries – Denmark, Finland, Norway and Sweden – and pose the following research question:

How do different lock-in mechanisms of socio-technical regimes influence new transition pathways?

The paper is based on a comparative analysis of case studies of four Nordic countries. We selected one technology platform for each country: advanced biofuels for Finland and Sweden, battery electrical vehicles (BEV) for Denmark and fuel cell electrical vehicles (FCEV) and hydrogen for Norway.

The paper is organised as follows: in the next section, we review the academic literature on path-dependency and lock-in mechanisms and develop the analytical framework for the comparative analysis. In the third section, we describe the methodological approach and data used. In the fourth section, we discuss the technological and institutional lock-in mechanisms at work in the selected technology platforms for each country. Section 5 discusses the lock-in mechanisms across the different cases and the value of the concepts of lock-in mechanisms when analysing transition processes. Finally, we draw conclusions for further research.

2. Theory: lock-in mechanisms revisited

There have been a number of studies of technological change and innovation in economics and in organisation and institutional research, which attempt to conceptualise different lock-in mechanisms in economic, institutional and organisational development.

Early studies by Brian Arthur and Paul David have focused on increasing returns of adoption, positive feedbacks and path dependency (Arthur, 1988, 1989, 1994b) and on the role of historical small events and elements of chance in achieving a dominant market position to realise economies of scale and decreasing cost conditions (David, 1985). While neoclassical economic theory is built on the general paradigm of diminishing returns and equilibrium of prices and market shares, Arthur argues that resource-based sectors and knowledge-based sectors follow different logics. Resource-based sectors and factor-intensive technologies, like agriculture, bulk goods production, mining and power generation are mostly subject to "diminishing returns," while the knowledge-based parts of the economy are subject to "increasing returns" of adoption (Arthur, 1990, 1994a:25, 1994b:3). This difference is explained by large *initial investments* in research and development and tooling in the knowledge-based economy, where rather cheap *follow-up investments* in incremental innovation are sufficient

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[1] This issue is considered in a paper that analyses selected path creation processes in Nordic energy and road transport systems (Hansen et al., 2015, in preparation). The paper also discuss the theoretical framework for path creation (i.e., Garud and Karnøe, 2001), which highlights the important role of agency in creating new trajectories.

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to improve the processes and products (ibid.). As a result, the cost of producing high-tech products falls over time, while the benefits of using them increase. This gives the producer an advantage because of several mechanisms such as (a) being able to produce greater numbers of products at lower cost; (b) developing higher quality products and improving processes by incremental innovation, and; (c) achieving a kind of early de facto standard setting in networks which require compatibility. Arthur calls these mechanisms 'network externalities'. Increasing returns mechanisms can also cause economies to become locked into an inferior development pathway, which is difficult to escape (Arthur, 1990, 1994b:10). Technologies which have been chosen for sound engineering reasons become locked-in because of user externalities and, therefore, adopting more advanced and more appropriate technologies becomes more difficult (Arthur, 1994a:25). Sunk costs, learning effects and coordination costs contribute to such locked-in trajectories (Arthur, 1994c).

Later contributions from other social science fields such as organisation theory, institutional theory and transition theory, have addressed lock-in mechanisms from a different perspective. Importantly, Foxon (2002) emphasises that technological lock-in should be distinguished from institutional lock-in. Foxon follows Pierson (2000) in his understanding of the interlocking effects of technological and institutional lock-ins, which compound the interaction between technological systems and governing institutions. Also in institutions, increasing returns are at work, but here they are related to the acceptance of institutions and their adoption by organisations (Lachman, 2013).

North points out that symbiotic relationships exist between institutions and organisations that have evolved as a response to the incentives put in place by those institutions and that these symbiotic relationships favour incremental changes instead of radical changes (North, 1990:7). Following North's work on institutional change (1990), Foxon identifies the following factors as institutional lock-in mechanisms:

"the central role of collective action; the high density of institutions; the possibility of using political authority to enhance asymmetries of power, and the complexity and opacity of politics" (Foxon, 2002:3).

Geels et al. (2004:6f.) summarise the mechanisms which lead to increasing returns to the adoption of a technology and finally to path dependency as, "…economies of scale, leading to lower cost, learning-by-using, network externalities, informational increasing returns, and technological interrelatedness". They also find that institutional aspects are important, including user routines, cognitive routines and formal regulations. Firms have sunk investments and built-up capital to consider, while suppliers and users have developed interdependent networks. Lastly, consumption patterns, user practices and lifestyles also contribute to path dependency (Büttner and Grübler, 1995; Kallis and Norgaard, 2010; Marechal, 2009).

In summary, we find that literature from different disciplines focuses on various types of lock-in mechanisms. While empirical studies have underlined the importance of these lock-in mechanisms individually, a synthesising analytical framework of lock-in mechanisms has not yet been established. We argue that such a framework is particularly important in order to understand transition processes that are highly complex such as road transport systems since multiple lock-in mechanisms may be important in explaining path dependencies. Specifically, we distinguish between nine lock-in mechanisms. These are presented below and their operationalisation in the current study is also explained.

2.1. *Learning effects*

Following Arrow (1962) who addressed the effects of learning-by-doing on increasing productivity, Arthur (1990) points out that increasing returns lead to learning effects: they facilitate the development of higher quality products and the improvement of processes by incremental innovation. Learning effects occur when knowledge, skills and organisation routines increase with cumulative production. Increased adoption may also lead to learning-by-using, providing important feedback about the needs of users for incremental product development. The learning effects lead to lower costs, which eventually can be measured by learning curves (Juninger et al., 2010). This sequence of historical events points to the role of national scientific and technological specialisation (Cimoli, 1994; Klitkou and Kaloudis, 2007). Cimoli concludes that: (1) technological learning and the accumulation of increasing returns interact with national consumption patterns, and; (2) unfavourable consumption patterns in a given sector combined with high dynamic increasing returns and learning capabilities may "result in a process of falling behind" (1994:141).

In the context of our specific study, we have traced learning effects by analysing a range of phenomena: the specialisation of business actors active in the development and deployment of the technology; cluster development for the different technologies; specialisation and strength of R&D organisation; strength of designated RD&D programmes and the education of technical personnel.

2.2. *Economies of scale*

Economies of scale emerge when sunk costs from earlier investments in production capacity are spread over an increasing production volume in the socio-technical system. Economies of scale can be explained by increasing returns as fixed costs are spread over more units of production output and by the functions of the built-up infrastructure, especially for larger technical systems such as energy production or transportation (Hughes, 1983, 1987). Infrastructure such as electricity generation or transport systems becomes more efficient and gains momentum when more users are plugged into the system. However, the inertia of this infrastructure locks the system into a chosen direction. However, Arthur (1989:117) also points out that not all technologies achieve increasing returns regarding economies of scale, e.g. hydroelectric power plants become more costly as the size of the dams increases.

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We analysed economies of scale by scrutinising the number of registered alternative cars (BEVs, biofuel cars, FCEVs), the volume of produced advanced biofuel, imports of first generation biofuel, the number of filling stations for biofuels, BEV charging points, fast chargers, battery switching stations and hydrogen filling stations.

2.3. *Economies of scope*

The widespread use of a technology may allow for economies of scope, i.e. cost advantages induced by the production and use of a variety of products rather than specialising in the production of one type of product. Panzer and Willig (1981) emphasise the potential of achieving cost efficiency as a result of economies of scope. This is connected to product diversification in different niche markets. Economies of scope have been identified by studying emerging niche markets for the respective sustainable road transport technologies which combine involved infrastructure with other types of business: parking, amenities, ICT-based services, the emergence of new actors in all parts of the value chains, not just car producers, and product diversification in bio-refineries.

2.4. *Network externalities*

Network externalities emerge because of early de facto standard setting in industrial networks, which require compatibility and because many consumers purchase compatible products (Katz and Shapiro, 1986). This mechanism is especially important for infrastructure development in ICT or railroad systems, but also for the adoption of technology by end consumers such as mobile phones, computer software and BEVs. To identify network externalities, we identified business actors who were active in the development of international standards, and the compatibility of existing infrastructure with new infrastructure (joint infrastructure or separate development).

2.5. *Informational increasing returns*

Informational increasing returns occur because the adoption of a technology means that it receives greater attention which in turn stimulates other users to adopt it (Van den Bergh and Oosterhuis, 2008:158). To discuss informational increasing returns, we analysed reports on public opinion regarding alternative cars and fuels, consumer interest in alternative cars measured by the number of newly registered alternative cars, the education of maintenance personnel, the visibility of alternative cars in user forums, information campaigns, the deployment of distinguishing marks for BEVs or FCEVs, and discussions on health and safety issues for biofuels and hydrogen.

2.6. *Technological interrelatedness*

Technological interrelatedness occurs because the adoption of a technology favours the development of complementary technologies, decreases technological uncertainty, while potential users may adapt their expectations regarding quality, endurance and the performance of the technology. Technologies which are incompatible with the dominant technological regime are, however, locked out (Van den Bergh and Oosterhuis, 2008:159). This lock-in mechanism was analysed by examining the compatibility or incompatibility of the incumbent energy and transport system with the emerging road transport technology, the compatibility or incompatibility of the new technology with other types of technology, and by investigating the competition between different generations of technology, e.g. first generation biofuels vs. advanced biofuels, normal charging points vs. fast chargers, and hydrogen for combustion engines and for FCEVs.

2.7. *Collective action*

Collective action refers to the emergence and subsequent reproduction of societal norms, customs, consumption patterns and formal regulation through coalition building in associated networks of individuals and organisations (Foxon, 2002). These were studied by comparing the dominant and emerging norms in support of private and collective road transport solutions. A comparison of the share of transport by car vs. by bus and coach was conducted. Additional relevant topics include the public procurement of more sustainable public transport vehicles, new types of collective ownership (car sharing), new types of operators for mobility services which take advantage of lower operational costs, and the emergence and strength of interest organisations.

2.8. *Institutional learning effects*

Institutional learning effects are the outcome of the increased adoption of institutions, which makes them rather complex and difficult to change, even when mistakes have been clearly identified, while at the same time providing improved coordination and adaptive expectations (Foxon, 2002). Here we studied the coordination of policy domains in favour of the incumbent regime or a new trajectory, for example, energy, transport and taxation, policy coordination between

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Table 1
Interviews for the case studies.

	Firm interviews	Stakeholder organisation interviews
Denmark	1	1
Finland	2	2
Norway	3	2
Sweden	2	2

municipalities and regional authorities, the emergence of non-governmental institutions for knowledge sharing vs. the existing knowledge networks for the incumbent regime, and public R&D programmes for sustainable road transport.

2.9. Differentiation of power and institutions

Asymmetries of power, institutional complementarities and symbiotic relationships contribute to institutional lock-in. Asymmetries of power means that strong political actors can impose rules on others and force changes to the rules to enhance their power (Foxon, 2002). Institutional complementarities means that different institutions are complementary when the enhancement of one assists the provision of the other (Ostrom et al., 1993). For example, complementarities exist between corporate governance and labour regulations. Institutions and organisations develop symbiotic relationships as a response to the incentives put in place by those institutions and favour incremental instead of radical changes.

Here we studied national targets regarding the use of renewable sources in road transport, the use of tax exemptions and other incentives for alternative cars and fuels, and the existence of strong state-owned industry players specialised in production of electricity, cars, and biofuels which encourage/discourage new trajectories for sustainable road transport.

3. Methodological approach and data

The paper is based on a comparative analysis of case studies on the role of lock-in mechanisms for path-dependencies in four Nordic countries. We draw on the results of selected case studies in a joint project as examples of the influence of lock-in mechanisms in transition processes: e-mobility in Denmark based on (Borup, 2014) and a follow-up documentary and data review, advanced biofuels in Sweden and Finland (Hansen and Coenen, 2013; Wessberg and Eerola, 2013) and hydrogen and FCEV case studies in Norway (Scordato and Klitkou, 2014). When selecting the cases, our intention was to cover the most advanced, but also different technology platforms in the respective countries.

Besides the selected case studies, we draw from a number of other case studies on advanced biofuels in road transport (Amer and Bolwig, 2013; Bolwig and Amer, 2013; Ericsson et al., 2013; Fevolden, 2013a,b; Klitkou, 2013; Wessberg and Eerola, 2013), on BEVs (Iversen et al., 2014; Røste, 2013), on FCEVs and hydrogen (Ihonen, 2013), which inform our discussion of lock-in mechanisms for the selected cases. The case studies are based on a review of the relevant literature and semi-structured interviews with key actors in industry and stakeholder organisations, although the Danish case is mainly based on documentary reviews, while drawing on interviews with participants in a large BEV demonstration programme in Denmark carried out as part of the InnoDemo project (Klitkou et al., 2014). The reviewed literature includes corporate reports and presentations, industry analyses, data files, media reports as well as academic literature. The interviews focused on attempting to understand the barriers and opportunities for the wider diffusion of the given technology platforms. This included specific attention to the role of industrial characteristics, up and downstream actors and the institutional context. Table 1 lists the number of firms and stakeholder organisations interviewed.

Each of the four case studies gives the empirical background for the discussion of the nine lock-in mechanisms specified in the theoretical framework.

4. Case analyses

This section discusses the main lock-in mechanisms of the Nordic countries' energy-based road transportation systems and concentrates on three technology platforms: (a) advanced biofuels in Finland and Sweden; (b) renewable electricity and BEVs in Denmark, and; (c) hydrogen and FCEVs in Norway. We discuss the role of technological and institutional lock-in mechanisms for energy production, road transport and related infrastructure. Further, we distinguish between the negative and positive effects of the lock-in mechanisms on the development of the technology platforms thus highlighting how the preconditions set by the lock-in mechanisms may also support a transition towards sustainable road transportation systems.

4.1. BEVs in Denmark

The high and increasing share of wind power in the Danish energy system favours solutions, which can help to level out the variable electricity production, e.g. e-mobility and smart grids. There have been significant learning effects within this area: The Danish regime is keen on stimulating learning processes related to energy storage and flexible demand due to a highly variable renewable energy source (wind). This regime trait favours electrical vehicle system integration. A high share

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of public RD&D funding has been allocated to electricity transmission and distribution and the Danish government and the European Union have supported several RD&D projects on electric vehicle systems, infrastructure and smart grid integration over the last 5–10 years (Borup, 2014). The Danish Energy Agency funded electric vehicle pilot projects with a total of DKK 50 million over the period 2008–15 with the aim of gaining practical experience with BEVs and related infrastructure. This includes a demonstration project to test 200 BEVs over four years including the automated collection of geo-referenced data on the operation of BEVs as well as technical and behavioural analyses (Klitkou et al., 2014). The Danish Transport Authority also supports several BEV initiatives including the latter as well as the use of BEVs in car sharing arrangements. Moreover, e-mobility is often a key component of learning processes taking place through ‘smart’ and ‘low-carbon’ city projects.

Concerning economies of scale, the fact that Denmark has a denser and more evenly distributed population compared to other Scandinavian countries makes the establishment of nation-wide charging infrastructure for BEVs more feasible. Denmark was the first European country to implement Better Place BEV infrastructure. Between 2010 and 2013, the company installed 17 battery switch stations, 8 fast-charging stations and 1400 charging points (plugs) (Borup, 2014). However, Better Place failed to attract enough customers for their new service infrastructure, which eventually led to the firm’s bankruptcy in 2013. Today, Denmark has around 500 publicly accessible charging stations (see below), which only service around 3000 vehicles.

Economies of scope in BEVs are created by the combination of conventional forms of electricity distribution and the operation of EV charging infrastructure. Denmark’s largest electricity distributor, Dong Energy, was one of the main shareholders in Better Place before the bankruptcy. Today, electricity companies dominate public EV charging infrastructure: E.ON Denmark operates 341 normal charging stations plus 13 fast chargers. Five Danish utilities jointly own the company CLEVER, which operates 346 charging points, of which 330 are fast chargers. Ownership of parking facilities and amenities (service stations, restaurants, etc.) in cities and along major highways offers economies of scope for the placement of recharging infrastructure, which is illustrated by new collaborations between charging infrastructure owners and municipalities and vehicle fuel retailers.

Regarding network externalities, Denmark has no automobile producers and, therefore, little influence on standards for electric vehicles. Worldwide different, mutually incompatible systems for recharging of electric vehicles exist. The European Commission has stipulated that Type 2 together with the Combo2 plug be the common European standard for both slow and fast charging connections and that Member States must incorporate this standard in their national policy by the end of 2016. The introduction of this standard will reduce investment costs and increase user access.

Informational increasing returns have been hit by the bankruptcy of Better Place, which contributed to uncertainty among potential EV users in Denmark. However, the increasing number of charging stations and car models on the market is likely to have increased Danish consumer interest in BEVs. A survey from 2014 suggests that since 2013 consumers have become less sceptical towards electric vehicles while sales have doubled. However, 69% of Danish consumers are still reluctant to buy a BEV as their next car (Michelin Nordic AB, 2014). At the end of 2014, there were less than 3000 BEVs on the roads with about three-quarters being owned by public or private enterprises, and only one-quarter by private households.

Technological interrelatedness is of significant importance in Denmark as the electrification of the Danish energy system is driven by increased wind power and favours – and partly depends on – the electrification of road transport over, e.g. biofuels. In this regard, vehicles can be charged at times of relatively low net electricity demand (i.e., demand minus any fluctuating renewable production), which typically occurs at night. It has been estimated that it will be possible to charge 200,000 electric vehicles during the night in 2020 without adding extra capacity to the energy system (Christensen et al., 2012). Such intelligent charging will increase overall system efficiency, improve the economy of wind power, and put less strain on local electric grids (Ibid), although its implementation requires that consumers are incentivised to charge vehicles during off-peak hours through time variable tariffs or other means. Providing such economic incentives for optimal (from the view point of vehicle owners) charging will result in the increased intra-day flexibility of the power system, but not in increased storage or day-to-day flexibility (Delikaraoglou et al., 2013). The increasing number of private home-based photovoltaic systems can be used to charge electric vehicles in lieu of selling the electricity to the grid at a low price. There were 90,000 such systems installed in 2014.

Formal regulation in terms of tax exemptions is the single most important type of collective action to promote the adoption of BEVs in Denmark. Electric vehicles are exempt from all registration fees and road taxes, and electricity delivered by charging stations is taxed at a lower rate than for private households. The tax exemption should be seen in the context of very high registration fees for conventional cars. The tax exemption is typically extended by 3 years with the current exemption running to the end of 2015. In late 2014, the Danish Energy Association and the Danish Electric Vehicle Alliance, together with E.ON, publicly voiced concerns that a decision to extend the tax exemption to the end of 2018 had not yet been made arguing that such a decision is essential for the future of BEVs in Denmark. A gradual reform of the vehicle tax system would over time favour BEVs as wind and other renewables replace fossil fuels in the Danish energy system. Public opinion generally supports these positions (YouGov, 2014). Emerging e-mobility operators can take advantage of rather low operating costs for BEVs thereby giving e-mobility renewed momentum (Dijk et al., 2013). The experience with Better Place has, nevertheless, shown that customers are hesitant to adapt these business models since it means renting and not owning the batteries. In sum, perceived delayed political action has created uncertainty in the EV market in the midst of careful optimism regarding BEV sales and consumer perceptions. A second key regulatory issue concerns the non-implementation of time-variable electricity prices, which, as noted above, means that BEV owners presently have no incentive to charge their vehicles at optimal times for overall power system flexibility and performance.

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Concerning institutional learning effects, municipalities and regional authorities have introduced BEVs in their fleets in order to reduce CO_2 emissions and local air pollution. Knowledge-sharing networks have existed for municipalities and regions since 2009 and since 2014 for private firms, while the Capital Region of Denmark has a secretariat dedicated to the promotion of electric vehicles. Demonstration projects such as the one mentioned above testing 200 BEVs have often been implemented through collaboration between a very wide range of stakeholders (Klitkou et al., 2014). At the national level, energy and transport are traditionally two separate policy domains, but some coordination regarding BEV deployment takes place, e.g. with support schemes. The overriding importance of tax exemption means that coordination is necessary between the two latter policy domains and that of taxation. A number of non-governmental institutions have been involved in building knowledge on EV systems, charging infrastructure and smart grid integration. These include the Danish national transmission system operator for electricity and natural gas, the Danish Energy Association, the Danish Electric Vehicle Alliance, energy companies and charging infrastructure operators, car rental and leasing companies and other fleet managers, as well as universities. These institutional initiatives have often been developed as a reaction to policy initiatives and have reinforced each other (Borup, 2014).

Finally, with regards to differentiation of power, Denmark has no automobile producers so the main economic interests in e-mobility are related to charging infrastructure, smart grid integration, electricity production, EV imports and retailing, and EV fleet operation. Danish companies and knowledge institutions involved in these activities founded The Danish Electric Vehicle Alliance in 2009 under the Confederation of Danish Industry, which has 50 members including several large companies.

4.2. Hydrogen and FCEVs in Norway

Learning effects have contributed to early experiments with hydrogen in FCEVs. These learning effects come from two different technological trajectories: Statoil was mainly interested in using natural gas to produce hydrogen, while Norsk Hydro focussed on electrolysis to produce hydrogen from abundant hydroelectric power. Since the 1980s and 1990s, Norwegian companies have engaged in R&D on different fuel cell types, hydrogen production technology and hydrogen storage, with Statoil, Norsk Hydro and Kværner being the most prominent companies (Godoe and Nygaard, 2006; Klitkou et al., 2007). In the 1990s, despite co-funding from the public research funding agency, NTNF, the big industrial R&D projects – NorCell I and II and Mjøllner – failed (Godoe and Nygaard, 2006). The natural gas trajectory was dismissed, while the electrolysis trajectory developed further, but with much less economic funding than the natural gas trajectory and involving other actors. Some important public research organisations are active in the field of FC and hydrogen in Norway (Klitkou et al., 2007). However, the main challenge is that there is no strong domestic industry to support the ongoing research at the public research organisations. Competencies in some fields such as hydrogen storage and electrolysers have been developed by industrial actors and have contributed to the ongoing experiments with hydrogen and FCEVs in Norway. However, the maintenance personnel for vehicles and the refilling infrastructure are educated to serve the fossil fuel road transport system, while knowledge on the FCEVs and hydrogen filling stations is still limited to a number of projects with a small number of experimental filling stations, public fuel cell buses in Oslo and participation in European hydrogen projects. There have been some learning effects regarding the assessment of risks and safety issues. Here one of the main global certification bodies, DNV GL, has used competencies developed for the oil and gas sector.

Economies of scale have dis-incentivised investments in hydrogen and FCEVs. Firstly, the significant Norwegian oil and gas industry favours the use of fossil fuels over hydrogen. Secondly, hydropower favours e-mobility with BEVs without the “detour” via hydrogen. Thirdly, Norway does not have a domestic car production industry to drive the development of hydrogen powered cars. However, economies of scope are becoming more important as some Norwegian firms have specialised in the production of some key products for realising FCEVs in Norway, such as hydrogen production units via electrolysis or via landfill conversion and composite tanks for the storage and transportation of hydrogen. Cooperation with other foreign niche actors, especially in Denmark, has been essential.

Network externalities of the dominant fossil transport regime hinder the introduction of new infrastructure for hydrogen filling stations. However, standards for safety issues for hydrogen filling infrastructure developed in international projects with the participation of strong Norwegian actors such as DNV GL have also contributed to the early deployment of hydrogen and FCEVs in Norway.

Informational increasing returns are limited to the capital region and are not so well developed. In Norway, all BEVs are marked with EL on their license plate and all FCEVs are marked with HY and fuel cell buses are decorated with large banners identifying them as FCEVs. Information campaigns for alternative vehicles are supported by the public transportation agency and regional and municipal authorities. This increases the visibility of the FCEVs, although there are still too few of these vehicles to have made an impact so far. If safety issues are clearly dealt with, public acceptance of FCEVs has the potential to be greater than for BEVs due to the longer range of FCEVs.

Technological interrelatedness can be traced for firms engaged in technologies related to the transport and storage of hydrogen and other types of gas and related technologies. This interrelatedness results in some synergies for actors who are active in both fields such as Hexagon and DNV GL.

Regarding collective action, society is based on norms which support individual car use, maximum mobility and road systems and less on collective solutions or shared ownership models. The share of passenger transport on land by passenger car is at 87.7% the highest in the Nordic countries. The regulations are mainly oriented towards privately owned cars. FCEVs have been rather expensive which has limited their use as collective transport solutions. Public procurement of a few fuel cell buses has been too limited to have made a difference to public transport. Interest organisations for hydrogen and FCEVs collaborate with local and regional authorities, researchers and the emerging firms, which strengthens their position.

Institutional learning effects have dis-incentivised the introduction of FCEVs in Norway. Some public actors engage in the strategic prioritisation of FCEVS such as the Akershus regional authorities, and the transportation agency, which has funded demonstration projects. However, at the government level, this has a lower priority even though the Ministry of Petroleum and Energy and the Ministry of Transport and Communications jointly established the Hydrogen Council in 2005 with the mandate to act as an advisory board in matters related to hydrogen. The government supports public R&D programmes on renewable energy and CCS, but does not prioritise R&D on sustainable transport and especially FCEVs.

Differentiation of power occurs especially because of asymmetries of power which strengthen the fossil transport regime. However, the Norwegian government has imposed rules to promote more sustainable solutions. All fuel cell electric vehicles benefit from a number of incentives: they are exempt from purchase tax and VAT, receive a 90 % discount on annual road tax, pay no toll or municipal parking fees, get free ferry passage and have access to bus lanes. However, hydrogen is not free as opposed to the free electricity provided at public recharging points for BEVs. Both FCEVs and BEVs can make use of the very high share of E-RES (105.5% in 2011). An example of a symbiotic relationship is the close connection between the state-owned Statoil company and a number of R&D organisations, which favour R&D on oil and gas, while R&D on hydrogen and FCEVs is lacking business funding.

4.3. *Advanced biofuels in Finland*

The forest industry has been an important export industry in Finland since the 1600s and strong learning effects have contributed to the development of advanced wood-based biofuels. This wood processing expertise is used by the forest company, UPM, which started to produce wood-based biodiesel in 2015 in East Finland. The production plant is located next to a pulp mill and utilises tall oil as a raw material from the pulp mill.

Another significant learning effect in Finland is the learning cluster in advanced biodiesels that has developed around the fuel industry, in particular the energy company Neste Ltd., which started in 1954 as an oil refinery processing imported fossil fuel. Neste's specialisation in diesel production has stimulated incremental competence development within biofuels. Neste Oil initiated the production of biodiesel from certified palm oil in the 2000s, and the company has recently started to cooperate with the Danish company, Inbicon, to produce advanced biodiesel from straw.

The pulp and paper industry, and energy production related to it, have traditionally been an important industrial sector in Finland and has, hence, created economies of scale. Economies of scale lock-in mechanisms are also found around the existing fossil fuel based road transport regime—most of the vehicles used are ICE cars using fossil fuels or blends with biofuel. Energy production processes integrated with pulp mills create a large share of renewable energy production in Finland. It is, therefore, common to see pulp mills integrated with energy production as well as with transport fuel production. Transport fuel production is bulk production which takes advantage of large-scale production capacity and large markets with the potential for economies of scope emerging due to the potential of product diversification in pulp mill based bio-refineries.

Network externalities of the dominant fossil transport regime inhibit the spread of other transport energy technologies such as electricity or hydrogen in Finland. However, fossil fuel cars and distribution network are available for drop-in (bio-ethanol or biodiesel blended fuels) and advanced wood-based biofuels. Biofuels are, hence, technologically well integrated with the existing fossil fuel regime.

Concerning informational increasing returns, such drop-in biofuels are widely accepted by Finnish car owners. At first, in 2010, consumers were sceptical and wary of the 10% biofuel suitability of cars, but now they are used to it and believe that the biofuel will not harm their cars and that it is also usable at low temperatures. Finland is a large, sparsely populated country which is based on norms which support private car use (collective action) with the current regime favouring fossil fuel cars. However, in the four largest cities, public transport systems are well developed and are continually developing.

Regarding collective action, the Finnish government has set a national target to increase the use of biofuel in road transport to 20% by 2020. Thus, contrary to Sweden (see below), the Finnish government has set a more ambitious target than that required by the EU. This represents a change as Finland is a latecomer to transport biofuel policy despite some early statements in the early 1980s (Kivimaa and Mickwitz, 2011). Support for first generation biofuels was lacking, but in 2009–10 Finnish policy changed dramatically and began to target advanced biofuels while Finnish oil companies decided to produce advanced biofuels (Lovio and Kivimaa, 2012:785). Due to EU regulations, biofuels from waste products can count twice. Tall oil is regarded as a waste product of pulp mills and, hence, a biofuel producer using tall oil can count biofuel factors twice, which makes the fuel production even more profitable.

Concerning differentiation of power, there is a battle going on between the wood-based biofuel producers, such as UPM, and chemical industry actors who are trying to develop advanced chemicals made from wood, especially from tall oil. At the same time, the price of tall oil is increasing on the market, which reduces the profits of the chemical industry in particular. The forest industry is also worried that state subsidies may shape the energy system so that forest owners sell their timber to energy producers instead of the forest-based industries. Forest energy use may lead to an increase in the price of timber and timber processing side products and in that way affect the market.

4.4. Advanced biofuels in Sweden

Learning effects have been very important for the diffusion of bioethanol for transport in Sweden, in particular, the existence of relevant and related competencies within pulp and paper, an industry which is of key economic importance to Sweden. Sulphite pulping mills developed units to produce bioethanol as a substitute for imported fuels during World War II. Consequently, ethanol production was carried out at 32 Swedish pulp and paper mills in the middle of the 20th century. While pulp mills were gradually abandoning the production of ethanol for fuel use in the post-war period due to the renewed availability of imported petrol, a competence base had been developed. Building on this, substantial research activities into, firstly, methanol and subsequently ethanol fuel production have been conducted in Sweden since the 1970s. Designated research programmes for ethanol research funded by the Swedish Energy Agency have been running since 1993 (Joelsson and Tuuttila, 2012), and the share of public RD&D budgets on energy for biofuels is highest in Sweden. A second important learning effect is the strong Swedish competencies within vehicle manufacturing. For example, the Swedish truck and bus producer Scania initiated an R&D project in the early 1980s which focused on developing bus engines specifically for running on ethanol, which led to the introduction of the first ethanol bus in 1985, which has since been improved successively (Johnson and Silveira, 2014). In summary, competencies from existing industries have significantly influenced opportunities for developing and diffusing bioethanol for transport in Sweden.

Economies of scale have mainly dis-incentivised investments in lignocellulosic bioethanol for transport. Firstly, the significant Swedish hydroelectric power and nuclear power production favour e-mobility over bioethanol. Secondly, the pulp and paper industry has traditionally focused on large-scale production of a limited number of products with little attention to product differentiation. However, economies of scope are becoming increasingly important as the demand for paper decreases, opening up for further diversification. Still, the degree to which lignocellulosic bioethanol will take up a central position in the product portfolio of a diversified pulp and paper industry remains to be seen.

Technological interrelatedness between conventional fossil fuel cars and bioethanol powered cars is a general advantage of bioethanol relative to e-mobility as it only entails minimal changes to engine design, refuelling, driving style and range. Thus, users perceive the step from conventional fossil fuel to bioethanol as relatively small. A related aspect, categorised as a network externality, which is of central importance to transport in Sweden is, as in most other countries, the existing fuelling infrastructure. In the Swedish case, the E85 pump infrastructure is well developed and integrated with conventional fuelling infrastructure, thereby significantly supporting the diffusion of bioethanol for transport. A second important network externality which influences the use of bioethanol for transport is that the Swedish automobile industry has been involved in standard setting for biofuels.

As in most other countries, informational increasing returns have supported the diffusion of fossil fuel based cars in Sweden. While the growing visibility of bioethanol is likely to have supported the now significant diffusion of this technology in Sweden, a number of public debates continue to question the benefits. Firstly, the food vs. fuel issue continues to be debated, in particular because most of the ethanol is imported from developing and emerging economies. Secondly, questions have been raised concerning the negative effects on engines resulting from running on ethanol. Consequently, an increasing number of owners of flexible fuel cars are choosing conventional petrol over ethanol according to the Swedish Energy Agency. And thirdly, researchers have raised concerns regarding the health effects of using bioethanol in vehicles (López-Aparicio and Hak, 2013; Sundvor and López-Aparicio, 2014).

Regarding collective action, individual car use is still the dominant norm in Sweden. Americanisation has significantly influenced Swedish society, including the perception of the car as a central element in everyday life (O'Dell, 1997). Furthermore, being a large and sparsely populated country, public transport and even to a large extent e-mobility cannot fulfil the transportation needs of a large share of the population. However, biofuel powered cars fit quite well into the dominant norm.

The impact of institutional learning effects that follow from increasingly complicated regulation and coordination of all aspects of car use in Sweden are similar to many other western countries: the conventional fossil fuel car is firmly embedded in Swedish society. However, while the institutions regulating car use are characterised by inertia, a quite significant policy-push has been initiated by the Swedish government in recent years to promote bioethanol. Many of these initiatives build on conditions described under the previous lock-in mechanisms, e.g. the Swedish Pump Act, which required larger gas stations to sell renewable fuels, or the public procurement of flexible fuel vehicles from the automotive industry.

Finally, concerning the differentiation of power, the decision-making power on most key issues such as funding for the development and demonstration of new technologies resides with the central Swedish government. Still, like all other members of the EU, Sweden must fulfil EU requirements concerning the use of renewable energy in the transport sector, but the current use of first generation bioethanol allows Sweden to meet this obligation (Hillman and Sandén, 2008; Hillman et al., 2008). However, this has been found to hamper the diffusion of advanced biofuels in Sweden (Hillman, 2011) as the EU provides no clear incentives to move beyond first generation bioethanol (see also the sister paper on path-creation: Hansen et al., in preparation).

5. Discussion

In the following, we discuss the results of the four case studies to answer the research question. The section has three main topics: (1) the importance of the different lock-in mechanisms for the transition towards a Nordic sustainable energy and road transportation system; (2) the interconnectedness of the lock-in mechanisms, and; (3) the implications for transition theory.

5.1. *Importance of the different lock-in mechanisms*

In order to summarise the effects of the lock-in mechanisms, Table 2 highlights the role of each of the nine lock-in mechanisms for each of the four cases. Importantly, the preconditions set by the lock-in mechanisms do not necessarily inhibit the development of a given technology platform, but may also effect it positively. Table 2 distinguishes between such positive and negative effects.

5.1.1. *Learning effects*

Learning effects are a central lock-in mechanism for reinforcing path-dependencies in the Nordic countries and they favour the selected technological trajectories to different degrees. They are based on the industrial specialisation of the four countries: the deployment of wind technology in Denmark and related efforts to manage the variable electricity production, the forest and pulp and paper industry in Finland and Sweden, the automobile industry in Sweden, and the oil and gas industry and electro-chemical industry in Norway. Learning effects also occur in the replacement of fossil fuels by biofuels, both in Finland and Sweden. These effects are reinforced by public funding priorities for research, the development and demonstration of new technologies, the education of technical personnel, favourable consumption patterns, and the formation of knowledge clusters around central companies, especially in Finland and Sweden.

5.1.2. *Economies of scale*

Economies of scale have influenced the four cases differently. The significant Norwegian oil and gas industry favours the use of fossil fuels over hydrogen, while large hydroelectric power capacity for production favours e-mobility with BEVs. Swedish hydroelectric power and nuclear power production favour e-mobility over bioethanol. In Finland, there is a large incumbent pulp and paper industry, which tries to exploit the potential of advanced biofuels on a large scale. In Denmark, wind energy production is large and growing and the cost of off-shore wind power is decreasing, which, in combination with a densely populated country may favour e-mobility including the deployment of BEV recharging and smart grid infrastructure. However, the low number of BEVs on the road has contributed to the underutilisation of the existing charging infrastructure and dis-incentivises further infrastructure development.

5.1.3. *Economies of scope*

To date, economies of scope have mainly been achieved in the bio-economy, but product diversification is still much less developed than in the fossil economy. However, economies of scope are becoming increasingly important in all four cases and are easier to achieve for smaller economies than economies of scale. This can be explained by the crisis of the traditional pulp and paper industry and product diversification of the up-coming bio-refineries, niche markets for hydrogen technologies and the co-location of recharging infrastructure with parking facilities, service stations and amenities. Product diversification towards higher value products in bio-refineries may, however, also have a negative impact on the production of advanced biofuels that are of relatively low value. In Sweden, bio-refinery operators are, thus, increasingly regarding biofuels as less profitable by-products.

5.1.4. *Network externalities*

The fossil transport fuel infrastructure is well developed in all four countries and biofuels are used as a drop-in and are, therefore, well-integrated in the infrastructure. The nature of infrastructure systems for transportation is important here as these systems are not just national, but cross borders and have to integrate the transport system of several countries. There is an interplay between the different infrastructure systems (Frantzeskaki and Loorbach, 2010). The supplementary infrastructure system for hydrogen competes with the fossil fuel and the biofuel infrastructure (i.e. providing very different types of fuels), but the co-utilisation of infrastructure systems is also possible. For e-mobility, we highlight the co-evolution of the charging infrastructure and the electricity system, and the co-utilisation of smart grid infrastructure to fulfil different tasks and to allow adaptation to fluctuations in net demand.

Standards are important in most of the cases: The Swedish automobile industry contributed to national and EU standard setting for biofuels, while Norwegian companies and other actors have been active in international networks, which developed safety standards for H_2/FCEV infrastructure. In Denmark, the deployment of EU standards for charging BEVs will allow network integration and network externalities for BEV users crossing the Danish borders. This will contribute to reduced investment costs.

5.1.5. *Informational increasing returns*

Informational increasing returns can be achieved by becoming more visible to the public through different channels: (1) Information campaigns by public and private actors; (2) Public debate on the advantages and disadvantages of the competing technologies; (3) Access to different vehicle models and related infrastructure; (4) The development of user forums and mobile phone applications, and; (5) The education of maintenance personnel. However, concerns regarding the sustainability of a solution, high costs, range anxiety, safety and health issues and economic constraints inhibit informational

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Table 2
Summary of positive and negative effects of lock-in mechanisms. Bold text indicates a negative effect of a lock-in mechanism for the development of a given technology platform, while text in italics denotes a positive effect.

Lock-in mechanism	Denmark Battery electric vehicles (BEVs)	Finland Advanced biofuels	Norway Hydrogen and FCEVs	Sweden Advanced biofuels
Learning effects	*Publicly funded, often multi-stakeholder RD&D projects have been important for building competences on BEV use and fleet management and on the role of BEVs in the power system*	*Competences in incumbent industries have been important to advanced biofuel technology development*	*Competences in parts of the incumbent industries (Norsk Hydro) and strength of public R&D actors have been important for early experiments with hydrogen technology for road transport*	*Competences in incumbent industries have been important to advanced biofuel technology development*
Economies of scale	**The low number of BEVs on the road means under-utilisation of existing charging infrastructure and is a disincentive for further infrastructure investment**	*Pulp industry as well as the existing fossil oil based transport regime create economies of scale, which accelerate the development towards advanced biofuels*	**Economies of scale in oil & gas and in hydropower have dis-incentivised investments in hydrogen and FCEVs**	**Existing economies of scale in energy production dis-incentivise investments in advanced biofuels**
Economies of scope	*Electricity companies exploit existing electricity distribution infrastructure and competences in the deployment and management of recharging infrastructure. Placement of recharging stations at parking spaces and service stations creates economies of scope regarding the use of this infrastructure*	*Increasing importance of economies of scope in the pulp and paper industry provides opportunities for advanced biofuel production*	*Economies of scope are becoming important due to specialisation in key elements for deploying hydrogen in road transport*	*Increasing importance of economies of scope in the pulp and paper industry provides opportunities for advanced biofuel production* **Product diversification in bio-refineries might turn biofuels into less important by-products**
Network externalities	*The deployment of new EU technical standards for slow and fast charging connections increases user access and reduces investment costs*	*Utilisation of existing fuelling infrastructure supports advanced biofuel diffusion*	**Network externalities of the dominating fossil transport regime hinder the introduction of new hydrogen infrastructure**	*Utilisation of existing fuelling infrastructure supports advanced biofuel diffusion*
Informational increasing returns	*Consumers have become less sceptical of BEVs and sales are increasing from a very low base. Greatest acceptance is among private and public enterprises*	*Drop-in biofuels are well accepted by Finnish car owners*	**Informational increasing returns are limited to the capital region and not so well developed in general due to strong position of incumbent ICEs**	**Knowledge about advanced biofuels is limited relative to conventional fossil fuel powered ICEs**
Technological interrelatedness	*BEVs are a potential source of needed intra-day flexibility in an energy system increasingly reliant on variable renewable energy sources, while BEVs can benefit from cheaper electricity at off-peak hours (low net demand)* **Regulatory failure to introduce variable electricity prices means sub-optimal charging practices**	*Advanced biofuels benefit from high technological interrelatedness between cars running on biofuels and conventional fossil fuel*	*Hydrogen technology for road transport benefits from interrelatedness with other type of gas related technologies, especially natural gas*	*Advanced biofuels benefit from high technological interrelatedness between cars running on biofuels and conventional fossil fuel*
Collective action	**Most consumers perceive BEVs as inadequate for long-distance trips and even daily needs** *Tax exemption of BEVs enjoys broad support amidst absence of long-term political commitment*	*Advanced biofuels fit well with the dominant norms, which emphasise individual use and frequent long-distance trips*	*The dominant transport norms favour individual car use and maximum mobility, which could fit with FCEVs* **FCEVs are less compatible with collective solutions or shared ownership models due to high costs despite of tax exemptions**	*Advanced biofuels fit well with the dominant norms, which emphasise individual use and frequent long-distance trips*

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Table 2 (*Continued*)

Lock-in mechanism	Denmark Battery electric vehicles (BEVs)	Finland Advanced biofuels	Norway Hydrogen and FCEVs	Sweden Advanced biofuels
Institutional learning effects	*A wide range of public and private actors build knowledge on BEV infrastructure and vehicle operation, often through joint projects* **Institutions regulating private mobility still favour ICEs**	*The national target is to increase the use of biofuel in road transport to 20% in 2020*	*Institutional learning effects to some degree positive in the capital region* **Extensive adoption of institutions regulating conventional ICEs has dis-incentivised introduction of FCEVs**	**Wide-spread adoption of institutions regulating conventional fossil fuel cars inhibits transition to advanced biofuels**
Differentiation of power	*Large electricity companies have invested in BEV infrastructure* *Presence of organised, multi-stakeholder lobby organisation* **Absence of strong BEV vehicle producer interests**	**Chemical industry and advanced biofuel production compete for the same wood-based resources** *Public R&D funding favours non-food based biofuels*	**Despite public incentives for FCEVs the strong oil and gas business sector provides few incentives to invest in new companies commercialising hydrogen for road transport**	**International commitments provide little incentive to invest in a transition to advanced biofuels**

increasing returns. Compare this also with Dijk et al. (2013) who identified range and price as being important consumer preferences. The cases show different effects of this lock-in mechanism. For BEVs in Denmark, public acceptance has improved while biofuels have been well received in Finland. In Sweden, sustainability concerns for first generation biofuels and limited knowledge of advanced biofuels had a negative effect on the deployment of the latter. In Norway, hydrogen and FCEVs are still marginalised and activities are visible mostly in the capital region.

5.1.6. *Technological interrelatedness*

Technological interrelatedness between conventional fossil fuel cars and biofuel cars is a general advantage of biofuels relative to e-mobility, as changes in refilling, engine design, driving style or range are minimal. Thus, users perceive the step from conventional fossil fuel to biofuels as relatively small, while the deployment of BEVs has to overcome bigger barriers, such as range anxiety and different refuelling systems. However, also for e-mobility, such technological interrelatedness may become favourable due to the co-utilisation of the charging infrastructure and the electricity system (compare Network externalities) and access to greater flexibility in the electricity system. However, sub-optimal BEV charging practices may hamper the deployment of BEVs. BEVs and FCEVs deploy the same type of electrical drive train and, therefore, both alternatives may gain momentum from technological interrelatedness. Technologies related to transport and the storage of hydrogen may gain from competencies and experiences regarding natural gas technology.

5.1.7. *Collective action*

The Nordic countries are based on norms which support individual car use, high mobility, and well developed road systems, but do not support to nearly the same extent collective solutions or shared ownership models. Regulations underpin these norms. However, there are differences between the countries and tendencies for change. Car ownership is lowest in Denmark compared to the other countries. In Danish cities, cycling is popular and is supported by infrastructure. The share of passengers using collective road transport solutions is higher in Denmark and Finland than in Sweden and Norway. Collective actions are strengthened by favourable taxation of alternative vehicles and fuels, public procurement of more sustainable public transport vehicles and coalition building between consumer organisations, environmental NGOs, local authorities, business actors and academia. Emerging e-mobility operators can take advantage of rather low operating costs for BEVs and these lower costs can, therefore, give e-mobility a new momentum (Dijk et al., 2013). However, range anxiety hampers the wider deployment of BEVs.

5.1.8. *Institutional learning effects*

Policy coordination between different policy domains such as energy, transportation, environment, climate, taxation and research can contribute to institutional learning effects despite the inertia of institutions regulating car use. Such policy coordination is developed to varying extents in the four countries. A significant and coordinated policy-push was initiated by the Swedish government to promote first generation biofuels and by the Finnish government to promote advanced biofuels. These efforts were based on taxation, research policy and policy targets for biofuels use. Involvement of local and regional authorities can reinforce such policy initiatives. Alternatively, local authorities can initiate such policy in the absence of national policy coordination, as illustrated by the case of hydrogen in the capital region of Norway. Collaboration between public and private actors in joint projects can have a positive effect on institutional learning, as shown by the BEV case in Denmark.

5.1.9. *Differentiation of power*

Asymmetries of power are often reinforced by state regulation favouring the incumbent transportation regime. Yet the cases highlight how the national governments have promoted sustainable transport pathways in different ways, including setting targets for alternative fuels (to adhere to EU policy), providing tax rebates and exemptions, and funding RD&D on alternative fuels. There are clear differences regarding the involvement of strong industrial actors and the emergence of small and medium-sized enterprises in these new pathways, which allow different degrees of symbiotic relationships. Biofuels have received a lot of attention from industrial actors, especially in Finland and Sweden, but in different ways: the Finnish government did not support first generation biofuels, but now has much higher biofuel targets based on advanced biofuels (Lovio and Kivimaa, 2012). In Sweden, the initial success of first generation biofuels (Hillman and Sandén, 2008; Hillman et al., 2008) has turned into a barrier to advanced biofuels (Hillman, 2011). The development of hydrogen and FCEVs has suffered under asymmetries of power since strong industry players have not supported these technologies nor have they been prioritised in national policy. In the case of BEV in Denmark, various forms of state and municipal support for e-mobility have been in line with the interests of large power companies as well as smaller industry actors involved in BEV charging and operation; yet the recurring debates over the extension of the electric vehicle tax exemption suggests an underlying tension between state (i.e. tax revenue) and industry interests that is likely to intensify as, or if, the number of BEVs grows to a significant share of the Danish fleet.

5.2. *The interconnectedness of the lock-in mechanisms*

The comparative analysis of the three cases has shown that while it is useful to distinguish between the nine lock-in mechanisms for analytical purposes, it is evident that they are naturally interconnected. Unruh's (2000) work on carbon lock-in draws attention to the broader scope of lock-in than just technological lock-in, the connection to institutional factors, and the need for alignment between the lock-in mechanisms. Thus, it is interesting to note how these mechanisms relate to each other. Therefore, we highlight some of these interactions below.

There are several interactions of learning effects with other lock-in mechanisms. Learning effects and technological interrelatedness can reinforce each other. A highly specialised economy and R&D and innovation system leads to learning effects, but also reinforces the development and deployment of complementary technologies as long as they do not hamper the dominant technological trajectory. Economies of scale and of scope increase learning effects while network externalities may also contribute to learning effects. For example, the high degree of integration of the E85 refuelling infrastructure with conventional fuelling infrastructure in Sweden has supported the diffusion of the technology, but also stimulated learning about consumption patterns. Thus, the absence of network externalities will also hinder learning effects. Informational increasing returns can reinforce learning effects and vice versa. Examples here are the learning of users in user forums and the education of maintenance personnel.

Asymmetries of power can reinforce or weaken collective action. Governments can develop ambitious targets for the deployment of new technologies and can reinforce these targets with regulations favouring collective solutions such as the procurement of public transport vehicles, implementing sustainable solutions or they can simply establish the targets without underpinning them with regulations. The latter alternative shows weak political leadership.

Symbiotic relationships between strong industry actors in the incumbent regime and important political and R&D institutions can undermine institutional learning effects of policy coordination since the actors of the incumbent regime will favour incremental changes and not radical changes.

5.3. *Implications for transition theory*

The MLP has been criticised for a poor delineation of niches and regimes (Berkhout et al., 2004). Berkhout et al. (2004) raised concerns that the multi-level perspective on transition processes does not sufficiently explain the processes, which destabilise the dominant regime and overestimates the role of emerging niches while underestimating the importance of regime transformation which is initialised inside the regime (p. 56). They point out that there is a need to reflect on the "diversity and resilience of wider social commitments to different technological trajectories and the extent to which particular commitments might be withdrawn" (p. 59), and call for more thorough analyses of regime change which combine the two analytical perspectives: the coordination of actors within the regime and the availability of resources for the change within or outside the regime. While more than a decade has passed since this call, we still have insufficient knowledge about how regime actors hinder or facilitate transition processes (Geels, 2014).

While the MLP acknowledges the importance of lock-in and path-dependency, it problematizes lock-in in a rather totalising way. Our specification of the nine lock-in mechanisms helps overcome this weakness. Complementing the traditional MLP framework with the analytical perspective introduced in this paper facilitates a detailed understanding of the specific lock-in mechanisms that support the current regime as well as those that may promote future niche development. Some lock-in mechanisms are more or less pervasive across the globe, e.g. gas station infrastructure, which favours biofuels over BEVs or FCEVs (network externality). Other lock-in mechanisms are context-specific, e.g. dependent on competences in existing industries (learning effects). To understand the potential for sustainability transitions in specific places, it is important to focus on the latter.

Our analyses highlight how the incumbent socio-technical regime is not just fossil-based, but can also include well-established, mature niches specialised in the exploitation of renewable sources as exemplified by hydroelectric power in Norway, wind energy in Denmark, and first generation biofuels in Sweden. This implies that there is a need to distinguish between lock-in mechanisms which favour, respectively, the old fossil-based regime, well established (mature) renewable technological trajectories, and new technological trajectories. This is in line with Martin and Sunley's argument that economic evolution is the result of a continuous interplay between path-dependency, path creation and path destruction (2006:408). Furthermore, the lock-in mechanisms which favour mature renewable energy technological trajectories may also reinforce radically new technological trajectories such as e-mobility or the use of hydrogen in transportation. However, even renewable technological trajectories can act as barriers to other more radical trajectories because they bind physical or financial resources. An example is the conflict over the use of bio-resources for the production of hydrogen versus advanced biofuels. Another is the conflict between tall oil for wood-based energy, chemicals or advanced biofuels, and a third is the competition over scarce RD&D funds between, e.g. biofuels and e-mobility.

6. Conclusion

This paper has discussed the role of lock-in mechanisms in sustainable transition processes, specifically for road transport in the Nordic countries.

The analytical framework has been used to conduct a comparative analysis of case studies on battery electric vehicles in Denmark, hydrogen and fuel-cell electric vehicles in Norway, and advanced biofuels in Finland and Sweden.

The paper identifies nine institutional and technological lock-in mechanisms that can affect sustainable transition processes such as the transition from a fossil to a renewable energy-based road transport system. In doing so, we drew on diverse literature mainly from the social sciences which revealed the specificity and potential importance of each mechanism and its possible connectedness with other mechanisms. The result, we claim, is an improved theoretical framework for understanding transition processes. We further argue that studies using variants of the multi-level perspective may benefit from such an approach by achieving a more detailed understanding of the specific lock-in mechanisms that support the current regime, as well as those important for niche development. By distinguishing between the nine lock-in mechanisms we can specify how the characteristics of existing regimes set the preconditions for the development of new transition pathways.

Regarding our research question, we have identified quite different lock-in mechanisms at work in the four cases representing three distinct road transport technologies placed in different socio-technical contexts. These contexts concern especially the energy system, the industrial structure, actor constellations, and policy. Important lock-in mechanisms at work across all case studies were learning effects, (dis) economies of scale, network externalities, and public regulation at the national or EU level – whether in the form of collective action, institutional learning effects, or the differentiation of power. Economies of scope and technological interrelatedness were only important in some cases, while the case studies revealed little in terms of the importance of informational increasing returns. There were important interactions between the different lock-in mechanisms, reinforcing or weakening technological trajectories. These interactions need further research.

At a more general level, the case studies suggest that the new technological trajectories do not develop undisturbed since all actors have to relate to and interact in a socio-economic context, which is influenced deeply by the incumbent socio-technical regime. Furthermore, the incumbent socio-technical regime is not just fossil-based, but may also include mature renewable energy trajectories. This implies a need to distinguish between lock-in mechanisms favouring the old fossil-based regime, well-established (mature) renewable energy trajectories, or new emerging trajectories. We have shown that the preconditions set by the lock-in mechanisms do not necessarily inhibit the development of a given technology platform, but may also effect it positively. Finally, we observe that the lock-in mechanisms favouring mature renewable energy trajectories can reinforce radically new technology trajectories such as e-mobility or the use of hydrogen. However, new paths can act as barriers to other more radical paths because they bind financial or physical resources.

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