Journal of Evolutionary Economics manuscript No.
(will be inserted by the editor)

Incremental by Design? On the Role of Incumbents in Technology Niches

An Evolutionary Network Analysis

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Received: date / Accepted: date

Abstract In this paper, we study the evolution of governance structures in technological niches. At the case of public funded research projects and the resulting cooperation networks related to smart grid and systems in Denmark, we raise the questions which actors over time inherit a central position – associated with high influence on the development of research trajectories – in the network. We are particularly interested in what role incumbent actors, connected to the old regime of fossil based energy production, play in shaping future technological trajectories. The protected space theoretically created by such public research funding offers firms an environment to experiment in joint learning activities on emerging technologies, shielded from the selection pressure on open markets, thereby facilitating socio-technological transitions. Generally, the engagement of large incumbent actors in the development of emerging technologies, particularly in joint research projects with entrepreneurial ventures, is positively perceived, as their resource endowment enables them to stem large projects and bring them all the way to the market.

However, growing influence of incumbents might also alter niche dynamics, making technology outcomes more incremental and adapted to the current technological regime. Potential influence on rate and direction of the technological development can to a large extend be explained by actors' positioning in the network of the niche's research activities. We create such a directed network of project consortium leaders with their partners to analyze if network dynamics of joint research projects in technological niches favor incumbent actors in a way that they are able to occupy central and dominant positions over time. To do so, We deploy a stochastic actor-oriented model of network dynamics, where we indeed discover path-dependent and cumulative effects favoring incumbents. Our findings suggest a development of the network towards an incumbent-dominated structure.

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Keywords innovation networks · industry dynamics · network evolution · public funded R&D · incumbents · technological change

1 Introduction

In order to address the environmental sustainability challenge many of the established large infrastructure related systems have to be transformed. One central area is the energy system. The shift from fossil based to renewable energy production is increasingly embraced as the solution, but the intermittent characteristics of electricity generated by sun and wind lead to severe implications for the electricity grid in its current architecture that is designed to transport steady energy from large central power plants to consumers. The construction of a smart grid and working towards a smart energy system is seen as a possibility to address this challenge. One issue that emerges in relation to this upcoming transformation is the ambivalent role of established firms from the energy sector. Their resources, capabilities, and cooperation are needed for this new development, yet they are likely to be the players that have a strong interest in maintaining the established systems unchanged.

In this paper, we study the evolution of governance structures in technological niches. At the case of public funded research projects and the resulting cooperation networks related to smart grid and systems in Denmark, we raise the questions which actors over time inherit a central position – associated with high influence on the development of research trajectories – in the network. We are particularly what role incumbent actors connected to the old regime of fossil based energy production play in shaping future technological trajectories.

The multidisciplinary literature on system innovation, often empirically focused on sustainability transitions, outlines the significance of niches for the protection and development of path-breaking technologies in early stages (Geels 2002; Hoogma et al 2004; Geels 2004; Kemp et al 1998). Public funded research, development and demonstration (R&DD) protects represent such a protected space, offering firms an environment to experiment in joint learning activities on emerging technologies. In the same vein, literature originating from the Technological Innovation Systems (TIS) approach also highlights the importance of creating protected spaces to foster market formation and diffusion (Hekkert et al 2007b; Bergek et al 2008).

The engagement of large incumbent actors in the development of emerging technologies, and especially joint research projects together with young SME's, is generally positively perceived as they have the capabilities to fulfill necessary systemic functions in a better way than new start-up firms (Suurs and Hekkert 2005). Apart from the direct effect of the engagement, it is likely to have a positive signaling effect. Thus, it might contribute positively to the status of the niche, improving financial viability and triggering interest of other companies (Smith et al 2005). Arguably, the involvement of incumbents might, however, alter niche dynamics, making technology outcomes more incremental and adapted to the current unsustainable socio-technical regime. This is particularly evident if the emerging technology is a potential substitution to the existing solutions (Tushman and Anderson 1986; Bower and Christensen 1995a). Indeed, literature on sustainable transitions suggests that incumbent actors – who over time carried out fixed investments in infrastructure, developed technological competences and secured market shares – have a high incentive to protect and replicate the old regime's logic and reinforce existing technological trajectories rather than develop new ones (Geels 2011). This reflects a more critical and nuanced consideration of network structures in research collaborations, which may not necessarily be fully cooperative and consensus oriented, as mostly envisioned in innovation system and networks oriented approaches.

The incumbents' ability to influence the trajectory of technological development can, to a large extent, be explained by their position in the niche network. Here, a large body of literature on networks of innovators has produced ample theoretical reasoning and empirical evidence on how a firm's strategic positioning in interorganizational networks affect it's innovative performance (e.g. Powell et al 1996; Baum et al 2000), and the structure of the overall network affects the innovation output on the aggregated (Fleming et al 2007) and firm-level (Schilling and Phelps 2007; Kudic 2014) alike. Consequently, firm-level cooperation choices build the micro-foundation for the rate and direction of innovation and technological chance in innovation networks. It is further argued that networks of innovators by no means are static constructs in time and space, but rather constantly rearrange in an evolutionary process, which is to a large extend path dependent (Doreian and Stokman 2005; Powell et al 2005; Kilduff and Tsai 2003). Existing ties often tend to become more persistent over time (Burt 2000), and preferential attachment makes the likelihood of creating new ties influenced by the actors stock (Barabási 2005) – leading to a process of structural reinforcement (Gulati 1999). This effects are also well known determinants influencing the allocation of public research grants (Viner et al 2004). In the terminology of innovation and transition literature, that relates to the development of a niche into a “proto-regime” (Geels and Raven 2006) with increasingly established institutions and emerging stabilization mechanisms. While these stabilization mechanisms are well-known features of social networks (e.g. Barabási and Albert 1999), the question how characteristics and rationales of central actors affect the outcome of such networks is discussed seldom from a network perspective.

Yet, when envisioning public funded research networks as technological niches, this question becomes particularly important for two reasons. First, the organization of public funded R&DD projects distinguishing between a project consortium leader and further project consortium partners by design imposes a governance structure, where project leaders are able to determine main parts of the project's content. Consequently, actors in central positions of such networks are likely to have a high influence on the rate and direction of future research through their higher social influence and their role as “knowledge hubs”. Second, a main argument put forward to protect the space within technological niches is that they offer the actors the opportunity for broad experimentation which is not influenced by the selection pressure of the current regime (Smith and Raven 2012).

Having that said, to allow path-breaking ideas to unfold in technological niches, it becomes crucial that they initially contain a broad set of actors with heterogeneous knowledge bases as well as “hidden preferences” regarding the future development of the niche's technological trajectory. While over time evolutionary processes will lead to a concentration and consolidation of the network, in early phases broad experimentation in different direction is needed. A requirement for this endogneous selection processes to unfold is the emergence of internal selection logics. However, the smart grid as a technological niche is heavily connected to the current energy system, in terms of infrastructure and other physical assets as well as applied knowledge. Furthermore, public authorities who allocate resources in this niche are likely to be in some way connected to the old regime.

To conclude, path-dependent and cumulative characteristics representing the old regime and favoring incumbent players are replicated in the technological niche of smart grid research, evolutionary processes will enable them to obtain central and dominant positions and thus shape the niche's further development by their will.

Following earlier argumentation, actor-strategy driven network dynamics in technological niches can be assumed to lead to more incremental outcomes which reinforce old technological paths if (i.) the network evolution is driven by endogenous and cumulative effects, such as the actors size, age, reputation or network position; (ii.) incumbent actors embodying such characteristics are involved; and (iii.) there exist possible new niche trajectories which lead to an underutilization of their accumulated resources.

The empirical context is the evolution within the Danish electricity grid-infrastructure network of joint participation in public funded R&DD projects in the period 2009 until 2012. Companies and projects were identified by exploring the Danish research project database. The Danish case is of particular interest because of the explicit political aspiration to become a European technology hub for the development and testing of advanced energy grid technologies (KEMIN 2013). A national smart grid strategy from May 2013 emphasizes the importance of interaction between research institutes, utilities and technology producers, and the development of various technologies. A number of research programs were established to support R&DD projects from basic research to large-scale demonstration and commercialization.

The purpose of the present paper is to study structural dynamics and path dependencies of research networks in technological niches at the case of public funded research projects. In particular, deploying a stochastic-actor-based model (Snijders et al 2010a), we analyze if network dynamics of public funded R&DD in technological niches favor incumbent actors in a way that they are able to occupy central and dominant positions. Against the empirical and theoretical background, we conceptualize the research network as consisting of directed ties between the actors, assuming the project-leader to project-partner link as a hierarchically ordered relationship. By doing so, we are able to analyze up to now unobserved cumulative and self-reinforcing effects of network dynamics.

As a result, we indeed find such path-dependent and cumulative effects in the development of the research network that favor incumbent actors, in the long run leading to a a reinforcing process of structural stabilization with central and influential positions.

The remainder of this paper is composed as follows: The following section 2 aims at linking different streams of literature that advocate for the creation and protection of technological niches with network theory. This connection is made to understand strategies of different niche actors and possible macro outcomes of their behavior. Section 3 provides an overview of the technological and policy context of the smart grid development in Denmark. In section 4 we introduce the stochastic actor-based model deployed to identify the evolution in the niche-network, and describe the research networks data used for the analysis as well as our empirical strategy. Section 5 presents the results, and the final section 6 concludes.

2 Theoretical Background

2.1 Inertia at micro and meso levels in large technical systems

The achievement of the environmental sustainability goals – such as the reduction of greenhouse gas emissions, exhaustion of natural resources, and destruction of ecosystems – in highly dependent on the determination and ability to transform a number of large technical systems (LTS's) worldwide. LTS's, such as the energy grid, the transportation or the agri-food sector build complex, extremely interwoven technical, economic, institutional and administrative structures (Hughes 1987). Such sectors heavily build and rely on existing tangible and institutional infrastructures (e.g. development and trial systems, supplier and distribution networks, energy transmission grids, and other complementary assets). This dependence leads to high entry barriers in aforementioned industries and explains why key players are likely to be large companies (e.g. electric utilities, car manufacturers, railway operators).

Incumbent firms with substantial shares of their resources bound in an established technological regime are said to struggle in maintaining a certain level of innovation activity - particularly when facing radical, discontinuous technological change (e.g. Wagner 2010; Bower and Christensen 1995b).[1] In case of *competence-enhancing* technological innovation, established firms have incentives to actively engage in and support the development of the technology updating the existing (Gilbert and Newbery 1982) regime.*Competence-destroying* innovation in turn appears as more likely to be pioneered by newcomers (Anderson and Tushman 1990; Tushman and Anderson 1986).

Over time, incumbents might also develop adoptive capabilities, enabling them to absorb knowledge on more radical novelties and combine it with their stock of knowledge to develop superior products and processes (Bergek et al 2013). This can be done i.a. by engaging in joint R&D projects with entrant firms or the acquisition of their technology (e.g. Wagner 2010). However, once internalized, the absorbed novelty is likely to be aligned with existing resources in a complementary way. Therefore, when engaging in joint R&D projects, we assume that established firms – given the power – will influence technological trajectories in a way that makes the outcomes more compatible with their established assets and therefore potentially less radical.

Once a LTS has gained momentum these strategies become part of the resistance mechanisms against change on the system level (e.g. Walker 2000; Van der Vleuten and Raven 2006). The resulting set-up creates a power and capability imbalance between usually small enterprises that are pioneering the development of sustainable solutions and incumbent actors (Hockerts and Wustenhagen 2010). As long as production and distribution processes within existing trajectories are economically favorable, incumbents will not see urgent reasons to make large investments and reorganize existing production structures. On the contrary, they are most likely to defend the system against change (Walker 2000). In the most extreme case this leads to inertia and lock-in (Arthur 1989), as one might observe in our current fossil fuel dependent energy system Unruh (2002, 2000a).

[1] One can broadly distinguish between *competence-enhancing* innovation building upon existing technological and organizational structures, and *competence-destroying* innovation turning them obsolete (Tushman and Anderson 1986). This distinction to a certain extent reflects the notions of *incremental* and *radical* innovation.

2.2 System innovation thinking

Technological change embedded in large systemic context has been conceptualized and analyzed throughout the past three decades. The technological innovation system TIS sub-orientation (Carlsson and Stankiewicz 1991; Bergek et al 2008; Hekkert and Negro 2009) within the innovation system (IS) literature is increasingly used for the analysis of emergent industries on the basis of radically innovative technologies and the institutional and organizational changes that accompany the technological development (Truffer et al 2012). A number of system functions (Hekkert et al 2007b) focusing on the support and nurturing of emerging technologies are seen as intermediate variables between the structure of the system and its performance, emerging out of the interplay between actors and institutions (Jacobsson and Bergek 2011). While it is acknowledged that incumbent players may employ strategies to prevent disruptive innovation (Hekkert et al 2007b), their participation in the TIS is generally seen as fruitful – highlighting their resources, knowledge integration capabilities (e.g. Bulathsinhala and Knudsen 2013) and the positive signalling.

In the recent decade, a second stream of literature situated closer to the science, technology and society (STS) tradition gained considerable attention. The multi-level perspective (MLP) at the center of the transition literature explains socio-technical transitions by the interplay of three systemic concepts. The landscape on the macro-, the socio-technical regime on the meso-, and niches on the micro-level respectively (Geels 2002, 2005). The character and intensity of the interplay between the three levels define the paths, which a socio-technical transition might take. The key concept of the MLP is the regime, which represents a coherent, stable structure at the meso-level, combining established products, technologies, and institutions (routines, norms, practices). The regime is characterized by a high level of "structuration" (Coenen and Díaz López 2010), well articulated rules, and hence path-dependency and mechanisms for self-stabilization. It corresponds in many respects to the selection environment in terms of evolutionary economic theory and generates entry barriers for innovative technologies.

2.3 Niches & protected spaces

Niches are conceptualized as spaces that shield path-breaking innovations in early stages of development from selection pressure on mainstream markets (Kemp et al 2001; Schot 1992; Hoogma et al 2004). These spaces help overcome the lock-ins existing in the current unsustainable system due to economic scale and scope effects (Arthur 1989), and institutional regime stabilization mechanisms that are constantly reinforced by established actors (Unruh 2000b). Given alternative selection criteria, population and interaction dynamics, niches can develop own technological trajectories substantially differing from the established regime.

The direct funding of R&DD in selected technologies of interest represents an integral component of modern innovation policy. Shielded from the selection pressure of open markets, these research projects present an ideal platform for a broad, experimental and long term oriented search for new technologies. Nurtured with public investments, new entrants and incumbents alike are able to stem projects which would, due to their high technological uncertainty and long payoff periods, not be carried out otherwise. Given the proper institutional set-up, public R&DD financing offers a powerful tool to directly influence rate and direction of research activities (Pavitt 1998) and to create technology niches.

A challenge for policy-makers is the selecting of the appropriate protection level as well as its continuous assessment. Failure to find the right balance between protection and exposure to the selection environment can result in overprotection of "poor innovations" (Hommels et al 2007), incompatibility with the surrounding technological context, or a too low level of protection of promising emerging technologies(Smith and Raven 2012). The latter can happen when actors belonging to the established unsustainable technological regime achieve dominance in spaces that are actually meant for the development of solutions that are potentially meant to replace parts of the current regime. As Smink et al (2013) conclude "innovations with significant sustainability gains tend to be non-incremental and are therefore likely to have adverse effects on the business interests of regime actors". Therefore, we assume that their presence as dominant actors – and especially positioning as project leaders – in such niches might undermine the efficiency of the sustainable innovations under development.

2.4 A network perspective on technological niches

Cooperation and interaction between various actors involved in processes of technology development such as universities, firms, intermediate, and end users, are said to be of high importance for the smooth functioning of innovation systems (e.g. Lundvall 1992; Hekkert et al 2007a; Malerba 2002). A major task for science and innovation policy is therefore to facilitate the development of favourable R&D network structures (Carlsson and Jacobsson 1997), triggering interaction between heterogeneous actors and the generation of technological variety. Organizations form collaborative alliances in order to get access to their partners' technological assets and capabilities. Yet, potentially fruitful interaction with other corporations also comes at the risk of opportunistic technology appropriation by the counterpart, making careful selection of partners crucial (Li et al 2008).

One can broadly distinguish between two categories of information that actors can use in cooperation and partner selection decisions. First, reputation, mostly stemming from past performance in similar settings (Shapiro 1983), and their demonstrated capabilities. Second, information about an actor's position in relevant networks (Benjamin and Podolny 1999; Burt 1992; Granovetter 1973), where usually better connected actors appear also as more attractive partners for further cooperation. Both appear to be highly interdependent, since an actor's reputation can be influenced by the reputations of past and current exchange partners (Benjamin and Podolny 1999; Podolny 1993) and collective reputations can be transferred to the a groups individual actors (Schweizer and Wijnberg 1999).

From a network perspective, a certain level of progressive centralisation and increasing dominance of incumbent players is therefore expected. Against the backdrop of the argumentation found in the transition literature, a strong centralization would however mean that niche protection is only limited. Particularly if incumbent actors, increasingly assume project-leader roles, the development of sustainable innovation is virtually handed by the regime.

2.5 Summary

Overall, the above presented streams of literature draw a similar picture from their respective point of view: Innovation is particularly complex and costly in systemic set-ups. Path dependencies are especially pronounced in sectors with a high share of infrastructure. Frameworks that inform policy measures to spur change in these areas agree on the need to actively create technological and market niches in order to foster alternative technologies and in general solutions. Yet, the role of incumbent player within these niches needs more inquiry.

Innovation paths that are compatible with regime technologies are attractive for established firms. Resulting innovations can address some of the existing problems on the regime level – to use the MLP terminology – without compromising existing socio-technical structures. Established firms are therefore likely to initiate or engage in niche activities, such as R&DD projects, which investigate such applications.
Facing radical or architectural technological change, they will not directly support the early development of path-breaking innovations, but rather aim at gaining control, acquiring, and integrating novel and existing technologies (Pavitt 1986; Bergek et al 2013). Strong ties to the existent structures and technologies on the one hand and technological uncertainty, on the other lead to a relatively late but determined entry of incumbents into the development of these technologies. We assume that this may alter the particular innovative technology towards a less radical solution. In the case of sustainable technologies that would mean that generally more desirable superior solutions are possibly devaluated as they become compatible with the existing unsustainable system. From a policy perspective, and in the particular context of public research funding, that also raises the question related to *outcome additionality.*

3 Sociotechnical context of the smart grid development in Denmark

In order to understand and assess the structural dynamics of Danish smart grid and systems R&DD projects, it is important to consider the technological and policy context of the smart grid development. This section will introduce the fundamental technological concepts, components, and challenges related to the ongoing paradigm shift in the Danish and many other energy systems. Furthermore, the second part of this section will provide a brief overview of the policy ambitions that inform and guide the setup of publicly funded research programs. We fully acknowledge that funding programs and specified calls are intended to direct the technological trajectories of research projects. To some extent selection procedures by public authorities also predetermine their composition in terms of which types of actors and consortia constellations are awarded with grants and which not. Yet, the duality of selection in content as well as actor characteristics might lead to politically unintended developments regarding the evolution in the resulting research network – such as the rapidly growing dominance of certain actors.

3.1 Paradigm shift in energy production and the response in the grids

The traditional architecture of the electricity grid assumes a unidirectional energy flow from centralized energy plants via the transmission and distribution grids to consumers, where energy production levels are constantly adjusted to match the over time fluctuating energy demand (Farhangi 2010; Fox-Penner 2010). Embracing the renewable energy paradigm, centralized energy production is gradually replaced by decentralized energy farming. The harmonization between production and consumption has to move from the traditional generation side into the transmission and consumption areas. ICT technologies will play a central role in supporting this process (Mattern et al 2010).

In the Northeuropean set-up, two options are possible and currently discussed. Firstly, the construction of a European transmission super-grid to allow, for instance, energy exports from Denmark to Germany in wind-peak times. Secondly, the development of a national *smart grid*, that is able to transmit energy and information in both ways, thus allowing for harmonization by the means of flexible consumption. This requires the upgrade of the existing grid by adding a *layer of intelligence* - advanced measurement, communication and control technology - thus making the grid able to handle a higher share of decentralized renewable energy generation and the recently evolving consumption patterns (Elzinga 2011). This process is not primarily related to the development of radically new technology but to the recombination and integration of existing technology in order to achieve new functionality that would optimize the efficiency of the established system. If flexible consumption can be activated by the introduction of smart functionality, costly investments in the reinforcement of the distribution system can be moved into the future or avoided (Forskningsnetværket, Smart Grid 2013). This may be a favorable outcome for the country as a whole but might undermine profits of established actors that would benefit from capacity increase of the system.

3.2 Danish smart grid research and aspirations

Denmark is already today counting the largest amount of R&DD projects within the smart energy area in Europe (Giordano et al 2011, 2013). The extremely high ambition of the national energy agreement, passed by the government in 2012, targets a wind-power share of 50 percent by 2020, and the more recently announced Smart Grid Strategy sees the country as a European laboratory for innovative energy solutions (KEMIN 2013).

Following the target setting of the policy package, a “Smart Grid Research Network” with key organizations from the technical universities and practitioners from the Danish TSO energinet.dk, the Danish Energy Association, and the energy group within the Confederation of the Danish Industry were established. In 2013 the network published a report commissioned by the Ministry of Energy, Utilities and Climate, which draws up a roadmap for the development of the Danish smart grid. The report identifies fields which will require considerable research efforts but also areas with strong Danish competences and experience that can attract foreign investment or contribute to technology export. Overall, it concludes that the development of the smart grid should be put first but not seen in isolation. Rather the interactions with the other energy related systems, such as heating, cooling, gas, and transport should be considered at all times.

In their latest inventory report Giordano et al (2013) outline, that compared with other European countries, Denmark manages to develop a large amount of smaller projects which spurs technological diversity (Borup et al 2013). This is in line with the findings by Jurowetzki (2014). Exploring the scope of the national smart grid and systems research he found that, research projects span from topics that are closely related to the pure electricity smart grid, such as consumption flexibilization to the interaction areas of different systems (e.g. the role of electric vehicles, heat pumps, and the district heating system).

That can be interpreted as a sign of successful niche development and the gradual merge of the electricity, gas, cooling, and heating systems into one smart energy system (Copenhagen Cleantech Cluster 2014). This context also offers entry and influence opportunities for different types of established actorsfrom technological areas that yet have not been associated with the electricity system.

At the core of this research is the question of whether public funded R&DD activities are well constructed to provide necessary shielding in order to develop and introduce the needed amount of technological variety in the changing energy grid sector. The here proposed evolutionary network analysis can not provide direct answers to this question. Yet, the evolving structure of the research network can shed light on the likely development of the technological field.

4 Modelling Network Evolution

4.1 Data

Network Data

As a source for public funded research projects, we utilize the database provided by *Energiforskning.dk*. Combining data from several energy technology research and development programs, this database represents the most comprehensive source for public funded energy research in Denmark, covering projects funded by the *Strategic Research Council, ForskEL, ForskNG, ForskVE, ELFORSK, Green Labs DK, Danish High Technology Foundation* and the *European Union*. For the current analysis records from the *smart grid and systems* category were exported containing information on projects from 2009 to 2012 on yearly basis – overall 75 projects with 277 participants, and 132 single firms. Among those actors we identify 27 incumbent firms and 21 research institutions with the rest being either established diversifier companies or new entrants[2].

We include all private firms and other organizations that participated in at least one public funded R&DD project during the 2009 - 2012 period. Further Thereby we exclude actors which have unsuccessfully applied for public funding, actors who would have liked to join such a research project as partners but have not been selected, or have been selected in the initial project application but where for some reason excluded from the official consortium at the start of the project. When assuming such actors to be systematically different from successful project leaders and

[2] A detailed description of the applied classification methodology is described below

partners, this obviously introduces a selection bias and limits the concussions we are able to draw from this analysis. Consequently, we are able to analyze if public research grant allocation decisions *per se* favor actors with certain characteristics. Neither we can investigate the general mechanisms of partner selection in the "hypothetical" network of available research partners. Yet, working with the "revealed" network of realized cooperation still allows us – in line with our research objective – to analyze the emerging governance structure of public funded R&DD networks.

The directed edges in the network represent join affiliations with the same research project, which are active from the official -start until the end of the project, where they are set to be inactive again if no further joint project follows. Technically, we project the two-mode network of actors-to-project to a one-mode network of direct actor-to-actor affiliation. In line with our research objective to analyze governance structures in this network, we do not connect all participants of a project with each other, but only create one-directional edges between the assigned project consortium leader in direction of every other project partner.

In order to utilize models of network dynamics, the dataset under observation has to fulfill certain properties in line with the underlying assumptions of this model class. First, the network has to show some variation between its periods. However, too rapid changes indicate that the assumption of gradual change – compared to the observation frequency – is violated. To ensure the validity of the gradual change assumption, we consult the Jaccard index to be found in table 3, a common measure of similarity between two networks.[3] Snijders (2002) suggest this index to be higher than 0.3 and never drop beyond 0.2, which is given in our data. Overall, after a first preliminary inspection, the network data appears to have suitable properties in line with the assumptions of stochastic actor oriented models. Some further descriptive statistics on structural network measures and their development over time are provided in table 4 in the appendix.

A graphical presentation of the network under observation and its change over time is provided in Figure 2 in the appendix. On first glance, a formation of structural clusters around some incumbent actors can already be seen over time.

Actor Data

Data on firm characteristics, such as their age, size, legal form *et cetra* was extracted from the Danish firm database Navne & Numre Erherv (NNE). For additional information about firms' technological capabilities and their range of activity where gathered by studying annual reports, press articles, corporate websites *et cetra.*

4.2 Modeling network dynamics

Our attempt is to analyze the dynamics of interorganisational networks of joint participation in public funded research projects. In particular, we are interested in which firms over time move towards central positions in the network. The analysis of such dynamic networks represents an empirical challenge which calls for distinct

[3] The Jaccard index as a measure of similarity between two network waves is computed by $\frac{N_{11}}{N_{11}+N_{01}+N_{10}}$, where N_{11} represents the number of ties stable over both waves, N_{01} the newly created and N_{10} newly terminated ties in wave 2 (see Batagelj and Bren 1995).

statistical models and methods. The main problem stems from the very nature of social network formation processes. Many drivers of individual tie-formation decisions, such as transitivity, reciprocity, and popularity effects, by their very nature lead to endogeneity and dependencies of observations (Rivera et al 2010), since multiple characteristics of the current network structure influence its future development. This usually violates the assumptions of most standard statistical model types at hand (Steglich et al 2010).

The class of stochastic actor-oriented models (SAOM) originally developed by Snijders (1996) represents an attractive solution to address the inherent endogeneity problems of longitudinal network analysis, which scholars have lately started to deploy in the context of inter-organizational innovation networks (e.g. Balland 2012; Balland et al 2012; Buchmann et al 2014; Ter Wal 2013; Giuliani 2013). At its core, a SAOM combines a random utility model, continuous time Markov process estimation procedures, and Monte Carlo simulation. Originally, SAOM was developed in a sociological context and designed to model group dynamics in interpersonal networks (e.g. Van De Bunt et al 1999). However, actor-oriented modeling has also proven to be suitable to depict the interaction between macro outcomes and firms' micro choices (Macy and Willer 2002; Whitbred et al 2011) in inter-organizational alliance formation process. Here, structural change of the network is driven by individual firms' collaboration decision derived from a random utility model. Firms are assumed to observe the current network structure and characteristics of its population, and reorganize their ego-network in an utility-optimizing manner. Given the context of the study, we consider SAOM as the most suitable class of dynamic network models and deploy it for the empirical analysis to follow.

Snijders (1996) firstly proposed to address the problem of multiple endogeneity in the evolution of social network with transforming discrete datasets of panel waves into a continuous set of micro-changes (single reconfiguration decision) to be estimated by Markov-chain Monte Carlo simulation (MCMC).[4] Unobserved changes between the panel waves are simulated as continuous actor choices at stochastically determined points of time. Formally, following a Poisson function of rate λ_i, the actors (in our case, individual firms) are allowed to create, maintain, or dissolve ties until the network is transformed to the new structure χ. The decision of actor i to change the state of one tie to another actor j leads to a new overall state of the network χ, where the probability P_i for an actor choosing this structure is given by:

$$P_i(\chi^0, \chi, \beta_k) = \frac{\exp(f_i(\chi^0, \chi', \beta_k))}{\sum\limits_{\chi' \in C(\chi^0)} \exp(f_i(\chi^0, \chi', \beta_k))} \quad (1)$$

It technically resembles a multinomial logistic regression, modeling the probability that an actor chooses a specific (categorical) new network configuration P_i as proportional to the exponential transformation of the resulting networks objective function $f_i(.)$, with respect to all other possible configurations. The parameters' coefficients are stepwise adjusted by Monte Carlo simulation techniques in order to obtain convergence between the estimated and observed model, and finally, held fixed to allow their comparison and post-estimation analyses. The objective function

[4] Besides all its merits, the usage of estimations based on continuous-time Markov processes also has its drawbacks. It by definition does not allow for path dependencies. Yet, it is still possible to include variables aggregated over time to the current state.

contains actor i's perceived costs and benefits of a particular network reconfiguration leading to a network state χ, χ, which are represented by the random utility model:

$$f_i(\chi^0, \chi', \beta_k) = \sum_k \beta_k s_i(\chi^0, \chi, \nu_i, \nu_j, c_{i,j}, \epsilon, r) \quad (2)$$

It depends on the current state of the network χ^0, the potential new one χ, the ego i's and alter j's individual covariates ν_i and ν_j, their dyadic covariates c_{ij}, exogenous environmental effects ϵ, and a random component r capturing omitted effects. The underlying assumption is that the actors observe the current structure of the network χ^0 and the relevant characteristics of its actor set and make their collaboration decisions in order to optimize their perceived current utility (Jackson and Rogers 2007).

4.3 Empirical Strategy

Theoretical considerations

We model the tie creation process between ego i (project consortium leader) and alter j (project partner) as unidirectional from $i \Rightarrow j$. Thus, existing ties do not have to be reciprocal – a characteristic we find in many real-life networks such as friendships, mentorship, or producer-consumer relationships. Since we are interested in the ability to steer technological development of public funded research networks, we assume project consortium leader to have a significantly higher influence on the project's content than other participants. From this point of view, the directed network resembles the governance structure of there networks, and the actors outdegrees can be interpreted as a measure of influence. In our case, this appears as reasonable since the leaders of such projects are usually the ones applying for the corresponding grant, determining most of it's content, and selecting further partners. We chose a unilateral confirmation setup, where tie creating is only conditional to the ego's – but not the alter's – choice. By doing so, we assume potential partners to automatically join research projects when invited. This appears as a strong, but realistic assumption. Such a participation represents a safe source of income (and potentially knowledge), where the main upfront work, such as the grant application and determination of the content, is mostly carried out by the project leader. SAOM usually model tie creating as well as tie dissolution, where actors might choose to break up ongoing relationships which turn out to now offer negative utility. Since in our case the timeframe research projects is determined *ex-ante*, we only model the creation of new ties, where we exclude egos with already existing collaborations from the ego's choice set.

The nature of our network data calls for further consideration. In order to create a direct network among actors, we first have to project the two-mode network between actors and research projects to a one-mode network in actor space. Our resulting network is unweighed, meaning that the relationship between a project-leader and all project-members has the same quality, independent of the number of members. One might obviously assume that the size of project consortia systematically differs in a way that certain actors (probably larger and/or more experienced) actors show a tendency to include more members than others, thus establish more outdegrees per project than others. Further, it has been argued that the quality relationship between actors arising from a joint association with a second-mode differs with the number of actors this affiliation is shared. Newman (2001) for example argues that the quality relationship and interaction arising from scientific cooperation via co-authored publications substantially decreases with the amount of co-author. To account for this effect, one could weight the projected edges by the number of edges of the second mode (Opsahl 2013). While this is true for many types of relationships in different social settings, we do not believe it to be in our case. We explicitly aim to model governance structures emerging in public funded R&DD networks, given by the actors number of outdegrees. Consequently, the more alters a specific ego reaches increases their influence in determining research agendas, indecent of the fact that these outdegrees are established in one large or many small projects.

In addition, there undoubtedly exist some caveats when mapping networks based the common participation research consortia funded by public research grants. First, these networks only to some degree evolve naturally, since they are subject to a selection by the responsible public authorities. Selection criteria may be found, among others, in (i.) the reputation and credibility based on past performance and other forms of accumulated advantage of consortia members, (i.) the characteristics of the project such as the applied technology, (iii.) or the favoritism of certain consortia constellations. Second, since the actors are anticipating a selection according to these criteria, they have an incentive to consciously form consortia according to them. Thus, consortia formation are subject to selection biases *ex-ante* and *ex-post* to the project application. Consequently, the results have to be interpreted not as the outcomes of natural network evolution, but rather the channeled evolution in a socially constructed selection environment designed by public authorities, which might be subject to criteria (ii.). With the choice of the study's empirical context, we attempt to minimize systematic biases caused by criteria (ii.) and (iii.). First, Danish research funding in renewable energy technology is designed to generate the broad technological variety necessary for the sustainable transition of the energy system (Lund and Mathiesen 2009), where favoritism of certain technology should explicitly be avoided. Second, by including several research funding programs of independent governmental and non-governmental agencies in Denmark and the EU, spanning different industries as well as preferred development stages of funded projects, we avoid systematic bias caused by preferences of particular programs or policy initiatives.

Dependent Variable

We model collaboration choices driving the evolution of the network as the outcome of the actors' mutual attempts to optimize their expected utility with respect to their own and their potential alters' covariates, and the current network structure. Thus, our model's dependent variable represents the probability P_i that the focal actor i chooses a reconfiguration of the own network that leads to a tie with a corresponding alter j. This tie is directed from the project-consortium leader (ego) to a participating project partner.

Independent Variables

In the following, we discuss our independent and control variables, where we integrate covariates referring to the characteristics of the actors, as well as effects referring to their position in the local and global network[5] Since we are primarily interested in what makes actors establish – rather than receive – new ties, all independent variables refer to the characteristics and network structure of the focal ego i. A detailed description of all independent variables – and their calculation – deployed is provided in table 2, and all network related effects are illustrated visually in 1.

Actor covariates: This set of variables represents the effect of individual actor characteristics on their likelihood to establish new ties with other organizations.

In order to examine the `role` of actors in the combined network, we use a set of industry experts[6]. We differentiate between three roles, where we are particularly interested in the role of energy incumbents and the strategic deviations of these actors as compared to other actors involved in smart grid research projects. `Role incumbent`: This category aims at grouping actors with an origin in the energy sector that have an vested interest in protecting the established infrastructure from significant change. The experts were asked to identify "firms with a strong background/track-record and stakes in the traditional energy sector". This includes utilities, producers of transmission and distribution infrastructure, and producers of measuring devises. Apart from the utilities that went through a Europe wide policy induced organizational restructuring process, companies were founded before 2000. `New Entrant`: This group summarizes companies which were mostly founded after 2000 and have their main activity in the energy sector. The firms provide a broad range of products and services. Many of the firms develop ICT related solutions for the envisioned communication structure of the smart grid. Another large share are technology consultancies that are often responsible for analysis and system integration. It, however, also includes mature firms from other fields diversifying in the energy sector. `Role Others:` This class contains private and public actors that have shown interest in the development of a new grid infrastructure by participating in a research project. Actors are rather heterogeneous and have not had a background in the energy grid sector. This set of actors represents the reference group.

The `size` of a firm is also supposed to influence it's capabilities of successfully obtaining research grants, as well as to occupy central and dominant position in the resulting research networks. However, `size` is difficult to compare between different forms of organizations such as private companies, public organizations and research institutions. Therefore we only use a rough categorical classification of small (up to 25 employees, `firm small`), medium sized (up to 100 employees, reference groups), and large organizations (more than 100 employees, `firm large`). Generally, we expect large firms to establish more outdegrees for a set of reasons, where the most obvious is their higher internal capacity and resources to manage more projects at once than their smaller counterparts.

While maturing, firms are able to increase their competences in how to successfully formulate a research grant application, establish an intensify formal and informal relationships to industry partners and public authorities, and develop routines how to manage research partnerships. Since we expect these benefits to increase with decreasing marginal effects, and furthermore the distribution of firm age in our

[5] Where local and global refer to the network position of the actor and not to a geogaphical context.

[6] The experts are 3 energy related association managers from the Copenhagen Cleantech Cluster, Intelligent Energy alliance and the Lean Energy Cluster respectively

sample is highly skewed (start-ups as well as traditional firms established over a hundred years ago), we use the natural logarithm of the ego's `age` in years instead as control variable, which we generally expect to have a positive impact on the establishment of further outdegrees. Yet, the opposite might very well be true, if older firms loose their innovative edge and participate less in R&D projects.

Some further descriptive statistics of these actor-oriented measures are provided in table 5.

Local (ego) network effects: This set of variables captures structural characteristics of the actor's ego-network, which include dyadic and triadic tie-configurations with other actors. Literature suggests these effects to be among the most important driving forces of network dynamics. Given the context of our study, however, they mostly represent control variables and are not emphasized in the following analysis. Reason therefore is the local nature of these variables, referring to effects only in and on the close neighbourhood in the network space.

The most basic effect is defined by the `outdegree` of actor i, representing the basic tendency to form an arbitrary tie to possible alters j, regardless of their individual characteristics. Since most social network structures observed in reality are rather sparse (meaning their density is way below 0.5), this effect tends to be negative, meaning the costs of establishing a tie *per se* in absence of a particular beneficial characteristic outweigh the benefits if no further characteristics make this tie particularly attractive (Snijders et al 2010a).

Another basic feature of most social networks is `reciprocity`, the tendency of an ego i to respond to a former $j \Rightarrow i$ with the establishment of an $i \Rightarrow j$ tie (c.f. Wasserman 1979). In our context this effect captures a tendency of current project leaders to invite partners to join a project. In most social relationships such as friendship this effect has shown to be positive and of high explanatory power. Yet in our case of directed relationships, we expect this effect to be less pronounced, since project partners due to their characteristics might not necessarily qualify to be project leaders, thus might not have the chance for reciprocal action.

`Transitivity` is a measure for the tendency towards transitive closure, sometimes also called the clustering coefficient. Formally, it determines the likelihood a connection between $i \Rightarrow j$ and $i \Rightarrow h$ is closed by a connection between $j \Rightarrow h$ and/or $h \Rightarrow j$, or in other words that "partners of partners become partners" (e.g. Davis 1970). In our case we make use of the measure for transitive triads, which measures transitivity for actor i by the number of other actors h for which there is at least one intermediary j forming a transitive triplet of this kind. In line with a large body of earlier research, we expect this effect to be positive.

Global network effects: Global network (or degree-related) effects express global hierarchies in a way that they reflect actors positions in the overall network. They capture the tendency of actors to send and receive ties according to their amount of out- and in-degrees, independent of their particular position in the network. Such effects can only be analyzed in a directed networks. They are of particular interest against the background of our study, since they are – in contrast to commonly applied triadic measures – suitable to analyze the tendency of certain actors to establish central and dominant positions in the overall network structure. Therefore, in our analysis we primarily focus on outdegree-related global effects.

`Out-degree popularity` captures the reputation and social recognition effect of the network on the activities of actor i. A positive parameter indicates that actors sending a higher amount of ties are also considered as more attractive to receive them in terms of higher indegrees. It in a way represents the global version of the local `reciprocity` effect, leading over time to a convergence of in- and outdegrees. This can in our case be interpreted in a way that actors leading many research projects also happen to often get invited to become partners in other projects. From a governance perspective, a positive `Out-degree popularity` effect leads to a more even distribution of power, since actors participate more equally in leading as well as following positions in research projects. Yet, in the same way as we argue in the case of `reciprocity`, we leave the direction of this effect to be an empirical question.

Of particular interest for this study is the `Out-degree activity` effect, which is the tendency of actors with high outdegrees to establish even more. A positive parameter indicates a self-reinforcing mechanism leading to an increasing dispersion of out-degrees in the network (Barabási and Albert 1999). It can be interpreted as the in network-structuralic impersonation of what is called the "Matthew Effect" (c.f. Merton 1968, 1988), cumulative advantage (Price 2007) or preferential attachment (Barabási and Albert 1999). Networks driven by this effect tend to stabilize towards a core-periphery structure around some very central, well connected, and influential actors. In the case of public funded research network, a positive `Out-degree activity` will lead to an ongoing and reinforcing concentration of governance structure and agenda-setting around particular actors. Technically, it resembles the squared version of an ego's outdegrees.[7]

Finally, we also include an interaction term between `Out-degree activity` and `role incumbent`, to test if the posited Matthew effect works particularly strong for incumbent actors.

Model Specification

To analyze the influence of actor characteristics and endogenous structural effects, we run a set of three models. All of them contain a set of standard structural dyadic and triadic ego-network control variables. Model I traditionally tests for ego (project leader) covariates, which are assumed to affect the capabilities of creating new outgoing ties. Model II instead tests for degree-related structural effects. In comparison to the set of dyadic and triadic structural effects, degree related effects are related to the overall number of in- and out-degrees of alter and ego, independent of their position in the others network. Thus, while the first set of controls refers to the local hierarchy of the actors ego network, degree related effects refer to a global hierarchy in the overall network. Finally, in model III we test for the joint effects of actor covariates and degree related effects simultaneously.

All parameters are estimated under full maximum likelihood according to the algorithm proposed by Snijders et al (2010b), which has proven to be more efficient

[7] In the interpretation of this effect, one should take in the understanding that the outdegree effect itself is also included, and the parameters will be estimated such that the balance between creation and termination of ties agrees with the data. Taking a given function and then adding a positive coefficient multiplied by a quadratic function of the outdegree, (and note that the added quadratic function will because of the estimation be centered at the value where the balance occurs) imply that for current low oudegrees, the push to lower values will be relatively amplified, while for high outdegrees, the push to higher values will be relatively amplified.

for small datasets. Technically, we make use of the SAOM application of SIENA (Ripley et al 2013), a package for the statistical environment of R.

5 Results

Goodness-of-fit evaluation

As a first goodness-of-fit measure one can consider the t-convergence values of the parameters, indicating whether the simulated values deviate from the observed values. For a good model convergence, Snijders et al (2010a) suggests to only include parameters with t-values of convergence between estimated and observed parameters below 0.1, what is given for all parameters in all corresponding models. The values in general show better convergence in later models, which confirms the effectiveness of our applied forward-selection strategy of model choice (cf. Lospinoso and Snijders 2011). Since the class of stochastic actor-oriented models is still under development, there exists no direct equivalent to the R^2 indicator of least squares regression models. Latest advances, however, offer a set of instruments to asses the model fit in stochastic settings. Score tests for each variable proposed by Schweinberger (2012), lead to overall satisfying results and gradually increased from model I to III. To account for changing dynamics over time, i.e. due to different policy focus and overall funding available, we carry out the test for time heterogeneity proposed by Lospinoso et al (2011), which indeed shows a significant effect. As a result, an interaction term between year dummies and the actors outdegree is included in all models.

Also, we perform the Monte Carlo Mahalanobis Distance Test proposed by Lospinoso and Snijders (2011). Here we test the null hypothesis that auxiliary statistics such as indegrees, outdegrees and geodesic distance of observe data is distributed the results of Monte Carlo simulations on the estimated coefficients of our SAOM model, using the network in period one as point of departure. The purpose is to evaluate how well our stochastic model simulates transformation from the initial to the final network in terms of different degree distributions. The underlying logic is to evaluate if a simulated process of network evolution based on our estimated coefficients leads to a network embodying the same structural characteristics as the observed one, the underlying mechanics of network change are appropriately modeled.[8] We here use the classical structural characteristics proposed by Lospinoso and Snijders (2011) indegree (how many nodes receive $1, 2, \ldots, n$ incoming ties), outdegree (how many nodes establish $1, 2, \ldots, n$ outgoing ties), geodesic distance (who many actor-dyads have a shortest path of $1, 2, \ldots, n$ that connects them in the network), and triad census (how many actor-triads show a certain connection pattern). We thereby also provide first validation of the ability of our model to predict future developments of research networks based on our estimated coefficients. The results are illustrated in figure 3.

The results suggest that our model is very well suited to predict the indegree and geodesic degree distribution, where the simulation results are very close to the observed values. Same holds for most forms of triad constellations. The only weakness of the model up to now appears to be the inconsistent identification of low outdegrees.

[8] Note: We here do not compare the characteristics of individual nodes, but the aggregated characteristics of the whole resulting network.

While the model performs very well for high outdegrees, the simulated statistics for nodes with zero up to two outdegrees deviates highly from the observed values. However, since we are primarily interested in the distribution of the high degrees (the dominant nodes in the network), we consider the accuracy of prediction on the low end only as second priority.

Models of network dynamics generally have a tendency to suffer from colinearity problems, since a main share of variables originate from the same source, an actor's out- and indegrees.While building our models, we carefully checked for high correlations among the coefficients, where we in no case found a correlation of network related effects above 0.5. We also observed carefully the estimate stability when in- or excluding network-related variables, and found our models to be sufficiently stable.

SAOM regression models

Table 1 reports a set of SAOM on the probability of ego i to establish a new outgoing tie, depending on the egos characteristics, ego network, and global degree related effects. In our context that means that a project consortium leading firm i establishes a collaboration with some project partner firm j.

Table 1: Stochastic Actor-Oriented Model: Probability of Tie Creation Ego→Alter

	Model I		**Model II**		**Model III**	
Variable	Coef.	Std. Er.	Coef.	Std. Er.	Coef.	Std. Er.
Structural ego-network effects						
outdegree	-4.314^{***}	0.540	-5.913^{***}	0.342	-6.264^{***}	0.453
reciprocity	1.143	0.622	1.411^{**}	0.582	1.034	0.594
transitivity	1.791^{***}	0.345	0.319	0.228	0.229	0.191
Actor level effects						
size small	0.990	0.873			1.601^{**}	0.681
size large	2.644^{***}	0.832			1.629^{**}	0.726
role incumbent	3.424^{***}	0.611			2.759^{***}	0.476
age (ln)	-0.793^{**}	0.267			-0.448^{**}	0.227
Degree related effects						
out-pop			0.085^{**}	0.029	0.077^{**}	0.030
out-act			0.372^{***}	0.047	0.413^{***}	0.073
out-act ∗ role incumbent					1.430^{***}	0.347

Note: *, **, *** indicate significance at 10, 5, 1 percent level, two-tailed

In the first model we jointly test for basic ego-network and ego-characteristic effects. `The outdegree` effect shows, as in most real-life sparse social networks, a negative coefficient. The positive and significant coefficient for `transitive ties` indicates local clustering over time, when partners of "partners become partners" on their on. Actors of `size large` as well as of `size small` establish significantly more outdegrees than their peers of the `size medium` reference group, where the coefficient is higher for large firms. This might reflect the preference of grant allocation decision makers for more stable large firms leading research consortia, or just the higher resource endowments of large players enabling them to manage the coordination of multiple research projects simultaneously. The `age` of the firm, however, *ceteris paribus* manifests in decreasing outdegrees. Allocation preferences towards stable project leaders again should lead to favoring older firms not subject to the liability of newness and the associated high failure rate (Freeman et al 1983). An explanation could instead be found on the demand side, when aging firms loose their innovative drive and stop engaging in early stage research. An interesting finding is the high positive and significant coefficient of `role incumbent`, providing first evidence that the smart grid research network indeed over time tends to be dominated by incumbent actors.[9] Since we are not able to disentangle supply and demand effects of public research funding, this finding again offers different explanations. First, it can be interpreted of revealed preferences of public authorities for consortia led by incumbents, possibly reflecting incumbents strategic advantage of infrastructure ownership or their exercised influence on policy making. On the other hand, it is also possible that incumbents actively strive for consortia leadership positions enabling them to influence early stage research on the future energy grid infrastructure – possibly to preserve the "old regime".

In model II, we test for ego-network and global network degree-related effects. An interesting finding is that, after introducing global degree related network effects, the coefficient of `transitive ties` drops in magnitude as well as significance. This finding demonstrates the usefulness and additional insights of including degree related effects when analyzing directed networks. Since actors increasing high outdegrees, they naturally will also have more potential to form reciprocal ties in their choice set. However, in this case global centralization outweighs local clustering in the further evolution of the network, indicating the development towards a core-periphery rather than a small world like structure. Both `outdegree popularity` and `outdegree activity` show a high positive an significant coefficient, where `outdegree activity` dominates.[10] These findings indicate that the current selection environment in the technological niche of public funded smart grid R&DD indeed shows a tendency to develop towards a global hierarchy. This network-structural "Matthew Effect" over time leads to a development of the network towards a centralized network structure with a high dispersion of degrees. In such network structures, some actors continuously move in a reinforcing manner towards dominant positions. Such tendencies can be observed in many real-life networks. For instance, in a comparative analysis of different sectors of the Danish renewable energy research, Hain (Mimeo) finds universities to over time occupy central hub positions in the windpower as well as hydrogen research community. Thus, the question is which actors benefit from this effect.

Therefore, in model III we jointly test for the impact of ego-characteristic and global degree related network effects on an actor's establishment of further outdegrees. While ego-network effects remain roughly unchanged compared with the former model, the investigation of actor level effects reveal some interesting insights. Again, the effects of `size large` and `role incumbent` are significant and show positive coefficients, even though with decreased magnitude. However, the degree related effects `outdegree popularity` and `outdegree activity` both remain positive and

[9] While we first categorized new entrants separately, we decided to in our final analysis only contrast incumbents with all other actors, who we assume to not share the same incentives to stabilize the existing system. Further, in an unreported analysis including also a dummy for new entrants, we find no significant effect for this variable.

[10] Note that all parameters in SAOM are standardized (divided by their mean), thus making a direct comparison of their magnitude difficult within a model, but easier between models.

significant, where the latter even increases in magnitude. Thus, `outdegree-activity` appears to be a major driving force in the evolution of public funded smart grid research networks, an effect that appears to be even stronger when controlling for firm characteristics.

Overall, the results of this final model suggests incumbents indeed to be in a favorable position to inherit dominant roles in the research network over time. While they are generally more likely to establish outgoing ties, preferential attachment and accumulated advantages reinforces this tendency over time. Finally we introduce an interaction term between `outdegree-activity` and `role incumbent` to test if degree-related effects work particularly in favor of incumbent firms, which appears to be the case. It shows a high positive coefficient, significant at one percent level, providing further evidence for the advantageous effects incumbents enjoy in the development of their network position. Here we are able to provide evidence not only of the benefits incumbents *per se* in leading research consortia, but also that powerful mechanisms of network evolution work in their favor. If these effects are driven by the demand or supply side of public research funding can only be speculated. So may it be that incumbents due to factors like their political influence and ownership of the energy grid infrastructure are generally more successful in grant applications, but the ones who decide to massively exercise their influence on energy grid technology development will enjoy structural forces of network evolution supporting them to do so.

This process can easily be forecasted in a simple Monte Carlo simulation of network evolution using the parameters estimated in our SAOM for calibration. After 10 period, such a network already shows a very strong core-periphery structure, where the core is almost exclusively populated by incumbents.

Robustness tests

Our main results are primarily dependent on a correct classification of the actors' roles, which in our case is determined by the categorization of industry experts. To cross-validate these sensible results, we ran all models with alternative classification strategies. First we apply a simple subjective classification strategy similar to the one used by Erlinghagen and Markard (2012), where we determine incumbents by certain combinations of NACE codes, size, and age of an actor. However, a classification exclusively based on these objective measures would often fail to identify actors. Second, we use a computational approach, where we collected approximately 550 Danish industrial publications related to energy system topics from the period 1995-2000 and used a fuzzy string matching process to identify actors that appear in the analyzed research projects within the description parts. We assume that actors that appear in a "energy context" can be considered established in the industry.

Furthermore, as already discussed, the number of an ego's outdegrees can in the projection of a two-mode network (project association → actor) to an one-mode network (actors →) actors) be influenced by the number of projects lead by an actor as well as the number of participants in such projects. To test for bias arising from the tendency of certain actors to establish smaller or larger project-consortia, we rerun all models including a variable representing the average number of members in projects the ego-actor participated in, in the current and last year. In all cases, the results point in the same direction but are less pronounced, which speaks in favor of using industry experts for the identification of nuanced roles such as energy industry incumbents. All additional regressions mentioned are – for the sake of brevity – not reported, but available on request.

6 Conclusion

In this paper, we studied the influence of incumbent firms on the structural dynamics of research networks in technological niches at the case of public funded research projects. Drawing from innovation system, sociotechnical transitions, and network evolution literature, we identify a set of structural – as well as firm-characteristic – effects that might enable incumbents over time to move towards dominant positions in the research network. These effects generally originate from the supply side of public grant allocation, for instance the preferences of public authorities towards certain firms, technologies, project types. In addition, we identify demand side effects related to strategic motives of incumbents to participate in technological niches, and draw implications for the rate and direction of technological change as an outcome of research network dominated by incumbents.

To do so, we conduct a stochastic actor-oriented network analysis, where we model the hierarchy and power structure in the network with directed ties between research project leader and partners. We assume the leader of such projects as mainly influencing the context of conducted research as well as the selection of further participants, thus strongly influencing the development of technological trajectories in such niche networks. In contrast to mostly pronounced function of "knowledge diffusion" in research and innovation networks, we focus on governance structures as a result of project leadership. By doing so, we are able to analyse up to now unobserved cumulative and self-reinforcing effects of network dynamics and relate them to firm strategies and vested interests.

Our results indicate path-dependent and cumulative effects of firm characteristics such as size, and degree-related "Mathew effects" in the development of the research network, which over time lead to a centralization of the network structure. While we find incumbents *per se* to enjoy benefits in establishing new outgoing ties, we find path-dependent effects to work particularly in their favor. Overall, the observed dynamics suggest a development of the network towards a structure where incumbents occupy the most central positions.

By emphasizing governance and influence related aspects combined with firm characteristics and strategies, we provide an alternative – and perhaps more critical – perspective on research and innovation networks, and the role of the state in their coordination. The development of the electricity grid into a smart grid is not envisioned as a radical process that threatens the existence of the established regime. Rather it is a process of upgrading and adaptation to new types of energy generation. Yet, the strong centralization effects in the network and the high probability of incumbent players to lead research projects are surprising, particularly against the backdrop of the literature arguing for niche protection when developing sustainable technologies. Methodologically, we demonstrate the richness of stochastic actor-oriented models to answer such questions by modeling collaboration decisions on actor level, and relating them to macro outcomes of structural network evolution. We further contribute to a more nuanced discussion on the role and behavior of incumbents in sociotechnical transitions by identifying which firm-characteristics and structural forces of network evolution facilitate them to - for the better or the worse - increase their influence in the formulation of early stage research agendas. Our findings also provide implications for policy. Whether these increasingly incumbent-dominated networks are favorable or not is a rather normative discussion, which would go beyond the scope of this research.

However, the here unveiled interplay between firm characteristics, strategy and network dynamics have to be considered carefully, since they are to some extent policy orchestrated and not fully subject to natural evolution. The supply side selection environment is subject to *ex-ante* biases of grant allocation preferences of public authorities, as well as *ex-post* biases of firms observing these preferences and probably optimizing their project constellation patterns. Further, demand side effects related to firm strategies and vested interests affect the extent to which they participate in public funded research projects or choose other forms of collaboration, and which positions they prefer in such projects. While we derive some suggestions from theoretical reasoning and existing (mixed) evidence, we are not able to analytically disentangle supply and demand side effects. Even though this is supported by prior results on the same data (c.f. Jurowetzki 2013), we yet do not provide a direct analytic link between the identified structural change of research networks and outcome characteristics in terms of more radical or incremental innovation.

Consequently, we consider future research separating supply and demand side effects of public funded research network formation as a promising avenue for further research. Here, the combination of rich supply side data, such as evaluations of project grant applications together with firm-level data on motives and strategies appears to be particularly promising to disentangle supply and demand side effects in public funding of R&D and the resulting network dynamics. While the empirical link between the network structure and innovation outcomes can be – and has been – established using network data to explain innovation output measures such as patents, the link between micro-level actor behavior and network dynamics with macro-level outcomes faces some empirical challenges. One obvious challange is the endogeneity caused by interdependence of actor behavior and network position. Co-evolutionary models of networks and actor behavior as proposed by Snijders et al (2007) and applied by Checkley et al (2014); Veenstra and Steglich (2012); Steglich et al (2010) could be an attractive solution. Furthermore, additional empirical cross-country and cross-industry evidence is needed to clarify the role of incumbents in research networks and sustainable transitions in general. We hope our work stimulates further work on this issue, which we consider as a promising avenue for future research.

Acknowledgments

We would like to thank all participants of the Jena ISS conference 2014, the Nice KID workshop 2014, the Copenhagen DRUID society conference 2014, the Stanford Network Forum ST2014, the IKE research seminar series 2014, the Oxford AIE conference 2013 and the Halle ENIC workshop 2013 for invaluable inspiration and feedback. All opinions, and errors, remain our own.

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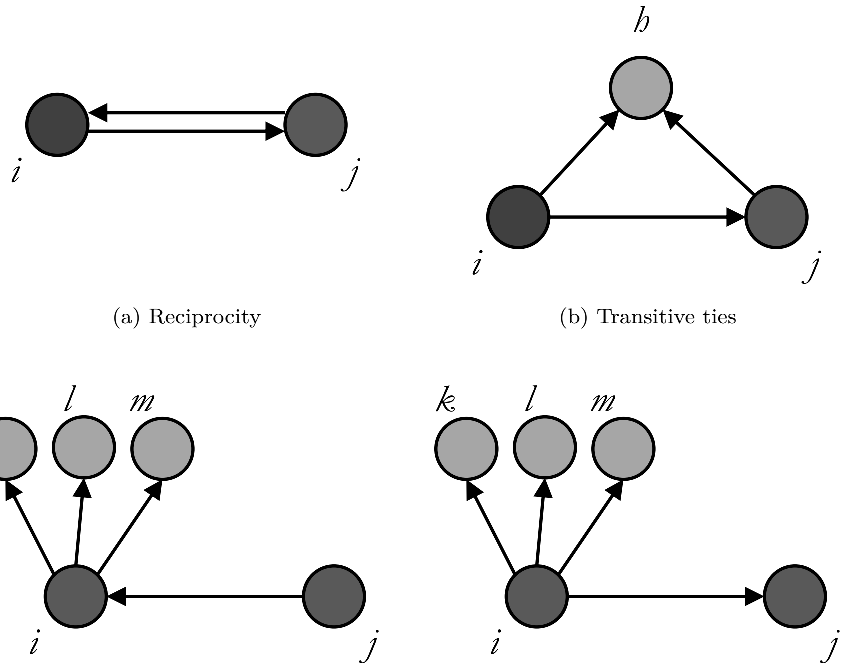
Appendix

Fig. 1: Illustration of Ego-Network and Degree-Related Effects



(a) Reciprocity

(b) Transitive ties

(c) Outdegree popularity

(d) Outdegree activity

Note: The variables in the illustration are unrelated to the proposed model and analysis.

Table 2: Variable Descriptions

Variable	Formal	Description
outdegree	$s^{net}_{i1}(\chi) = \sum_j \chi_{i,j}$	Sum of outdegrees of ego i
reciprocity	$s^{net}_{i2}(\chi) = \sum_j \chi_{i,j}\chi_{j,i}$	Sum of reciprocal ties between ego i and alter j
transitivity	$s^{net}_{i3}(\chi) = \sum_{j<h} \chi_{i,j}\chi_{i,h}\chi_{j,h}$	Number of transitive patterns in ego i's relations (ordered pairs of alters (j, h) to both of whom ego i is tied, while also j is tied to h)
size small		Dummy variable, taking the value of 1 if ego i is in size category small ($<$ 25 employees), 0 otherwise
size large		Dummy variable, taking the value of 1 if ego i is in size category large ($>$ 100 employees), 0 otherwise
role incumbent		Dummy variable, taking the value of 1 if ego i is categorized as incumbent, 0 otherwise
age (ln)	$ln(age^{year})$	Age of ego i in years, natural logarithm
out-pop	$s^{net}_{i15}(\chi) = \sum_j \chi_{i,j} \sum_h \chi_{j,h}$	the sum of the out-degrees of alters j to whom ego i is tied
out-act	$s^{net}_{i19}(\chi) = (\sum_j \chi_{i,j})^2$	the squared out-degree of the ego i

Table 3: Network turnover frequency

Periods	$0 \Rightarrow 1$	$1 \Rightarrow 0$	$1 \Rightarrow 1$	Jaccard
$1 \Rightarrow 2$	22	3	42	0.627
$2 \Rightarrow 3$	30	2	62	0.660
$3 \Rightarrow 4$	53	39	53	0.366

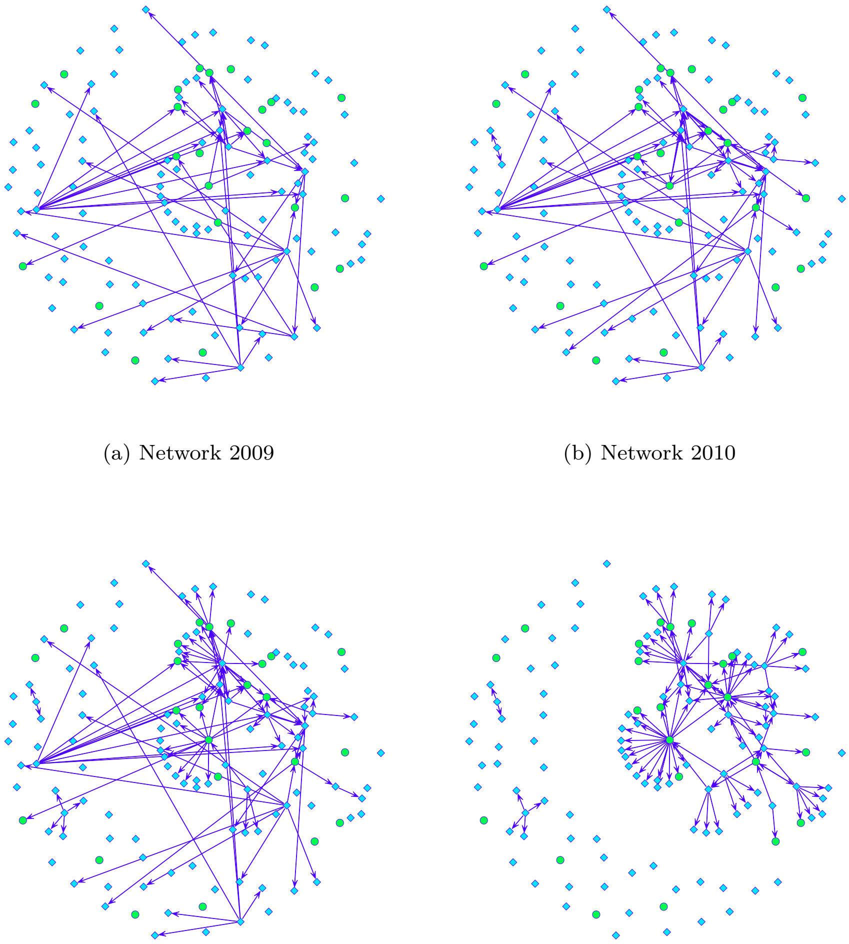
Table 4: Network density indicators

Periods	1	2	3	4
Density	0.003	0.004	0.005	0.006
Average degree	0.341	0.485	0.697	0.803
Network rate	0.383	0.490	1.406	-
Number of ties	45	64	92	106
Mutual ties	0	2	4	3
Asymmetric ties	45	60	84	100

Table 5: Descriptive Statistics

Variable	Min.	Max.	Mean	Std. Dev.
size small	0	1	0.356	0.481
size large	0	1	0.432	0.497
Role: Incumbent	0	1	0.182	0.387
Role: Newcommer	0	1	0.106	0.309
Firm age	1	110	22.437	22.130

Fig. 2: Network Development in Public Funded R&D in Smart-Grid Research



(a) Network 2009

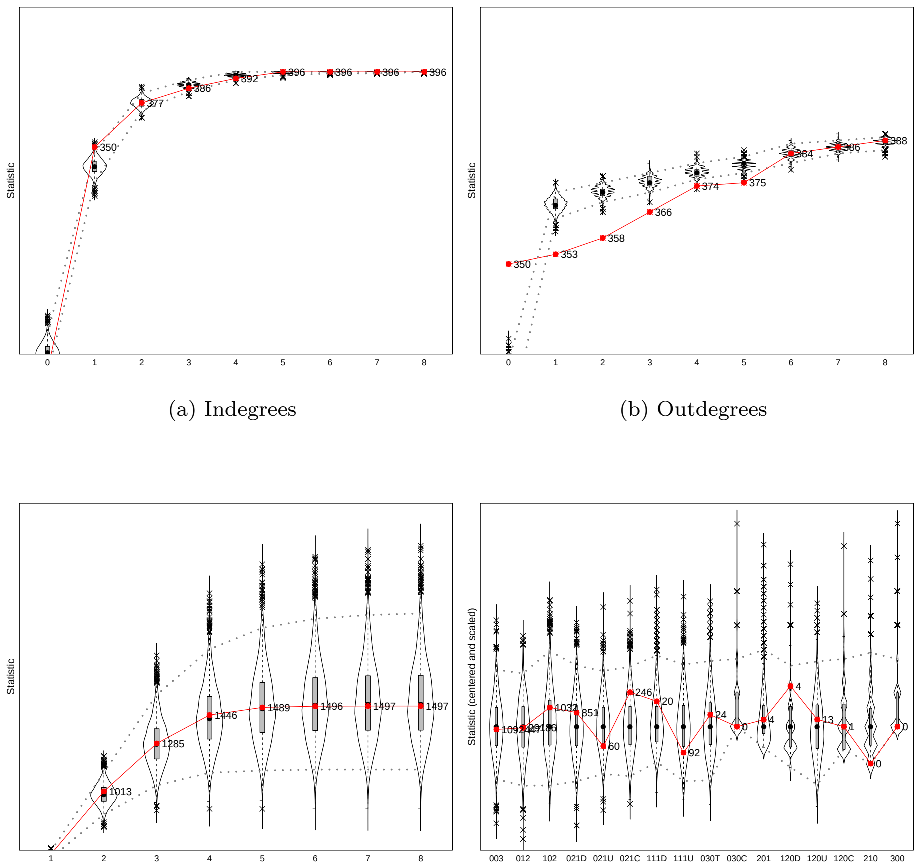
(b) Network 2010

(c) Network 2011

(d) Network 2012

Note: Research network on basis of joint public funded research projects. Ties are directed from project-leader ⇒ project partner. Circles represent incumbents, squares all remaining types of organisations. The graphical presentation was done with the R package *Igraph*.

Fig. 3: Goodness-of-Fit: Monte Carlo Mahalanobis Distance Test



(a) Indegrees

(b) Outdegrees

(c) Geodesic

(d) Triad Census

Note: X-axis: P-value obtained by the Monte Carlo Mahalanobis Distance Test proposed by Lospinoso and Snijders (2011), testing null hypothesis that auxiliary statistics of observe data is distributed according to plot.
Y-axis: Value of auxiliary statistic (indegree, outdegree, geodesic distance, triad census).
Solid red line the observed values equal auxiliary statistic.
"Violin plots" show simulated value of statistic as kernel density estimate and box plot of 95% interval.