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Technological development for sustainability: The role of network management in the innovation policy mix

Patrik Söderholm[a,*], Hans Hellsmark[b], Johan Frishammar[c,d], Julia Hansson[e,f], Johanna Mossberg[g,h], Annica Sandström[i]

[a] Luleå University of Technology, Economics Unit, Luleå, Sweden
[b] Chalmers University of Technology, Environmental Systems Analysis, Gothenburg, Sweden
[c] Luleå University of Technology, Entrepreneurship and Innovation, Luleå, Sweden
[d] Stockholm School of Economics, House of Innovation, Stockholm, Sweden
[e] Chalmers University of Technology, Maritime Environmental Sciences, Gothenburg, Sweden
[f] IVL Swedish Environmental Research Institute, Gothenburg, Sweden
[g] RISE Research Institutes of Sweden, RISE Bioeconomy, Gothenburg, Sweden
[h] Luleå University of Technology, Energy Science Unit, Luleå, Sweden
[i] Luleå University of Technology, Political Science Unit, Luleå, Sweden

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A B S T R A C T

Despite the key role of actor networks in progressing new sustainable technologies, there is a shortage of conceptual knowledge on how policy can help strengthen collaborative practices in such networks. The objective of this paper is to analyze the roles of such policies – so-called network management – throughout the entire technological development processes. The analysis draws on the public management and sustainability transitions literatures, and discusses how various network characteristics could affect the development of sustainable technologies, including how different categories of network management strategies could be deployed to influence actor collaborations. The paper's main contribution is an analytical framework that addresses the changing roles of network management at the interface between various phases of the technological development process, illustrated with the empirical case of advanced biorefinery technology development in Sweden. Furthermore, the analysis also addresses some challenges that policy makers are likely to encounter when pursuing network management strategies, and identifies a number of negative consequences of ignoring such instruments in the innovation policy mix. The latter include inefficient actor role-taking, the emergence of small, ineffective and competing actor networks in similar technological fields, and a shortage of interpretative knowledge.

1. Introduction

While the development of new sustainable technologies is essential for addressing the climate and environmental challenges facing society, such technologies face significant hurdles, not the least since incumbent technologies tend to be intertwined with dominant business models, value chains, industry standards, as well as institutions (e.g., Walrave et al., 2018). Transitions towards more sustainable production patterns are therefore often characterized by relatively long development periods during which technology-specific systemic structures – i.e., actor networks, value chains, institutions, etc. – must be put in place and aligned with the emerging technologies. This implies that sustainable technological change may experience multiple market, system and institutional failures (Weber and Rohracher, 2012), in turn requiring the adoption of multi-faceted policy interventions: innovation policy mixes (Borrás and Edquist, 2013; Flanagan et al., 2011; Flanagan and Uyarra, 2016; Reichardt and Rogge, 2016; Rogge and Reichardt, 2016). For instance, it has long been acknowledged that a combination of technology-push and demand-pull instruments is required for stimulating innovation.

In this paper, we address the question how effective innovation policy mixes for sustainable technological development can be identified and pursued by devoting specific attention to the performance and, not least, the management of actor networks. Our main thesis is that network management, i.e., activities deliberately implemented to influence the structure and the substance of actor networks as well as the

* Corresponding author.
E-mail address: patrik.soderholm@ltu.se (P. Söderholm).

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collaborative processes taking place in these networks, will be an essential component of the innovation policy mix.

The technology-specific structures that need to be developed in order to support an emerging technology will be shaped by a wide range of collaborating actors, all with a stake in that technology. These may include technology providers, research institutes, end-users, but also various authorities such as government agencies at national level and local authorities. Indeed, in most modern societies, public policy processes are not only associated with administrative hierarchy; they concern different levels of government and tend to be created within informal, multi-actor networks beyond formal hierarchies (Hooghe and Marks, 2003; Pierre and Peters, 2005). Such collaborations have, however, proved inherently difficult to organize and manage (Markard et al., 2012; Ollila and Yström, 2015; Sharma and Kearins, 2011). For this reason, innovation policy mixes should not only focus on raising the rate-of-return on risky investments in long-term R&D and/or commercial-scale demonstration plants; they also need to provide support to collaborative processes in actor networks.

Even though the literature has recognized the importance of actor networks for progressing the development of sustainable technology (e.g., Borrás and Edquist, 2013), there exists very limited conceptual analyses of how policy can help strengthen the collaborative practices in such networks. For instance, the Technological Innovation System (TIS) literature includes assessments of the system weaknesses hindering the development of sustainable technologies and, in subsequent steps, of the policy interventions needed to overcome these barriers. Still, TIS studies tend to privilege structure while downplaying actors' agency. In addition, they typically lack conceptual foundations for studying the effectiveness of actor networks, e.g., in terms of addressing various types of knowledge coordination problems (Frishammar et al., 2018). Other studies recognize the importance of actors' agency, and view it "as the result of a collective and embedded capacity, and hence developed and reproduced through actor networks," (Smith and Raven, 2012, p. 1031). Still, also this line of research lacks conceptual analyses of policies purposefully designed to influence the performance of these networks (see Section 2.2 for further references).

The overall objective of this paper is to analyze the role of network management throughout the technological development processes. The analysis builds on the notion that the research on sustainability transitions (Markard et al., 2012) could benefit from cross-fertilizations with the policy network literature (e.g., Klijn, 2005; Marsh and Smith, 2000). In the paper, we draw on these two strands of research, and discuss the roles of various network characteristics for sustainable technological development as well as how different network management strategies could be used to influence the collaborative processes. The key contribution of the paper is an analytical framework that addresses the changing roles of these strategies at the interfaces between various phases of the technological development process.

Prior literature provides key inputs to the analytical framework, and we also draw heavily on previous empirical studies of the development of advanced biorefinery technology in Sweden (Coenen et al., 2015; Frishammar et al., 2018; Hansen and Coenen, 2017; Hellsmark et al., 2016a, 2016b; Karltorp and Sandén, 2012; Mossberg et al., 2018; Novotny and Laestadius, 2014; Peck et al., 2016; Bauer et al., 2018). These studies provide illustrations rather than empirical evidence of the validity of the proposed framework. From a network management viewpoint, the biorefinery case is highly relevant. Biorefinery technology centers on different but yet complementary platform technologies that can be used to produce a wide portfolio of products, i.e., fuels, materials and chemicals in combination with heat, electricity etc. (Pandey et al., 2011). Achieving this, however, requires extensive collaboration across organizational and governmental boundaries, not least since most of biorefinery concepts are immature and characterized by small production volumes as well as substantial technical and market-related uncertainties (Hellsmark et al., 2016a).

It should be noted that network management will be important in many geographical contexts, also at the global level. Our analysis is however especially relevant for countries that aim at pursuing industrial policy ambitions, thus supporting national and local networks around certain technological fields. Our focus on *sustainable* technological development is motivated by that in such cases policy plays a particularly important role. In this case, policy instruments aim at *redirecting* technological innovation rather than merely dealing with the effects of technological innovation as it diffuses throughout the economy (e.g., Acemoglu et al., 2012). Moreover, the emergence of effective actor networks tends to be a particularly complex process in the case of sustainable technological development. For instance, incumbent industries will often benefit from failures of internalizing the environmental costs of existing technologies, but at the same time the adoption of sustainable technology is sometimes contingent on the involvement of the incumbent industry actors (Hansen and Coenen, 2017). Incumbents assert control over key complementary infrastructure and resources, but may have conflicting perceptions about the desired goals and outcomes. Also in this respect, biorefinery technology offers valuable empirical lessons with several incumbent actors along the value chains, e.g., pulp and paper sector, chemical industry, etc. (e.g., Hellsmark et al., 2016b). Still, in spite of the focus on sustainable technologies, the analysis also offers generic lessons.

The paper proceeds as follows. Section 2 discusses the innovation policy mix, i.e., introduces the roles of technology-push, demand-pull and systemic policy instruments throughout the technological development process. Particular attention is devoted to motivating the paper's focus on network management, i.e., a subset of systemic instruments. Section 3 introduces the policy network literature, and discusses a number of the factors that may influence the outcome of collaborative processes in networks. The role of network management in the technological development process is then illustrated in two consecutive steps. In a first step (Section 4), we introduce different forms of network management and three strategies that can be pursued to affect network structure, substance and process. In a second step (Section 5), we discuss the changing characteristics and roles of network management strategies at the interface between the various phases of the technology development processes. Throughout Sections 3–5, we illustrate each key argument by referring to the biorefinery case. Finally, Section 6 concludes the paper and highlights some avenues for future research.

2. Innovation policy mixes in sustainable technology development

2.1. Technology-push, demand-pull and systemic policy instruments

There is a consensus in existing literature that innovation policy, not least that focusing on sustainable technological development, needs to build on a mix of various instruments. The weaknesses in emerging socio-technical systems are typically diverse and multifaceted, and include not only market imperfections (e.g., negative environmental externalities) but also structural and transformational system failures (Klein-Woolthuis et al., 2005; Metcalfe, 2005; OECD, 2015; Weber and Rohracher, 2012). Examples include various institutional constraints, the absence of diversity in the actor base, knowledge gaps, lack of collaboration among key actors, etc. (e.g., Frishammar et al., 2018; Wieczorek and Hekkert, 2012).

Fig. 1 provides an overview of the various phases of the technological development process (following IEA, 2015), and introduces three broad categories of innovation policy instruments and their respective roles in this process (Borrás and Edquist, 2013; Rogge and Reichardt, 2016). These include:

(a) *Technology-push instruments* that facilitate provision of basic and applied knowledge inputs, e.g., through R&D grants and loans, pilot plants, patent law, tax breaks, etc.
(b) *Demand-pull instruments* that support the formation of new markets,

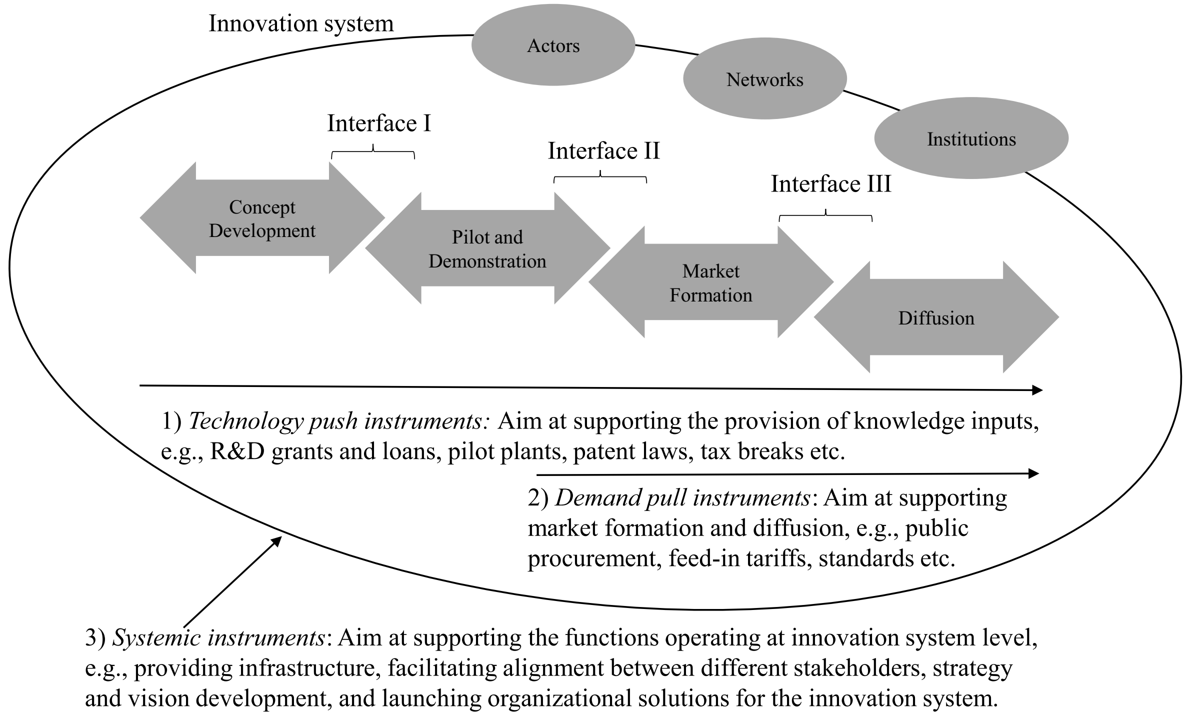

Fig. 1. The role of different policy instrument mixes in progressing new technologies.

and the diffusion of new technology, e.g., through public procurement, feed-in tariffs, standards etc.

(c) *Systemic instruments* that support the functions operating at the innovation system level, such as by providing infrastructure, facilitating alignment among stakeholders, stimulating strategy and vision development, and providing organizational solutions.

Fig. 1 also introduces three interfaces between the phases of the technological development process. These interfaces provide an appropriate starting point for discussing the role of innovation policy mixes throughout this process, and are later used in our analytical framework.[1]

The existing literature has mainly focused on the role of technology-push and demand-pull instruments, respectively. At the interface between the concept development and the pilot and demonstration phases (Interface I), there is a need to expand the scope of learning processes beyond advancing scientific knowledge and reduction of technical risks, towards promoting both general and proprietary knowledge development such as learning-by-doing (Edler et al., 2013). For instance, a mix of public R&D support and co-funding of pilot and demonstration plants can help create variation, and permit new inventions to be verified, optimized and up-scaled (Jacobsson and Bergek, 2004).

Interface II, i.e., between the pilot and demonstration and the market formation phases, is characterized by an intensified focus on various learning processes (e.g., learning-by-using). Technology-push instruments still play a key role, but the establishment of niche markets through the use of technology-specific demand-pull instruments (e.g., quota, production price premium, public procurement, etc.) is equally important (Lehmann and Söderholm, 2018).[2] Thus, novel technologies must be tested in markets with real customers, and governments need to create the conditions for firms to raise long-term loans in areas where the established financial organizations have not yet been willing to provide sufficient funding (Kemp et al., 1998; Del Río and Bleda, 2012).

Finally, at the interface between the market formation and the diffusion phases (Interface III), there is further focus on learning from the feedback of customers and the broader society, e.g., developing standards and gaining legitimacy. Innovation policies must recognize the need to amend existing regulations, and make sure that technology-neutral demand-pull, e.g., carbon taxes, are in place to internalize the external costs of incumbent technologies. Public support to knowledge development is still essential, but could now be more biased towards supporting permanent test centers that can support producers in a wide range of ways, from initial R&D experience to product certification (Hendry et al., 2010).

While there is a rich conceptual and empirical literature on technology-push and demand-pull instruments, much less attention has been devoted to the assessment and conceptualization of different types of systemic instruments (e.g., Borrás and Edquist, 2013). To the best of our knowledge, this instrument type was first introduced by Smits and Kuhlmann (2004), who noted that systemic instruments are tools that focus on the level of the innovation system rather than on the various functions of the system (see also Wieczorek and Hekkert, 2012), and with an emphasis on the provision of infrastructure, facilitating alignment among stakeholders, as well as stimulating strategy and vision development. Thus, while technology-push and demand-pull instruments represent the engines of innovation policy, systemic instruments can help that engine run more efficiently.

Even though the existing transitions (e.g., TIS) literature has identified system weaknesses in the form of poorly functioning actor networks, vague policy visions, lack of infrastructure, etc., little attention has been devoted to how policy can address and manage these weaknesses throughout the entire technological development process (see further Section 2.2). While a few policy lessons have been identified, e.g., policy visions can stimulate R&D strategies already early in technological development and infrastructure support will be important in the latter interfaces, there is scope for more systematic research on these issues. This paper targets this research gap in the specific context

[1] By referring to *various interfaces*, we aim to emphasize the iterative character of the technological development process, i.e., with important feedback loops.

[2] An innovation policy mix based on technology-push and demand-pull instruments also creates opportunities for 'followers' to benefit vicariously from the learning generated by early investments (Bergek et al., 2008).

of network management, i.e., a subset of systemic instruments, whose goal is to bridge gaps and stimulate co-operations across different actors with various backgrounds and institutional positions.

2.2. Managing actor networks in innovation policy: lessons from the literature

The importance of actor networks for innovation has been emphasized in several strands of the literature. One prominent example is the sustainable transitions literature (Geels and Raven, 2006; Markard et al., 2012). This includes, for instance, the TIS literature in which actor networks represent a key concept (Bergek et al., 2008; Jacobsson and Johnson, 2000). The Strategic Niche Management (SNM) literature has focused on 'experiments' as key arenas for socio-technical development (Schot and Geels, 2008), and how these can bring together actors in shared networking and learning processes. Furthermore, the management literature has emphasized the importance of innovation ecosystems, which refer to how companies form networks among each other (e.g., Oh et al., 2016). For instance, de Vasconcelos et al. (2018) study how single entrepreneurs are dependent on other actors, which together have to address various collective uncertainties.[3]

In spite of some recent contributions – see also Musiolik et al. (2012, 2018) as well as Chen and Hung (2016) – scholars criticize the existing literature for not adequately considering the role of actor networks. Kern (2015) calls for more elaborate studies of the political agency of diverse sets of actors, and how actor networks shape sustainability transitions. Musiolik et al. (2012) argue that even though the literature has addressed inter-organizational networks and their role in different learning processes, "the role of networks in supporting collective action and system building has been less in focus," (p. 1033) (see also Farla et al., 2012). In addition, de Haan and Rotmans (2018) make a strong case for better recognizing actors and agency in sustainability transitions, and the authors propose a preliminary theoretical framework that can address this.

Overall, there is thus a lack of conceptual research on the role of actor networks and network management in innovation systems and policy. Specifically, many studies often make clear *what* was done by different actors in terms of progressing new sustainable technology, but fail to address *how* this was achieved (e.g., Newell et al., 2017). The processes by how something is done are at the heart of network management, and we argue that neglecting the importance of these issues in the design of innovation policy mixes will miss opportunities to better understand how the various collaborative network activities can be strengthened. Such neglect could also lead to less effective technology-push and/or demand-pull policies, e.g., in the case where new actors with complementary resources and skills are not activated. Moreover, the roles of network management *throughout* the technological development process have also not been addressed in previous research. This is in spite that there are several reasons to expect varying roles for network management at the interface between one phase of this process and another. For instance, different types of actors are needed as technological development progress from exploring novel knowledge to exploiting this in the formation of new value chains.

In this paper, we address the above research gaps by drawing on key lessons from the policy network literature (e.g., Börzel, 1998; Carlsson, 2000; Thatcher, 1998), which in turn roots in organizational science, political science and policy science (Kickert et al., 1997; Klijn, 2005). We combine this with insights from the sustainability transitions literature (e.g., Markard et al., 2012). The reasons for this approach are several. *First*, while policy network theory addresses the internal alignment of various actors, e.g., in innovation systems, it also recognizes the importance of the broader socio-technical setting, i.e., including institutions, incumbent regimes, etc. This is in contrast to actor network studies in the innovation management literature, which tends to have a sole focus on the former (Walrave et al., 2018).

Second, an important point of departure in policy network studies is that policy-making does not only concern top-down steering; it also emerges within decentralized actor networks, and thus more or less stable patterns of social relations among interdependent actors (e.g., Marsh and Smith, 2000).[4] In these networks, state and regional authorities may assume a mediating role rather than operating based on their top-down power (see also Section 4.1). Still, in other instances, the emerging actor networks may align with established associations that provide infrastructure, organizational structure, etc., and with key policy actors primarily playing a supportive role. Musiolik and Markard (2011) provide an illustration of this in the empirical context of the development of stationary fuel cells.

The recognition of such complexity in terms of actors and levels of governance in the policy network literature is well aligned with the most recent innovation policy studies, maintaining that the design of effective policy mixes for sustainability transitions is a complex and highly context-specific undertaking (e.g., Flanagan et al., 2011; Flanagan and Uyarra, 2016; Rogge and Reichardt, 2016). Innovation policy research should therefore abstain from simplified normative notions about policy mixes regardless of context, e.g., without recognition of the policy process, as well as from idealized characterizations of policy makers. Innovation policy mixes also ought to be understood as complex arrangements of different visions, goals and tools that evolve over long periods (e.g., Kern and Howlett, 2009).

3. Actor network characteristics and performance

3.1. The network approach

The concept of a network is increasingly being considered as an analytical lens through which different collaborative processes, including policy-making, can be understood (Kickert et al., 1997; Marsh and Smith, 2000). Networks are structures of resource exchange and negotiation among interdependent actors. In this paper, we are primarily concerned with what Musiolik et al. (2012) refer to as *formal networks*, i.e. "an organizational structure with clearly identifiable members where firms and other organizations come together to achieve common aims," such as the progressing of a given technological field (p. 1034). The development of such fields requires firms, funders, research institutes, consultants, consumers and public authorities, each of these possessing various competences, resources and interests, to coordinate. The network approach puts emphasis on both structure and agency; this rests on the notion that the patterns and qualities of relationships – the network structure – could have important effects on actors' behavior and collaboration. Thus, actors' interests, resources and interaction will influence the outcomes of the collaborations, e.g., R&D actors influencing the trajectory of innovation (e.g., Verbong et al., 2008).

Still, establishing effective actor collaborations where resources are shared and negotiations are productive, are not straightforward processes (Provan and Milward, 2001; Siegel, 2009). Besides scarce resources, various uncertainties regarding the strategic choices made by the actors involved, and the overall institutional framework, need to be addressed (Koppenjan and Klijn, 2004). The various actors typically represent different sectors, and operate according to different organizational logics and agendas. For this reason, they may have diverging believes about future developments, policy challenges and the solutions to these. Complications may also arise as a result of high transaction

[3] Some recent research has also used social network analysis to shed light on technological development and dominant designs (e.g., patent citation networks) (Huenteler et al., 2016a, 2016b).

[4] This also relates to what the public policy literature sometimes refers to as procedural instruments; these may be used for supporting alternative network configurations in order to gain (or regain) legitimacy (e.g., Howlett, 2005).

costs (Agranoff, 2006). As noted above, too uniform networks among incumbent actors may result in myopic behavior, technological lock-in and path-dependent processes (Coenen et al., 2015).

The biorefinery technology case illustrates the importance of establishing actor networks that represent a wide set of roles, i.e., technology developers, infrastructure manager, commercial users, funders, etc. (Mossberg et al., 2018). It also, though, illustrates challenges in activating actors that are deemed essential for the further progressing of the technology. Specifically, previous empirical studies confirm that several development projects in the biorefinery field have lacked participation from the incumbent forestry and chemical sectors, in part due to the industries' limited ability to translate new knowledge into profitable business opportunities. The absence of incumbent firms has caused difficulties in establishing strategic partnerships with actors from industries along the new value chains (Hansen and Coenen, 2017; Hellsmark et al., 2016b; Karltorp and Sandén, 2012; Novotny and Laestadius, 2014; Peck et al., 2016).

3.2. Characteristics of effective actor networks

From a technology development perspective, actor network performance concerns the added value of collaboration in progressing new technology (c.f. Provan and Kenis, 2008), not least in terms of the ability to create and shape collective system structures and resources (e.g., funding, knowledge, etc.). For this reason, it is important to understand the pros and cons of networks in relation to market and hierarchies, and how well actor networks can deal with different challenges, such as varying commitments to overall network goals, institutional and cultural clashes, and turf battles (McGuire and Agranoff, 2011). Although there is no established blueprint for defining effective actor networks, there exist theoretical arguments as well as empirical evidence indicating that certain features tend to be important for overall network performance (e.g., Garigulo and Benassi, 2000; Provan and Milward, 2001). The literature on this issue is limited, but three examples of antecedents for successful actor networks are discussed below, and with special references to actor networks in sustainable technological development processes.

First, one important antecedent to high network performance is *actor diversity*. Since diversity requires the involvement of a number of actors, this feature might be associated with network size. At the same time, large networks are not by necessity diverse, which is why it is more appropriate to focus on actor diversity. Structures composed of a heterogeneous set of actors taking different roles tend not only to be more resilient but also more successful in securing the necessary resources (e.g., competence, funding, etc.). Moreover, actor diversity will often encompass bridging ties connecting the network to other critical clusters and/or organizations (Garigulo and Benassi, 2000; Burt 2000). For instance, actor networks represent structures that facilitate the exchange of different types of knowledge and expand the resource base of individual firms (Musiolik et al., 2012). The need to develop the entire socio-technical system around emerging technologies, i.e., to establish new markets and align institutions in addition to pure technical and engineering work, requires networks comprising actors with very diverse competences and resources (including also public actors).

Second, the *level of integration* is often brought forward as another important antecedent to high-performing actor networks; it can be understood in terms of how densely connected and centralized the network is. It is often argued that networks with many connections and a clear coordinating unit are better equipped to define common challenges and make the necessary priorities (e.g., Provan and Kenis, 2008; Provan and Milward, 1995; Sandström and Carlsson, 2008). Several sustainability transitions studies have highlighted the transformative character of prominent coordinating actors in the technological development process, such as brokers (Belso-Martínez et al., 2015), intermediaries (e.g., Howells, 2006), change agents (Rogers, 2003), prime movers (e.g., Jacobsson and Johnson, 2000), and system builders (e.g., Hellsmark and Jacobsson, 2012). In a recent paper, Musiolik et al. (2018) distinguish between three modes of system-building (based on the availability and the distribution of resources required for novel technological development), which in turn differ in their level of coordination across actors.

Third and finally, while flexibility is considered a relative advantage of networks in relation to hierarchies (e.g., Powell, 1990), *sufficient stability* has also been pointed out as an important antecedent of high network performance. In this context, stability refers to, for instance, prior relationships, durability and level of formalization. Predictability, trust and actors' willingness to share resources are likely functions of network stability (Bryson et al., 2006). It should be noted, however, that stability can be a mixed blessing in technology development processes; the initial actor networks are often limited and undeveloped and there is a need to activate new actors (see also Section 4.2). In addition, overly stable networks where actors neither exit nor enter may create inertia, and this could hamper the development. Stability must thus often go hand in hand with substantial changes in actor network structures.

The case of Swedish biorefinery development can be used to illustrate the above antecedents for effective networks. The importance of actor diversity is well illustrated by the recently emerging actor network around the biofuel producer RenFuel that has developed and patented a method to refine lignin from black liquor, a byproduct from paper pulp production, into lignin oil. This can be further refined into renewable gasoline and diesel. Initially, the main researcher teamed up with an industrial entrepreneur through a Swedish Mentor for research program. These engaged venture capitalists, the forest industry, technical expert companies, and persons with extensive knowledge about refinery technology and received funding from the Swedish Energy Agency (Peck et al., 2016). In a second stage, they have more formally teamed up with other parts of the forest industries as well as with the refinery sector, and are jointly planning to build a lignin production plant, thus indicating successful development so far. The network's ability to activate important incumbent actors, distinguishes it from other (less successful) biorefinery development projects in Sweden.

Other development initiatives in the biorefinery field have also struggled with a lack of well-defined coordinating actors, thus contributing to low levels of integration in actor networks (Mossberg et al., 2018). Furthermore, Hellsmark et al. (2016b) emphasize that coordination among Swedish policy actors has been particularly weak, not least among the government ministries at the national level as well as among various actors at the national and regional levels, respectively. In addition, the low level of integration has negatively affected the actors' ability to manage the interface between the pilot and demonstration phase and the market formation phase. The difficulties experienced when taking the step from successful technical verification experiments in pilot plants to broader market formation activities, could also have important repercussions for the future stability of the actor networks. Significant actors may leave the field, and key competences will be lost (Hellsmark and Söderholm, 2017).

4. Network management: forms and strategies

Given the central role of actor networks in sustainable technological development processes, the question how to influence and improve the evolution of effective structures, not least through various policy initiatives, is imperative. In the public management literature, this is labeled *network management* (Klijn, 2005; Klijn et al., 2010; O'Toole Jr. and Meier, 2004). It can be defined as the actions taken to support and further develop the interactions in actor networks (Koppenjan and Klijn, 2004).

Previous research has emphasized that attempts to influence and improve the evolution of actor networks have often been far from straightforward, and constitute a balancing act (e.g., between stability and flexibility) (Provan and Kenis, 2008; Saz-Carranza and Ospina, 2010).[5] The ways in which such challenges play out and are managed, will depend on what stage the actor network is in, thus acknowledging the role of network dynamics (c.f. Human and Provan, 2000). In addition, it will depend on the *form* of network management that is in place (Provan and Kenis, 2000), as well as on the *types* of network management strategies that are employed (Klijn, 2005). A discussion of the last two issues follow in the remaining parts of this section, while Section 5.1 is devoted to the dynamic issue of managing networks at the various interfaces between stages in the technological development process.

4.1. Forms of network management

Based on Provan and Kenis (2008), we can distinguish between three categories of network management in the context of formal actor networks. *Shared management* refers to networks with no formally defined management entities. The involved actors perform the management tasks on emergent bases, enhancing inclusiveness and flexibility but with the risk of becoming inefficient. It should be noted that shared management does not necessarily imply a high level of coordination among actors and/or shared understanding of the most critical issues; indeed, the early stages of technological development may often be characterized by the opposite and this can be entirely consistent with shared management as defined above.

The second form of network management reflects a network in which a *lead organization* has formally adopted the role as network manager, i.e., an actor who actively pursue strategies to influence the process and the outcomes of policy networks. This management form can be efficient and legitimate due to the increased coordinating capacity, but the central role of the lead organization might result in low commitment from other actors and a questioning of the motives of the network manager (Kenis and Provan, 2009). Finally, the third form involves a *network administrative organization*, i.e., a network manager in the form of an entity formed with the *sole* purpose to manage collaboration. An important advantage of this arrangement is the ability to overcome inefficiencies while still mitigating the potential conflicts associated with the lead organization mode.

The particular role of government actors (state level or regional level) in these arrangements, i.e., if they participate as one actor among others or adopt the role as network managers (in any of the forms above), has been acknowledged (e.g., Kickert et al., 1997). Some networks are initiated and mandated from the top while others emerge through self-organizing bottom-up processes (Laranja et al., 2008).[6] Still, for our purposes, one should note that in the case of emerging technological fields, network management might be differently organized, but public actors tend to play significant roles. Often they "perform the function of a 'mediator', facilitating alignment between stakeholders, equipped with a 'shadow of hierarchy'," (Smits and Kuhlmann, 2004, p. 8). In other instances, though, smaller, sometimes highly technology-focused, organizations may assume network managing and/or mediating roles (e.g., Musiolik and Markard, 2011).

Swedish biorefinery development provides an illustration of technology companies assuming the role of network managers. In the late 1990s, an actor network centered on black liquor gasification (BLG) technology emerged, with the technology company Chemrec functioning as the network manager (Peck et al., 2016). Government support was provided to construct an industrial-scale pilot plant to verify the BLG technology, and with a focus on dimethyl ether (DME) as an alternative fuel to replace diesel in buses and heavy trucks. The new pilot plant began its operations in 2005, and Chemrec managed to activate a large number of commercial actors along the value chain deemed necessary for introducing DME as a new vehicle fuel (Volvo, Haldor Topsoe, Preem, and Total). However, in 2012 potential investors backed off a full-scale plant, largely due to the political uncertainties associated with carbon dioxide tax exemption for biofuels in Sweden (Hellsmark et al., 2016a).

4.2. Network management strategies

A network manager, disregarding management form or sector-belonging, may influence the collaborative process and solve tensions between different actors and challenges, by means of several *strategies*. These may be directed towards: (a) the network structure; (b) the network substance; and/or (c) the network process (e.g., Agranoff and McGuire, 2001; Klijn et al., 2010). Klijn (2005) notes that network managers can influence these in two main ways: *institutional design* and *process design*. Institutional design refers to strategies employed to influence the underlying rules for collaboration, e.g., the legislation affecting patenting activity, contracts, profit sharing, etc. In this paper, we do not address institutional design in any detail. A key point of departure, though, is that similar institutional preconditions do not necessarily give rise to similar actor network outcomes, thus making it essential to acknowledge the role of various process design strategies.

Process design strategies can be used to influence the collaborative process in actor networks within given institutional framework conditions (Klijn et al., 2010).[7] Based on Klijn (2005), we outline three different categories of process design strategies with direct relevance for the progressing of sustainable technology: Activation – or deactivation – of actors and resources, Goal-achieving strategies, and Interaction guiding and organizational arrangements. Fig. 2, which builds on Newell et al. (2017), summarizes these strategies while also illustrating how each of them can be linked to the structure, the substance and the process of actor networks. The different strategies may also complement each other, e.g., organizational arrangements facilitating the use of goal-achieving strategies.[8] The remainder of this section elaborates on the nature of these different strategies, and provides empirical illustrations from the Swedish biorefinery field.

4.2.1. Activation (or deactivation) of actors and resources

This network management strategy aims at influencing the structure of networks, e.g., through engaging new actors with complementary resources, build coalitions, etc. In this way, the network manager can ensure that the necessary resources, such as knowledge and funding, are made available. As noted above, diversity in the actor networks is critical in progressing novel sustainable technologies given the need to develop the socio-technical systems surrounding them. The need for deliberate attempts to activate actors as a part of the innovation policy mix will be a particular concern when incumbent actors control key complementary resources and infrastructure in the emerging network.

Swedish biorefinery development provides plenty of examples of informal network managers taking explicit action to broaden the network to also include a wider range of actors along the value chains,

[5] In the case of emerging industrial technologies, there may also be tensions associated with the presence of so-called coopetition, i.e., simultaneous cooperation and competition among actors (e.g., Bengtsson and Kock, 2000).

[6] This has been referred to as government-mandated versus emergent networks (Provan and Lemaire, 2012).

[7] This paper's focus on process design strategies implies that we assume that the institutional preconditions are exogenously given. In practice, of course, an important goal of actor networks in sustainability transitions will be to question and alter existing institutions. Actors are not simply passively complying with existing rules; they are also active in developing new ones (Geels and Schot, 2007). The relationship between institutional and process design is therefore an important avenue for future research.

[8] In the paper, we do not address the question of which network management strategies perform better under which management form (and vice versa). This is also an issue for future research.

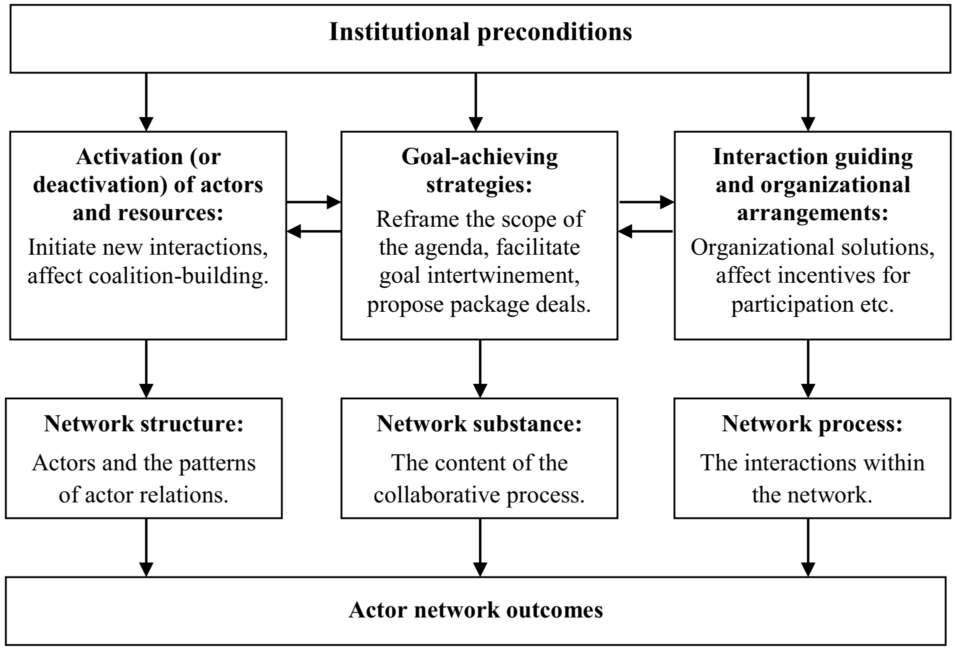

Fig. 2. The influence of process design strategies on different components of actor networks (building on Newell et al., 2017).

including the potential users of the new technology. One of these is Chemrec's attempts to create an extended value chain around DME (referred to above). Another example concerns ethanol production based on biochemical conversion processes. In the mid-1980s, major actors in the Swedish forest and agricultural industries joined forces and established the Foundation for Swedish Ethanol Development (SSEU), which made attempts to fund large pilot and demonstration plants to further develop a relatively well-known technology option (e.g., Hellsmark et al., 2016b). However, the national government prioritized the support to basic R&D on more advanced technologies (Ulmanen, 2013). For this reason, SSEU instead acted to raise awareness and broaden the network by initiating vehicle fleet trials based on conventional ethanol. In this way, the vehicles and the infrastructure were put into commercial operation. Several Swedish municipalities joined this demonstration program, the manufacturer Scania supplied buses and trucks, whereas a local Ford dealer introduced the first flexible fuel vehicles (FFVs). By the late 1990s, over 300 buses and 300 FFVs had been tested in over ten Swedish cities. Ulmanen (2013) argues that these trials helped build coalitions and mobilize broader actor support, which turned out to be critical for paving the way for a new public R&D program with a strong focus on building an industrial-scale demonstration plant.

Finally, empirical studies show that Swedish biorefinery development projects have typically lacked participation from the forestry, pulp/paper and chemical industries (e.g., Hansen and Coenen, 2017; Hellsmark et al., 2016b; Karltorp and Sandén, 2012; Novotny and Laestadius, 2014). One reason has been these industries' limited ability to absorb new knowledge, and use this for pursuing long-term opportunities outside their core business segments. Instead, they have continued to pursue investment in incremental improvements of existing technologies.

4.2.2. Goal-achieving strategies

While diversity in networks is critical for securing the necessary resources and for facilitating different types of learning processes, it also increases the likelihood that various actors will perceive the objectives of the development activities differently. While this heterogeneity is a strength (e.g., it may prohibit premature closure, and force actors to clarify the rationale for their positions), conflicting views may also slow down or even stall technology development if not resolved. For instance, in a pilot and demonstration plant context, some actors may want to continue discovering suitable market opportunities by investigating even more applications of a given technological field, whereas others instead want to target specific applications and concentrate resources solely on these (Frishammar et al., 2015). Under such circumstances, goal-achieving strategies may constitute an important component of innovation policy mixes. These are attempts by network managers or meditators to facilitate goal congruency and goal intertwinement among the involved actors, e.g., through reformulating the agenda to better correspond with the interests of key actors. This could also be pursued by proposing package deals that combine different objectives – e.g., regional economic development and climate mitigation – thereby enlarging the actor coalition in support of the emerging technology.

Empirical studies of biorefinery development suggest that the use of goal-achieving strategies may be particularly important in this field, this due to the high complexity in emergent value chains of the different processes. Biorefinery technology can be used to produce a multitude of different products based on a variety of feedstocks, including agriculture-based, forest-based, and other waste streams (oils, fats, etc.) (Pandey et al., 2011). These products can be bulk or high-value; platform products can be used for different purposes, e.g., in the chemical process industry or for fuel or electricity generation.[9] Recent studies of Swedish biorefinery development indicate that several actors express concerns that the potential options are too many to fully grasp, and that there is an urgent need for guidance from policy in combination with further R&D to limit the scope of alternatives (e.g., Frishammar et al., 2018; Mossberg et al., 2018). In other words, in the absence of clear visions and goals for the future, further up-scaling and commercialization of selected technological pathways and value chains could be hampered.

Swedish biorefinery development also highlights the need for improved coordination between regional and national policy-making levels as well as goal intertwinement. The development of biorefinery technology has a strong base in different regions, e.g., in Örnsköldsvik

[9] Given the important role of incumbent industries in biorefinery development, there are also a multitude of options for integration with existing industries and industrial value chains.

adjacent to the so-called Domsjö pulp mill (Coenen et al., 2015). At the regional level, an important goal intertwinement strategy has concerned linking biorefinery development to both climate policy ambitions as well as to regional growth and job creation. At the national level, the Swedish government has expressed strong support for development of a biobased economy, not least since this could help reach national environmental policy goals, while at the same time increase the competitiveness of the country's forest and chemical industries. Still, these policy ambitions have resulted in few targeted technology-specific goals that encourage actors to enter the technological field and concentrate resources on a limited number of options. As noted above, there has been a lack of coordination between the national and regional levels, as well as between the relevant government ministries at the national level (e.g., Ministry of Finance, Ministry of Enterprise and Innovation, etc.) (Hellsmark et al., 2016b).

4.2.3. Interaction guiding and organizational arrangements

While actor-activating network management strategies aim at mobilizing the knowledge and skills necessary for technological progress, goal-achieving strategies ensure that the efforts pursued by the actors in the formal networks concentrate on one or several shared goals. Still, this must be facilitated by interaction guiding and organizational arrangements, which involve efforts to influence how the development process is organized and how to make the new collaborations and compromises possible. From a policy perspective, government actors could adopt the roles as brokers and mediators between actors, as well as initiating boards, advisory groups or project organizations.

The significance of interaction guiding and organizational arrangements can be illustrated by the experiences from Swedish biorefinery development. In the late 1990s, cellulosic ethanol development benefitted significantly from a government-funded R&D program, which had a strong focus on an industrial-scale pilot plant to verify the results generated in earlier R&D projects. To make this new arena for collaboration a reality, two key organizational steps were taken to strengthen the network process (Hellsmark et al., 2016a). First, the industrial interests formed an alliance, ECN, which had the main task to develop the ethanol technology and construct the plant. Second, in order to ensure neutral ownership of the plant, maximize the opportunities for public funding, while at the same time complying with EU state aid rules, a new publicly owned company was formed. The pilot plant was formally owned by the holding companies of two Swedish universities, but these were passive owners as the new company took responsibility for the operation of the plant. A similar legal arrangement was used in the case of the above-mentioned BLG program, as well as the DME plant operated by Chemrec (Hellsmark et al., 2016a).

Furthermore, the important role of incumbent industries in biorefinery development makes the case for interaction guiding strategies particularly strong. Hansen and Coenen (2017) analyze the investment decisions of pulp and paper companies in Sweden and Finland, and conclude:

> "[…], regarding the new value chain relations, the analysis suggests that facilitation of contact to downstream actors is very important for the commercialization of biorefinery technologies, especially in light of the emphasis on product diversification. Thus, policy can potentially play an important role in facilitating network formation by creating arenas for interaction between pulp and paper firms and potential downstream actors. While such venues are often organized according to single industry platforms, this suggests that it might be more important to take prospective value chains as a starting point." (p. 509).

In Sweden, a number of policy measures have been introduced to address these (and other) challenges, e.g., R&D programs run by f3 and Bio-innovation jointly with governmental actors such as the Swedish Energy Agency and Vinnova and with a focus on collaboration among actors with complementary knowledge. The Swedish government has also initiated so-called strategic innovation agendas that demand sector-bridging collaboration at the national level. Still, Hellsmark et al. (2016b) conclude that so far collaborations over knowledge and organizational boundaries have been relatively weak in Swedish biorefinery development (see also Bauer et al., 2018).

The development has also suffered from unclear organization and management of important research infrastructure (e.g., pilot and demonstration plants). A large number of actors have been involved as owners, funders and managers of these plants, in turn leading to difficulties in identifying who is responsible for and has mandate over each plant (Mossberg et al., 2018). The degree of leadership and commitment to the plants is likely to differ across various types of actors (e.g., private versus public, R&D firms or users of the technology). Moreover, since the objectives of a plant tend to change over time, e.g., from technology verification to diffusion, so must also the organization and ownership solutions.

5. Network management in the technology development process

While the previous section introduced three network management strategies and discussed how each of them could play out in practice, this section outlines an analytical framework that addresses the role of these strategies throughout the entire technological development process. Specifically, in Section 5.1 we depart from the interfaces between the various phases of this process (see Section 2.1), and ask what may constitute some of the key network management challenges at each of these interfaces. The main points/arguments in this analytical framework come from both the existing sustainability transitions literature and, not least, from the case of biorefinery development. The network management challenges that are presented are generic, and should thus be valid in several contexts. Still, this does not preclude that future empirical research will provide additional insights and arguments.

In Section 5.2, the analytical framework is extended by also identifying: (a) some important challenges in designing and implementing network management strategies; and (b) potential drawbacks of ignoring such strategies in the innovation policy mix. Also here, the analysis relates directly to the interfaces between the phases in the technology development process.

5.1. Network management throughout the technology development process

Table 1 displays the three interfaces between the phases in the technological development process, and identifies – for each interface – typical forms of network management and the role of network management strategies. Specifically, in the latter case, it illustrates network activities clustered under the network management strategies, thus representing the "realized" strategies. It should be emphasized that these activities are judged to be important in each interface, not in the normative sense that they must all be pursued by policy actors (e.g., other actors in the networks may already have addressed some of the pertinent issues). Table 1 can rather serve as a checklist over potentially important network management activities.

Throughout the technology development process, actor networks will likely be characterized by various types of management forms. In the first interface, this form is likely to be informal and "shared" in the sense that there is no formal management entities. Still, as noted above, only a subset of the relevant actors may be well-coordinated. The interface between the pilot and demonstration phase and the market formation phase may instead be characterized by increased coordination capacity due to the presence of a lead organization. Finally, in the last interface we are more likely to experience a lead organization that has been formed with the key purpose to manage collaboration among actors. Nevertheless, the significance of network management forms in technological development processes is an issue for future empirical research, as is the question how well-equipped the various forms are in pursuing effective network management strategies.

Table 1
Role of network management strategies at the interfaces between various phases of the technology development process.

	Interface I: Concept development phase and pilot and demonstration phase	Interface II: Pilot and demonstration phase and market formation phase	Interface III: Market formation phase and diffusion phase
Key technological development challenges	Expand the scope of learning processes beyond advancing scientific knowledge and reduction of technological risks to promoting both general and proprietary knowledge development (learning-by-doing) and intermediate-level verification and optimization of new technology.	Development of proprietary knowledge that helps to reduce production costs and market-related risks. Intensified focus on learning-by-using and learning-by-interacting processes, which both help private firms develop products and value chains.	Further focus on learning from intermediate-scale production, feedback of customers and from the broader society, e.g., developing standards and gaining legitimacy. This means improving cost/−performance ratios, the identification of critical infrastructure and regulatory hurdles.
Typical forms of network management	*Shared management* with no formal management entity (and not necessarily tight collaborations)	A *lead organization* with increased coordinating capacity has adopted the role as network manager.	A *network administrative organization*, an entity formed with a key purpose to manage collaboration.
Key network management activities and strategies	*Activation (or deactivation) of actors and resources:* • Expand from small actor networks (e.g., university labs), closely aligned to the original actors' interests, towards more complex actor networks involving e.g., private firms. • Key is to engage new actors (e.g., existing producers) or coalitions that can help co-fund industrial- and commercial-scale pilot plants. Public funding of experiments still important.	*Activation (or deactivation) of actors and resources:* • Make use of existing research infrastructures to stimulate interactions among incumbents and new actors, with a focus on the future formation of a few complete value chains. • Stimulate interactions between suppliers and customers by creating incentives for the first customers. Encouraging feed-back from end-users and from the policy sphere.	*Activation (or deactivation) of actors and resources:* • Establish actor networks needed to secure and legitimize supporting institutional structures and political arenas. • De-activation of inefficient solutions and actors by increasing competition along the value chain. • Engage R&D-based actors that could develop complementary technologies and address wider system issues (e.g., in permanent test centers).
	Goal-achieving strategies: • Align interests among key actors in terms of the goals of technological experiments, while at the same time allowing for various alternative solutions to develop in parallel. • Deliberate explorations of possible long-term goals, visions and desirable futures, along with discussion on how these may be induced or hampered by policy/goals of other actors.	*Goal-achieving strategies:* • Stimulate joint sense-making process involving entrepreneurs, established private firms, policy actors, research community, end-users etc. • Establish shared views on system strengths and weaknesses, and how to address these. • Take the step from exploration to exploitation of new knowledge, and set specific long-term goals (e.g. production volumes, market shares).	*Goal-achieving strategies:* • Revisit goals and revise if necessary, identify new long-term goals, and establish a joint agenda on how to address the policies and institutions that hamper further growth. • Coalition-building to fund R&D infrastructures that serve a wide set of actors and which make continuous improvements and test new options.
	Interaction guiding and organizational tools: • Initiate organizational structures and project managements that focus on the exploration of options, permitting going back and forth between concept development and pilot tests. • Increased role for mediators that can assist in managing the balance between (a) commercial interests to verify new technology along specific value chains and (b) public funding.	*Interaction guiding and organizational tools:* • Initiate organizational structures focused on the exploitation of new knowledge, e.g., through research infrastructure that permit technology suppliers' access to customer feedback. • Create arenas for interaction along prospective value chains, ensuring that the human capital that has been developed separately is integrated in commercial projects aiming at up-scaling.	*Interaction guiding and organizational tools:* • Refocus of existing test infrastructure to support deployment and incremental improvements in products and services. • Further technological development efforts by engaging neutral actors that balance diverse commercial and science-based interests. • The management of intellectual property rights is essential.

In the remainder of this section, we focus on the role of network management strategies at the interfaces between the different phases of the technology development process. We discuss each strategy separately, including additional empirical illustrations from the biorefinery case.

5.1.1. Activation (or deactivation) of actors and resources

In early stages of technological development, the focus is typically on scientists and engineers attempting to verify and optimize technology solutions to permit up-scaling (Frishammar et al., 2015). From a network management perspective, an important activity for promoting this development is to actively involve new actors in the network. Still, this will take different shapes depending on the key technology development challenges faced.

At the interface between the concept development and the pilot and demonstration phases, the key is to broaden the network to increasingly include various specialized industrial actors. It is not least important to activate actors that can help fund industrial-scale pilot plants. By contrast, moving further into the market formation phase requires stronger focus on engaging incumbent industries and end-users (Harborne and Hendry, 2009). The research infrastructure that has been built up, in the form of pilot plants etc., often represents the central collaborative arenas for network actors. These can therefore provide an important meeting arena for new actors, including end-users, incumbents, technology providers, etc. (Hellsmark et al., 2016a). Finally, at the interface between the market formation and diffusion phases, the scope of the actor-activating strategies need to expand further, e.g., by engaging various R&D actors and technical consultants that can develop, test and evaluate complementary technologies and address wider system issues (e.g., Hendry et al., 2010).

In sum, actor-activating strategies, with the aim to influence network structure and foster actor diversity, are important throughout the technological development process; however, some actors will be more important than others, and the role of being a key actor varies depending on what phase the development process is in.

5.1.2. Goal-achieving strategies

The adoption of goal-achieving activities also needs to change as the technology development process transcends from one phase to another. At the interface between concept development and pilot and demonstration phases, the emphasis is typically on the nature of the technical experiments. It is here important to strike a balance between forming a shared understanding of the objectives of these tests on the one hand, and allowing various alternative solutions to develop on the other (e.g., Karlström and Sandén, 2004). Even at this early stage, though, deliberate explorations of potential long-term visions, goals and desirable futures will be important, as these will guide the scope of lab experiments and pilot plant tests. This does not, however, exclude the continuous re-evaluations of prevailing agendas. In other words, even though these activities will largely concern technical challenges and visions (e.g., expressed in terms of efficiency, cost performance, etc.), government also plays an important role by clarifying the political directions, e.g., through the setting of long-term goals relevant to the field (see, for instance, Andersson et al. (2017) for an application to marine energy).

At the interface between the pilot and demonstration and the market formation phases, it is imperative to move from exploration to exploitation of knowledge. From the perspective of goal-achieving strategies, this requires a stronger focus not only on *what* should be achieved, but also on *how* this can be accomplished in practice given the presence of any remaining institutional obstacles, policy uncertainties etc. (e.g., Smith and Raven, 2012). In other words, shared views on system strengths and weaknesses need to be established, including ideas on how the actor network could work collectively to resolve the prevailing weaknesses.

Such joint sense-making is important also at the interface between market formation and diffusion, but here there will also be a stronger focus on establishing shared visions on how the new value chains can be supported by continuous, incremental improvements of processes and products as well as through experimenting with new technological options. A particularly important challenge is to ensure coalition-buildings that can assist in the funding of permanent R&D infrastructures, which can serve a wide set of actors by permitting continuous tests and improvements of the existing technology.

In sum, the goal-achieving strategies are needed to influence the actor network content, enable joint-image building and balance the tension between diversity and stability in the network. The urgency of these different challenges will however vary across the various phases of the technological development process.

5.1.3. Interaction guiding and organizational arrangements

Table 1 outlines how the need for interaction guiding and various organizational arrangements is likely to vary at the various interfaces between the technology development phases. The role of intermediaries, e.g., in the form of government organizations working in-between actors, may be important in taking the step from the concept development phase to the pilot and demonstration phase. This is not least important for managing the balance between the goals of public R&D funding (e.g., a broad dissemination of knowledge) on the one hand, and the commercial interests of private actors to verify the new technologies along specific value chains and protect the knowledge gained on the other (Kivimaa, 2014). This challenge was addressed by Lefevre (1984) in his early assessment of major energy demonstration projects in the USA. In a same vein, Harborne et al. (2007) and Hendry et al. (2010) conclude that the presence of knowledge spillovers in renewable energy technology development has often not been properly addressed when designing and managing pilot and demonstration projects.

As the technological field progresses, it also becomes essential to launch new organizational arrangements to ensure that the new knowledge and the human capital that has (often) been developed separately, becomes integrated in commercial projects aiming at up-scaling and commercialization.[10] Furthermore, the management of intellectual property rights, and thus the balancing of diverse commercial and science-based interests, remain important, and could require the engagement of a neutral ownership of test infrastructures, etc. (Hellsmark et al., 2016a).

5.2. Network management strategy effectuation

While Section 5.1 elaborated on the role of network management strategies, the discussion did not explicitly address the role of *public policy* in supporting such activities. The role of policy is likely to be highly context-dependent; in some instances the public authorities may assume a mediating role while they in other cases may have to act as formal network managers and/or actively select and support certain leading actors. There simply is no straightforward generic recommendation to make here; the potential 'fit' of any proposed policy intervention with its management context has shown to be very important, and it is often constrained by previous policy choices (Howlett and Rayner, 2007). Still, potential policy interventions may benefit from considering the different challenges policy makers can face if they choose to implement network activities (or support existing ones), as well as the potential negative consequences of abstaining from acknowledging network management in the innovation policy mix. These two issues are discussed in the remainder of this sub-section.

[10] This would typically imply a move from shared management to a situation where a lead organization (e.g., an established association) adopts the role as network manager (Musiolik and Markard, 2011). However, as noted above, the relationship between network management forms and strategies remains an issue for future empirical research.

Table 2
Network management in the innovation policy mix: What are the challenges and why is it important?

	Interface I: Concept development phase and pilot and demonstration phase	Interface II: Pilot and demonstration phase and market formation phase	Interface III: Market formation phase and diffusion phase
Key policy challenges in the design and implementation of network management strategies	● Challenges associated with engaging the right actors and development projects, including project-funding conditions, in pursing actor-activating strategies. ● Volatile political and economic environment, thus making not least the introduction of goal-achieving strategies difficult. ● Prevent the domination of incumbents and a reliance on "outdated" institutional logics, e.g., when promoting organizational solutions.	● Adapting the network management strategies to the prevailing government levels, i.e., local, national etc. Applies to all three strategies. ● Some new technologies (e.g., biorefineries) may have several promising value chains, thus making prioritization and goal-achieving strategies difficult to pursue. ● The formal network manager may be difficult to identify and activate, in turn making the adoption of organizational structures hard.	● Difficult to decide what processes require active (policy-induced) network management policies. Applies to all three strategies. ● Ensuring that the process of de-activating actors and activities – including the changing of the agenda of test infrastructure – can be pursued in a legitimate and efficient manner. ● Various types of demand-pull instrument may imply different needs for network management strategies. Could apply to all three strategies.
Potential negative effects of ignoring the importance of network management in the innovation policy mix	● If new actors (including incumbents) are not activated, there will be a lack of resources and interpretive knowledge, in turn leading to more of the same being generated (e.g., bias towards further verification of technology). ● Too dominant incumbent actors may lead to path dependence and technological lock-in (i.e., a bias towards incremental innovation). ● Existing actors have to assume roles in the network for which they are not well-suited.	● Difficulties in achieving effective coordination between national, regional and local goals. ● Demand-pull instruments could carry different meanings for affected actors. Without goal-achieving strategies, the problem of diverging interpretations and priorities would then linger. ● In the absence of goal-achieving and actor-activating strategies, important technological fields may develop solely based on a large number of small and competing actor networks	● The allocation of resources (e.g., financial funding, human capital, etc.) may become too scattered across competing networks, all with a limited ability to further develop the technology. ● In the absence of actor-activating strategies, some actors (e.g., SMEs) may face significant barriers to entry during the growth phase, not least if some demand-pull instruments (e.g., tendering schemes) and/or legal rules tend to favor incumbent actors.

5.2.1. *Challenges in network management design and implementation*

Table 2 adds to the conceptual framework presented in Table 1. The first part of this table outlines a number of potential challenges associated with designing and implementing various network management strategies. It is important to emphasize that several of these policy challenges will likely have to be addressed throughout the entire technological development process, such as:

- achieving the right timing when supporting selected activities – or mix of activities – so that sufficient overlaps between the different stages in the technology development process are created;
- achieving coordination among different government agencies with different power, responsibilities and institutional logics; and
- addressing significant institutional obstacles to certain organizational arrangements (e.g., EU state aid rules making private ownership of research infrastructure difficult).

However, some challenges tend to be more profound at some interfaces between phases of the technological development process than at others. Table 2 (first row) summarizes these, and it also links these challenges to the three network management strategies.

At the interface between the concept development and the pilot and demonstration phases, a key challenge concerns the engaging of the right actors and development projects. While this selection typically will be based on standard peer-review evaluations, the resulting process is often not free from policy concerns. These include the need to specify appropriate funding conditions regarding the dissemination of new knowledge, as well as to avoid a situation where only incumbent actors are able to control the scope of the development activities. Specifying funding conditions may also imply favoring some technology options over others, something that of course represents a challenge in itself.

Difficult policy choices are inevitable also at the other interfaces. Often these will be further concerned with which value chains are worth pursuing. Specifically, several novel sustainable technologies – including biorefinery technology – may have several promising value chains, thus making prioritization very difficult. This is, not least, an issue of concern at the interface between pilot and demonstration and the market formation phases, and complicates the design of goal-achieving strategies (e.g., identifying political visions that can bring together actors with different goals, motives, etc.). At this interface, the policy challenges may also involve identifying network management activities that are well-aligned with the various government levels, e.g., providing links between the national and local levels of governance (e.g., Coenen et al., 2012). For instance, it may be difficult for a national policy-implementing agency to assume the role as mediator in networks where strong local actors act as network managers.

Finally, at the interface between the market formation and the diffusion phases, the policy challenges may concern finding the appropriate role for network management in the transfer from targeted technological development activities (e.g., in pilot plants) to the introduction of more generic and permanent test infrastructures (e.g.,Hellsmark et al., 2016b). This may even require the de-activation of actors from the network. Moreover, policy makers also need to acknowledge that different demand-pull instruments may require different types of network management initiatives. For instance, some policy instruments will primarily encourage the entry of large, established actors (e.g., the traditional energy companies) while other types of demand-pull policies could provide incentives also for the entry of more innovative, small- and medium-sized companies (see also below). The call for network management in the form of deliberately activating actors could therefore be more urgent in the former case.

Several of the biorefinery illustrations that have been outlined above in this paper exemplify some of the policy challenges presented in Table 2, not the least when it comes to the issue of prioritization among technologies and value chains. The empirical experiences show that the goal-achieving strategies of the Swedish government, e.g., the goal of a fossil-free transport sector by the year 2030, have likely not been successful in advancing biorefinery technology in the country. As noted above, such policy ambitions have often not been translated into technology-specific goals that encourage actors to enter certain technological fields and thus concentrate resources on a limited number of options.

However, examples where ambiguous goal-achieving strategies and a lack of actor-activating policies have led to a focus on a very limited set of products can also be found. For example, Chemrec's focus on DME production (Section 4.1) turned out to be a too narrow product strategy; it failed to sufficiently address the existing technologies and infrastructure. DME production was technically efficient, but the resulting actor network was not well aligned with the broader customer bases (beyond Volvo) and with the prevailing institutions (Hellsmark et al., 2016b). In this case, more intense mediating activities on the part of public agencies (e.g., the Swedish Energy Agency) could have led to a different outcome.[11]

5.2.2. Negative consequences of ignoring network management in the policy mix

The added value of network management could be addressed by asking the question what would be the negative consequences of ignoring such strategies in the innovation policy mix. Table 2 (second row) therefore outlines a number of potential negative consequences of a sole reliance on only technology-push and demand-pull instruments. The consequences will also differ across the various interfaces.

At the interface between the concept development and the pilot and demonstration phases, key actors need to take active steps to broaden the actor networks. If this is not achieved, e.g., with the support of government actors supporting certain collaborative arenas, the lack of necessary interpretative knowledge needed to further develop the technology may prevail (Frishammar et al., 2018). A possible negative consequence of this could be a bias towards further verification of the technology/application at the expense of increasing efficiency along value chains and getting access to the knowledge and experiences of potential users. Brown and Hendry (2009) provide an example of such risks in the context of European wind power development. Yet another risk at this first interface is that the existing actors in the network may have to assume roles in the network for which they are not well-suited (e.g., universities hosting larger pilot and demonstration plants).

Addressing a situation of diverging interpretations among actors regarding the potential future technological pathways is challenging. Improving the rate-of-return on risky investments, e.g., through demand-pull policy instruments, could in part solve this problem, at least if such an instrument targets certain applications. If policy makers contribute to lower investment risks in this way, there will be increased learning about institutional and market-related risks. Such measures are particularly important at the interface between the pilot and demonstration and market formation phases. Nevertheless, the introduction of demand-pull instruments may also lead to increased uncertainty and ambiguity concerning the future challenges and priorities as technical, economic and social issues become more intertwined (Frishammar et al., 2018), not least if these instruments target a very broad portfolio of technologies and products.

In other words, in the absence of active goal-achieving strategies, the underlying problem of diverging interpretations and priorities could then linger. Indeed, even rather discrete and non-complex technologies involve multiple applications (e.g., Schmidt et al., 2016); this requires efforts to more directly influence actors' perceptions and possibly, as noted above, even opt-out certain applications. If such policy efforts are not pursued, important technological fields may develop based on a large number of small and competing actor networks, but where none of these has the ability to make the necessary progression towards commercialization.[12] Of course, if the technology development process does in fact stall, key competences could be lost, thus creating a further need for actor-activating network management activities.

Furthermore, acknowledging the particular role of incumbent actors is important throughout the entire technological development process. It is often important to engage these actors in more radical development project, but it is also important to make sure that they do not obtain a too strong position in the emerging actor networks. In this balancing act, actor-activating strategies will play particularly important roles, already at the interface between the concept development and the pilot and demonstration phases (see Table 2).

Even though a traditional policy mix of technology-push and demand-pull instruments would make incumbent industries more interested in investing in emerging technologies, Hansen and Coenen (2017) argue that policy makers also need to devote explicit attention to the potential conflicts within – as well as between – firms in order to maximize the pay-off from such policy support. Policy should thus actively facilitate network formation by establishing arenas for collaboration, e.g., between incumbents and innovators. Top-level management should likely be a prime target in such learning processes.

At the same time, however, policy makers should be careful in not (incidentally) providing incumbents with too dominant positions. For instance, at the interface between the market formation and the diffusion phase, some policies and existing legal rules may do exactly that. In such cases, actor-activating network activities (in combination with institutional changes) will likely play a particularly important role. Munksgaard and Morthorst (2008) provide an example from the wind power industry, and argue that the choice between a feed-in tariff and a tendering scheme (both options for providing financial support to wind power installations), may well influence the type of actors (e.g., new ones or incumbents) choosing to participate in the technology development process.

Swedish biorefinery development provides several illustrations of negative effects following the neglect to pursue actor-activating strategies, such as how the absence of more effective goal-achieving and actor-activating strategies has contributed to a bias towards verification of new technology at the expense of further development of the necessary value chains and end-user relationships (e.g., the case of DME production). Moreover, Mossberg et al. (2018) show that that some of the actors in the networks surrounding new biorefinery concepts have had to assume roles for which they may not be well suited. One example of this concerns the owners of some of the existing biorefinery pilot and demonstration plants in Sweden. The main task of a few of these plants has changed over time, i.e., from a focus on verification of a limited set of applications (e.g., DME, ethanol etc.) to the operation of more open permanent test centers focusing on broader sets of experiments (see also Hellsmark et al., 2016a). However, this means that the business logic for managing the plants has changed, and the managers of the plants increasingly need to act as "salesmen and marketers" although they may not have the suitable capabilities. The lack of end user focus in Swedish biorefinery development has also made national universities contemplate about their roles, not least how far they should go in pursuing commercialization of new technologies (Mossberg et al., 2018; Perez Vico et al., 2015). This, therefore, illustrates the importance of

[11] The Chemrec case can be compared to the growth of Swedish HVO (hydrogenated vegetable oil) production based on raw tall oil. In the latter case, the technology company Kiram managed to act as a bridge between the forest industry and the refining industry, and assumed the role as lead organization in the build-up of the network (Peck et al., 2016). The raw tall diesel is first separated from the raw tall oil in the jointly owned Sunpine facility, and then the raw tall diesel is processed to HVO diesel fuel by Preem (Grahn and Hansson, 2015). In this particular case, though, there was less need for public actor involvement in terms of network management activities; the technology was more mature and the value chain much more developed.

[12] As indicated in Table 2, this lack of prioritization may also spillover to the interface between market formation and diffusion.

activating the right actors and resources, but also the need to make sure that the allocation of tasks – as well as authority – between those involved is organized efficiently.

6. Concluding remarks and avenues for future research

This paper has built on the notion that technological development processes, which typically unfold over extended time periods, can be more or less guided, e.g., by the existence of long-term policy goals, visions, etc., and purposefully pursued by a broad range of actors who can be more or less coordinated and aligned with each other. Existing literature often regards actor networks as structures that facilitate knowledge exchange and expand the resource base. This paper's central message has however been that policy analysis, design and implementation in the context of sustainable technological development must increasingly address the character, the performance and the outcome of actor networks. This implies emphasis on how different actors collaborate, and, not least, on the different types of management strategies that can be used to influence network collaboration.

Our main contribution has been an analytical framework that addresses the changing roles of network management strategies at the interface between various phases of the technological development process, illustrated with the empirical case of advanced biorefinery technology development in Sweden. This framework also addresses challenges that policy makers may encounter when pursuing the various network management strategies, and identifies a number of negative consequences of ignoring such instruments in the policy mix. The latter includes inefficient actor role-taking, the emergence of small, competing and fairly ineffective actor networks in similar technological fields, and a shortage of interpretative knowledge, in turn leading to poor and/or delayed decision-making. To address such problems, key activities from different network management strategies can be combined. As the analytical framework has made clear, at the interfaces between the various phases in the technology development process there is often a need for different sets of activities where some root in the activation of actors, others under the label of goal-achieving strategies, and still others under interaction guiding and organizational tools. In other words, the various network management strategies do not represent discrete activities; they will be effectuated by combining activities from all three domains.

The analysis presented should be of interest for both the actors involved in the technological development process, including policy actors, as well as for scholars in the sustainability transitions field. In the former case, the analytical framework could provide a useful starting point for actors (e.g., technology providers, entrepreneurial firms, university researchers, etc.) to contemplate about their own roles in the technology development process. In addition, it also helps actors to better understand what can (and needs) be done to further the development by strengthening various network activities. This is of course particularly relevant for policy makers, both at the national and the regional levels. In this paper, we have emphasized that innovation policy mixes incorporating network management, typically requires coordination between, for instance, the national government (various ministries), the implementing agency, as well as regional and local authorities. The analysis should therefore concern a wide range of policy actors; the implementing agency and the local authorities often represent particularly important actors since these often play key mediating roles in the emerging networks. Thus, while the paper has no ambition to provide specific policy recommendations, it seeks to fuel the discussion about the critical role of network management in innovation policy mix, and encourage the different actors to consider their own positions.

The analytical framework also has implications for scholars in sustainability transitions (e.g., TIS) research. In this literature strand, the policy support structure has largely been treated as external to technological development, and as such it has tended to neglect that these structures are also created and shaped by firms and other actors, including public ones, with their own stake in the new technology (Kern, 2015). For instance, TIS studies recognize that the progress of new technology depends heavily on actor network collaboration; innovation system weakness can therefore often be traced back to failures to establish effective networks (Frishammar et al., 2018). It is however surprising that relatively little attention has been devoted to providing a clearer understanding of the roots of such system weaknesses, and of how to better manage the evolution of actor networks throughout the technology development process (see Musiolik et al. (2018) for a recent exception).

Our analysis may also provide input to the innovation ecosystem approach in the management literature (e.g., Oh et al., 2016); it provides a clearer link to the overall socio-technical system, including incumbent regimes, institutions, and, not least, the various policy actors that engage in actor networks. Finally, previous work that has addressed the design of innovation policy mixes (Borrás and Edquist, 2013; Rogge and Reichardt, 2016; Smits and Kuhlmann, 2004), does recognize that support to actor networks constitutes an important component of this mix. Still, this paper has added more analytical depth to this statement, not least by addressing the changing roles that such support is likely to play at the interface between the various phases of the technology development process.

Nevertheless, it should also be clear that there is plenty of scope for more in-depth conceptual and empirical analyses. The impacts of innovation policy instruments in general and network management initiatives in particular are likely to be highly context-dependent (e.g., Flanagan et al., 2011), and this should be increasingly recognized in future empirical work. We have pointed to the need for studying the relationship between process and institutional design in sustainable technological development, not least since an actor network does not only emerge within a given institutional framework; it is also formed to influence that same framework. In other words, the conceptions of users, technologies, and regulations are not only tested but also questioned (e.g., Hoogma, 2000). As noted above, the question how the different types of network management strategies perform under various management forms, is also an issue for future research.

Furthermore, while the maintained thesis in this paper has been that network management should constitute an important component of the innovation policy mix, the analysis has not addressed in any detail the question how the different instruments interact and affect each other. Specifically, the network challenges facing actor collaborations may differ depending on which type of policy instruments are put in place (e.g., Munksgaard and Morthorst, 2008). Finally, in the introduction to this paper, we remarked that network management is relevant in several geographical contexts, including the global level. Binz and Truffer (2017) present a framework for the analysis of technological development processes in transnational contexts, and such analyses could therefore also benefit from emphasizing the role of actor networks and the management of these at the global level.

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Patrik Söderholm is professor of economics at Luleå University of Technology (LTU), Sweden. His research focuses on energy markets and energy and environmental policy instruments, including substantive work on technology learning and innovation. He has been a research fellow at the Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology (MIT), and at the International Institute for Applied Systems Analysis (IIASA). During 2014–2015, he was a guest professor at the Helmholtz Centre for Environmental Research – UFZ in Leipzig. Söderholm has published over 100 papers in international scientific journals.

Hans Hellsmark is a researcher at Chalmers University of Technology and coordinator of Chalmers Initiative for Innovation and Sustainability Transitions (CIIST). The purpose of CIIST is to support actors in academia, industry and policy involved in transitions, with an arena and knowledge support. Hellsmark's main research interest is research and innovation policy from a sustainability transition perspective. He is particularly interested in the socio-economic benefits of pilot and demonstration plants in the bioeconomy, as well as in the interaction between policy, industry, research institutes and universities for creating and facilitating societal transformation processes.

Johan Frishammar is a professor at entrepreneurship and innovation at Luleå University of Technology, Sweden, and an affiliated research fellow at the House of Innovation, Stockholm School of Economics, Sweden. Most of his research centers on innovation management in established companies with a focus on innovation measurement, open innovation, front end innovation, platforms, and sustainability transitions. Frishammar's work has appeared in *California Management Review*, *Journal of Product Innovation Management*, *IEEE Transactions on Engineering Management*, *Technovation*, *MIT Sloan Management Review*, *Research Policy*, *Long Range Planning*, and others.

Julia Hansson is a researcher at IVL Swedish Environmental Research Institute, and at Chalmers University of Technology, Maritime Environmental Sciences, Gothenburg, Sweden. Her research provides perspectives on future bioenergy use and trade and renewable fuels for transport in a Swedish and European policy context. The research is mainly based on energy system analysis, policy analysis and sustainability assessments. During 2009–2012, Hansson worked as a senior policy advisor at the Swedish Energy Agency, with a focus on renewable fuels for transport. She has contributed to the assessment and development of policies in this area.

Johanna Mossberg is a researcher and focus area manager for the area of Fossil Free Transport at RISE Research Institutes of Sweden, as well as a guest lecturer in energy science at Luleå University of Technology (LTU). Mossberg received her PhD in industrial energy systems in 2012, and holds in-depth knowledge of environmental improvement assessment of industrial production and biorefinery concepts. Her current research interests are analysis of industrial transition and industrial collaboration between the pulp and paper industry and the chemical process industry, barriers, drivers and the role of public policy. Her previous achievements include the position as managing director of f3 – the Swedish knowledge center for renewable transportation fuels.

Annica Sandström is professor in political science at Luleå University of Technology (LTU), Sweden. Sandström's research focuses on environmental policy and governance, and her publications include empirical studies on the socio-political complexities of natural resources (c.f. water and wildlife) and energy transitions, as well as theory-driven pieces on multi-level governance, policy implementation and policy networks. She normally combines qualitative and quantitative methods in her work and several studies apply quantitative social network analysis (SNA) to map and analyze policy processes related to the environment.