Fostering sustainable technologies – a framework for analysing the governance of innovation systems

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Abstract

There is an ever-growing recognition among policy-makers, industries and analysts that the development and diffusion of technological innovations need governing in order to contribute to societal goals related to sustainability, such as climate change mitigation and resource efficiency. Yet, little is known about how different types of governance influence innovation processes, and what may be effective governance arrangements to pursue to influence the development and diffusion of sustainable technological innovations. This paper develops a framework for the analysis of governance arrangements aimed at fostering more sustainable technological innovations. The framework addresses important debates in governance and innovation research. First, it addresses a critical gap in the literature on technological innovation systems (TISs) which is the connection between governance arrangements and the functionality of the TIS. Second, it contextualizes this connection in relation to the multi-level perspective (MLP) to transitions, assuming that governance arrangements influence in different ways the functionality of the TIS depending on the structure, stability and positioning of the TIS in relation to the regime. Third, it develops a comprehensive heuristic to examine the prevalence, role and effectiveness of various modes of governance, departing from a simple typology of "who governs", "how do they govern", and "what is governed". The framework prompts a temporal causal analysis of predominantly qualitative nature.

Keywords: governance, technological innovation systems, socio-technical transitions, sustainability

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1 Introduction

There is an ever-growing recognition among policy-makers, industry analysts and managers that technological innovation needs to be governed in order to contribute to societal goals related to for example sustainability. However, although the literature on technological change and innovation now and then touches upon governance, policy and institutional responses (e.g., Fagerberg et al. 2006), there is relatively little systematic analysis of what types of governance arrangements that affect innovation processes, and in what ways they work. In addition, there is not a comprehensive theoretically derived model, which explains the governance of technological innovation systems Jordan (2008: 29). Therefore, our aim is to suggest a theoretical framework for the analysis of governance of innovation systems. Our approach is that researchers of technological innovation systems (TIS) have identified a number of key processes necessary for the development, diffusion and use of technological innovations (Bergek 2002; Hekkert et al. 2007; Bergek et al. 2008b). The main task for governance of technological innovations would then be to foster such key processes – called functions – under the influence of external factors. Complementing the TIS approach, the context for the emergence of technological innovations is fruitfully described by the multi-level perspective (MLP) to socio-technical transitions (Rip and Kemp 1998; Geels 2002).

In this paper, we address what we perceive as a critical gap in the literature on TISs and socio-technical transitions, which is the connection between governance arrangements and the functionality of the innovation system, i.e. how well the functions are served. In addition, we contextualise this connection in relation to the different levels of the MLP. The paper outlines a framework, aimed to support the analysis of how governance affect and foster technological innovation systems (TISs). The purpose of such an analysis is to generate empirically grounded and theoretically robust advice on how different types of governance arrangements influence innovation processes. In effect, this will support the design of proper governance arrangements.

A secondary purpose of the paper is to address some critical debates in governance research. Principally we are interested in two generic issues that permeate most of these debates. The first is how to structure empirical evidence about the diffusion of different governance arrangements, and the second is how useful and effective different governance arrangements might be in fostering innovation processes. Multiple definitions of governance exist, typically involving societal coordination (Pierre 2000), goal setting and intervention to achieve the goals (Jachtenfuchs and Kohler-Koch 2004). This is potentially an overwhelmingly broad field of study. We are primarily interested in governance arrangements initiated by one or several actors aimed at influencing the functionality of a particular TIS. In such governance, not only the state can be the central actor: there is a range of possibilities of actor roles and responsibilities involving different combinations of state and private actors.

Our assumption, then, is that governance arrangements of different kinds, such as regulatory standards, market manipulations by the state, and public-private partnerships influence in different ways the functionality of the TIS. We further assume that the influence of governance arrangements on the TIS will be quite different depending on external factors, such as the relation to established technologies, the general political agenda, and the economic situation.

In developing a theoretical framework, we describe complex processes in simple terms, realizing, however, that reality is neither simple nor linear. We base the framework on theoretical contributions published in scientific literature. It is not specific for particular types of technologies. However, we consider sustainable technologies particularly relevant, which may have bearing for other technologies and sectors. There are several reasons why we illustrate our reasoning with the aid of sustainable technologies, such as biofuels for transport, fuel cells and hybrid vehicles.[1] First, there is a clear need for governance due to the fact that the environment is a public good and that there are a number of externalities related to sustainable technologies (e.g., Oltra and Saint Jean 2005). Second, such technologies typically suffer from a number of disadvantages; they compete head-on with incumbent technologies and niche markets are often absent (e.g., Raven 2005). Third, there is a large range of governance arrangements implemented in relation to sustainability.

The paper structure is as follows. The first section motivates the main components of the framework and elaborates on their theoretical origin. Section two outlines a model of the innovation system and its dynamic processes, describing what is (or could be) governed. A conceptualisation of governance follows this (Section 3). Section 4 presents the resulting framework for analysing governance of technological innovations. Finally, a closing section offers some concluding remarks (Section 5).

2 A model of the innovation system

To understand the development of technological innovations, we consider technologies as systems of social and technical elements interacting with each other, as proposed in the literature on large technical systems (LTS) (Hughes 1987) and socio-technical systems (Geels 2004). Such systems can be defined in various ways. In this paper, we adhere to the socio-technical system approach, which includes the elements necessary to fulfil a certain societal function (Bijker 1995; Geels 2004). This entails that not only the producer side is included, but also users and the market make up important parts of the system.

The rich literature on innovation systems propose a number of approaches to study the fostering of innovations. These are characterised by, e.g., national, regional or technological sectoral boundaries (Carlsson and Stankiewicz 1991; Lundvall 1992; Nelson 1993; Carlsson and Stankiewicz 1995; Asheim and Isaksen 2002; Asheim et al. 2003; Bergek et al. 2005). The innovative capacity of the system is then regarded as an outcome the system elements and the dynamic interaction between them. Because of our focus on specific technological innovations, the technological innovation system (TIS) approach seems to be the most useful starting point, but we perceive the general framework to be useful independently on the specific type of innovation system under study.[2]

Technological innovation systems are "socio-technical systems focused on the development, diffusion and use of a particular technology" (Bergek et al. 2008a: 408) and they are typically defined by their constituting structural elements. Either 'technology' can refer to a knowledge field, such as biotechnology or nanotechnology, or it can refer to a product used for certain applications (Carlsson et al. 2002).[3] Our cases, biofuels, hybrid technology, and hydrogen/fuel cells for road vehicles are examples of the latter.[4] Typically, a TIS may cut across national, regional and sectoral boundaries (Hekkert et al. 2007; Markard and Truffer 2008), though in many cases such boundaries can be

[1] With sustainable technologies, we mean (new) technologies that are proposed to radically reduce the environmental burden without sacrificing societal and economic standard. Parallel to the development of this framework, we have initiated three case studies of selected ongoing innovation processes concerning sustainable technologies in the road transport sector: biofuels, hybrid technology, and hydrogen/fuel cells. In this paper, we use these case studies to exemplify certain aspects of the framework, and we will later use them to test and refine the framework

[2] In the TIS literature, different degrees of 'systemicness' occur. In some cases, the interaction between elements is yet to be developed.

[3] The focus on technology in TISs does not signify a focus on technology push, or that market mechanisms are excluded. Rather, the technology definition is used as a starting point to delineate the system.

[4] It should be noted that a TIS can be seen at various levels of aggregation. For example, more narrow technologies could be studied, such as ethanol from wheat or parallel hybrid technology powered by Li-ion batteries.

motivated by weak interconnections between localities or industries. The influence of external factors, i.e. factors that are not focused on the specific technology and/or located outside the selected boundary, is not systematically included in the TIS approach. Therefore, we will use other streams of literature to include such factors in our framework (see below).

Due to diverging origins and the emphasis of different aspects, various typologies for structural elements exist. The common typology found in the TIS literature refers to actors, networks and institutions (and technologies). For the framework, we use a typology from the literature on socio-technical systems suggested by Geels (2006), including actors, rules, and material and technical elements. Actors can be individuals but are often organized in different kinds of networks, such as firms, universities, authorities and Non Government organizations (NGOs), as well as less formal associations. They can relate to the studied technology in various ways, for example as suppliers, producers, users or policy makers. Material and technical elements include physical artefacts, such as infrastructure, machines, equipment and controlled natural resources.

Rules guide what actors can and should do, how they interact in networks and use material and technical elements. A useful distinction between regulative, normative and cognitive rules is suggested by (Scott 1995).[5] Regulative rules typically refer to the explicit, formal rules that steer interactions between actors and within networks. Normative rules concern the belief systems and value basis of actors and networks. They concern the formulation of 'meaning' for organizations; what it is there for and what it aims to achieve; but also norms of appropriate behaviour and procedure. Cognitive rules involve the shared understanding and perception as well as formal knowledge basis about how things function (including risks, costs, technology potentials, etc.). We will see later that governance often work through affecting some or all of these rules.

The system elements are mutually interrelated in a number of ways (Geels 2004) (Figure 1). Actors form and carry out rules, while rules also guide actors' actions and perceptions. In addition, rules can be embedded in material and technical elements. Material and technical elements shape and constrain rules, while also setting conditions for what actors can do. Finally, material and technical elements do not function without the involvement of actors.

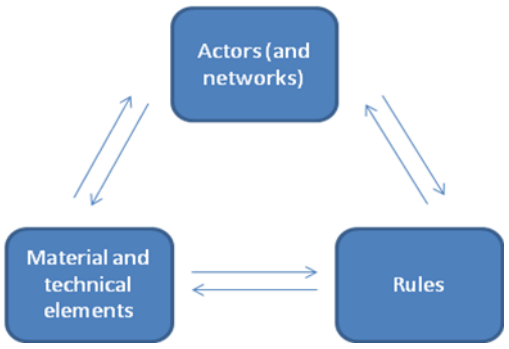

Figure 1: The structural elements of a technological innovation system (TIS), with arrows representing relations between the elements.

2.1 Key processes

The analysis of structural elements has proven not sufficient for the understanding of determinants of change of innovation systems (Hekkert et al. 2007). To bridge this gap several scholars study the processes shaping the evolution of innovation systems. In the TIS approach, the analysis of internal dynamics has been formalised by the identification of a number of key processes – *system functions* –

[5] Scott (1995) calls these the three pillars of institutions. However, we follow Geels (2004) and use the closely related concept of *rules*.

necessary for the *overall function* of developing, diffusing and using a particular technology (Bergek 2002). Based on thorough literature reviews and numerous case studies slightly different sets of functions are proposed in the TIS literature (for an overview, see Bergek et al. 2005; Hekkert et al. 2007; Bergek et al. 2008a). We choose the set of functions proposed by Bergek et al. (2008a) (Table 1).

Table 1: The set of functions proposed by Bergek et al. (2008a: 414-419).

Function	Description
Knowledge development and diffusion	The generation of breadth and depth of the knowledge base of the TIS, and the diffusion and combination of knowledge, taking into account different types of knowledge (e.g., scientific, applied, patents) from different sources.
Influence on the direction of search	The existence of incentives and/or pressures for actors to enter the TIS, and to direct their activities towards certain parts within the TIS (e.g. technologies, applications, or markets).
Entrepreneurial experimentation	The probing into new technologies and applications, unfolding a social learning process reducing uncertainty.
Market formation	The timing, size and type of markets that have actually formed.
Legitimation	Legitimacy is a matter of social acceptance and compliance with relevant institutions: the new technology and its proponents need to be considered appropriate and desirable by relevant actors in different parts of the TIS to acquire political strength.
Resource mobilisation	The extent to which the TIS is able to mobilize competence/human capital through education in specific scientific and technological fields as well as in entrepreneurship, management and finance, financial capital (seed and venture capital, diversifying firms, etc.), and complementary assets such as complementary products, services, infrastructure, etc.
Development of positive externalities	The interconnectedness between different parts of the TIS, and between the TIS and the external environment, in fulfilling the other functions (see also Bergek et al. 2008b).

The mere existence of certain structural elements cannot explain the functionality of TISs. Functions are causes of the structure, as they are the result of actions taken within the system, by actors using technical and material elements guided by different kinds of rules. Nevertheless, external factors also influence the functions. Then, the functions are the cause of a renewed structure, and the loop is closed (Figure 2). We can thus measure the potential for development, diffusion and use of a technology by how well the functions are served, i.e. the functionality of the system.

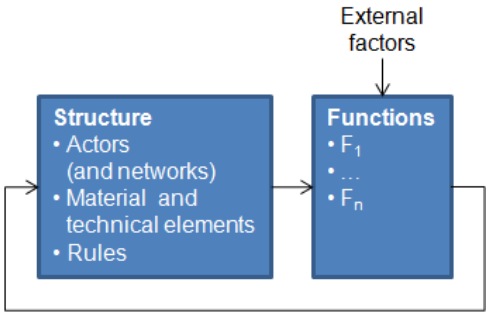

Figure 2: The relationship between structure and functions of technological innovation systems under the influence of external factors can be illustrated by a loop.

2.2 Interplay between levels

The TIS framework has been criticised for not making visible the distinction between external and internal factors (Geels et al. 2008; Markard and Truffer 2008). To overcome this deficiency, we suggest analysing the TIS's position in the larger socio-technical system, i.e. the complex of actors,

rules, and material and technical elements, providing for a certain societal function, such as transport, healthcare, and water and food supply (e.g., Elzen et al. 2004; Geels 2005).[6] Literature on socio-technical transitions studies the development of such systems. In particular, this literature emphasises the importance of regimes, i.e. the alignment of dominating rules in certain parts of the system, providing for stability and a focus on less radical changes (Markard & Truffer 2008). Regimes do not determine the development but provides for alignment of actions performed by the actors of the system. TISs can be more or less aligned with regime rules, and the degree of alignment may change over time. For example, in the case of biofuels for road transport we can identify multiple influential regimes, of which some are also part of other socio-technical systems. In this example, the regimes centred on cars, heavy vehicles (trucks and buses), fuels and agriculture are particularly important.

Literature on socio-technical transitions claim that radical innovations emerge and grow primarily in protected spaces isolated from regimes, called niches. Particularly the work on strategic niche management focuses on the fostering of niches and novelties emerging in niches (so called niche innovations). However, in recent publications the difference between niche and regime has been played down (Raven 2005; Raven 2006; Raven and Verbong 2007; Schot and Geels 2007). In principle, niches and regimes are similar kinds of structures, but niches are characterised by unstable and less developed sets of rules and smaller networks (Geels and Schot 2007). In Raven's (2005: 48) words, a niche can be considered "a loosely defined set of formal and informal rules for new technological practice, explored in societal experiments and protected by a relative small network of industries, users, researchers, policy makers and other involved actors". Over time, niches may develop increasingly stable rules, and their relation to regimes may change. In particular, different transition paths for innovations are explored in historic studies, mainly with a focus on external dynamics and with little systematic treatment of the innovation process (Markard and Truffer 2008).[7] As mentioned above, the focus on such processes is one of the main strengths with the TIS approach. Our assumption is that they are also valuable for the analysis of governance; hence, we adhere to this approach of studying TIS dynamics.

Transitions can be described as an interplay between multiple levels, captured by the multi-level perspective (MLP) (Rip and Kemp 1998; Geels 2002). This perspective centres on socio-technical regimes, i.e. the regime level, which is above the niche level. Above all, there is a third landscape level of societal developments (e.g. the general climate debate and the economic situation) largely unaffected by separate changes on regime and niche levels. The main idea is that transitions between socio-technical regimes come about due to the interplay between the three levels; in short, changes on landscape level may destabilise regimes and open up for niche development. In addition, Geels and Raven (2006) highlight that there is a level below the niche level, where uncoordinated experiments are made. Such 'local projects' may or may not add up to the development of a niche.

Transformation processes within socio-technical systems may take place both on niche and regime levels, and may change character over time. As pointed out by Konrad et al. (2008) it is difficult to predict if an innovation will eventually be part of a larger transition process.[8] Any specific TIS typically develops its own set of increasingly stable rules, while over time showing varying alignment with regime rules. Actors that are part of regimes can develop innovations, while also being part of niche developments with a different set of selection criteria.

Figure 3 schematically illustrates the relation between a studied TIS and the levels in the MLP. For our purpose, the most useful contribution of the MLP is the existence of a landscape level, the stability of

[6] It is suggested that the importance of various functions differ according to the development phase of TISs (Carlsson and Jacobsson 1997; Jacobsson and Lauber 2006; Bergek et al. 2008a), and it is acknowledged that 'more research is needed to establish the nature of the different phases' (Bergek et al. 2008a: 420). We propose an alternative approach to consider TIS status inspired by Markard and Truffer (2008), i.e. to analyse the TIS's relation to the larger socio-technical system.

[7] However, in relation to SNM three broad important processes in niche development are proposed (Kemp et al. 1998; Raven 2005; Schot and Geels 2008).

[8] To emphasize the uncertain nature of innovation processes the term innovation journey is used in some publications (see, e.g., Van de Ven 1999; Geels et al. 2008).

TIS rules and the alignment between TIS and regime rules. Some TIS rules may be very unstable and uncoordinated, typically on the level of projects, while others may show a certain degree of stability, i.e. niche characteristics. A change in TIS structure (resulting in changed functionality) depends on factors on the landscape level, on the present structural status of the TIS, and on how rules on the different levels in the socio-technical system relate to its rules.

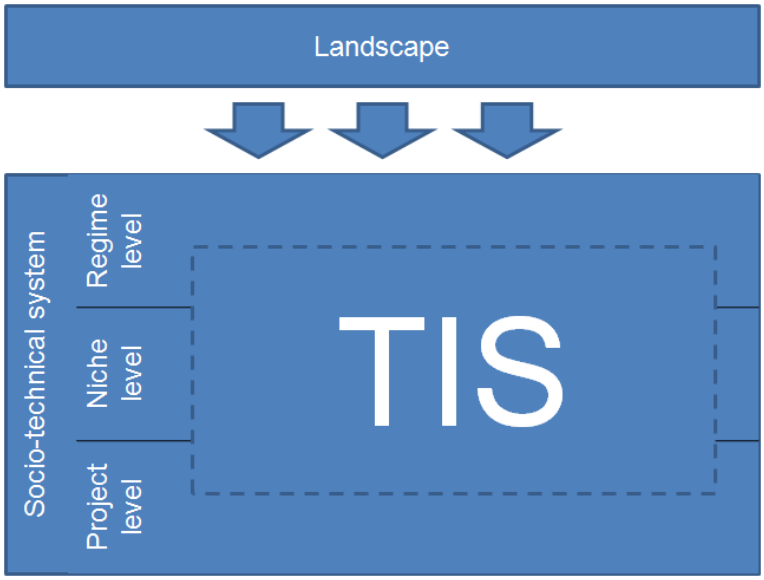

Figure 3: The relation between a studied TIS and the levels in the MLP.

3 Governance – key elements and debates

Governance has become a very popular term over the last two decades, often replacing 'policy' in contemporary debates about social systems coordination. The conceptual shift from policy to governance has principally occurred to highlight that processes of preparing, deciding on and implementing measures to coordinate and advance societal objectives, increasingly involve – and should involve – stakeholders other than the nation state, such as NGOs, the private sector, and local/regional and international organisations. Governance is also advanced to denote that the rules that shape interactions between actors, as well as the use of different instruments, have changed. Moreover, the coordination necessary to achieve, for instance, sustainable innovations, relies on forms of social initiatives that often take place outside traditional policy instruments such as coercive measures and regulation from the state.

Analysts have argued that during the last 20 years there has been a shift from traditional regulatory approaches such as standards, bans and taxes to measures and arrangements that focus on consensus, voluntarism, and procedure, such as soft law and public-private partnerships (Treib et al. 2007). In particular, the European Union has promoted these latter arrangements as a way to increase the efficiency and effectiveness of public affairs through gaining stronger ownership and implementation capacity. However, a closer empirical look shows that 'old-style' regulation and taxation still stands strong and it is far from evident whether there has been a shift in governance in reality (Nilsson et al. 2009). Notwithstanding, the merits of such a shift are constantly called into question, e.g. whether it leads to a better problem-solving capacity be it in innovation policy, environmental protection, or public policy more broadly. In addition, *if* there has been such a shift, recent developments may suggest that it is now reversing: in Europe and elsewhere the use of regulatory standard setting increases as a driver of sustainable innovations through for instance efficiency standards for cars and domestic utilities and bans on light bulbs (*ibid*). Furthermore, the reality in many sectors is that there exists a wide and colourful blend of governance arrangements that mix traditional top-down regulation with voluntary and informational measures – what has been called 'hybrid arrangements' (Hey et al.

2007). At the same time as the salience of policy objectives such as sustainable innovation grow, the ways in which governments and other actors are trying to achieve these objectives are becoming increasingly varied and fragmented (Jordan et al. 2003).

Thus, we understand governance as a broader and more fundamental concept than policy. Howlett (2009: 76) suggests that different modes of governance constitute an overarching long-term arrangement that is not as easily changed as policy objectives or instruments: "[…] while the specific content of abstract policy goals will change from context to context, it has often been observed that high level government goals and implementation preferences are not random but rather tend to cluster over time into favoured sets of ideas and instruments, or governance modes [...]. The existence of these fairly long-term and stable governance arrangements helps explain relatively constant general implementation preferences […]". These modes may shift historically within particular jurisdictions, or they may vary across jurisdictions and perhaps even across sectors, setting specific boundaries and context for policy.

3.1 Governance in relation to MLP, TIS and complex systems

The literature on socio-technical transitions and TISs both make assertions about governance. Indeed, both Strategic Niche Management (SNM) and Transition Management (TM) have been defined as governance arrangements in themselves (Kemp and Loorbach 2003; Schot and Geels 2008). For instance, TM places a significant weight on the role of visioning and experimentation, and argues that they play a number of important functions, such as to induce influence on direction of search, actor/network mobilisation, and legitimating (Rotmans and Kemp 2001). TM and SNM are primarily normative theories and offer little guidance for empirical testing under the pretexts of our study. Still, the underlying assumptions merit further scrutiny and can be tested empirically, such as whether the influence of governance arrangements is affected by niche-regime-landscape interplay, and whether niche creation and vision making are particularly influential on functionality. Smith et al. (2005) link MLP and governance analysis to certain functions in their suggested heuristic typology for mapping 'transition contexts', which can be used to guide the analysis of governance for regime transformation. They suggest that the availability of resources and the ability to coordinate responses constitute the *adaptive capacity* available for regime transformation.

The TIS literature has long attuned to governance, in that it has emphasised the importance of considering different actors' governing activities, where there is a vast range of private actors influencing the innovation system. TIS analysts emphasise in particular the importance of demonstration, the formation of networks, government procurement, assured market sales or subsidy (see, e.g, Edquist et al. 2000; Jacobsson and Bergek 2004; Nygaard 2008). Governance may shape markets but also influence perceptions of what is important, problem understanding, and goal setting among different actors active in the TIS. As well, the need for technology-specific market measures such as price fixing has been highlighted (Jacobsson and Lauber 2006). Through the functional entry point, which describes mechanisms such as legitimation and influence on direction of search as challenges in need of governance responses, TIS analysts have also pointed to the role of actor constellations (networks) and rule systems (institutions) in promoting innovation. Still, TIS literature often treats governance as part of the functionality rather than something that causally contributes to it. In turn, this restricts the possibilities to analyse how governance arrangements actually influence TISs.

In this context, it is useful to turn to a recent strand of normative literature on 'adaptive governance', which has emerged out of social-ecological systems research. This entails stakeholder participation and integrated planning, experimentation and linking institutions across scales (Olsson et al. 2006), essentially implying that the development and implementation of governance is an integrated process. Proponents of adaptive governance assert that this approach is needed in particular for highly uncertain and complex situations. This seems relevant to consider in the case of innovation systems, as these embody complexities, risks and uncertainties that behave in non-linear, abrupt, self-organizing and many times unpredictable ways, thus behaving as so-called 'complex adaptive systems' (Leach et

al. 2007). Responding to such challenges, adaptive governance, like TM, emphasises the need for experimentation, consensual processes and social learning as necessary for guiding complex systems to favourable trajectories. Proponents of the related concepts of 'reflexive' governance have also advocated the opening up of governance processes to social learning and networked participatory processes (Voss et al. 2006). However, there are also countering arguments. Based on in-depth studies of governance for innovation in the Netherlands, Nooteboum (2007) found that effective governance (in terms of functionality) fundamentally depends on establishing trust between actors that normally do not interact much. In his study, he finds that such trust can emerge in so-called 'adaptive networks' which are able to create innovative action and manage breakthroughs in different regimes – what he calls 'power networks'. He argues that these networks, although being also experimental, self-organizing and learning based, cannot emerge publicly, but rather in informal and closed situations.

The importance of developing shared knowledge to learn from is one of the most important assertions in adaptive governance. It is seen as a key governance mechanism also in the work of Haas (1992) on epistemic communities. Haas argues that advances in policy and mediation across interests can be facilitated through a common epistemological basis. Such aspirations have recently become popular across governments. The EU along with many member state governments have put in place appraisal procedures to make governance increasingly knowledge-intensive, i.e. that decision making is based on best available knowledge (Radaelli 2005). Analytical tools that attempt to capture complex systems dynamics are promoted (Nilsson et al. 2008). That the development, use and uptake of knowledge is central to governance can also be deduced from empirical studies in policy analysis, which have shown that knowledge is a major currency in the political bargaining (Weiss 1979; Owens et al. 2004). Some argue that modern politics and power is to a large extent about whose knowledge gets to dominate (Jasanoff and Wynne 1998). While this literature on knowledge in governance tends to avoid offering clear testable propositions, the assertions about the instrumental and learning role of knowledge appears worthwhile examining empirically in the context of a TIS analysis. In order to capture these dynamic processes we therefore need to assess the functionality of a TIS during an extended time period.

Attempts, so far, to introduce more explicitly governance variables into analytical frameworks of TIS and MLP have operated much on a niche level and in a normative mode, promoting particular policy instruments such as strategic niche management and constructive technology assessment (Shot 2001; Kemp et al. 1998; Shot and Geels 2008). This literature has taken little impression from core debates about governance in the political sciences. As far as we know, no comprehensive framework for the analysis of governance of innovation systems has been presented to date. Furthermore, literatures have been vague concerning what constitutes governance and what does not. For instance, some of the proposed functions or indicators of functions are essentially policy or governance measures (see, e.g., Bergek et al. 2008a). This may not be problematic for a descriptive account of functionality. However, for our purposes of causal analysis of governance and its role in innovation systems functionality, it is necessary to make a more strict analytical division. In the following, we will introduce the core elements of the delineated governance part of our framework, aiming to address some of the core debates in the state-of-the-art governance literature.

3.2 Key analytical dimensions of governance

The complexity and ambiguity of the governance concept and its fundamental properties entail an analytical challenge. Past attempts to conceptualise modes of governance has sometimes led to more confusion than clarity (see, e.g., Homeyer forthcoming). One reason, as noted above, is that governance is a multi-faceted concept and it is not always clear what particular angle different theorists are deploying. Better analytical clarity is needed to arrive at operationalisations useful for empirical research (Treib et al. 2007). For the purposes of this framework and its ambition to say something about the connection between governance and TIS functionality, a concrete manifestation of the concept is required to enable tracing governance arrangements over time, and to analyse/evaluate the effectiveness of different arrangements in fostering TIS functionality.

Our concrete departure points are two recent conceptual contributions by Treib et al. (2007) and by Newell et al. (2008). Both these authors acknowledge that governance needs to be understood as a multi-dimensional concept. Using the plainest possible language, in line with Newell et al. (2008), our framework departs from three core questions; who governs (the actors that initiate or coordinate the arrangement), how do they govern (through what instruments, mechanisms and rules), and what do they govern? In the following, we elaborate on each of these dimensions, detail how we wish to address them in the framework, and discuss the academic debates, of which they are part.[9]

1. Who governs?

The 'Who?' dimension concerns the representation of different actors and interests in the initiation and coordination of the governance arrangement. The first aspect to consider is the balance between private and public actor initiative. There is a range of possibilities of actor roles and responsibilities involving various combinations of state and private actors. Different nomenclatures exist; common concepts include statism, corporatism, pluralism, and network governance (Kohler-Koch and Eisling 1999). These form a continuum from a strongly state-centric model to one where the state is completely passive and coordination occurs in self-governing networks in civil society. Pierre and Peters (2006) describe five governance models with differential role allocation between the state and private actors. In their description, they associate each role with a characterisation of the instruments and rules used. However, following Treib et al. (2007) we assert that actors and rules need to be separated analytically. It is not clear that a certain actor participation model necessarily entail a certain set of policy instruments – the state (or a private entity) can on its own devise and deploy a wide range of instruments – from coercive to market and network based. Such clustering of dimensions may be an empirical fact, but one should not assume it a priori.

The second aspect is the level of governance, ranging from global, through national and regional and down to local. One important debate is the relative influence of national states versus other agents and levels of governance, and the alleged dissolution of the nation state as the major agent in governance – through processes of regionalisation and localisation (Baker and Eckerberg 2008). Kaiser and Prange (2004) argue that both these trends are evident in the field of innovation, and that regulatory activities in this area have gradually moved away from national states to organizations at multilateral and regional levels. Another debate has to do with the particular concerns in the EU, and the process of Europeanization in governance. It is well known that the EU aspires to very far-reaching coordination, both across sectors and at multiple levels (Jordan and Schout 2006). Hence, it exert considerable pressure on member states to oblige through harmonising and aligning their policy frameworks (Knill and Lenschow 2005).

The third aspect is the openness in the relationship between actors, i.e. how open or closed the governance arrangement is. Governance literature broadly advocates that more inclusive and open network processes help to introduce debates that are more informed, promote civic debate and introduce contentious visions in social processes. Consequently, such processes are particularly relevant in situations where institutions and practices are still not settled, such as new problem domains (and an emerging TIS is arguably such a domain). Advocating more participation and open processes is of course very much a mainstream 'good governance' argument. However, there are also counter arguments, and it has long been acknowledged that deliberative and reflexive ideals may be inappropriate or unrealistic in situations of interest conflicts and power asymmetries (Leach et al. 2007), or in situations where trust between actors need to develop incrementally (Nooteboom 2007).

[9] This is closely related to Treib et al. (2007), who suggest that it can usefully be described in three distinct and separate dimensions: the policy dimension (what instruments are used?), the politics dimension (who participates?), and the polity (institutional) dimension (what are the rules of interaction?).

2. How do they govern?

The 'How?' dimension is central from an analytical point of view, as it concerns the mapping of mechanisms and rules in various modes of governance. The first aspect concerns the basic portrayal of mechanisms of steering, the most succinct and established arguable being the 'hierarchy-market-networks' typology for coordination of social systems (Scharpf 1993; Peters 1998). The associated policy instrument debate, which we already alluded to, concerns the role of coercive regulation versus the role of markets or network management as main tools for intervention. These are represented in a wide pallet of instruments currently in use – ranging from product standards, bans and regulations, to market-oriented measures, such as market designs and green taxes, and through to network-oriented approaches including voluntary and informational processes, co-regulation and cooperative procedures such as private-public partnerships or even fully private-sector initiatives. The governance literature has both argued positively (this shift has happened) and normatively (it should be this way) for a shift towards softer and more networked forms (Hey et al. 2007). The EU has been important in this debate and has also developed a set of policy measures to live up to it, most notably the Open Method of Coordination (OMC), which relies heavily on benchmarking of performance, joint evaluations and communications surrounding progress. This is the backbone of the Lisbon Agenda agreed on in 2002, and it has permeated the EU's innovation policy for instance through the publication of the European Innovation Scoreboard.

The second aspect, somewhat related but still a distinct analytical category, concerns the character of the institutionalised rules that the governance measure changes. These may be in the form of routines and knowledge consulted in different processes, but also regulative formal rules carried directly by certain governance arrangements (March and Olsen 1989). Rule changes as a result of governance may thus be of either cognitive or normative character or of a more regulatory character (Scott 1995). *Cognitive* rule changes are in focus in the literature on adaptive governance that emphasise the development of consensual knowledge and the 'better argument' as a key to make decision making more ecologically rational, as well as to strengthen actors with less material resources. This cognitive realm may be considered particularly interesting in the field of innovation, as this in itself is a knowledge-development process. *Normative* rule change is another central aspect of adaptive governance, but relates more to development of values and beliefs about 'what is good' (i.e. preferences), than to 'how things are' (i.e. perceptions). These may relate to organizational processes ('logic of appropriateness'), as well as substantive visions and goals. *Regulative* rule change, finally, may follow more directly from a governance arrangement, for instance, enforcing certain behaviours and procedures on organizational decision-making.

The third aspect of the 'how' dimension concerns interplay with other arrangements. We need to account for the fact that governance and institutions never operate in a vacuum. Rather various actors introduce these into a complex web of existing institutions and complementary or competing governance arrangements. There are different theoretical possibilities of how these will interact. One governance arrangement may be adverse, beneficial or neutral in relation another arrangement (Oberthur and Gehring 2006).

3. What do they govern?

While there may be a number of operationalisations of the 'What?' dimension, in our case it follows more or less from our application of the TIS approach. This approach suggests that the functionality of the innovation system should be the target for governance. This includes well-functioning processes of knowledge development and diffusion, direction and search, experimentation, market formation, legitimation, and resource mobilisation (Bergek et al. 2008). Furthermore, we take one particular technology as a starting point to delineate the system and define the field of analysis. In addition to this, there are three aspects relating to the issue 'what do they govern'.

One first aspect relates to the intended function addressed by the governance arrangement. The seven functions presented in Table 1 are more or less explicitly the target of various governance arrangements put in place to influence the TIS. More often than not, we expect to see primary as well as secondary functions addressed, while a complete analysis would also reveal potentially unintended, sometimes unwanted, effects on functionality. For example the Swedish clean car bonus, which was introduced in 2007, primarily aimed at stimulating the market, but it also had a secondary effect in that it served to educate car distributors as well as the public on how to define environmental performance in car purchase.

The second aspect relates to the actors that constitute the intended targets of the governance arrangement. Here, we may differentiate between for instance public and private sector users of a product, household users, producers, and researchers. [10]

The third aspect regards the specificity in terms of system and technology. Here we want to capture that governance arrangements may address different technologies and a different number of technologies. In fact, arrangements can be placed on a scale from economy wide to technology specific ones (Sandén and Azar 2005). As discussed earlier, literatures such as SNM and much of the TIS literature proposes that niches and very specific support systems are the most effective ones in certain situations. Our framework will enable empirical tests of this proposition.

4 The analytical framework

We have now introduced the constituents of our framework, and provided some detail to the variables that we are interested in and their principal relationships. This section summarises and organizes these elements into a coherent framework that helps analyse how governance influence the functionality of a TIS. Of particular importance is that we place the TIS in a context of interplaying levels of the socio-technical system. The framework consists of three principal sets of variables: the governance arrangements, the TIS structure and multilevel interplay, and the functionality of the TIS (Figure 4). Our assumption is that governance arrangements, over time, influence in different ways the functionality of a TIS. To capture these dynamic developments, we need to analyse the functionality at a number of points in time.

Following the TIS approach, we consider the challenge for governance being to remedy poor functionality (Bergek et al. 2008a), i.e. to address weak system functions. In fact, each TIS is typically conditioned by a particular mix of governance arrangements, which typically spans across modes, from standard setting to market signalling and softer approaches such as provision of information about the technology. They intervene in the TIS unfolding, both as part of the context and more specifically infusing political or market signals into the system. Governance is to some extent also part of the system itself, reproducing patterns of influence (Leach et al. 2007). We further assume that the influence of governance arrangements will be quite different depending on the prevalence of important landscape factors, the specific TIS structure, and the stability of TIS rules and their alignment with regime rules.

[10] Note that this is different from the initiator/representation in the coordination, as discussed above.

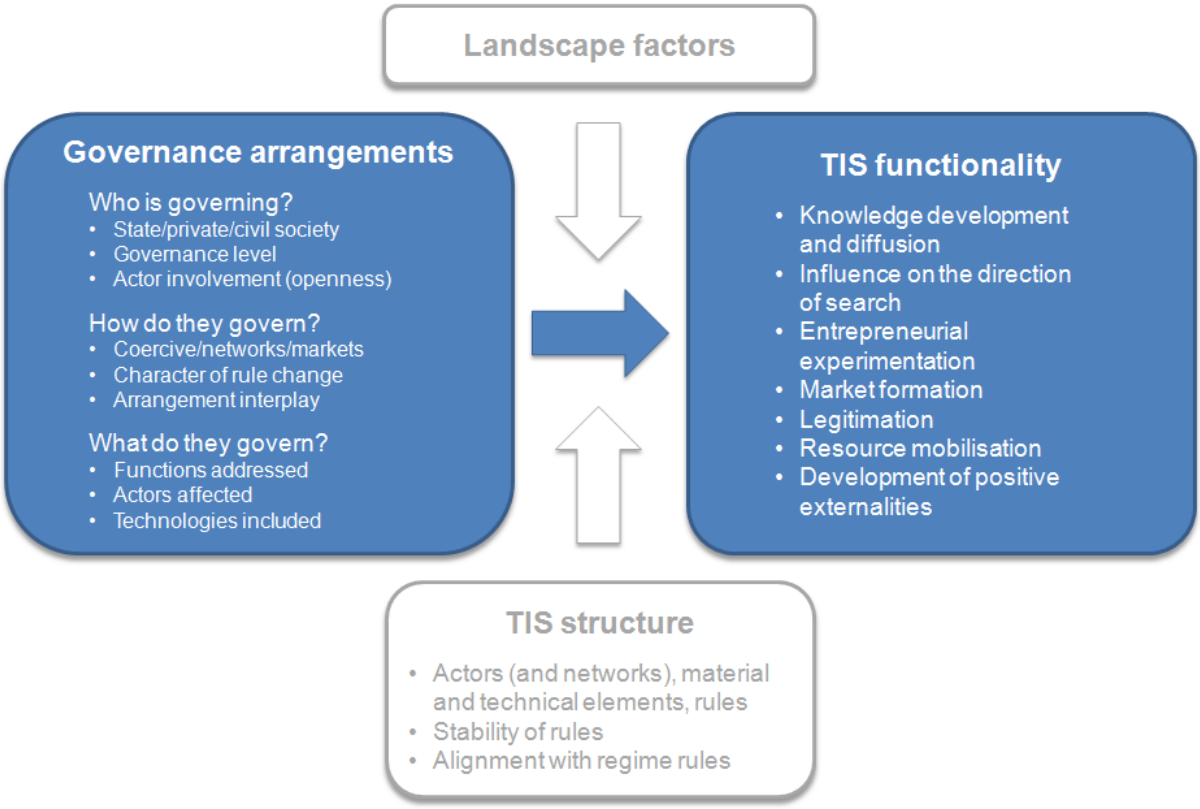

Figure 4: Schematic presentation of the analytical framework. The system involves numerous feedback loops (not included in the figure).

Part 1. Functionality

Our scheme of analysis requires a clear means-to-ends separation of governance from functions. Functionality is our dependent variable. To be able to trace how governance arrangements influence functionality we need measurements at (at least) two points in time, i.e. before and after the implementation of the arrangement. Most TIS studies measure functionality in a predominantly qualitative manner. However, some recent publications propose some quantitative indicators (see examples in **Error! Reference source not found.**). In addition to these mostly quantitative indicators, functionality may be captured through actors' perceptions of, e.g., knowledge supply and diffusion, uncertainties, bottlenecks, sufficiency of guidance, availability of resources, etc. (Hillman et al. 2009). In general, one may use both quantitative and qualitative data from archival records and interviews data to 'measure' these indicators.

Table 2: The set of functions and examples of indicators

Function	Examples of indicators
Knowledge development and diffusion	• Volume of publications and citations, degree of variety • Number and size (money, number of people) of R&D, pilot and demonstration projects, degree of variety • Number of patents, assessments, and studies • Number of conferences, workshops • Volume of co-patenting, co-publishing, number of alliances between actors, joint ventures, platforms/branch organisations
Influence on the direction of search	• Relative prices, price performance ratios • Coherence, and completeness of supportive standards, regulations and targets/goals (i.e. reduction of uncertainty) • Believed growth potential, visions and expectations (e.g. from assessments) • Official project plans, clear user demands (e.g. orders)
Entrepreneurial experimentation	• Number of new entrants and diversifying established firms, degree of variety • Number and degree of variety (technologies, applications) of experiments/projects
Market formation	• Market size (different measures), infrastructure • Number and degree of variety of niche markets and customer groups • Purchasing processes (e.g. stated shares)
Legitimation	• Public opinion towards the technology, captured by e.g. surveys of views Total number of articles/features, and ratio between positive and negative ones • Number and degree of variety of lobby groups active in the system • Number and degree of variety of lobby actions • Number and 'weight' of actors • Total number of assessments, and ratio between positive and negative ones
Resource mobilisation	• Total volume of money available in different parts of the system • Total number of people working with the technology (number of engineers, managers, etc.)

The set of functions were proposed by Bergek et al. (2008). These authors proposed an additional function - development of positive externalities – not included in our overview as the indicators of this function mainly overlap with those of the above mentioned functions. The examples of indicators are from our own review (based on Hekkert et al. 2007; Bergek et al. 2008a; Bergek et al. 2008b; Suurs 2009; van Alphen et al. 2009).

Part 2. Governance arrangements

The specific mix of governance arrangements is our independent variable.[11] Inspired by conceptualisations by Treib et al. (2007) and Newell et al. (2008) we characterise three dimensions of governance arrangements answering the questions of who is governing, how they govern, and what they govern.

For the 'How?' question, a number of distinctions may be addressed through the analytical framework. First, there is a scale from coercive laws and standards, to governance arrangements based on markets and network management. Second, the nature of the primary rules change, i.e. whether they are cognitive, normative or regulative in character. Third, the interplay aspect capturing the degree (from strong to weak) and nature (from conflictual to synergistic) of the interplay with other governance arrangements.

[11] This is a simplification of reality. Analytically, some aspects of governance may be considered part of TIS structure (through its 'rules') as well as contributing to its functionality. However, to make some analytical simplifications we consider these arrangements to occur and develop independently and being imposed on the TIS.

For the ‘Who?’ question, we make three main distinctions. First, to what extent the state or private and civil society actors orchestrate the governance arrangement. Second, the level at which the arrangements are orchestrated, including levels below and above the nation state. Third, the involvement of, and relationship between actors, in particular how open or closed the governance arrangement is.

The ‘What?’ dimension concerns the target of the governance arrangement in terms of functions, actors, and technology. This includes intended effects on system functions, affected actors, and the specific technologies included. In this case, there may well be both primary and secondary effects.

A typical example of governance arrangement used to promote biofuels is the exemption from fuel tax, characterised in our three dimensions as follows. The tax exemption is a regulative measure working through market mechanisms, and it may involve a strong and often synergistic interplay with a number of other governance arrangements. It operates both on regime level (small shares of biofuels blended in petrol and diesel) and on niche level (pure biofuels for dedicated vehicles). The state orchestrates the arrangement on the national level, with little involvement of other actors. Finally, it aims to influence market formation for all potential users of all kinds of fuels produced from biomass.

Another example of arrangement is national R&D programs, providing funding for the development and demonstration of hybrid vehicles. Such programs are supportive measures, directed at a set of actors including vehicle manufacturers, suppliers, universities and users. Being orchestrated by state level agencies, such programs may operate on both regime and niche levels, but they may also support uncoordinated experiments at even lower levels. Such R&D programs may operate in isolation from other governance arrangements. However, as they primarily aim at resource mobilization and knowledge development and diffusion, interplay with government arrangements that influence other TIS functions may be advisable.

Part 3. TIS structure and interplay between levels

We treat landscape factors, the TIS structure, the stability of its rules, and its alignment with regime rules as interacting variables. First, we suspect landscape factors such as political debates and the economic situation to condition the governance arrangements’ influence on functionality. Second, most likely there are specific elements of TIS structures that are crucial for the influence of governance, such as the availability of natural resources or the existence of certain organisations. When it comes to TIS structure we are also interested in the stability of TIS rules, and their alignment with regime rules (Figure 5). First, a TIS with a low degree of stability is typically loosely connected, its actors have diverging views of the technology, and coordination is absent. A TIS with a higher degree of stability will then have the advantage of being a more developed system that is susceptible to any kind of influence. Second, a TIS that show a low degree of alignment with regime rules will likely suffer a range of institutional constraints and governance deficits that stall some functions, whereas TISs that show a higher degree of alignment will be favoured. In reality, TISs are typically situated somewhere in between. In the example of the biofuels TIS in Sweden, its rules are increasingly aligned with those of the car regime and partly with those of the agricultural regime. At the same time, a new set of rules are developing in relation to fuel production and non-food raw materials, indicating an increasing degree of stability.

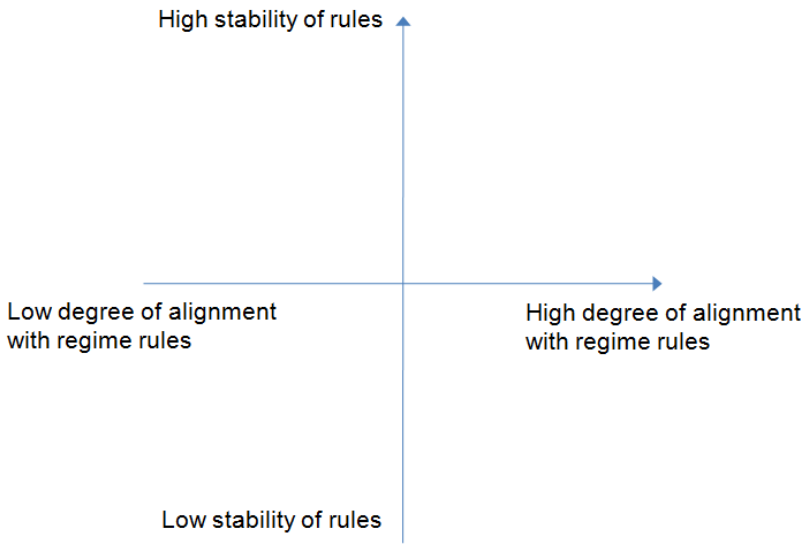

Figure 5: The stability of TIS rules and the degree of alignment with regime rules treated as interacting variables.

Part 4. Synthesis and 'causal attribution'

The fourth part of the framework is a synthesis of the three parts above in a temporal analysis, that is of changes in functionality (Part 1) and changes in governance (Part 2), and contextualise the relationship between these two through the TIS structure and interplay between levels, which also change over time (Part 3). We envision different approaches to organise and interpret data for this purpose. The predominant methodology for the synthesis will be qualitative, involving interpretations of complex social phenomena, based on the in-depth understanding of processes and details. A wide sample of interviews with both industrial, scientific and government actors are probably crucial to develop this understanding. In combination with published evaluations, interviews will help tracing the connection between governance and functionality.[12]

By relating the functional analysis to the MLP, it is possible to evaluate the effectiveness of governance addressing TISs of different stability and with differing relations to regimes. As an example, in the early 1990s, when the Swedish biofuels TIS had developed little stability, the lobbying initiative of the Swedish Foundation for Ethanol Development (SSEU) had a direct influence on the direction of search. In fact, the first projects of a large governmental demonstration programme for biofuels in heavy vehicles came from a list prepared by SSEU (Arnold and Thuriaux 1997).

5 Concluding remarks

The framework to analyse the governance of sustainable technological innovations presented above serves several purposes. First, it provides a heuristic to engage in rigorous empirical study of the role of governance in relation to innovation systems. This involves tracing in a comprehensive way the proliferation of governance arrangements affecting a TIS, examination of their effects on functionality, and an attempt for causal attribution through the insights gained.

Second, it makes a theoretical contribution by merging three recent streams of literature that so far has enjoyed very limited cross-fertilization, that of innovation systems, socio-technical transitions and state-of-the-art theoretical understanding of governance in the political sciences. Although the outlined framework does not emanate in a new theory, it assembles and combines existing theories in a new way.

[12] Methodological issues are further studied by Hillman et al. (2009).

Third, it enables a robust empirical contribution to various central debates about governance, such as modes of governance and Europeanization, both as regards trends in the uptake of different governance arrangements, and their role in and effectiveness for stimulating innovation processes. Here, it could be worth stressing that the framework is looking upstream on the relationship between governance and innovation *system functions*, and is not concerned with the ultimate outcome of the functionality, that is the *overall function* of development, diffusion and use of a particular technology. This would require a separate set of analytical tools.

We have developed the framework with the aim to study technological innovation systems. It should be applicable at different geographical and temporal scales. Empirical applications may therefore be advanced at, e.g., national, European or global levels, depending on the focus of interest. We foresee future empirical testing in several case studies as a vital part of further developing the framework. These tests will aim not only for validation, but also in further refinement and simplification. We will primarily test the framework for sustainable technologies. This is a good field of application as it has been subject to very active and plentiful governance arrangements over the last two decades, and it displays a strong need for governance. We would of course also welcome opportunities for future collaborations and applications by other groups, in other regions of the world, and in other sectors and technological domains.

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