Sustainability-oriented innovation systems – managing the green transformation

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Abstract:
Global warming and other impending environmental mega-problems call for a new technological paradigm. The urgency of the development and deployment of technological solutions is such that governments will need to make widespread use of 'carrots and sticks' to ensure that next-generation technologies are developed and deployed, more demanding standards and regulations are applied and stricter enforcement is guaranteed. To capture the main elements of this paradigm shift, we introduce the concept of Sustainability-oriented Innovation Systems (SoIS). SoIS make particularly high demands on governance, because governments need to disrupt unsustainable technological pathways and encourage alternative technologies long before they reach the stage of commercial viability. This implies picking winners in situations of technological uncertainty and highly disparate stakeholder preferences. SoIS also build on new types of policies that help to internalise environmental costs. The policy-driven nature of technological development may possibly result in a wide divergence of national technological trajectories.

Keywords: sustainability; innovation; low carbon; governance; technological trajectory

Introduction: a new approach to innovation systems research

In the past, economic growth has been achieved at the expense of natural resource depletion, without stocks being allowed to regenerate. Ecosystems have been widely degraded and biodiversity has been lost at an unprecedented pace (Millennium Ecosystem Assessment, 2005). If current resource-intensity continues, environmental tipping points may create ecosystem disequilibria that will threaten human livelihoods.[1] While climate change is the most pressing challenge, many other environmental imbalances are expected to become unsustainable in the near future.

A group of Resilience Alliance researchers has identified nine 'planetary boundaries' that must not be crossed if major risks to humanity are to be avoided. They include limits to freshwater use, ocean acidification, loss of biodiversity and chemical pollution (Rockström et al., 2009). At the same time, the global economy is experiencing a phase of unprecedented growth which is putting an enormous strain on global and local ecosystems. Humankind is approaching the planetary boundaries at high speed.

Changing to sustainable patterns of development while ensuring decent levels of resource access for all the world's citizens is the greatest challenge of our time. It calls for what Freeman (1992) termed a green techno-economic paradigm shift: while the need for new generations of resource-efficient technologies is undisputed, a paradigm shift will also entail a change in societal norms and values, motivating new life styles, different ways of accounting for development and economic incentive schemes that systematically internalise environmental costs. In the same vein, the German Advisory Council on Global Change (WBGU) calls for a 'new global social contract for a low carbon and sustainable global economic system' to achieve a transformation similar in scope to the Neolithic and industrial revolutions (WBGU, 2011, p.1).

This paper sets out to develop a conceptual framework for the analysis of the innovation efforts required to embark on such a sustainable development path. Building on groundwork done by Stamm et al. (2009), we develop the conceptual foundations for Sustainability-oriented Innovation Systems (SoIS). This concept is based on evolutionary innovation systems research, but places far greater emphasis on governance and introduces relevant additional dimensions. The starting point is the need to accelerate the development and deployment of environmentally sustainable technologies. In pursuing this objective, SoIS are confronted with particularly serious market failures. Innovation systems research traditionally concentrates on the market failure of non-appropriability: as the social benefits of science, technology and innovation tend to exceed privately appropriable benefits, the services concerned are frequently undersupplied.

While this also applies to SoIS, the current rules of market economies are even less effective when new generations of environmentally sustainable technologies are to be developed: firstly, because they allow economic agents to externalise many environmental costs, which then have to be borne by society as a whole now and in the future. Secondly, SoIS need to disrupt unsustainable technological trajectories and foster the development of sustainable substitutes, some of which may

[1] 'Tipping points' are critical thresholds of complex systems at which the system changes abruptly from one state to another (Scheffer et al., 2009, p. 53).

require more than a decade or two to become competitive. Supporting these clean technologies of the future is fraught with coordination and information failures.

This has important ramifications for policy and future technological trajectories. As will be shown later, the multiple market failure calls for governments to play a more active guiding role and for a very distinctive range of policy instruments and may result in diverging national technological trajectories, reflecting specific societal preferences, power constellations and policy frameworks.

This paper is divided into three sections. Section 1 stresses the urgency of changing innovation efforts to the search for environmentally sustainable solutions and considers the extent to which innovation systems research has already taken up the challenge. Section 2 advances the existing literature further by developing the concept of SoIS. It highlights important differences between 'business as usual' innovation systems and those aimed at disrupting unsustainable trajectories and accelerating the development and deployment of 'clean' technologies. The three sub-sections of Section 2 are devoted to these differences: increasing demands on governance; different sets of policies; and potentially diverging technological trajectories. Section 3 concludes by identifying relevant topics for future research.

1. Innovations for environmental sustainability: relevance and conceptual debates

1.1. An evolutionary perspective on innovation

The concept of innovation systems (Freeman, 1995; Lundvall, 1992) seeks to explain the systemic nature of innovation. More specifically, it helps us to understand how technologies, industries and institutions co-evolve and shows how technological paradigms are created and how they give rise to specific technological trajectories. Thus the concept provides in principle a suitable analytical framework for understanding the implications of a paradigm change from a fossil fuel-based economic system to one of resource-efficient sustainable production. The core principle of the innovation systems approach is that innovation is a relational, interactive and cumulative process that occurs between producers and users of goods and services, including private industries, universities, providers of knowledge-intensive business services, trade organisations and public support institutions. This relational nature means that technological knowledge cannot be fully codified and traded like any other good. Innovation is described as a process whereby institutions and technologies co-evolve in particular ways (Nelson, 1994): as initial institutional conditions differ – in terms of how markets operate or of societal values and product preferences, for example – different technologies necessarily evolve differently, which in turn leads to particular adaptations of the institutional framework.

Central to this evolutionary understanding of innovation are the notions of technological paradigms and technological trajectories. According to Dosi (1982), a technological paradigm is a kind of directed research programme aimed at discovering solutions to a specific set of perceived problems. Importantly, a paradigm implies 'strong prescriptions on the directions of technical change to pursue and those to neglect' (Dosi, 1982, p. 152). Once a technological paradigm has gained hegemony, the development of new technologies follows a certain direction of advance within its boundaries: a technological trajectory. As progress on a technological trajectory is cumulative, the search for new technologies reinforces its initial direction. As we argue later, this in-built path-dependency and inertia of technological trajectories constitutes the main challenge for sustainability-oriented innovation systems that try to disrupt firmly established, but environmentally unsustainable trajectories.

Traditionally, policy frameworks for technological innovation have been defined mainly at the level of nation states. This has given rise to the notion of national innovation systems. While these are mostly understood as a ‘permeable territorial formation, the borders of which are crossed by numerous linkages within global-local production networks’ (Coe et al., 2004), the focus on national systems and country-specific patterns of technological specialisation nevertheless means that home-country determinants, such as linkages between national firms and research institutions, are deemed more important than cross-border linkages. The popular debate on the ‘competitiveness of nations’ (for example, Porter, 1990) builds on the same premises.

With increasing globalisation, however, the number of international regulations has proliferated. Global and regional bodies have gained considerably in importance as sources of norms and standards to which national actors must adhere. Similarly, international sources of knowledge and transfer mechanisms are becoming increasingly important for technological learning. Among these new international conduits of technology acquisition are the integration of firms into global value chains, joint ventures, mergers and acquisitions, the formation of international research networks in both the public and the private sphere and international labour migration (Altenburg et al., 2008; see also Lema and Lema in this volume).

Innovation systems are therefore characterised by increasingly complex forms of multi-level governance. Nation states still have an important role to play in setting regulatory frameworks, defining national research priorities and promoting networks among national firms and supporting organisations. However, a growing body of rules and regulations is negotiated at international level and then further specified at lower levels – regional, national and sub-national. As we will show in Section 2, multi-level governance is particularly challenging when it comes to innovations in the field of global public goods.

1.2. The need for a paradigm change towards environmental sustainability

For more than two decades, the global economy has experienced a phase of unprecedented growth, fuelled mainly by the dynamism of Asia’s emerging economies. Since the 1990s, the annual growth rate of the global economy has averaged about 3% (World Bank, 2011). This growth has led to rising demand for scarce natural resources, including food, energy and mineral raw materials, which has in turn contributed to accelerated growth in regions that are net exporters of these resources. A particularly noteworthy phenomenon is the rise across the globe of urban middle classes emulating the resource-intensive life styles of the West (Kharas, 2010; Ravallion, 2009), which is exerting additional pressure on scarce natural resources. Energy supplies, for example, would have to double by 2050 to meet the growing demand of all households worldwide (World Energy Council, 2007).

The economic activities of the past have already pushed the planet close to its ecological boundaries. Climate change poses one of the most urgent challenges. Owing to the accumulation of greenhouse gases in the atmosphere, the global mean temperature is rising. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change calculates that total greenhouse gas emissions should peak around 2015 and then gradually fall to 50% of 1990 levels by 2050 (IPCC, 2007). Taking current economic growth rates into account, the 2°C limit can be respected only if the carbon intensity (that is CO2 emissions per unit of economic output) of the world economy is drastically reduced. Technological innovation for climate change mitigation is therefore becoming crucial and needs to be accelerated substantially.

While greenhouse gas emissions are currently the most urgent topic, the traditional pattern of economic growth is depleting other environmental resources, too, particularly water, fertile soils, forests and biodiversity.[2] To focus solely on low carbon innovations would therefore be to take too narrow a view: interdependencies between different resource scarcities need to be taken into account. As an example, producing bio-ethanol as a substitute for fossil fuels may have negative effects on food production, water resources and soil fertility.

Market economies are already developing innovations that reduce resource consumption per unit of output. In OECD countries, energy and non-energy material consumption, CO2 emissions and municipal waste generation are rising more slowly than GDP (OECD, 2011, p. 19). However, the current speed of decoupling is far too low, and the resource-saving effects of new technologies are at least partly offset by growing consumption ('rebound effect': Schipper, 2000). The manifold threats to the earth system reflect the fact that economic incentives globally are geared to accumulating physical, financial and human capital without regard for environmental sustainability (UNEP, 2011). Investors can still externalise environmental costs to a large degree. Hence, what is needed is the consistent internalisation of environmental costs in economic decision-making. Ultimately, the way welfare is measured must change. Conventional indicators, such as GDP, are distorted measures of economic performance since they fail to capture the extent to which economic activities deplete natural capital (WBGU, 2011). As long as the ultimate aim of economic activities is not measured appropriately, the result will be wrong policies.[3]

The financial efforts required to manage the transformation are considerable, but bearable. According to UNEP (2011), the shift to a low carbon, resource-efficient path in 10 central sectors of the economy would require 2% of global GDP annually. We do not yet know how soon this paradigm change will occur. After the no more than incremental successes of the Durban Summit there is little likelihood of the reforms needed to limit global warming to 28C being undertaken in time. However, according to McKinsey (2009, p. 8), 'a 10-year delay in taking abatement action would make it virtually impossible to keep global warming below 28C'. We do know that most resources currently in use are finite.

Failure to take immediate action will overstrain the atmosphere's absorptive capacity, induce worse global warming and lead to much higher abatement costs in the future. The question is thus not whether the global economy will adopt resource-efficient (and particularly low carbon) production or not: it will have to. The question is whether this transition will be organized before major environmental and economic crises occur or whether abatement action will be taken only under the pressure of acute crises and at a far higher cost.

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[2] See Rockström et al. (2009) for a discussion of the various 'planetary boundaries'.

[3] Efforts to build environmental sustainability into economic accounting are currently being made on several fronts, for example the UN Statistical Division's System of Environmental and Economic Accounting and the adjusted net national savings methods developed by the World Bank (WBGU, 2011, 79).

1.3. Earlier attempts to incorporate environmental sustainability into innovation systems research

The goal of internalised environmental costs is not new. Even in the early 1970s, growing concern about the environmental impact of sustained economic growth led to an increase in interest in environmental sustainability. In 1972, the Club of Rome initiated a study on the 'Limits to Growth', which is regarded as one of the foundation stones of sustainability research (Meadows et al., 1972). In this study, a team of researchers built a comprehensive model of the world, in which several complex systems interacted. Among other things, the model simulated interrelations between population density, food resources, energy and environmental damage. The various scenarios developed on the basis of different policy options all led to similar outcomes: if the current trends were to continue, the world would see a catastrophic decline in population and standards of living within a century.

In the later 1970s, environmental economists such as Herman Daly took up this concern and began to criticise the externalisation of environmental costs in growth accounting. Daly attributed the systematic underpricing of natural resources to the societal dominance of the other production factors, capital and labour. Without an effective 'lobby', natural resources were seen as prone to overexploitation. He therefore promoted the concept of steady-state economics, implying that the economy does not grow beyond a certain level of wealth to preserve limited natural resources (Daly, 1977).

Another milestone was reached in 1987, when the World Commission on Environment and Development presented the Brundlandt report to the United Nations. This report advanced the understanding of sustainability by stating that 'environment' and 'development' are inseparable. It defined sustainable development as meeting 'the needs of the present without comprising the ability of future generations to meet their own needs'. As the authors of the report saw it, the limits that sustainable development implies are not absolute, but set both by the ability of the biosphere to absorb the effects of human activities and by the state of technology and social organisation. The enhancement of both technology and social organisation thus opens up avenues for future growth.

Despite this pioneering work, mainstream neoclassical economics has failed to incorporate the environmental dimension systematically both in its concepts (for example, economic growth accounting) and in its incentive systems. This, unfortunately, is also true of most approaches in evolutionary economics and innovation systems research. The main thrust of innovation systems research has been the attempt to increase allocative efficiency and profitability in terms of monetary value. Based on Schumpeter (1942), an innovation system was regarded as successful when it created 'new combinations' that could not easily be copied by competitors, thus allowing the innovator to reap above-average profits for a certain period of time. As environmental goods 'without price tags' had no impact on innovation rents, they were not considered relevant variables.

It was not until the 1990s that some innovation scholars began to incorporate sustainability concerns into their research. Following the concept of techno-economic paradigms, Freeman (1992) introduced the notion of the 'green techno-economic paradigm' as a new structural era of economic development. The 'green' era potentially follows the eras of steam power, electric power, mass production, information and communication technologies. It is seen as a precondition for sustained economic growth in the twenty-first century. However, it will not occur automatically.

As necessary preconditions, Freeman refers to a combination of such institutional changes as the effective regulation of pollution and major modifications to the pattern of inputs. Segura-Bonilla (1999) takes up this concept and applies it to an analysis of the Central American forestry sector. Drawing on the systems of innovation approach and ecological economics, he introduces the 'sustainable systems of innovation' approach. This concept considers the possibility of including nature-human relationships in the 'systems of innovation' approach. Lundvall's (1992) definition of innovation systems is expanded through the explicit inclusion of natural elements: 'A sustainable system of innovation is constituted by human and natural elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge' (Segura-Bonilla 1999, p. 79).

More recently, a related strand of discussion has emerged under the heading of 'sustainability transitions' (Grin et al., 2010). The sustainability transitions school originates from environmental research. It builds on the idea that the challenges of sustainability and sustainable development cannot be addressed with end-of-pipe solutions for mitigating environmental impacts or with incremental environmental improvements. Instead, this school of thought analyses the evolution of 'systems innovations' that would enable larger jumps in environmental efficiency (Elzen et al., 2004, p. 1). Its ultimate goal is to develop points of reference and promising tools for 'transition management'. Transition management is conceptualised as a multi-phase and multi-level concept based on the conviction that, although transitions cannot be entirely planned and managed, the direction and pace of the transition of socio-technical regimes can still be influenced. Transition management therefore aims at better organising and coordinating transition processes as well as influencing the speed of transitions, while steering them into a sustainable direction (Loorbach and Rotmans, 2006).

In sum, a number of attempts have been made to incorporate environmental sustainability into innovation systems research. In addition to the aforementioned conceptual papers, a growing body of literature discusses the emergence of specific technological trajectories in 'green' technologies (for example, Jacobsson and Bergek, 2004; Foxon et al., 2008). All these authors agree that the objective must be to internalise environmental costs into economic decision-making. Few authors, however, explicitly address the implications for governance. Among them are Hübner et al. (2000), who argue that eco-innovations 'usually need state assistance and/or a strong and consistent long-term policy framework for economic actors,' but do not generalise the concept beyond their case study of the German automobile industry.

The literature thus still lacks a systematic overview of all the implications that the sustainability paradigm has for the structures and functions of innovation systems: how it affects the design of policy packages; how governance systems need to be adapted to be able to organise a major paradigm change; and how changing governance structures and policies impact on technological trajectories. The following section seeks to fill this gap.

2. The specificities of sustainability-oriented innovation systems

Building on previous work by Stamm et al. (2009), this section operationalises the concept of 'sustainability-oriented innovation systems' (SoIS), highlighting what is fundamentally different when innovation systems are developed with a view to 'greening the economy'.

We define SoIS as networks of institutions which create, import, modify and diffuse new technologies that help to reduce environmental impacts and resource intensity to a level commensurate with the earth's carrying capacity.[4] The argument centres on the need to decouple economic growth from resource consumption through technological innovation, which has three fundamental implications for the way innovation systems will unfold in the future:

1. Demands on governance are particularly high, because innovation systems need to disrupt environmentally unsustainable technological pathways and encourage alternative technologies, in many cases long before these reach the stage of commercial viability. This presupposes choosing and subsidising specific technologies on the basis of uncertain assumptions about future cost-benefit ratios – with all the risks that such interventions entail.
2. Fundamentally new policies are needed to internalise environmental costs into economic decision-making and accelerate the deployment of 'green' technologies.
3. The fact that future technological pathways are highly policy-driven and dependent on societal preferences suggests a considerable divergence of national technological trajectories.

The following sections explore these distinctive features in greater detail.

2.1. High demands on governance

In facilitating the transition to sustainable 'socio-technical systems' (Geels, 2004), governments have a particularly important and challenging role to play. Given the growing pressure on global ecosystems, policymakers cannot sit back and wait for market actors to develop clean technologies on their own. Even if environmental costs were fully reflected in market prices (which, owing to strong political resistance, is unlikely to happen in the near future – see, for example, the failure to establish a global emissions-trading system), new technologies would most probably not emerge at the pace dictated by the need to avoid ecological tipping points. New generations of technology usually require many years of research, development and pilottesting before they become commercially viable.

The sustainability transition thus calls for pro-active and targeted policies to accelerate the development and deployment of 'green' technologies. Under conditions of considerable uncertainty about future prices and technological options, this makes particularly high demands on governance:

- first, there is the need to overcome the multiple market failures in developing new technologies well ahead of their commercial viability, which presupposes the ability to pick the right future technologies and to manage subsidies in such a way that these technologies can be developed with a minimum of misallocation and political capture;
- second, the choice of technologies implies difficult trade-offs and affects stakeholders in different ways. Hence the need for consensus on the overall direction of change and for political settlements to compensate the losers in reforms;

[4] The definition is based on Freeman (1987), with the addition of the environmental dimension.

- third, change must be brought about under considerable time pressure. Especially where greenhouse gas emissions are concerned, fundamental policy changes must be made within the next 10 years;
- fourth, there is a serious need to harmonise national and international policy frameworks so that there may be a response to, and benefit may be derived from, the international environmental governance regimes that are currently evolving.

Market failure and technology selection

In market economies, technological innovations are mostly driven by market prices and developed by private actors. Such market-based search processes, however, have their limitations when it comes to developing fundamentally new technologies for coping with environmental problems. This is due to a combination of multiple market failures plus the pressure to develop solutions in the time remaining before ecological tipping points are reached.

The urgency of environmental problems calls for the development of some new technologies that are indisputably necessary for any pattern of human development that is in line with the earth's carrying capacity. Renewable energy sources with sufficient supply potential, such as solar energy, are one example; low-emissions transport systems are another. Similarly, developing carbon capture and storage technologies may become inevitable if the world fails to decouple economic growth swiftly from the use of fossil fuels for energy generation.

This may require substantial technology-specific public support, especially when new technologies take years or even decades to become commercially viable. A combination of market failures make it fairly unlikely that market-driven search processes will suffice for the development of timely solutions:

- Externalities: There is a lack of incentives to internalise environmental costs in private investment decisions. While market-based incentives may be used to incorporate such costs, full internalisation is impossible for ethical and political reasons.[5]
- Coordination failure: Many new technologies require simultaneous investment in correlated activities, and individual investors will not make major commitments unless someone guarantees that the associated investment on which he or she depends will be undertaken at the same time. Such coordination failure is particularly serious when entire socio-technical systems (Ropohl, 1999) rather than specific artefacts are to be changed – as is often the case in sustainability transformations. The successful establishment of offshore wind-farms, for example, calls for synchronised outlays on wind turbines, underwater steel structures and grids. A technology-specific and coordinated 'mission-type' approach may be required to initiate such systemic innovations.[6]

[5] From an ethical perspective, it is difficult to define the monetary value of a species, for example. Politically, it has proved difficult to agree on the international prices of environmental public goods, not least because there are no generally accepted principles for the allocation of usage rights. If countries set prices individually, incentives for free-riding and trade distortions are created.

[6] Industry consortia – such as the Desertec Industrial Initiative formed to exploit the renewable energy potential of desert regions (http://www.dii-eumena.com/dii-answers/in-partnership-with-north-africaand-the-middle-east.htmlmay) – may also alleviate coordination failure, but they are difficult to manage owing to high

- Non-appropriability: Innovators need to bear search costs individually, whereas the innovation rents that can be obtained in successful cases rapidly dissipate as followers copy the innovation. Thus the pioneer's individual benefits are lower than the social value of their innovation (Hausmann and Rodrik, 2003). Again, this market failure is particularly serious when established technological trajectories are abandoned.

An additional obstacle to the development of new 'green' technologies is path-dependency, which is linked to, but goes beyond, coordination failure. Once a technological path has been embarked on, economies of scale and network externalities lead to reinforcing patterns which give incumbents a competitive advantage that makes switching to alternatives difficult. Many technological patterns have been established at times when fossil fuels were abundant and climate effects largely unknown. Now that circumstances have changed, high switching costs discourage the development of alternatives. Overcoming this 'carbon lock-in' (Unruh, 2000) requires deliberate action to disrupt established trajectories and promote alternatives in such a way that they, too, are able to develop the necessary economies of scale in production and to lower production costs. As a successful example, subsidised feed-in tariffs for solar energy created a market for mass-produced solar photovoltaic panels, which reduced prices by almost 80% between 1990 and 2010, bringing solar energy ever closer to grid parity (NREL, 2011, p. 60). Similarly, the French and Chinese governments subsidise the purchase of electric vehicles to kick-start production, assuming that, once certain minimum scales of production are reached, the price gap between these vehicles and conventional cars will narrow considerably.

In sum, the transition to 'green' technology needs pro-active government support if multiple market failures are to be overcome. Given the public goods nature of environmental goods and the need to change entire socio-technical systems, these market failures are more pervasive than those in incremental, 'business-as-usual' innovations. The support needed is technology-specific to the extent that more sustainable technologies are preferred to less sustainable ones. Identifying the best technology among a range of sustainable options can be left partly to market forces, thus enabling competition and creativity to be unleashed. Governments can, for example, define renewable energy targets and leave it to market forces to choose the best technology to achieve them. But even then there is a case for offering technology-specific subsidies: it may be appropriate to provide higher subsidies for the development of technologies that make use of abundant resources than for those with a small resource base. While markets would opt for technologies close to commercial viability (for example, first-generation bio-fuels or wind turbines), governments might prefer to encourage more expensive long-term solutions (such as second-generation bio-fuels or solar energy). Similarly, Kalkuhl et al. (2012) make the case for technology-specific quotas in order to 'learn' the best technology and avoid lock-in into an inferior technology.

Selective interventions entail considerable risks (Pack and Saggi, 2006), which increase with distance from commercial viability and size of the subsidy component. On the one hand, governments may bet on the wrong technologies. The development of sustainable technologies is often uncharted territory and requires experimenting with different options. When governments began supporting solar energy technologies, they could not know how much it would cost until these technologies

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transaction costs and the considerable risks involved in contractual arrangements for interdependent long-term investment.

reached grid parity, or whether it would have been better to invest in other sources of renewable energy. In their current decision-making on investment in low carbon mobility, they cannot know whether fuel cells, lithium-ion batteries, hybrid engines or other technologies will become the dominant design. Wrong choices may be very costly for taxpayers as well as for private investors who follow national policy signals. In India, for example, many poor smallholders lost money when governments encouraged them to cultivate biofuel plants which never became a viable business (Altenburg et al., 2009).

On the other hand, providing long-term subsidies under conditions of technological uncertainty is particularly prone to result in rent-seeking and fraud. Governments need to decide on subsidy allocation on the basis of scarce information. Similarly, they must be able to reduce or withdraw subsidies when new technologies approach commercial viability and to redirect them when more promising alternatives emerge. Of course, lobbyists will try to gain as much support as possible for their respective technologies, exaggerating both their future prospects and the need for subsidies. Quite often subsidies for 'green' technologies have been criticised as being too generous. Also, complicated schemes for managing environmental goods have led to cases of corruption, as in the case of the European Emissions Trading System.[7] SoIS therefore presuppose substantial government capabilities to 'manage rents' productively, meaning that governments need to interact closely with industry, identify the right degree of support required, establish good monitoring and evaluation systems, assess the performance of the industries supported and decide when subsidies can be withdrawn, either because they are failing to achieve the expected results or because they are no longer needed (Khan, 2004).

Building societal consensus on technology choices

In an incremental, 'business-as-usual' scenario of technology development, the choice of technology is largely determined by market forces. Countries specialise in goods that match their factor prices, technological capabilities and demand conditions. Our main argument here is that, in innovation for sustainable development, political settlements play an increasingly important role in determining the choice of technologies.

The transition to sustainable production makes it necessary to disrupt established technological trajectories and to support replacement technologies: coal-based power stations are gradually being replaced by renewables-based power stations, traditional light bulbs by light-emitting diodes and combustion engines by electric motors. These substitutions devalue existing assets and increase the value of others. Furthermore, polluting products and industries are taxed, 'clean' substitutes subsidised. Rents are thus taken away from incumbents and transferred to emerging industries. This process, of course, provokes resistance from those who stand to lose and encourages new industries to lobby for subsidies.

It is not only the interests of industries that are affected. The transformation also has many impacts on other stakeholders: how strictly environmental goods are regulated, how heavily resource use is taxed and how subsidies are used may have major repercussions for people's life styles. Societies are therefore often deeply divided on issues of sustainability transformation, as regards nuclear power,

[7] http://www.co2-handel.de/article58_15715.html, accessed 1 January 2012.

genetically modified organisms and carbon capture and storage technologies, for example. Even technologies that are accepted in principle – such as wind farms and new electricity transmission lines – often face strong resistance from local communities who do not want them built in their vicinity.

The choice of technologies and practicability in given political circumstances thus very much depend on societal preferences and the power resources of interest groups. On the one hand, technological preferences reflect deep-rooted national and local societal norms and values. Attitudes towards 'nature' and 'technology' vary significantly between nations, depending on differences in history, culture and living standards: societies with a marked preference for food safety are more likely to push for strict food standards and to accept the higher cost of organic food production; risk-averse societies are more likely to oppose the use of nuclear energy, carbon capture and storage, and other potentially dangerous technologies. The fact that French citizens are less concerned about nuclear risks than Germans and that Japanese consumers buy more eco-efficient cars than Americans is a clear expression of different norms and values.

On the other hand, interests differ within societies and lobby groups struggle to gain hegemony and influence national policies accordingly. Outcomes depend on the distribution of the power resources that can be used to influence interpretations of reality ('ideational power') and to ensure the implementation of specific options by providing, for example, financial resources and political backing ('material power').[8] The type of political regime also matters: authoritarian regimes typically find it easier to introduce risky technologies than open societies, in which stakeholders have many political channels through which to voice their concerns.

The choice of technologies thus depends heavily on political settlements, which – owing to differing preferences and power constellations – tend to be country-specific. This entails a major departure from the principle of the market-driven search which prevails in most other fields of innovation, where market failure is less pervasive and policymakers leave the choice of technologies largely to market actors. Understanding the power struggle between sustainability-oriented reform coalitions and veto players and how it affects technological trajectories is an important element of SoIS analysis.

Time dimensions: long gestation periods and the urgency of action

Policy decisions incorporating environmental restrictions need to have a particularly long time horizon. Moving technologies through all stages of maturity, from laboratory through pilot scale to full commercial operability, takes time. As Kramer and Haigh (2009, p. 568) show for a range of environmental technologies, it can take up to a decade after the invention stage to build a demonstration plant, overcome its initial setbacks and achieve satisfactory operability. Only then are investors confident enough to build the first full-scale commercial plant and it can take another decade to build a dozen. Governments therefore need to be able to make long-term commitments if they are to create credible investment incentives. Bringing solar energy to grid parity, for example, may require more than two decades of subsidisation. Companies need to be able to rely on these incentives and on their endurance. If they adapt early, they gain early-mover advantages. But they

[8] For material and ideational power see, for example, Fuchs and Glaab (2011, 730ff.).

put their competitiveness at risk if they adapt and find that policies, though announced, are not being implemented.

Furthermore, many industrial-scale technologies have depreciation periods of several decades. Coal-fired power stations, for example, have a life span of 30 to 40 years. Consequently, the emissions from those built today will be locked in until 2050, unless policymakers insist on an earlier decommissioning date. That, however, will reduce their profitability and meet with opposition from the respective lobbies.

The necessary long-term orientation of policy frameworks conflicts with the short-term nature of electoral cycles and calls for new accountability mechanisms that force politicians to take the interests of future generations into account. It also challenges the conviction of most industrial policymakers that governments should avoid engaging in the development of technological opportunities available only in the very distant future.[9]

At the same time, the paradigm change needs to be rapid and comprehensive. The time available for embarking on the new paradigm without overstretching the earth's carrying capacity is short. The clearest example is the atmosphere's shrinking capacity to absorb greenhouse gases: the longer the global economy remains on a high emissions track, the greater the irreversible ecosystem damage and the more costly the corrective and adaptive measures needed in the future. The same logic applies to other finite resources.

Harmonising national and international policy frameworks

As stated in Section 1, innovation systems generally tend to 'go global': the actors competing or collaborating to develop innovations are increasingly international, and regulatory frameworks and supporting institutions are formed at different levels of intervention – global, regional, national or sub-national. Hence the analytical focus must shift from national innovation systems to a multi-level governance perspective.

In SoIS, the degree to which framework conditions are negotiated internationally tends to be particularly high, mainly because governments cannot manage global public goods effectively at a national level. To name just a few of the issues, governments need to

- manage transboundary risks and environmental damage. The EU's efforts to agree on safety standards for nuclear power stations and to have Member States commit themselves to binding road maps in the search for sites for nuclear waste repositories are one example;
- distribute equitably rights to use finite resources, as in the case of carbon emissions and fish stocks;
- tax international air and sea traffic to reflect their environmental costs better and to raise revenues for necessary investments in climate change mitigation and adaptation;
- agree on new forms of multilateral cooperation on science, technology and innovation; and

[9] Most prominently, Lin and Monga (2010) call for 'latent comparative advantages' to be made the focus, meaning that support should be given only to industries that have already been successfully developed by countries with a similar endowment structure and a somewhat higher per capita income.

- resolve legal and sharing issues when it comes to investment in energy grids and other cross-border infrastructure.

Such agreements are difficult to achieve, not least because causality chains are not easy to establish in global ecosystems and environmental costs cannot therefore be clearly attributed to specific actors. The debate on 'embedded carbon' demonstrates the difficulties encountered in attributing environmental effects in an interconnected world (see for example, SEI, University of Sydney, 2008). Here, the question is whether the environmental cost of carbon emissions from industrial production should be borne by the producing or the consuming country. As long as such questions remain disputed, the 'polluter pays' principle will not be applicable. There are, moreover, major international disparities in terms of historical responsibility: to what extent were the 'early polluters', such as the forerunners of industrialisation in Europe, responsible for the depletion of natural resources in the past? Hence a need for agreement on baselines against which resource consumption can be measured and usage rights defined. While the basic idea that rich and poor countries have 'common, but differentiated responsibilities' (UNFCCC, Art. 3 and 4) is now widely accepted, agreement on a concrete burden sharing formula has yet to be reached.

As well as considering historical responsibilities, international agreements must take account of the international asymmetries in (absolute and per capita) rates of resource consumption and environmental degradation and of the political and financial ability of countries to cope with environmental challenges. As a rule, international transfers of finance and technology are therefore included in political deals between developed and developing countries. Examples in the environmental sphere include the Global Environmental Facility and the recently proposed Green Climate Fund; the implementation of projects under the Clean Development Mechanism (CDM); and the Climate Technology Mechanism, on which further progress was made during the UNFCCC negotiations in Durban in late 2011.

However, the need to harmonise national and international policy frameworks is not only a challenge, but also an opportunity. International cooperation, in research and development, for example, can produce spillovers and mutual benefits for the cooperating parties. Furthermore, it helps to share the public costs of sustainable innovation and fosters technology transfer across countries (OECD, 2011). Joint research by developed and developing countries can also help to focus minds on the specific needs of the latter.Where research is financed by private investors, it is usually focused on areas with the highest potential for profits and so overlooks countries with low market potential, but a high environmental risk profile. Research partnerships involving developing countries can address this by explicitly targeting local needs.

At national level, progress in the field of green technologies increasingly depends on the ability of governments to exploit the opportunities emerging from international environmental politics. The CDM is a good example of how widely developing countries differ in their ability to benefit from a market-based international transfer scheme. Hosting 43 and 25% of the world's CDM projects respectively, China and India are the two countries that have been able to benefit most from the CDM (UNEP Risoe, 2011). In contrast, less than 3% of all CDM projects were implemented in Africa. Jung (2006) ascribes this to the various host countries' institutional capacities and general investment climates, among other factors.

2.2. Different sets of policies

The many challenges associated with establishing SoIS call for a radical shift in policies. While existing environmental policies are a start, they need to be developed further, disseminated and complemented by new policies. Policymakers also need to make a careful choice out of the most efficient and effective measures for their specific country backgrounds.

To address the market failures in developing sustainable technologies, policymakers need first and foremost to internalise environmental costs in economic decision-making. Suitable measures may include cap and trade systems for carbon emissions and taxes on pollution. Such price signals foster innovations in and deployment of sustainable technologies. Their advantage is their technology neutrality: market actors rather than policymakers determine which technological solution is best suited to achieving the desired resource efficiency. It must be admitted that governments around the globe are still some way from correctly pricing environmental externalities, such as those caused by carbon emissions. On the contrary, price and production subsidies for fossil fuels are still widespread: they collectively exceeded US$650 billion in 2008 (UNEP, 2011, p. 6). Reducing these subsidies is a vital task for the coming years.

While pricing mechanisms form an essential part of sustainability policies, they also have their limitations. Many environmental costs cannot be calculated in monetary terms. In some cases, costs will become calculable only in the distant future. An international consensus on prices of environmental goods is also hard to achieve. If some countries do not join a trading system, or if some industries are exempted, factor allocation will be distorted and free riding encouraged.

Command-and-control measures[10] thus need to complement pricing instruments. It has been argued that, compared to pricing mechanisms, such measures may be less likely to encourage innovations. The incentive for further modernisation vanishes once the given limit value is reached (BMU, 2008, 14). However, this problem can be overcome by gradually imposing ever stricter environmental standards in a transparent and foreseeable manner. The appropriate mix of market-based instruments, and command and control measures depends on the type of public good to be protected and on country characteristics, for example, the maturity of markets and the enforcement capacity of governments.

Naturally, policymakers need a certain degree of societal support to be able to enforce sustainability policies, be they market-based or command-and-control. The degree of such support may differ from one country to another, and even from one group to another within countries. However, the support of societies and governments alike in the case of such long term issues as environmental degradation tends to melt away as soon as a pressing economic problem appears on the agenda. An example is the recent European debt and currency crisis, which largely crowded climate change out of minds and media in 2011 (Horn, 2011). The enforcement of sustainability policies is certainly easier when they can be linked to the achievement of other societal benefits, such as economic growth or the electrification of rural areas. In the ‘Hartwell Paper’, a group of 14 natural and social scientists go

[10] According to the OECD, ‘command-and-control policy refers to environmental policy that relies on regulation (permission, prohibition, standard setting and enforcement) as opposed to financial incentives, that is, economic instruments of cost internalisation’ (OECD, 2001).

even further in arguing that 'decarbonisation will only be achieved successfully as a benefit contingent upon other goals which are politically attractive and relentlessly pragmatic' (Prins et al., 2010). However, this approach may not suffice to prevent global ecosystems from collapsing, with potentially catastrophic consequences for humankind. This knowledge, derived from the complexities of climate science, needs to be translated and communicated to the broader public and included in school and university curricula.

To trigger technological change at the required pace, policymakers must also be prepared to intervene boldly in markets in order to depart from unsustainable 'business as usual' development pathways. The traditional aim of innovation policies has been to foster new activities expected to be more productive and/or to create important knowledge spillovers into different parts of the national economy. 'Creative destruction' (Schumpeter, 1942), meaning the diffusion of newly developed technologies and the crowding out of less efficient ones, was normally left to market forces. However, socio-technical systems are characterised by considerable inertia – because alternative technologies may not yet be available, because of lock-in effects of established technology systems or because consumers do not change their habits immediately. As the tipping points in global ecosystems are rapidly approaching, governments need to complement the above policies with a range of additional measures, such as public support for basic and applied research; the removal of entry barriers to sustainable technologies; sustained support for new 'green' technologies until they become cost competitive; and consumer education and information. Supporting the deployment of technologies is justified when it saves scarce environmental resources –in stark contrast to standard technologies, where governments should, and mostly do, not become involved in technology diffusion.

The mix of policy instruments must change as a technology moves along the deployment curve. Market incentives make sense only when a technology is relatively mature, and public research is inefficient when a technology is mature enough to attract private research activities. Once the technology is proven on a commercial scale, policymakers can make its use compulsory or subsidise its dissemination. These subsidies can, in turn, be phased out when the technology is fully competitive with less sustainable alternatives. For renewable energy technologies, Foxon et al. (2005) provide an overview of policies adapted to particular stages in the life cycle of products.

2.3. Diverging technological trajectories

Innovation systems research stresses that technologies and institutions co-evolve in interdependent ways, thus leading to country-specific trajectories (Nelson, 1994; Dosi, 1982). Similarly, Porter (1990) has shown that, even when factor costs converge, intra-industry specialisation may diverge owing to specific national factors, such as pools of experienced labour or particular demand conditions. Globalisation, however, has a balancing effect, as standards and business models are diffused through international competition and value chain integration. Whether national technological trajectories converge or diverge thus depends on the relative importance of country-specific factors.

Innovation policies geared to environmental sustainability are likely to lead to diverging patterns of specialisation, because technology choices are strongly driven by national policies, which in turn differ widely from one country to another, reflecting specific national preferences and political settlements.[11] We expect national technological trajectories of policy-driven industrial subsystems, such as electric vehicle manufacturing, to diverge far more than those of more mature and market-driven industries, such as the traditional car industry.

There is empirical evidence of diverging trajectories. An analysis of patent applications filed between 2003 and 2008 under the Patent Cooperation Treaty reveals that Japan specialises mostly in electric and hybrid vehicles (in terms of specific patents as a percentage of the country's total patent applications); The Netherlands shows strong specialisation in patents for energy efficiency in buildings and lighting; Germany specialises in the abatement of air pollution; and Australia focuses on technologies related to water pollution. More than 4% of Danish and more than 3% of Spanish applications concern renewable energies, compared to an OECD average of less than 0.7% (OECD, 2011).

The same patent analysis shows that sustainability innovations are concentrated in a fairly small group of countries, the USA, Japan and Germany accounting for the largest shares. Sector analyses indicate that country-specific policy packages were instrumental in the development of these patterns of specialisation: Denmark's decision to opt out of nuclear energy and subsidise the development of wind energy technologies as an alternative is a case in point (Lipp, 2007). In 2000 Germany became the first country to adopt a highly subsidised feed-in tariff for solar energy and went on to become a leader in solar energy technologies.[12] The world's strictest emission standards for cars led Toyota in Japan to set up an ambitious research programme for hybrid engines, a field in which it subsequently became a global leader. These cases confirm the views presented by Porter and van der Linde (1995), who showed that stricter environmental regulations increase the competitiveness of national firms vis a` vis rivals operating in less demanding policy environments.

The transition to sustainable development is a major paradigm shift and therefore often presented as an opportunity for technological leapfrogging (Goldemberg, 1998; Ho, 2006). Newly industrialising countries may bypass fossil fuel-based development and base their development directly on the latest generation of sustainable technologies. This may even give them a competitive edge over incumbents, whose accumulated investments and relationships may become a burden when radical technological change renders them useless.

Mastering (rather than just using) new technologies, however, requires multiple capabilities. In this regard, industrial latecomers are at a disadvantage. It may in fact be easier for old industrialised countries to mobilise spillovers from their established industries for the development of new 'green' competencies than for newcomers to create them from a weak technological base. In fact, there is (so far) little evidence of leapfrogging into sustainability technologies. The few promising cases relate to large, fast-growing economies, foremost among them China, Brazil and India. Here, the rapid expansion of markets and replacement of capital stocks, combined with substantial R&D budgets, may indeed facilitate leapfrogging. Electric vehicles, for example, may become a major breakthrough for China (see Altenburg, Bhasin and Fischer in this volume).

[11] This argument may also apply to other policy-driven fields of technology development, including military and space technologies.
[12] http://www.wind-works.org/FeedLaws/Germany/WhoInventedtheSolarFIT.html.

3. Conclusions and outlook

This paper has highlighted fundamental differences between 'business as usual' and sustainability oriented innovation systems (SoIS). The former mainly support incremental innovations along established technological trajectories, while the latter seek a policy-induced paradigm change and therefore need to navigate their way through uncertainty, long time horizons and multiple market failures.

Empirically, the shift to SoIS is comparatively recent. While the density of environmental regulations and the diversity of policies have increased over the last decade, and the share of 'green' technologies in patented inventions has grown rapidly,[13] this shift is still largely incremental in nature. So far, most of the improvements have been confined to established technologies, with few substantial changes to core technologies and institutions.

However, rapidly growing concern about planetary boundaries in general and climate change in particular calls for more radical and systemic changes in the near future. The expected resource scarcities are likely to increase the pressure on policymakers. The – still slow – progress of carbon pricing in several regions of the world and the establishment of pilot schemes that provide payment for ecosystem services may herald forthcoming institutional arrangements that oblige investors to internalise environmental costs more thoroughly.

As the importance of sustainability-oriented policies grows, more research into the changing nature of innovation systems is needed. Three particularly relevant future research issues are highlighted in the following:

First, comparative analysis of sustainability-oriented policies is needed. As this paper has shown, these policies entail particular risks of misallocation and political capture, since they are applied under conditions of uncertainty and with long time-horizons. Many countries are currently experimenting with such policies. Assessing the wealth of empirical experiments will help to identify policies that are effective in accelerating the necessary paradigm change while keeping the risks manageable.

Second, we have shown that country-specific political settlements are reflected in particular policy packages, which in turn lead to diverging technological trajectories. It is not clear, however, whether this divergence will endure beyond the point where technologies become mature and initial support is phased out. Only empirical research will show whether the levelling forces of competition will dissipate the pioneers' initial gains and technologies will migrate to locations with lower production costs, or whether early-mover advantages have self-reinforcing effects that lead to further divergence.

Third, the issue of leapfrogging is of particular relevance to latecomer development. Will the shift towards sustainable production revolutionise the international division of labour? How substantial

[13] Between 1999 and 2008, the number of patented inventions grew by 24% annually in renewable energy, 20% in electric and hybrid vehicles and 11% in energy efficiency in building and lighting, compared to an average annual patent increase of 6% (OECD, 2011, 28f.).

are the opportunities for leapfrogging, and how serious is the carbon lock-in in today's industrialised countries? Comparative analysis of SoIS and technological trajectories in old industrialised and emerging economies may help to answer these questions.

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