Drivers and Patterns of Change in Systems and Innovation Research

Jakob Edler and Rainer Walz

Abstract This chapter draws overall conclusions across all the contributions to this volume. Its first aim is to characterise each of the nine analysed systems and innovation research fields (SIR fields) in terms of their patterns and dynamics of change. How and why have the respective research questions and approaches evolved, and how has the role of each field vis-à-vis policy changed? The second aim is to draw overall conclusions concerning the dynamics of change across the fields. To achieve these two aims, the chapter first develops a change model of system and innovation research that is then applied to all fields. This model defines four drivers of change in the fields, i.e. policy processes, contextual developments, theoretical developments and developments in data and methods. It also takes into consideration the relationship of the SIR fields to traditional academic fields that were established prior to the evolution of our fields. Although we find some dynamics specific to each field, we also identify commonalities and similar patterns across the fields, mirroring the overarching zeitgeist changes of the last 50 years. The chapter closes with a few speculations and normative claims regarding the future development of our nine fields.

J. Edler (✉)
Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany

Manchester Institute of Innovation Research (MIoIR), University of Manchester, Manchester, United Kingdom
e-mail: jakob.edler@isi.fraunhofer.de

R. Walz
Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany
e-mail: Rainer.Walz@isi.fraunhofer.de

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1 Introduction

In this chapter, we want to explore whether there are commonalities and differences between the research fields analysed in the previous chapters of this book, and whether we can identify general patterns in their development. As a first step, we develop and apply a simplified systemic model of (research) field dynamics to help the analysis. This model has emerged inductively by analysing how these nine research fields covered in this book have developed over time. In the second step, we use this model to reflect on the development in each research field. In the third step, we draw conclusions. We use the experience from the nine research fields to reflect on the drivers behind the development of SIR research fields in general and to consider how research in the various fields of systems and innovation research (SIR) could and should develop in the future.

2 Systemic Model of (Research) Field Dynamics

Research provides new knowledge and helps to spur innovation. Thus, the heuristics used to analyse knowledge creation and innovation are also useful starting points for our systemic model.

Modern innovation research emphasises that knowledge creation and innovation are social processes driven by the interaction between different actors within an innovation system. They are characterised by co-evolutionary processes between the different elements in such a system, as well as by a cumulative process. In hindsight, we can conceptualise the development of research fields to follow a certain general—simplified—pattern. At the beginning, the traditional, long established research fields were perceived to be insufficient to tackle new needs. Thus, those needs were addressed with new research paradigms, a specific mode of research and a new set of actors, which led towards establishing new areas of research, subsequently developing into new research fields. This process has been cumulative and recursive, knowledge stocks thus created built on previous ones by combining existing knowledge with new insights, and in doing both challenge, influence and reconfirm the nascent research field. Over time, this process led to new established research fields with their own established epistemological structures and actor landscape. Therefore, SIR developed in a co-evolutionary processes with the external demands and an internal logic driven by the cumulative nature of knowledge and development of specific epistemic practices.

One of the specific and defining features of our SIR fields is the fact that they from the beginning have been strongly linked to policy making. Throughout their history, they have provided conceptualisation and empirical evidence to support, underpin or assess policies. Thus, in all nine fields, we see strong patterns of co-evolution between research activities and policy practice. Although this co-evolution differs in each field, and its nature changes over time, it is still possible to detect patterns concerning the mutual influence of policy and research. Analysing the histories of the nine research fields, and in order to take a comparative and systematic view of these dynamics, we propose to conceptualise this co-evolution in a four-dimensional systemic model. We assert that each of the four dimensions can be the source for the demand, orientation and shape of research in a given research field.[1]

As we are concerned with application and policy-oriented research fields, the most obvious dimension is the definition of what a *policy concern* is. The formulation or adaptation of policy problems requests sound, scientific advice that often necessitates adjusted conceptual underpinning and new forms of empirical analysis. A second dimension is formed by the new opportunities and challenges stemming from *contextual developments*, i.e. technological, economic, environmental, societal or (geo)political dynamics. Those developments can be of very different levels of gravity and severity. Some of the recognised, major societal challenges, such as climate change concerns may exert a somewhat dominant influence over time both on policy and on the academic community with re-enforcing dynamics across all dimensions of the model. Thirdly, from time to time, there are *new theoretical or conceptual developments* that have the power to bring about profound change in research fields. Fourthly, new *methodological developments* and the availability of new data sources can generate new questions and new types of empirical evidence. In particular the latter two dimensions are linked to established academic fields, which influence the behaviour of individual scientists, their career paths and options, as well as patterns of scientific exchange.

In addition to being influenced by these external dimensions, research field development is also driven by its internal logic. The above-mentioned cumulative nature of knowledge means that research questions and methodologies are also influenced by previous results within the research field, which interact with new developments in the external dimensions. Those dynamics influencing the development of the field are not uni-directional. Rather, the development of the field itself feeds back to the four dimensions of the field. Finally, and very importantly, the epistemic community of the SIR is not developing out of thin air. Rather, it draws upon theories, concepts, methods and data from established academic fields, which opens various options of mutual influence between new and established fields over time. Figure 1 depicts the conceptual model of SIR field development.

It can be expected that the dynamics and patterns of change vary, that each dimension can be the source, or the bottleneck, of further development of the demand for and supply of research for policy making in our fields. Also, there is seldom just one connection, one arrow in place in this model. Instead, dynamics from one dimension spill over to the other three. However, the analytical model

[1] When writing this chapter, this model was particularly inspired by analysing the first versions of the chapter on innovation indicators by Frietsch et al. and the chapter on water research by Hillenbrand et al. in this anthology, who pointed to the importance of elements from the four dimensions, and the feedback from research to policy making and economic and environmental developments. Subsequently, Frietsch et al. structured their analysis by using and further developing this model in a version tailored to the specificities of their research field.

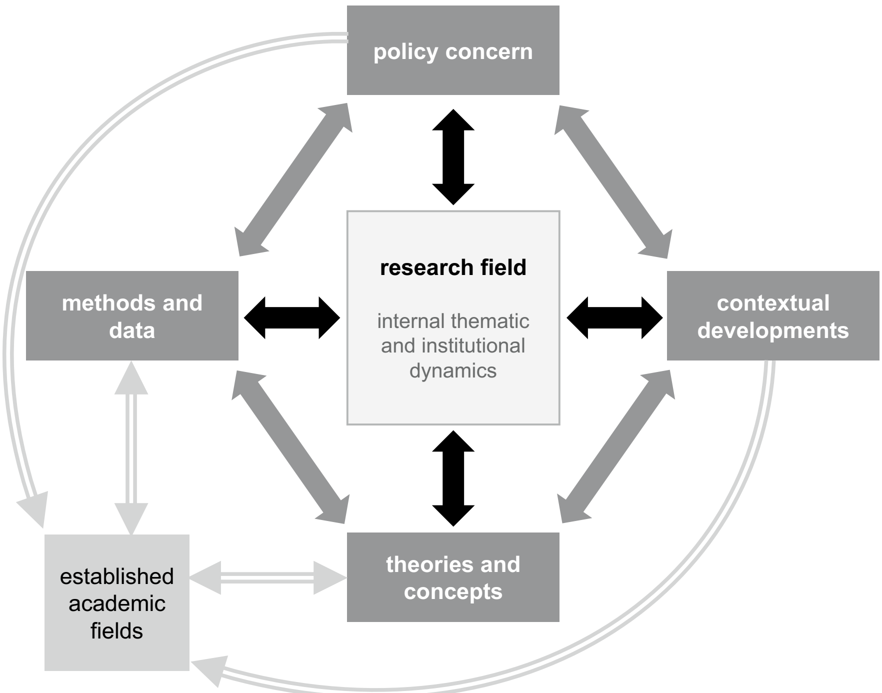

Fig. 1 Systems and innovation research change model. Source: own representation

allows us to look for the origin of developments and the timing and relative weight of the cross-influence between dimensions. It also allows us to detect the absence of influence, i.e. the lack of any policy consequence of, for example, new data availability or new scholarly concepts. In the following, we apply this model to reflect in brief on the nine contributions to this volume and to try and detect any overarching patterns.

3 Patterns of Change in the Research Fields

3.1 Understanding Paradigm Changes in Science, Technology and Innovation Policy: Between Science Push and Policy Pull

It is now widely recognised that the analysis and conceptualisation of STI policy has developed in three phases, with each phase characterised by a major STI policy paradigm. As these paradigms are additive rather than substituting each other, policy ambitions and policy instrumentation have broadened as a result. Academics have tried to understand and conceptualise policy for science and innovation and have drawn on theories and concepts concerning the specific role of the state. Thus, this area of SIR is a very good example of the interplay between theoretical paradigms, on the one hand, and policy concerns and instrumentation, on the other hand, throughout its five decades of history.

The first phase was dominated by the linear model of innovation and market-driven exploitation. The basic, dominant idea was that the state should support basic research and selected technologies in order to foster economic competitiveness and military security. One could argue that, in this phase, economists, who dominated the STI policy thinking at the time, were reacting to developments in policy ambition. Economists like Solow and Arrow explained and justified the role of the state for science and technology as it was unfolding, rather than driving that change. However, academics also suggested and supported the development of framework conditions and instruments in line with the dominant paradigm of supporting science production for subsequent technological and economic exploitation through market forces.

The relationship between scholars and policy making started to change in the 1970s and especially in the 1980s and 1990s. While the endogenous growth theory and economic geography developed as a response to the traditional macro-economic theory and amplified the relevance of knowledge and technology for economic and societal development, the influence on STI policy making was dominated by a new, complementary, albeit rather small class of evolutionary and institutional economists. As in other SIR areas of research, the (national) innovation systems approach and its institutional and policy-related implications began to prevail. These epistemic contributions were well received by politicians and policy makers seeking ways out of the stagflation crisis, a new phenomenon in the 1970s. The awareness of a deep crisis and concerns about the loss of competitiveness vis-à-vis new global players such as Japan catalysed both academic conceptualisation and the eagerness with which policy makers embraced systems thinking and its policy implications. Re-defining the role of the state in the system and broadening the instrumentation used were thus the result of the interplay between an academic paradigm change and the existence of an unprecedented crisis demanding novel solutions.

In the third and most recent phase, yet another relationship between the scholarly community and policy makers drove the development of both policy and of the scholarly community. One driver was again a crisis; this time a failure of policy to deliver on the ambitious economic goals of innovation enhancement announced in Europe and at a European level. Another driver was the normative turn in STI policy. A novel sense of urgency in society and policy making called for new ways to mobilise science and technology to address pressing societal challenges at national, European and UN level (SDGs). This finally opened the door to policy concepts that had already been immanent in the innovation systems thinking of the 1980s and early 1990s and that had already demanded the mobilisation of STI towards problems and its coordination with other policies to that end. In the late 2010s, the time was ripe for this policy paradigm. It was then popularised and further developed by innovation scholars and—importantly—by scholars in transition studies, who realised the leverage STI policy can and should have on transformations. The current turn towards mission-based and transformational policies is therefore the result of a co-generation of policy and broader governance approaches, in parts driven by explicit joint efforts,[2] in parts by efforts from policy-making organisations to take stock of and further develop these policies collectively.

At this point of the development, in the early 2020s, the community of STI scholars and policy practice are facing a dilemma. Evolutionary economists, STI policy scholars and transition scholars have, consciously and unconsciously, combined their efforts in the direction of the new normative paradigm of STI policy making. While this is promising, it has also led to demands for far-reaching changes in governance, the requirements for the state in terms of capability and institution building as well as policy coordination. Again, as with the Lisbon agenda of system enhancement for leading edge global competitiveness, there is a danger that governance and in particular STI policy practice will be overwhelmed by these demands. The role of the STI policy community at this point would have to be to offer support in very pragmatic, formative terms.

An additional concern that was already apparent in the 1980s but largely ignored is now coming to the fore, the need to consider STI development and the application of innovations within the context of sectoral policies. We still witness a dual compartmentalisation here: the division of responsibilities in ministries between STI policy, on the one hand, and sectoral, solution-oriented policies, on the other hand. It is important to note that this compartmentalisation is mirrored to a large extent by persistent separation of the scholarly community, where the convergence of innovation economists, STI policy scholars and transition scholars is still not sufficient.

Reflecting on the development of this research field over the last five decades also makes one think about the limitation of STI policy scholars in terms of focussing too narrowly on STI policy organised in innovation, science or economic ministries. Even as early as the post-World War II years have there been all sorts of purpose-oriented programmes supporting science, technology and innovation in sectoral policies. The value of scientific knowledge and in particular of new technologies and their application has always been part of policy making in sectoral policies such as energy, health or mobility. Against this background a more ambitious link between STI policy and sectoral policies should be possible.

3.2 Analysing the Nature and Dynamics of Innovation: Innovation Monitoring and Innovation Indicators

The research field of indicators occupies a very special position in innovation and systems research. While a stand-alone academic community has emerged here featuring a major journal (Scientometrics), European networks and a range of established conferences, science and innovation monitoring indicator development has

[2]The most prominent example is the transformative innovation policy consortium TIPC (https://tipconsortium.net/).

been at the service of other research fields from the very beginning. These fields include innovation studies, science studies, science and innovation policy studies, technology management studies, business economics and macro-economic analyses, and technological and systems analysis in sectors such as energy, mobility and so on.

In the same way, quantitatively measuring the key dimensions of innovation systems has been of great importance for policy making throughout the last five decades. Here, we see a mutually reinforcing dynamic, as new indicators have led to new policy demands, and new policy aspirations have led to new indicators. For example, if the state assumes responsibility for the performance of the science system, it becomes imperative to measure and map its internal dynamics, input, performance and connectivity to economic actors and to measure the relative contribution of science to economic dynamics. Likewise, if the support for innovations serves first and foremost to drive national economies, as was prevalent in the 1980s and 1990s, it becomes necessary to develop, test and apply a range of indicators and methodologies to analyse the contribution these innovations make to economic dynamics.

The critical importance of quantitatively monitoring the contribution of science and innovation to economic competitiveness and, more generally, to societal welfare has thus put indicator development at the forefront of policy concerns. This importance is backed by the actions of international organisations such as the OECD and the EU, which have supported the development of innovation indicators and ensured international comparability through standardisation and the formation of transnational epistemic and policy-making communities.

Further, this field is also characterised by a particularly pronounced interplay with the other three dimensions of our conceptual model. In the last five decades, the development of the field has been driven by the advent and dominance of new theoretical paradigms, such as the endogenous growth model and the linear model of innovation that stress input and output indicators, or the innovation system paradigm, which requires the definition and operationalisation of indicators to measure capabilities and connectivity. Due to these close links, major changes in the dominant model of technological development have necessitated adaptations to the focus of measurement. For example, the increasing prevalence of science-based technologies, the growing dominance of platform-based business models and the technologies enabling them, or the rising importance of the service economy have all required the adaptation of existing indicators or the development of new ones. In addition, methodological advances based on the availability of new data or the accessibility of new computational power have led to a novel perspective of the innovation system, as they allow, for example, more profound, inductive analyses at the micro level.

While these complex interactions have, all in all, contributed to the development of policy making, not all of the methodological aspirations have been successful. For example, the idea to quantitatively measure and map the development of a technology through technometrics did not succeed. Instead, it has proven necessary to mobilise additional methods from neighbouring fields with expertise in the specific technological area for technological system analysis. Similarly, early applications of big data analysis have not yet led to new theoretical concepts that can capture and assess the dynamics measured. The biggest contribution of this field has been to co-evolve so profoundly with all the dimensions of our model and to enable an operationalisation of the new theoretical paradigms in policy making.

The field's further development will be equally challenging if it is to support analyses of the contribution of science and technology to broader transformations in the wake of transformational policies. STI indicators have been used to analyse technological systems for some time already, but monitoring the transformation of systems and the relative role of S&T in this system transformation will require further methodological advances, as well as a novel joint discourse of yet diverse epistemic communities and new combinations of policy communities. For this development, it is of the utmost importance that all producers and users of indicators constantly remind themselves what the chapter on indicators in this book emphasises, i.e. that indicators are a means to an end and must not take on a life of their own. Indicators will always need contextualisation, which is even more challenging in the context of monitoring system dynamics and the related role of science, technology and innovation.

3.3 Foresight: From Detecting Futures for Strategising to Participatory Approaches for Governance

As the chapter on this research field shows, foresight has had a twofold function in systems and innovation research. It started as a means to reduce uncertainty in order to develop strategies. This was then complemented by collective reflection on possible futures that served to better understand the directions and drivers of change and to structure a discourse based on this about what is normatively desirable and how decisions can influence future developments. This field is a fascinating example of how changing demands in society and policy have interacted with intellectual and methodological developments in the epistemic communities.

Foresight was first developed as a technique for planning and strategising by the military and large corporations. The aim was to identify possible futures including estimates of plausibility using sophisticated foresight techniques such as systems modelling and technology forecasting as well as Delphi studies.

Policy-oriented foresight beyond military planning first began in the 1960s and intensified in the 1970s, in the era of "planification" and the dawn of cybernetic systems thinking. This was motivated by broad societal concerns and enabled by an increasingly active epistemic community and advanced modelling methods. The activities of the Club of Rome highlighted and supported the new ambition of predicting the future development of entire systems rather than specific technologies or limited problem areas. It does not seem to be a coincidence that foresight developed at the same time as other research fields of SIR, which sought to understand the systemic dimension and dynamics of technological development and were also driven by the normative appeal to inform policy and support the governance of system development.

As in other areas of systems and innovation research, the explicit and formalised innovation systems approach of the later 1970s and 1980s advanced this ambition even further. Foresight was increasingly applied to help understand and shape those national systems. The 1980s and 1990s saw mutually reinforcing dynamics between the conceptualisation and empirical analysis of systems dynamics, on the one hand, and concrete foresight activities, on the other hand, that solidified the very idea of national systems as the focus of policy concern.

Reflecting on and arguing about possible futures, their drivers and consequences also affected the policies aimed at influencing systems. Foresight thus became a policy tool in two respects: first, to explore the role of polices for alternative futures and second, to engage in broad stakeholder discourses on the very nature of existing systems and the factors influencing their future development. The foresight practitioners and academics therefore positively reinforced innovation systems thinking.

Subsequent developments in the field of foresight were driven by new data and methods as well as new epistemic and political aspirations. First, foresight in and for STI policy has been influenced by new data sources and methods. In the 1970s, new patent and publication data made it possible to detect technology development at an early stage and assess the contribution of technologies to the competitiveness of the—mainly national—systems. In more recent years, big data analytics and artificial intelligence tools have enabled the processing of much larger sets of unstructured data and thus increased the ability to detect early signals of trends and develop far advanced topic models to inform trend analysis and discourse.

Second, and more importantly for the development of the field, foresight has become a participatory and more reflexive practice. Having realised the limited possibility to predict or determine futures, scholars and practitioners began to appreciate the value of collective sense-making about possible future developments. This was pushed by a move towards recognising societal concerns and matters of the social responsibility of science and technology sparked by approaches like Responsible Research and Innovation and the orientation towards societal challenges. Forecast and modelling was complemented, and even substituted in parts, by participatory practices. Inclusive reflection and co-construction of alternative futures became a policy imperative, especially at European level, and traditional technology and scientific experts were increasingly complemented by broader stakeholder groups, in particular those societal groups affected by technological and scientific developments.

The growing methodological sophistication and diversification of foresight has been accompanied by the emergence of an increasingly diverse foresight community that is both inter- and transdisciplinary in nature. However, in conjunction with the problem-driven and application-oriented nature of foresight, this has also resulted in very slow institutionalisation into an academic field.

With the UN SDGs and transformational STI policy now at the top of policy agendas, foresight is, ironically, at a crossroads. It is called upon to support system change both by identifying the role of specific technologies or social innovation for transformation (predictive) and by a broad discourse on possible system trajectories, their material and normative tensions and how political and societal action can shape future developments. As this role of foresight unfolds in highly normative contexts, it will be important to define the role of different kinds of foresight exercises very explicitly and to address normative apprehension transparently—without falling back into the trap of the 1970s to claim prediction and systems engineering through advanced modelling even of behaviour.

3.4 Evaluating Public Research and Innovation Policies: A Short History of Co-Evolution

The main force driving developments in evaluation research has been the interplay between the theoretical development in innovation studies and changing practices and demands of policy makers. A succession of theoretical concepts such as market failure concepts (neoclassical economics), innovation systems approach (evolutionary economics) and mission orientation (based on a range of neo-interventionist approaches) have interacted with policy ambitions and instrumentation and defined research questions. Evaluation practitioners have developed operational concepts to measure the intended (and unintended) effects of policies that changed as a result of this co-evolution. Methods and data sources did not play a major role here, although there are instances of the co-development of policy intentions (connectivity) and new methods (network analysis).

In the 1960s and 1970s, public policy for science, technology and innovation was about steering the economy and increasing welfare systematically. Consequently, evaluation concerned the contribution of R&D programmes to economic growth and technological development and thus the accountability of policy and funding. Early methods in policy evaluation were based on input–output calculations of the innovation process (at the macro level). In parallel, questions were addressed regarding the implementation of programmes (at least in Germany, implementation research). From the mid to late 1980s, the dominant theoretical background was the innovation systems approach, focusing on the need for connectivity and capacity building in systems. This resulted in a broadening of methods from changes of outputs to encompass a number of indicator approaches (patents, publications, citations). This was accompanied by a further diversification of the research questions, which then also included the innovation activities of firms (behavioural additionality) and capacity building in the economy. Policy makers then wanted information about the networking effects of actors and how their relationships with each other changed as a consequence of complex, multi-measure, multi-actor programmes. In the 1990s, a wave of evaluations analysed system-level changes in structures and performance based on policy mixes. Further developments included questions about broader societal impact that became more important in the 1990s and 2000s and which have recently expanded to cover the contribution of research and innovation policy to specific missions and to system transformation. This has led to a search for and the application of new methods to assess the impact of STI policy on the development of transformations or the achievement of missions.

The demand for evaluation has evolved from giving a very crude account of the impact of interventions to a more sophisticated analysis of different types of impact. With its increasing complexity, however, evaluation has also become a device used to support learning, to accompany, monitor and influence policy implementation. Evaluators have become partners of policy makers, research and innovation funders as well as target group stakeholders. Looking ahead, it is likely that the need to understand the contribution of STI and STI policy will lead to further attempts to understand its impact on system developments and to model and monitor impact and transition pathways. The evaluation of STI policy will be even more closely linked to wider stakeholder groups and other disciplines. How this development will play out is not yet clear, but we may very well see much more formative evaluation efforts as well as a broadening of evaluation towards ex-ante systems modelling and systems monitoring. Finally, as evaluation now analyses policies that target system-level dynamics, in some instances, evaluators have begun to influence the societal and political debate about the very nature of the research and innovation system. This includes value judgements about the relative importance of actors and activities across systems and about policy support for the system.

3.5 Assessing Technological Innovations: From Early Warning to the Governance of Socio-Technical Transformations

This field of research has been driven less by the concerns of policy makers and more broadly by societal concerns and parliamentarians. Institutionalised technology assessment (TA) was initiated by US parliamentarians as a counterweight to the decision-making of the executive and the judicative. Growing societal concerns have led to a rising demand for TA. TA has been called upon to assess what to expect from a technology in the future and, in doing so, to support decision-making, regulation and also management with regard to the future development and deployment of technologies. More recently, another major modification is the shift towards systemic questions, such as what is the role of technologies in system transformation and how can systems be transformed more generally?

TA has also evolved into an approach to democratise the development of technology and to make it “more responsible” by involving multiple stakeholder groups (constructive technology assessment). TA has therefore expanded its methodological approaches and taken on the role of active moderator of a process that seeks to develop a vision of what a technology should deliver and ways to make that vision more likely to come true.

There are many different factors influencing the research questions in this field. In the context of our four-dimensional model, however, the main driving force is the interplay between basic attitudes towards technology (contextual development) that are translated into policy concerns and different kinds of academic communities.

Within TA, we can observe the dynamic interaction between defining societal and political problems, on the one hand, and mobilising different academic communities and their epistemological and methodological approaches, on the other hand. As the societal zeitgeist has passed through fluctuating waves of technology pessimism and optimism, so have the needs of parliamentarians, and increasingly of policy makers and societal groups to assess the future impacts of emerging technologies. With these changing needs, different kinds of academic communities have been called upon to participate in TA, themselves driving further changes in TA approaches and methodologies.

In simplified terms, the relationship between TA and society has passed—highly stylised—through three distinct phases, distinguished by a shift of roles and foci of different scientific communities in each. These changing roles reflect the dynamic interplay between problem perceptions and the different scientific communities, each with their own identity, methodological skill set and normative expectations. A first phase saw a particular strong role of modelling and technology experts (expert TA), while in a second phase process and moderation experts became more prominent (participatory TA). In a third phase we saw a stronger combination of technological experts and those with strong expertise in participatory processes, marking a broader shift towards identifying the possible technological and behavioural contributions to solutions for pressing societal problems (pragmatic TA).

Initially, technology experts were seen as the main sources for TA. However, as the users of TA and researchers became critical of the early technocratic modelling approaches employed, participation broadened to include interdisciplinary and some transdisciplinary approaches. Participatory TA was based on insights from the scholarly community of Science and Technology Studies (STS) and constructivist thinking, while later deliberation theories (Habermas) contributed to a more measured, mixed model. Scientific approaches to "the nature of technology assessment and deliberation" made a real difference to the identity and role of TA, as did advances in participatory methods. As a result, activists, especially those from the Science and Technology Studies community, started to question the predictive and warning role of TA and turned towards co-constructivist approaches (CTA). Finally, with the inclusion of the role of future technologies for system transformation, other academic communities from innovation systems and innovation studies as well as transition studies have been increasingly called upon and shown an interest in TA.

3.6 Understanding Paradigm Change in Industrial Production

This field of research has been evolving over the last 50 years through a succession of five successive technological and organisational production paradigms. Two of these paradigms have been driven by technology: computer and automation (CAM, or Industry 3.0), and cyber-physical systems and Internet of Things (Industry 4.0). The other three have been more organisational and comprise the quality of working life, lean management and perfected human–machine interaction.

The chapter on industrial production provides additional background, in particular, that research in this field has been driven very strongly by paradigmatic shifts, and identifies three such phases. Relating the paradigmatic shifts to the elements of our model allows us to interpret the development of production research in the logic of our systemic model of research dynamics.

Technological and economic developments, but also policy concerns have been key factors in research development:

- Most obviously, the production paradigms Industry 3.0 and Industry 4.0 represent technological developments in themselves.
- Changes in society's perspective of work from simply being a way to earn money to emphasising the well-being effects of working have also influenced research as well as policy concerns and working regulations.

The interaction of technological and economic developments with policy concerns has been the most influential driver of production research. However, the nature of this interaction has changed over time from a rather contradictory to a more complementary one: In the technological paradigm of phase 1, concerns about the quality of work and the need to increase productivity characterised research, driven by the conflict between greater productivity and labour conditions. The interaction of technological and economic development and policy concern was therefore contradictory in nature. In the second phase, globalisation meant that maintaining national competitiveness became an overarching political concern, and research reacted by analysing lean management as an organisational innovation that could enhance competitiveness in addition to industry 3.0. Therefore, the interaction of economic and technological development and policy concerns was complementary in influencing research. Finally, the third phase is characterised by the coupling of the physical and digital world, and with the emerging debate about taking a more human-centric approach to Industry 4.0, once again research is being shaped by the contradiction between technological and economic developments and societal concerns.

The development of the research field has also interacted with the institutional research environment. A specific research community developed, dominated by large collaborative projects between different research partners—many of them from non-university institutions—and companies. Methodologically, research predominantly took place as accompanying research of case studies, in which a paradigmatic innovation was applied as a pilot. However, globalisation and the increasing need to evaluate the competitiveness of domestic industry in comparison with competitors have led to a broadening of the types of methodology and projects and large-scale surveys undertaken by research institutes have been added to the research portfolio. The links between production research and socioeconomic theories are less clearly defined. New economic geography and the evolutionary theory of trade developed in the 1980s and 1990s have had the most obvious influence. These supported the need to continuously upgrade the capabilities for competitiveness, to "climb-up the ladder to stay ahead".

3.7 Exploring Innovation and Progress in Renewable Energy Development: From Niche to Mainstream

The chapter on renewable energy offers plenty of evidence for how the interaction of economic (geo)-political and environmental developments with policy concerns and measures drives the development of research. The first oil price crisis and the debate about finite non-renewable energy sources together with concerns about the security of supply amplified by the oil embargo in the early 1970s kick-started the research on renewable energy. In this first phase, research focused on technological solutions, in particular for heating, responsible for consuming the biggest share of imported oil. The second phase was marked by decreasing oil prices, which lowered the pressure to substitute oil. Political concern focused on the electricity sector in the aftermath of the Chernobyl accident, and subsequently on the need to reduce CO_2 emissions, especially those from burning coal. The targets set and measures taken defined the research in this second phase, which was focused on analysing the support schemes to foster the diffusion of renewable energy. Implementing these support schemes resulted in the increasing diffusion of renewables and rising electricity prices, which turned policy concerns towards the expansion of renewables with lower costs. This resulted in research focusing on market integration and the functioning of innovation systems to bring down technology costs. Finally, with climate-related risks becoming more apparent and the corresponding political targets of achieving net zero emissions, research is increasingly concerned with the transformation of the energy system towards renewable energy.

The research on renewable energy also shows the importance of the interactions with methodological developments. Advances in systems analysis and computing applications enabled the first energy system models, which identified the need for and the possibilities to move towards renewable energy sources. The political challenge of managing the increasing costs of renewables support schemes led to new ways to combine energy and economic models to analyse the economic impacts of renewable energy expansion. The favourable overall economic impacts demonstrated by these models supported the continuation of the support schemes and even more ambitious target setting. Analysing support schemes and acceptance issues of energy system transformation required interdisciplinary research approaches, which combined methodologies from economics and social sciences with more engineering-based concepts.

There are also very strong links between renewable energy research and the institutional and epistemic community. Renewable energy research co-evolved with the establishment of non-university research centres and institutes, which still dominate the technical research on renewable energy technologies. These non-university research institutions were also the first to pursue interdisciplinary research and provided the manpower and institutional homes for those driving the expansion of research. Finally, with renewables now becoming the main source of energy in the electricity sector, this field of research has become an established part of the university landscape as well. Interaction with social science theories first became apparent with the influence of neoclassical environmental economics and transaction economics on the analysis of support schemes. However, research on renewable energy has also led to further advances in innovation heuristics in a co-evolutionary process. Indeed, innovation studies in the field of renewable energy have greatly advanced the concept of technological innovation systems.

3.8 Analysing Energy Demand and Modelling of Energy Systems: From Little Knowledge to Differentiated Know-How

Similar to renewable energy research, the chapter on analysing energy demand and modelling of energy systems provides plenty of evidence for how the interaction of economic, (geo)political and environmental developments with policy concerns and measures has driven this research field over time. Three examples illustrate how substantial this influence has been:

- The first oil price crisis and concerns about the security of energy supply amplified by the oil embargo in the early 1970s instigated research challenging the existing paradigm that energy demand increases in line with economic growth. Technical analyses of energy efficiency potentials led to a new paradigm in analysing energy demand.
- In the 1990s, a new wave of research to identify additional barriers was triggered by limited energy efficiency improvements in practice despite the proven existence of large low-cost potentials to reduce energy demand.
- The growing importance of fluctuating renewable electricity resulted in research turning towards new ways to influence energy demand such as demand-side management and has ultimately led to broadening the scope of research by including sector coupling.

The research on energy demand also shows the importance of the interactions with methodological developments. Advances in systems analysis and computing enabled the development of energy systems models that could combine techno-economic analyses of energy efficiency potentials with structural changes within the economy. This made it possible to construct energy demand scenarios, which became more sophisticated over time. In turn, these scenarios influenced policy making and have formed the basis for policy decisions on CO_2 reduction targets ever since the recommendations of the German Enquête Commission on Climate change for Germany's first target to reduce CO_2 emissions. Increasing interdisciplinarity and integrating methodologies from economics and the social sciences have also helped to improve the methodologies in this field. This has opened the door to analysing topics such as energy efficiency behaviour and new instruments to alleviate obstacles, which have contributed to expanding the portfolio of energy policies.

The research on analysing energy demand and energy efficiency also co-evolved with the institutional community. In particular, energy system models co-evolved with the formation of a scientific modelling community, which allowed for scientific exchange and fostered continuous methodological improvement. There has also been some influence of theoretical developments on energy demand research, most visibly transaction and institutional economics, together with motivation theories, which have provided the theoretical background to analysing obstacles to energy efficiency.

The development of the research on energy demand is also influenced by the internal dynamics in the field. Research results have sparked new challenges leading to a broadening of the disciplinary background. For instance, the technical feasibility of energy efficiency options gave rise to questions of their cost-effectiveness. Extending analyses from the status quo to include future-oriented studies has required the integration of structural change and foresight into the research portfolio. The existence of low-cost energy efficiency options led to research on the barriers to energy efficiency and measures to overcome them. This internal logic has meant that research has become inevitably more complex and more interdisciplinary over time.

3.9 Understanding the Co-Evolution of Research and Water Protection Policies: From Single Technologies to Systemic Integrated Approaches for the Sustainable Use of Water

Water research was initiated and is still strongly driven by the deterioration of our bodies of water, underpinned by growing environmental awareness in society. This has caused increasing concern among policy makers and researchers and has triggered activities to reduce emissions and adapt water infrastructure to new challenges. At the same time, there are very close links between water research and policy making. Regulatory measures prescribe maximum emission thresholds which are technically feasible using current sewage treatment technologies. Any technological advances that make further emission reductions feasible directly influence regulatory standard setting, and goals to strengthen regulatory standards directly guide the research needed to provide the technical basis for that. This is backed by how the research in this field is funded at least in Germany, mostly by the federal and state governments, which are also responsible for policy making.

The co-evolution of research and policy making is not only influenced by the state of the environment, but also has repercussions on the level of pollution. This in turn leads to new priorities in policy making and a new phase of water research. This interplay between the environment, policy making and water research has been the main driver of water research over the last 50 years, and three phases can be distinguished: In the first phase, policy making and research emphasised the quick reduction of emissions by applying or improving single technologies. This reduced the emissions from sewage treatment plants, but was not enough to clean up water bodies, and the focus therefore widened to include diffuse emission sources as well. This contributed to the second phase of water research, which built on more integrated solutions in addition to improving single technologies in wastewater treatment plants. The increasing number of options called for a more systemic approach, which was supported by policy making that itself was more concerned with the management of water bodies rather than only the emissions of individual sewage treatment plants. At the same time, economic challenges in the form of rising costs for sewage treatment and the maintenance of water supply infrastructure further emphasised the need to look for least-cost options from a system perspective. Finally, climate change with the resulting changes in precipitation patterns and higher frequencies of both droughts and flooding triggered the third phase of research, which calls for greater integration of sewage treatment and water supply and a transformation of the entire sector.

There have been also interactions between water research and methodological improvements. Increasing abilities to measure pollutants and collect such data helped to identify new environmental challenges. Water research addressed these challenges, and systematically used this opportunity to develop new information tools such as emission inventories, which greatly facilitated the policy debates about target setting in water policy, e.g. with regard to micropollutants. These new challenges reinforced the need for more research on new emission control technologies and ultimately led to a broadening of the actors involved in water issues, such as the pharmaceutical industry, which is called upon to provide innovations to reduce the environmental burden of their products.

The development of water research is also characterised by internal dynamics, which constantly increases the scope and complexity of water research. The focus has shifted from single technologies to more systemic solutions integrating multiple different technologies. This has also had repercussions on the disciplinary nature of water research. Although it is still dominated by engineering-related scientists, social sciences are also playing a bigger role with issues like the acceptance of systemic solutions and the transformation of the sector gaining momentum. It has also had repercussions in the form of a growing scientific community with its own associations, which has institutionalised water research as an academic field and opened up new career perspectives for the scientists involved.

Other elements in our model show a lower level of interaction. This is especially true for the role of social scientific theories in shaping water research. The impetus of regulatory economics, which so strongly influenced the liberalisation of the energy markets, has only marginally affected water research. One explanation might be that, even though decentralised technologies have become more important, they are still not in a position to phase out monopolistic bottlenecks. Another, perhaps surprising lack of interaction is with innovation system heuristics and approaches. Despite an increasing number of actors and the need to analyse their interaction, and despite the importance attached to analysing the transformation of the sector, approaches such as Technological Innovation Systems and the Multi-Level Perspective have hardly been used in water research so far.

4 Conclusions

4.1 Dynamics of Research Fields and Patterns of Change

Before drawing the final, overarching conclusions, we need to reiterate the impetus for and aim of this volume. It was motivated by wanting to understand how scientific research has been analysing and supporting the development of innovation systems and of socio-technical systems, their interplay and their governance over the last 50 years. In order to do so, we first selected nine research fields in the area of systems and innovation research. While the delineation of the area of systems and innovation research and the selection of our nine fields are somewhat arbitrary and subjective, there are common qualities to the fields that define the area of systems and innovation research. All the fields defined in this volume are interested in phenomena that can only be understood using a systemic approach; any analysis of specific elements has always been put into the context of the functional system it is referring to; and as we can observe, this has happened with increasing intensity over time. All fields deal with the role and impact of innovations, of novelties that are put to practical use, albeit often on very different levels and in very different forms. Finally, all the fields have developed out of a normative impetus or concern to support the governance of systems, and they are all clearly application-oriented. Consequently, all the fields have co-evolved with the systems, in which they are embedded and, more concretely, with the governance and policy in these systems.

The final questions to answer in this concluding chapter are: How have the fields and their roles changed over time? Are there any overarching patterns beyond the idiosyncrasies highlighted in the nine contributions to this volume? If so, what do those patterns tell us about the specific nature and responsibilities of innovation and systems research and its future challenges?

Three Phases of Zeitgeist

It is possible to identify a few, very high level and severely simplified patterns across the fields. First of all, the demands on and roles of the fields have changed with the respective zeitgeist, a term we use slightly differently to the Oxford dictionary definition,[3] as the defining spirit or mood of a particular period of history nurtured by dominating ideas and beliefs of the time. Of course, those phases of changing zeitgeist are in themselves ambiguous, different ideological and ideational streams, some of them even contradictory, some co-exist and some compete. But very crudely, despite marked differences even between developed OECD countries, overall a few dominant phases of zeitgeist can be identified, which also shaped the activities and developments in our fields. A first phase in the 1960s and parts of the 1970s was characterised by strong economic growth and a general sense of optimism

[3] https://www.oxfordreference.com/display/10.1093/oi/authority.20110803133418753.

towards technological and societal developments. This sense of progress was buoyed up by the growing strong sense of the governability of systems and thus of a strong and pro-active role of the state. During that time, the field of innovation indicators and monitoring, for example, provided concepts and evidence to make sense of innovation dynamics and to optimise the allocation of research inputs, while STI policy concepts were developed that sought to improve the understanding of policy makers on how to steer innovation activities and sub-systems.

Decreasing economic growth rates culminating in stagflation in the late 1970s that posed severe challenges to economic and welfare systems, accompanied by growing environmental concerns, led to a zeitgeist shift. At the end of the 1970s and beginning of the 1980s, major Western countries, led by the US, UK and—to some extent—Germany, developed their own variants of a combination of neo-liberal and neo-conservative ideologies. In this eclectic ideological combination, the role of the state was—grosso modo—weakened and the role of the market enhanced. The political landscape became increasingly polarised with intensifying societal conflicts over the responsibilities of the state for economic development, social welfare and environmental concerns.

As a consequence of both the ideological turn and growing environmental and social concerns, the demands on and roles of our nine fields were ambiguous. On the one hand, there was a fading of the general optimism that new technologies are always favourable. The role of technology assessment broadened, with a number of countries following the US model of TA. Existing technological paths were questioned, such as the expansion of electricity systems based on centralised nuclear power stations. On the other hand, science and technology were increasingly seen as the engines driving economic growth, and the innovation systems approach was popularised through comparisons of national systems and their innovation-driven competitiveness. The field of innovation policy emerged and the paradigm shift in manufacturing industries was strongly supported by policy measures, all of which resulted in new demands in areas such as innovation system monitoring and analysis, industrial production research, STI policy analysis, evaluation and foresight. In the three vertical fields of renewable energy, energy demand and modelling, and water research as well, science and technology were seen as engines to address societal challenges and contribute to solutions. However, there is a significant difference between these three vertical research fields and the horizontal ones with regard to the second zeitgeist wave. Even during the neo-liberal era, traditional neoclassical economic theory supported a strong role of the state in these three sectoral research fields, although not to generate new innovation dynamics. Environmental economics clearly stated that environmental problems constitute a separate class of market failure, which justifies state action and calls for directionality towards environmentally-friendly technologies. Regulatory economics added sunk costs as an additional requirement to a natural monopoly for sectors to be classified as forming a monopolistic bottleneck. Even though this school of thought limited the number of sectors which should be subject to economic regulation, electricity, natural gas and water systems still belonged to this shrinking list of sectors. Taken together, the resulting environmental and regulatory policies in these sectors triggered a demand for technology innovations and therefore simultaneously acted as a demand-side innovation policy. Consequently, during the second zeitgeist wave, the three sectoral research systems shifted in another direction with a greater number of de facto innovation policies than the horizontal research fields.

The tide turned again in the late 2010s, catalysed by the severe financial crisis from 2007 to 2009 and the intensifying awareness of the severity of societal challenges, above all the climate crisis. Once again, the calls grew louder for a more pro-active role of the state to support economic and technological development. From the perspective of the research fields in the energy and water sector, it became increasingly clear that technology development alone does not suffice. In the horizontal research fields, the perception of the severity of societal challenges led to policy approaches that sought to give direction to technological development and deployment and to support transformations in functional systems such as the energy or mobility sector much more systematically. Thus, the zeitgeist in this phase brought all nine research fields closer together again. This led to a number of major changes. The development of the innovation system was now strongly linked to our transformational ambitions. As a consequence, new STI policy concepts were developed and strongly influenced STI policy making. STI evaluation broadened its approaches to understand the transformational impact of policy and policy mixes. Foresight, STI policy evaluation and some areas of technology assessment strengthened their formative role, supporting reflexivity and broad, inclusive discourse moderation. For research in the sectoral fields of energy and water, it became clear that more systemic transformations beyond the existing sectoral logic were and are required. Analysis in these areas increasingly took the user perspective into consideration and in doing so integrated questions of the acceptance of innovations and behavioural change. In particular in the research field of renewable energies, this led to an uptake of broader innovation system approaches as well.

Determinants of Field Developments

Within the broad, long-term phases outlined above, the fields developed in complex and often idiosyncratic ways over the five decades of our analyses. However, it is worth noting that there are a number of patterns in the mechanisms of change across the field. These patterns we can now express through the various dimensions of our SIR development model outlined above. While the various drivers for the development of the fields can be classified in one of those dimensions, we often see a combination of drivers from two or even three dimensions in complex interactions and feedback loops.

At first sight, the dominant drivers of the fields have been *disruptive developments in the societal, political, technological or economic context*. Obviously, if the context changes significantly, new challenges arise, new questions are posed. There are numerous examples in the history of our fields. For instance, the fact that science and large parts of society have realised how our economic model threatens to violate the planetary boundaries, endangers our water resources and changes the climate in dramatic ways has kick-started the fields of renewable energy and energy demand analysis and the sustainable use of water resources. Economic development and especially the structural changes brought about by globalisation have shaped the economic challenges perceived by national governments, and consequently the questions they ask. Worldwide developments towards a platform economy have slowly but steadily led to the need to develop new theoretical models and empirical methods to understand the development and role of innovations in an innovation system. The political momentum triggered by the formulation of the Sustainable Development Goals has called for new analyses in terms of broader dimensions of sustainability across our fields, led to new, broader forms of foresight activities and inspired mission-driven policies that have resulted in demands for conceptual and evaluative support. The geo-political disruptions seen since the mid-2010s, culminating in systems competition and military conflict, have driven politicians, policy makers and businesses to call for technology sovereignty as well as energy sovereignty, which poses new questions in the field of innovation monitoring and analysis as well as the fields of renewables and energy demand. The Covid pandemic has, among other things, provoked the question of how science systems can be organised to better support crisis management across a wide range of dimensions. This has meant new challenges in the field of STI policy conceptualisation, as STI policy was called upon to help tackle an imminent crisis.

However, the mechanisms through which those—exemplary—contextual changes are translated into developments in our fields are diverse. They depend on how and by whom contextual developments are interpreted and which interpretations become dominant in societal and political discourses. Developments in socio-technical systems can create societal pressure, they can be seen as political opportunities or threats, or they can trigger the research community itself to ask new questions or highlight new aspects of the system it analyses.

The most important mechanism through which the perception and interpretation of contextual changes are translated into demands for all nine fields is the formulation of concrete *policy concerns,* which is the second dimension in our model. This underlines the application orientation of systems and innovation research. One of the most prominent examples here is Technology Assessment, which grew out of the need of US parliamentarians for an independent source of evidence and reflection to support decision-making vis-à-vis the executive in relation to new, disruptive technological developments. Similar dynamics can be observed in STI foresight and STI evaluation. The latter only exists because policy makers expressed a need for accountability and learning; the former is an expression of policy planning ambition within the framework of increasing contextual uncertainty and complexity. The water and energy research fields display a similar pattern of interaction between policy concerns and research fields in their reaction to the changing environmental situation. Policy and research both influenced the environmental footprint of the water system, which sparked numerous feedback loops. Significant improvements in energy efficiency technologies led to new policy ambitions in terms of standard setting, which in turn triggered new research to achieve these ambitions on a wider scale. The field of production research also illustrates that the timing and direction of this mutual influence can change over time, with research and policy concerns preceding the diffusion of new production paradigms in earlier phases, and then responding to it in later phases. The same research field also illustrates that the interaction between context and policy concerns can be both mutually reinforcing and contradictory. All of these examples clearly demonstrate that the rather trivial insight that contextual factors, i.e. the combination of technological, economic, societal and political developments influence research needs closer examination to identify feedback loops and translation mechanisms through policy concerns.

New concepts and theories constitute the third dimension driving change in our fields and their role vis-à-vis stakeholders and especially policy makers. One early example is the linear model of the impact of science on the economy and societal welfare, a concept that led to the development of a number of indicators in the area of science and innovation monitoring and dominated analytical perspectives. Another prominent example is the development of the innovation systems approach. This approach has evolved into a powerful heuristic to understand and compare the functioning of national, and subsequently regional, sectoral and technological systems. While some fields in this volume specifically supported the construction and operationalisation of this approach, all the fields were affected in terms of the questions asked and the empirical research conducted. Equally, policy makers increasingly understood the need to contextualise their activities and in order to do so needed to ask broader, system-specific questions. In the vertical research fields, the effect of changes in theoretical concepts within the epistemic community has been much more indirect. This perhaps reflects the more heterodox approach of these research fields, where insights from different epistemic communities tend to be recombined, rather than following new insights from one epistemic community.

Methodological advances and *new data availabilities* are the final driver of change in our fields. We saw a very concrete example of this in water research, where a series of methodological improvements enabled the identification of previously undetected forms of pollution, triggering policy concerns and spurring research on technologies to reduce pollution even further. The most pervasive developments, however, were those in information processing. Again and again, this has allowed novel perspectives on systems performance and dynamics and also led to new questions that were subsequently taken up by policy makers. This is true for mining new sources of empirical evidence on the one hand, but also with regard to continuous improvements in empirical modelling, on the other hand. Particularly in the energy research fields, this has enabled huge advances in the ability to model complex energy system developments. This has led to research evolving from looking at individual technologies to a more systemic analysis of energy system developments.

Finally, the relationship between data and methods, on the one hand, and theories underpinning the field, on the other hand, is a complex one in our fields. Not in all cases did data analysis and method development build on an existing theory in a given field. Often, the methodological advances were underpinned by theoretical concepts in established academic fields. These included transaction and experimental economics and motivation theories, which delivered the conceptual background for analysing data on energy behaviour and the acceptance of new energy technologies. Another example is complexity theory, which was the impetus for new advanced approaches in modelling energy demand. In other cases, new data analysis and method development have long taken place without any distinct theoretical underpinning. For example, the availability of vast amounts of unstructured data since the 2010s that can be mobilised through new techniques using AI-supported data analytics has resulted in new maps of innovation performance. This has generated a whole list of new questions, and subsequently new analytical possibilities. However, much of the data, which can now be used for the construction of indicators have long lacked, and in parts still lack, a clear conceptual, let alone a theoretical base.

Reflections on the Epistemic Developments of and Relationship Between Fields

Having interpreted the developments of the fields along the four major edges of our model, we can now turn to reflections on the *epistemic developments*, i.e. the evolving disciplinary nature of our fields and the changing relationship between fields. We can make three major observations. The first relates to the relationship of fields and epistemic communities over time. All of our fields are, in the traditional categorisation of academic fields, multidisciplinary, fed by different disciplines and have developed interdisciplinary dynamics over time. At the same time, the composition of the disciplines in our fields and their interplay has been evolving along with the dynamics of the conceptual SIR research change model just outlined. Those dynamics led to (sometimes rather drastic) changes in research requirements, which called for contributions from those disciplines that promised to address the changing nature of problems or methodological advances. For example, the research fields on energy and water were much more engineering based during their earlier phases than the other, more social science-oriented research fields. The more systemic nature of the research questions and the need to increasingly look at mechanisms of market diffusions led to the integration of concepts from disciplines such as economics, political science and psychology. Equally, the more recent ambitions of STI policy to design and implement transformative missions has intensified the need for researchers in STI policy or innovation monitoring to understand the nature of the underlying technologies, markets and behaviours in the fields such as energy, mobility or health. The latter observation highlights a major finding of this volume: Overall, the broadening ambition of STI policy, on the one hand, and the need to transform sectoral systems, on the other, raise more holistic questions in all fields. The increasingly systemic nature of policy concerns heightens complexity, which in turn increases the need for in-depth interdisciplinary analysis. In fact, the vertical fields, such as energy, water, production, and the horizontal fields of policy analysis, evaluation, TA and foresight show more and more overlapping agendas. Thus, the need for an increasing level of in-depth interdisciplinary cooperation is also accompanied by a need to integrate vertical, i.e. sectoral, and horizontal competences.

This leads to a second observation, which is the changing pattern of development within horizontal and vertical fields and consequently also the changing relationship patterns between these fields. It appears that the sectoral fields and the horizontal ones have been rather isolated from each other[4] for quite some time. This is true for both policy practice and research. For example, a wide range of demand-side innovation policy instruments have been used in sectoral policies. Financial incentives, such as demand subsidies, environmental tax schemes or even new market designs, as well as command and control policies or information programmes have long been used as a major instrument for the production and diffusion of energy or manufacturing technologies. Here, the policies were framed and labelled as sectoral ones, not as innovation demand policy. This also meant that sectoral policies, by their very nature, have always been directional, seeking to steer their sector in certain directions. In contrast, in STI policy, demand-side instruments lay dormant for many years, only to make a comeback in the 2010s, and STI policies and STI policy analysis only discovered directionality and what it means operationally in late 2010. Both analysts and STI policy makers only slowly turned to the sectoral experience for inspiration.

At the same time, the importance of functional innovation systems for explaining improvements and diffusion in technologies has long been somewhat neglected in the vertical research fields. Water research is perhaps the field in which a broad innovation systems approach was embraced most recently and is still only partially so. As pointed out above, we see the neo-liberal zeitgeist as one driver that has contributed to a drifting apart of development in sectoral policies and STI policies in general. A second possible explanation for the different developments in vertical and horizontal fields are changes in the mode of research over time. All nine research fields were in "expert mode" at the beginning of the 1970s. In the following phase, however, the horizontal research fields in particular (e.g. foresight, technology assessment and evaluation) moved towards a much more participatory approach, whereas the vertical fields remained in expert mode for longer and only started to integrate participatory approaches considerably later. Thus, we can first observe some form of drifting apart again, certainly between the vertical and horizontal research fields, followed by an acceleration of interaction and mutual influence over the last decade, during which the vertical fields have opened up more to participatory approaches. This, we believe, is a pattern that will continue to be important.

A third observation as to the development of our fields is the *interplay with established academic fields*. Our fields—perhaps with the exception of water research—began outside the established arena of academic scientific disciplines, and all of them were problem-oriented, largely multidisciplinary and showed interdisciplinary dynamics. However, to varying degrees, all of them have been grown out of or are linked to established academic fields such as evolutionary economics,

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[4] As noted in the introduction to this volume, we do not discuss the growing field of transition studies, where vertical and horizontal perspectives have often been connected. However, this is being done to understand and conceptualise the dynamics of change and resistance to change rather than analysing the nature of sectoral fields as such.

sociology of science, political science, operation management and operations research in business administration and engineering. This epistemic origin had major implications for the development of our fields. Initially, at least in the first decades, scientific credibility in our fields had to be built on the quality criteria of established scientific areas. To give just one example, the standards set by evolutionary economics were important for the establishment of innovation monitoring and some areas of STI policy. Furthermore, scientific reputation had to be based on established journals in those academic fields. Only in a few instances, such as in water research, were the research fields associated with established academic institutions, which made it easier to access corresponding existing journals or establish new ones. For most of our nine fields, specialised journals have only recently emerged and gained scientific reputation—prominent examples are Research Policy (STI policy, Innovation Dynamics) and Energy Policy, or Renewable and Sustainable Energy Review (renewable energy, energy efficiency).

However, as our fields have always been problem- and application-oriented, they have generally been faster than established scientific fields to absorb the new demands of society and policy. In doing so, they have also influenced the quality criteria and directions of established fields, in particular by emphasising the importance of relevance in conjunction with traditional excellence. The prominent frame of the third mission or the inclusion of impact cases in the UK's Research Excellence Framework are two obvious institutionalised expressions of this shift. In some instances, this has also led to a growing acceptance of the application-oriented fields in established academic arenas. We can only speculate here, but we are currently observing a stronger and more rapid convergence of some of our application-oriented fields with established academic fields. This may well have to do with the fact that in other fields, such as evaluation of STI policy, Technology Assessment and Foresight, their difference to the established fields is the very mode of research, the idea of engaging and co-creating with stakeholders. This participatory approach is characterised by a very different rationale of the mode and purpose of research and may therefore reinforce rather than dismantle the walls to established academic disciplines; scientific reputation is harder to gain and established academics are less willing to open up. In contrast, the use of methodologies such as modelling and statistical analysis, which are highly accepted in various established academic communities, might have contributed to the closer links being forged between the vertical research fields and established academic fields.

4.2 Outlook

The last 50 years have seen major developments in our nine selected fields of systems and innovation research (SIR). Above, we have tried to capture and explain those developments in a highly condensed and simplified manner using our SIR developmental model. We have seen the changing role in all four dimensions of that model for the development of the fields over time, how our fields interacted with established academic fields and, in parts, developed traditional academic qualities themselves. The complex relationships between the fields are also apparent. These can be generally characterised by the limited convergence, in particular between the horizontal fields and the vertical ones. Finally, we have seen that the role of our problem-oriented fields vis-à-vis policy has also changed over time. Sometimes, academics were ahead of policy with conceptual and normative initiatives, then policy concerns again drove the fields to find evidence and develop models to support new challenges and demands.

We can only speculate as to the future developments of the fields considered in this volume. Applying our simplified model, we have the impression that, at the time of writing in early 2024, major contextual developments—translated mainly through growing policy concerns—will dominate the demands on our application-oriented fields and shape their dynamics. The strong push exerted by contextual developments relates, for example, to disruptive technological developments such as artificial intelligence or quantum technologies with rather unpredictable consequences in terms of economic and societal developments. It also relates to the growing pressure to mitigate and adapt to climate change and to move our systems towards sustainable development goals more broadly. It finally also relates to major geo-political power shifts, conflicts and tensions as well as societal and political fragmentation within all of the major democracies.

Whether these contextual dynamics will be embedded in yet another zeitgeist shift, we do not know. However, we can already see how developments in STI and in our vertical fields are being re-interpreted. A framework for sectoral as well STI policy is emerging whereby geo-political developments interfere with and dominate societal concerns in terms of SDGs, leading to competition between different systems and the re-nationalisation of policy initiatives. Dynamics in science, technology and innovation as well as in sectoral systems more generally are being interpreted and supported, not only in relation to economic growth or transformations towards SDGs, but with an overarching concern for national security. There are strong indications that these developments may very well intensify the current interventionist, transformative role of the state, albeit in a much more inward-looking and in parts defensive or even aggressive manner. While this does not render the SDG goals less urgent, it does place new constraints on their pursuit.

Against this background, our fields are being challenged in various ways. First, how will the profile and relationships of the fields develop? To start with, problem-oriented research, in which the very purpose of research is to contribute to solutions, may become more—not less—important in the future. The demand for supporting evidence and conceptual perspective may grow as a result. While this may fundamentally challenge more traditional scientific fields that have a different understanding of the purpose and criteria of excellence to reflect on the way they define and exert responsibility, it may further reinforce the SIR fields in their problem-oriented role to provide evidence and support the governance of future developments.

However, there are also a number of open questions ahead for SIR fields. The increasing urgency in terms of societal challenges in combination with growing technological and contextual complexity will demand more advanced, in-depth understanding of technological and sectoral dynamics. This will require even more flexibility in analysis and interaction and the combination of multiple perspectives in terms of understanding problem fluidity. Thus, it is essential that scholars in horizontal fields link more intelligently to scholars in vertical policy fields, as is done to various degrees in some centres across Europe (e.g. Utrecht/Kopernikus; SPRU, Fraunhofer ISI), but is still too limited. This compartmentalisation, as well as the compartmentalisation between policy areas, needs to be broken down if the relationship between the scholarly community in its broadest sense and policy making towards SDGs is to be conducive to supporting the socio-technical transformations needed. This also holds for the fragmentation of democratic societies and the social effects of innovations, which affect each of our nine research fields. At the same time, all the fields will have to further improve the way in which national—and EU level—policies are supported by reflecting upon and including geo-political and geo-economic developments conceptually and analytically, and they need to link this understanding to a broader variety of policy fields. In addition, the current trend towards a re-nationalisation of policy concerns may put further pressure on the freedom of science in terms of its openness to global knowledge flows and cooperation. To find the right balance between openness and international cooperation, on the one hand, and the necessary limitations with regard to the exposure to geo-political threats, on the other hand, will be a task not only, but especially for our application-oriented SIR fields.

However, it is far from given that the different SIR fields will continue to strengthen their links and converge to a greater degree. For example, will STI policy continue to be seen as a major means to steer societies and economies towards SDGs, or will it, in contrast, be once again defined as a major battleground for the competition of nations and systems, and thus revert to a focus on economic competitiveness? Against the background of those tensions, will the field of innovation monitoring support the development of indicators that help to map and model the system dynamics for transformation, or will it revert to economic dimensions and further differentiate the analytical portfolio to understand the economic dynamics of the platform economy? Will the growing importance of indicators and modelling approaches stemming from the vertical fields, with their system-wide, long-term perspective continue, and will vertical fields increasingly deliver those indicators in isolation from or in interaction with the innovation monitoring field? Will technology assessment be able to turn to transformation dynamics more broadly, or will the urgency of technologically-defined systems competition focus on the economic threats and opportunities of distinct technologies? The answers to these and many related questions are far from clear, but how they play out will define the purpose and identity of the fields in the years to come.

A second challenge is related to the need to increase true interdisciplinary cooperation and to integrate vertical and horizontal expertise as already outlined above. Such integration is also related to the increasingly heterodox approaches taken, while these approaches are simultaneously challenged with regard to their internal consistency. We can only speculate here if this will inhibit the ability of our nine SIR fields to establish links to traditional academic fields. But we see a need for SIR research fields to clarify how their field relates to the underlying concepts and theories, and how the different research modes and methodologies of the fields relate to each other as a prerequisite to entering a more integrated mode of research. Perhaps the development of explicit quality criteria for such heterodox research might help to confirm the rigorous quality standards to be met by such research. Finally, we have to phrase the question in the wider context of how academic excellence will be defined in the future. We see the first signs of questioning the established definition of research excellence, measured mostly by journal impact factors and citations. Increasingly, science is called upon to be more reflective on its societal responsibility, and we can only speculate that this might encourage traditional academic fields to be more open to heterodox approaches.

A third challenge is the way in which the fields define and develop their normativity. It has been a major legitimacy claim of the fields that they deliver evidence-based advice that is not biased or filtered by the normative claims of researchers. However, this claim has always been under pressure. In fact, the very origin of systems and innovation research was driven by normative concerns, not only of society and policy, but also of academics. For example, the concern about the competitiveness of European countries vis-à-vis the USA (late 1960s) or Japan (1980s) was a driver for the foundation and further development of fields such as STI policy and innovation monitoring. Academic concerns about exceeding planetary boundaries through energy production and consumption, among other things, supported the growth of energy efficiency and renewable energy research. As the need for and urgency of transformations have grown, so has the awareness of academics, especially in the vertical fields, about the importance of and necessity for research to support transformation. Equally, should science, technology and innovation continue to be framed within a competition between systems that includes a competition between value systems, any analytical work in our horizontal fields may be defined in much more normative terms, supporting shared values against external threats. It will become increasingly important for researchers to be very clear about their own role and how they deal with their own normativity.

In this respect, the development towards a participatory and formative turn we have seen in a number of our fields in different manifestations may have a number of effects. On the one hand, the more researchers accept the importance of input from and interaction with stakeholders and thus a growing plurality of normative claims in the systems, the more their own normative claims may reduce, or they may at least become more aware of their own biases in the process. On the other hand, broad participation may water down the specific role and responsibility of researchers. As they are participating in participatory normative processes themselves, they may, unconsciously or consciously, develop even stronger normative claims themselves. Thus, there will be a growing need for researchers, especially in the application-oriented SIR fields, to reflect on their normativity and their specific mode of responsibility. This will be a major task in order to retain legitimacy. This task will involve finding ways in which the fields can communicate with the general public that reflects this specific responsibility and role and supports, rather than endangers their legitimacy—a key prerequisite given the very close interaction between the application-oriented SIR research fields, politics and society.

Jakob Edler is Managing Director of the Fraunhofer Institute for Systems and Innovation Research ISI since October 2018. The Anglo-German is also Professor of Innovation Policy and Strategy at the Manchester Institute of Innovation Research (MIoIR), which he led from 2011 to September 2018. His research focuses on analysing and conceptualising governance, policy and management of innovation. J. Edler is Speaker of the Fraunhofer Group Innovation Research, member of the German Science Council, the German Academy of Science and Engineering (Acatech) and the Royal Society for the Encouragement of Arts, Manufactures and Commerce (UK).

Rainer Walz is Deputy Director of the Institute and Head of the Competence Centre Sustainability and Infrastructure Systems at the Fraunhofer Institute for Systems and Innovation Research ISI in Karlsruhe. He obtained his PhD and "habilitation" in economics. In 1991, Prof. Dr. Walz joined the Fraunhofer ISI. Prior employment includes the University of Wisconsin and the Enquête Commission "Protecting the Earth's Atmosphere" of the German Bundestag. He is also an adjunct professor of economics at the Karlsruhe Institute of Technology (KIT) and member of the EU expert group "Economic and Social Impact of Research".