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Policy mixes for sustainability transitions: An extended concept and framework for analysis

Karoline S. Rogge[a,b,*], Kristin Reichardt[c]

[a] Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI), Breslauer Straße 48, 76139 Karlsruhe, Germany
[b] SPRU—Science Policy Research Unit, Jubilee Building, University of Sussex, Brighton BN1 9SL, UK
[c] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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ABSTRACT

Reaching a better understanding of the policies and politics of transitions presents a main agenda item in the emerging field of sustainability transitions. One important requirement for these transitions, such as the move towards a decarbonized energy system, is the redirection and acceleration of technological change, for which policies play a key role. In this regard, several studies have argued for the need to combine different policy instruments in so-called policy mixes. However, existing policy mix studies often fall short of reflecting the complexity and dynamics of actual policy mixes, the underlying politics and the evaluation of their impacts. In this paper we take a first step towards an extended, interdisciplinary policy mix concept based on a review of the bodies of literature on innovation studies, environmental economics and policy analysis. The concept introduces a clear terminology and consists of the three building blocks elements, policy processes and characteristics, which can be delineated by several dimensions. Based on this, we discuss its application as analytical framework for empirical studies analyzing the impact of the policy mix on technological change. Throughout the paper we illustrate the proposed concept by using the example of the policy mix for fostering the transition of the German energy system to renewable power generation technologies. Finally, we derive policy implications and suggest avenues for future research.

1. Introduction

One of the main challenges in the emerging field of sustainability transitions is to improve our understanding of the policies and politics of transitions, such as for the move towards a decarbonized energy system (Markard et al., 2012). One important requirement for such a transition is the redirection and acceleration of technological change towards sustainability objectives. However, in this context technological change, often characterized by its three major stages of invention, innovation and diffusion (del Río González, 2009b), is faced with multiple market, system and institutional failures and thus requires multi-faceted policy interventions (Lehmann, 2010; Twomey, 2012; Weber and Rohracher, 2012). Responding to this challenge, in recent years scholars and practitioners in fields particularly relevant to eco-innovation (Kemp, 2011; Rennings, 2000) have called for a policy mix which combines several policy instruments (IEA, 2011b; Nauwelaers et al., 2009; OECD, 2007). However, policy mix studies tend to be limited to examining instrument interactions (del Río González, 2006; IEA, 2011a) or the policy processes associated with designing such mixes (Howlett and Rayner, 2007). Furthermore, the terminology applied in these studies is often ambiguous, particularly regarding the desired characteristics of a policy mix.[1]

This limited scope and ambiguous terminology of existing policy mix studies have two major consequences for the analysis of policy mixes and their impacts. First, the narrow scope of policy mix concepts may cause researchers to neglect important policy mix

* Corresponding author at: SPRU—Science Policy Research Unit, Jubilee Building, University of Sussex, Brighton BN1 9SL, UK.
E-mail address: k.rogge@sussex.ac.uk (K.S. Rogge).

[1] For instance, given the limitations of the EU emissions trading system, Matthes (2010) (p.6) calls for a “comprehensive, effective, economically efficient, robust, politically achievable, and inclusive climate policy mix.” Regarding climate innovations in the power sector Schmidt et al. (2012a) (p.476) stress the need for a “consistent and effective policy mix which is congruent to long-term targets.” Likewise, OECD (2007) (p. 22) recommends an increase of “the coherence of the instrument mix” for environmental policy and Nauwelaers et al. (2009) (p.11) underline the “need for coherence, coordination, and effectiveness of policy mixes” for R&D.

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Table 1
Definitions of the term policy mix in the literature.

Source	Definition
Guy et al. (2009) (p.1)	"An R&D and Innovation Policy Mix can be defined as that set of government policies which, by design or fortune, has direct or indirect impacts on the development of an R&D and innovation system."
Kern and Howlett (2009) (p.395)	"Policy mixes are complex arrangements of multiple goals and means which, in many cases, have developed incrementally over many years."
Nauwelaers et al. (2009) (p.3)	"A policy mix is defined as: The combination of policy instruments, which interact to influence the quantity and quality of R&D investments in public and private sectors."
Boekholt (2010) (p.353)	"A policy mix can be defined as the combination of policy instruments, which interact to influence the quantity and quality of R&D investments in public and private sectors."
de Heide (2011) (p.2)	"A policy mix is the combined set of interacting policy instruments of a country addressing R&D and innovation."
Ring and Schröter-Schlaack (2011) (p.15)	"A policy mix is a combination of policy instruments which has evolved to influence the quantity and quality of biodiversity conservation and ecosystem service provision in public and private sectors."

elements or processes in their analyses. This may lead to an insufficient understanding of the role of policy mixes for sustainability transitions, potentially resulting in fragmentary and oversimplified policy recommendations on how to redirect and accelerate technological change. Second, the lack of a uniform terminology could lead to apparently ambiguous findings and may render policy mix analyses difficult to assess, compare and synthesize. Ultimately, these obstacles to integrating our insights on the link between policy and innovation may further reduce the substance and impact of resulting policy advice.

In this study we address the identified lack of a comprehensive, uniformly defined policy mix concept for analyzing the link between policy and technological change, thereby heeding Flanagan et al.'s (2011) call for a reconceptualization of the policy mix for innovation. As a prerequisite of such empirical analysis, we take a first step in identifying and defining the key elements, processes, characteristics and dimensions of such an extended policy mix concept. For this, we review and synthesize the literature on innovation studies, environmental economics, policy analysis and strategic management. In doing so, we aim at deriving a policy mix concept that assists in a more systematic understanding of real-world policy mixes and serves as an integrating framework for empirical analyses addressing the role of policy mixes for technological change. Thereby, such an interdisciplinary analytical framework should enhance our understanding of the role of policy mixes for sustainability transitions and thus enable more precise policy recommendations.

Throughout the paper we illustrate the proposed policy mix concept using the example of the decarbonization of the German energy system, which requires accelerated development and diffusion of renewable power generation technologies (RPGTs) to realize the aspired system transition. The associated policy mix represents a good example with its feed-in law and several other policy mix elements as well as lively policy debates as to the best way to achieve the "Energiewende" (Agora Energiewende, 2012).

The remainder of the paper is structured as follows. In Section 2 we review the literature on policy mixes and their characteristics and derive requirements for an extended policy mix concept. Based on this, in Section 3 we present the three building blocks of the proposed policy mix concept: elements (Section 3.1), policy processes (Section 3.2) and characteristics (Section 3.3). In Section 3.4 we introduce relevant dimensions for delineating policy mixes, while Section 3.5 synthesizes the proposed policy mix concept. Finally, in Section 4 we discuss how the extended policy mix concept may be used as a framework for analysis for investigating the link between policy mixes and technological change (Section 4.1), and how to address the associated challenges of such empirical analysis, including boundary setting and operationalizing the policy mix (Section 4.2). Section 5 derives policy implications and concludes the paper.

2. Literature review

2.1. Policy mix

A growing number of studies in various scientific fields use the term *policy mix*, e.g. Lehmann (2010) in environmental economics, Nauwelaers et al. (2009) and de Heide (2011) in innovation studies, and Howlett and Rayner (2007) in the field of policy analysis.[2] In its most basic form, studies implicitly or explicitly define a policy mix as the combination of several policy instruments (Lehmann, 2012; Matthes, 2010). However, as stressed by Flanagan et al. (2011), a policy mix encompasses more than just a combination of policy instruments; it also includes the processes by which such instruments emerge and interact. As a consequence, studies focusing solely on the interaction of instruments should, more precisely, refer to the term 'instrument mix' (see Section 3.1.3).[3] Table 1 gives an overview of some policy mix definitions, with the more elaborate ones mainly originating from innovation studies and the policy analysis literature.

Three general features emerge from these definitions: First, they typically include the ultimate *objective(s)* of the policy mix, either in an abstract form (Kern and Howlett, 2009) or more typically as a specific objective of a certain policy field, such as innovation (Boekholt, 2010; Guy et al., 2009; Nauwelaers et al., 2009) or biodiversity (Ring and Schröter-Schlaack, 2011). Second, *interaction* is a central feature of the existing policy mix definitions (Boekholt, 2010; de Heide, 2011; Nauwelaers et al., 2009). It has been studied most extensively in the climate and energy fields, where the focus is often on its influence on the effectiveness and efficiency of instruments in the mix (del Río González 2009a, 2010; IEA, 2011b; Sorrell et al., 2003). Third, some of the definitions point to the *dynamic nature* of the policy mix, referring to it as having "evolved" (Ring and Schröter-Schlaack, 2011) and "developed incrementally over many years" (Kern and Howlett, 2009). This reflects that instruments and their meanings may change over time, causing interactions between them to change (IEA, 2011b; Sorrell et al., 2003).

Yet, in the context of sustainability transitions a policy mix concept is needed which goes beyond this narrow scope – interacting

[2] A review of the origins of the term in economic policy and its subsequent uptake in the fields of environmental and later also innovation policy can be found in Flanagan et al. (2011).

[3] This is done, for example, by OECD (2007), Braathen (2007) and Murphy et al. (2012). Similarly, Borrás and Edquist (2013) argue for a distinction between instrument mix and policy mix, while others use the term 'policy mix' interchangeably with 'instrument mix' (Ring and Schröter-Schlaack, 2011).

instruments aimed at achieving objectives in a dynamic setting – at least in three respects. First, aside from capturing its dynamic nature, an extended concept should consider more of the *complexity* of real-world policy mixes, thereby going beyond combinations of policy instruments and their interactions (Flanagan et al., 2011). Second, it needs to more explicitly incorporate *policy processes* "by which policies emerge, interact and have effects" (Flanagan et al., 2011, p. 702) since such processes and related politics help explain the evolution of policy mixes, but also the resulting effects (Foxon and Pearson, 2007, 2008). Third, a policy mix concept for sustainability transitions ought to include a *strategic component*. This tends to be neglected despite early works of Jänicke on the role of strategic approaches in environmental policy (Jänicke, 1998, 2009), the necessity of long time horizons for sustainability transitions (Markard et al., 2012) and recent empirical evidence on the importance of long-term climate targets for companies' innovation strategies (Rogge et al., 2011b,c; Schmidt et al., 2012b).

2.2. Characteristics of policy mixes

To describe the nature and performance of policy mixes it is useful to differentiate between policy mix characteristics and assessment criteria (OECD, 2003a; Sorrell et al., 2003). Terms belonging to the latter group represent well-established ex-ante and ex-post assessment criteria applied in impact assessments and evaluations of single policy instruments, such as effectiveness, efficiency, equity or feasibility (del Rio et al., 2012; IRENA, 2012). In contrast, the former group comprises terms specifically used for characterizing the policy mix, such as consistency, coherence, credibility or comprehensiveness (Foxon and Pearson, 2008; Howlett and Rayner, 2007; Kern and Howlett, 2009; Majone, 1997; Matthes, 2010). These characteristics may impact the performance of a policy mix in terms of the standard assessment criteria, particularly regarding effectiveness and efficiency.

However, most policy mix studies refer to these often ambiguously defined characteristics without clarifying what is actually meant. We will illustrate this ambiguity for the frequently used but particularly heterogeneously defined terms *consistency* and *coherence* (Den Hertog and Stroß, 2011; Picciotto, 2005). Based on a review of the – predominantly policy analysis – literature on these terms we identify three important points to be taken into account when establishing a more uniform terminology.

First, consistency and coherence are either seen as *identical or different characteristics*. The former suggests coherence is synonymous with consistency (Carbone, 2008; Hoebink, 2004; Matthews, 2011). As a result, coherence is often simply defined using the term consistency (Hydén, 1999; Picciotto et al., 2004), but there is no uniform definition.[4] In contrast, the latter distinguishes consistency and coherence as different characteristics (Howlett and Rayner, 2007; Mickwitz et al., 2009a; OECD, 2001), but again there is no agreement on the exact nature of this difference. However, the majority of these studies assert that coherence is more encompassing than consistency (Jones 2002; OECD, 2003a). That is, in its most basic form, consistency is seen as the absence of contradictions (Den Hertog and Stroß, 2011; Gauttier, 2004), while coherence calls for an achievement of synergy or positive connections (Missiroli, 2001; Tietje, 1997).[5]

Second, the literature differentiates between a *state and process perspective* of consistency and coherence, i.e. between what is being achieved and how it is achieved (Carbone, 2008), but again this is not treated uniformly. A first set of studies addresses the state of affairs at a certain point in time only (Duraiappah and Bhardwaj, 2007; Fukasaku and Hirata, 1995; Hoebink, 2004). A second set instead captures the process perspective (Jones, 2002; Lockhart, 2005; OECD, 2003a), often concentrating on the organizational setup to attain consistency/coherence. A third set of studies mentions – either implicitly or explicitly – both state and process perspectives, but uses the same term – typically coherence – for both (Den Hertog and Stroß, 2011; Forster and Stokke, 1999; McLean Hilker, 2004).

Third, some studies focus on *tools* for enhancing consistency and coherence (Ashoff, 2005; OECD, 1996, 2003a), a discussion which is closely linked to the literature on policy coordination[6] and integration[7] (Mickwitz et al., 2009a; Van Bommel and Kuindersma, 2008). However, as before, there is no common understanding of the terms consistency and coherence and how they relate to other concepts, such as coordination. One reason for this lack of a uniform terminology may be the often largely separated contributions addressing distinct policy fields, such as development policy (EU, 2005, 2010; Weston and Pierre-Antoine, 2003), climate policy (Kern and Howlett, 2009; Mickwitz et al., 2009b) and eco-innovation policy (Reid and Miedzinski, 2008; Ruud and Larsen, 2004).

To better deal with such diversity in meaning and the resulting difficulties in integrating findings across studies, an extended policy mix concept needs to propose uniform definitions of these terms that fulfill the following two requirements: First, these definitions need to clearly specify whether they refer to the state or process perspective of the policy mix, which might best be accomplished by separate terms for each of these perspectives. Second, at a minimum they should allow for the differentiation of a weak and strong form to capture the distinction between the absence of contradictions and actual synergies within a policy mix.

3. Building blocks of the policy mix concept

As derived in the literature review, an extended policy mix concept for sustainability transitions needs to address three basic requirements: first, the inclusion of a *strategic component*, second, the incorporation of associated *policy processes*, and third, the consideration of *characteristics* of policy mixes. In capturing this complexity of actual policy mixes it should also pay attention to their dynamic nature. Finally, to resolve concerns over ambiguous terminology, it needs to suggest precise definitions of key terms.

Based on these requirements, we define the policy mix as a combination of the three building blocks elements, processes and characteristics, which can be specified using different dimensions. *Elements* comprise the (i) policy strategy with its objectives and principal plans for achieving them and (ii) the instrument mix with its interacting policy instruments. The content of these elements is an outcome of *policy processes*. Both elements and processes can be described by their *characteristics*, including the consistency of

[4] While some base their definition on the absence of contradictions and non-conflicting signals (Forster and Stokke, 1999; Van Bommel and Kuindersma, 2008), others refer to the consistency or coherence among policies (Bigsten 2007; Di Francesco 2001; OECD, 1996), while still others speak of consistency or coherence between objectives and instruments (Fukasaku and Hirata, 1995; Picciotto 2005).

[5] An alternative view was developed by Howlett et al. who speak of consistency of instruments and coherence of goals (Howlett and Rayner, 2007) and also introduce congruence among instruments and goals as a third category (Kern and Howlett, 2009).

[6] Policy coordination is a formal policy process aiming to get "the various institutional and managerial systems, which formulate policy, to work together" (OECD 2003a, p. 9OECD, 2003aOECD 2003a, p. 9). Subsets of policy coordination are cooperation and collaboration (Bouckaert et al., 2010).

[7] Environmental policy integration means "the incorporation of environmental objectives into all stages of policy making in non-environmental policy sectors [..] accompanied by an attempt to aggregate presumed environmental consequences into an overall evaluation of policy, and a commitment to minimize contradictions between environmental and sectoral policies" (Lafferty and Hovden, 2003, p. 9).

elements, the coherence of processes, as well as the credibility and comprehensiveness of a policy mix. Finally, the policy mix can be delineated by several dimensions, including policy field, governance level, geography and time.

3.1. Building block 1: elements

3.1.1. Policy strategy

The importance of a long-term strategic orientation and strategic policy frameworks has been increasingly underscored in the literature addressing sustainability transitions (Foxon and Pearson, 2008; Quitzow, 2015a; Weber and Rohracher, 2012) and policy-triggered environmental technological change (Rogge et al., 2011c; Schmidt et al., 2012b). We therefore incorporate policy strategy as one of the elements in the policy mix concept and draw on the strategic management literature to derive a common definition for the content of a policy strategy. This literature highlights that strategy consists of a combination of interdependent ends (goals) and means (policies) to achieve the ends (Andrews, 1987; Miles and Snow, 1978; Mintzberg, 1999; Porter, 1980).

Building on Andrews (1987) and Porter (1980), we thus define policy strategy as a combination of policy objectives and the principal plans for achieving them. That is, the definition puts an emphasis on the output – the ends and means – of the strategy process, while the adaptive process of formulating, implementing and revising objectives and plans is captured by the processes building block (see 3.2). We will discuss these two main components of objectives and plans in turn, while recognizing that they are closely interlinked.

The first component of the policy strategy definition concerns *policy objectives* associated with sustainability transitions. These objectives tend to be substantiated by long-term *targets* with quantified ambition levels (Rennings et al., 2003; Schmidt et al., 2012b) and may be based on visions of the future (del Río et al., 2010; Kemp and Rotmans, 2005).[8,9] For example, one of the policy objectives of the EU is the reduction of greenhouse gas (GHG) emissions. This is concretized by a 20% GHG reduction target for 2020 and 40% for 2030, aiming at arriving at numbers in line with the internationally agreed target of 2 °C (EU, 2013).[10] In addition to environmental objectives, the policy strategy may also include social and economic issues (Daly and Farley, 2010), such as the support of growth, competitiveness and jobs (EU, 2013). Besides content-oriented objectives, a policy strategy can also contain process and learning objectives, which may be particularly relevant in the context of sustainability transitions (Kemp, 2007; Rotmans et al., 2001), e.g. in terms of the build-up or enhancement of the strategic capacity of governments (Quitzow, 2015b).

The second component of the strategy definition addresses the *principal plans* for achieving these objectives. Such plans outline the general path that governments propose to take for the attainment of their objectives and include framework conventions, guidelines, strategic action plans and roadmaps.[11] In communicating not only the ends but also the intended means to achieve these, the policy strategy gives direction to actions and decisions (Grant, 2005). An example of principal plans at the EU level is the Strategic Energy Technology (SET) Plan, while at the national level the German Energy Concept provides a key example.

The long-term perspective inherent in the policy strategy (Hillman and Hitt, 1999) can play a fundamental role in providing actors with needed guidance in their search and can thus support one of the functions of innovation systems (Hekkert et al., 2007). For example, research has shown the vital role of ambitious and stable long-term climate targets in steering R&D activities of companies in the power sector (Rogge et al., 2011b,c; Schmidt et al., 2012b). However, the same research has also pointed out that this strategic element of the policy mix on its own is not sufficient to change companies' innovation strategies but needs to be operationalized through concrete policy instruments.

3.1.2. Instruments

As the second element in the policy mix, policy instruments constitute the concrete tools to achieve overarching objectives. More precisely, they can be seen as tools (Salamon, 2002) or techniques of governance (Howlett, 2005) that address policy problems (Pal, 2006). They are introduced by a governing body (Sorrell et al., 2003) in order to achieve policy objectives (Howlett and Rayner, 2007), thereby translating plans of action (de Heide, 2011). Examples of policy instruments include the German feed-in tariffs incorporated in the Renewable Energy Act (EEG) and the EU Emissions Trading System (ETS).

A number of alternative terms are used, such as implementing measures (EU, 2013), programs (Komor and Bazilian, 2005), policies (IRENA, 2012), or policies and measures (UNFCCC, 2011). For simplicity, we use the term 'instrument' in the policy mix concept, with the clear understanding that it encompasses these alternative terms. However, as the term 'policy' is very broad and used differently across disciplines (Dye, 2008; Fischer and Preonas, 2010), we prefer not using it synonymously for 'instrument'.

Policy instruments are typically associated with specific *goals*. That is, while the policy strategy contains objectives which tend to be specified by long-term targets, we use the term 'goal' to characterize the intended effect of instruments that contribute to achieving overarching policy objectives. In addition, two key attributes of policy instruments are particularly relevant for innovation, namely instrument *type* (Section 3.1.2.1) and instrument *design feature* (Section 3.1.2.2).

3.1.2.1. Instrument type. The type of an instrument has been identified as a major determinant of environmental innovation, both in theoretical (Jaffe et al., 2002; Popp et al., 2009; Requate, 2005 Requate, 2005) and empirical studies (Hašcic et al., 2009; Hemmelskamp, 1999; Johnstone et al., 2010). First attempts at a combined typology of environmental and innovation policy instrument types tend to lack either a differentiated set of innovation (Rennings et al., 2008) or environmental policy types (Nauwelaers et al., 2009). Therefore, in Table 2 we propose a more balanced 3 × 3 matrix typology that combines three instrument types (economic instruments, regulation and information) with three instrument purposes (technology push, demand pull and systemic concerns). It may be most noteworthy that we include a systemic purpose of instruments by which we refer to "instruments that support functions operating at system level" (Smits and Kuhlmann, 2004,

[8] In making this distinction between objectives and targets we follow Tuominen and Himanen (2007, p. 390) who define a policy objective as "what the policy is trying to achieve, the overall goal; often quite abstract and qualitative" and a policy target as "more specific and quantitative than an objective [..] (e.g. 10% less emissions of air pollutants within 5 years). The target points out a clear sense of direction for policy measures."

[9] Targets can be characterized by a number of factors, including their ambition level, their type (e.g. specific, absolute), their governance level (e.g. EU, national), their scope (e.g. headline target, sub-target), their time horizon (e.g. long-term, interim), or their legal nature (e.g. binding, aspirational, voluntary), see EU (2013) and Philibert and Pershing (2001).

[10] This target (20% GHG reduction until 2020 compared to 1990) is one of the three EU headline targets (20-20-20 targets) which also include a 20% share for renewable energy sources in the energy consumed in the EU (EU, 2008a) and 20% savings in energy consumption compared to projections for 2020 (EU, 2008b).

[11] An alternative analytical lense is provided by Quitzow (2011, 2015a), which includes existing policy instruments and their design in the definition of the content of a policy strategy.

Table 2
Type-purpose instrument typology (with instrument examples).

	PRIMARY PURPOSE		
PRIMARY TYPE	Technology push	Demand pull	Systemic
Economic instruments	RD&D[*] grants and loans, tax incentives, state equity assistance	Subsidies, feed-in tariffs, trading systems, taxes, levies, deposit-refund-systems, public procurement, export credit guarantees	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulation	Patent law, intellectual property rights	Technology/performance standards, prohibition of products/practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information	Professional training and qualification, entrepreneurship training, scientific workshops	Training on new technologies, rating and labelling programs, public information campaigns	Education system, thematic meetings, public debates, cooperative RD&D[*] programs, clusters

Source: Own elaboration (based on del Río González, 2009a; Edler and Georghiou, 2007; Hemmelskamp, 1999; Hufnagl, 2010; IEA, 2011b; Mowery, 1995; Rammer, 2009; Rennings et al., 2008; Smits and Kuhlmann, 2004; Sterner, 2000; Wieczorek and Hekkert, 2012).
[*] RD&D = Research, development and demonstration.

p. 25).[12] Since this matrix is an oversimplification of reality, and as such not free of overlaps,[13] we qualify both instrument purpose and type with the word 'primary'. For each of the nine possible type-purpose-combinations, Table 2 includes some selected examples of instruments relevant for technological change.

3.1.2.2. Instrument design features. In the environmental economics literature it has been increasingly pointed out that a policy instrument's design features may actually be more influential for innovation than the instrument type (Kemp and Pontoglio, 2011; Vollebergh, 2007). Therefore, an increasing number of studies explicitly consider them when analyzing policy instruments and their innovation effects (Ashford et al., 1985; Blazejczak et al., 1999; Norberg-Bohm, 1999). In addition, design features may also impact an instrument's effectiveness and efficiency and may be a prerequisite for interaction analyses (del Río González, 2009a).

Design features can be differentiated by abstract and descriptive features. *Descriptive design features*, such as an instrument's legal form,[14] its target actors, and its duration, summarize the content of a policy instrument (del Río, 2012), which can serve as a first step in identifying how a policy instrument performs regarding abstract design features. A number of *abstract design features* have been proposed in the literature (Hašcic et al., 2009; Kemp and Pontoglio, 2011),[15] but there is no universally accepted list. In the context of sustainability transitions we argue that at least the following six may be important to consider: stringency, level of support, predictability, flexibility, differentiation and depth.

First, *stringency* addresses the ambition level of an instrument and is typically associated with regulatory and economic instruments, such as emissions standards or emissions trading. It can refer both to an instrument's goal and its design, with the individually perceived stringency ultimately determined by the characteristics of the instrument's target actor, such as its technology portfolio (Rogge, 2010). Although definitions and operationalizations of stringency vary across studies, findings point to a positive impact of stringency on innovation (Ashford et al., 1985; Frondel et al., 2007; Rogge et al., 2011a,c; Schmidt et al., 2012b).

Second, *level of support* captures the magnitude of positive incentives provided by a policy instrument, which may be particularly relevant for instruments providing financial incentives. A prime example is the level of feed-in tariffs, which aim at increasing the return on investments in renewable power generation technologies (Steinhilber et al., 2011). Another example is the volume of RD&D support, e.g. for fostering research and development activities for niche technologies.

Third, *predictability*, having gained attention particularly in relation to the EU ETS and a post-Kyoto international climate agreement (Engau and Hoffmann, 2009; Hoffmann et al., 2008), "captures the degree of certainty associated with a policy instrument and its future development. This concerns the instrument's overall direction, detailed rules, and timing" (Rogge et al., 2011c, p. 515). As such it ultimately addresses the effect of a policy instrument on investor uncertainty (Hašcic et al., 2009), which may be particularly important for long-lived capital-intensive investments and RD&D decisions. For example, the German EEG increases its predictability by granting support to investors for 20 years.

Fourth, *flexibility* captures the extent to which innovators are allowed to freely choose their preferred way of achieving compliance with an instrument (Kivimaa and Mickwitz, 2006; Norberg-Bohm, 1999). Johnstone and Hašcic (2009, p. 1) find that for "a given level of policy stringency, countries with more flexible environmental policies are more likely to generate innovations which are diffused widely and are more likely to benefit from innovations generated elsewhere". A prime example in this regard is the EU ETS which allows firms to freely choose between various compliance options.

A fifth abstract design feature concerns the *differentiation* specified in policy instruments (Kemp and Pontoglio, 2011), e.g. with regard to industrial sector, size of the plant, technology or geographical location.[16] Sixth, the *depth* of the policy instrument addresses the range of its innovation incentives, that is whether its incentives extend all the way to potential solutions with zero emissions (Hašcic et al., 2009).

12 Smits and Kuhlmann (2004, p. 25) distinguish between five systemic functions: "management of interfaces, building and organizing systems, providing a platform for learning and experimenting, provision of strategic intelligence and demand articulation."

13 For example, a trading system, such as the EU ETS, is primarily viewed as a demand-pull instrument, but the change in relative prices not only affects diffusion but also innovation (Jaffe et al., 2002), making it reasonable to classify it as an economic instrument serving a system-wide purpose. However, empirical evidence suggests that the primary effect occurs in the adoption of technologies, not on RD&D (Rogge et al., 2011c; Schmidt et al., 2012b), thus making it meaningful to classify trading schemes as economic instruments that primarily serve demand-pull purposes.

14 The legal form determines, for example, the binding character of an instrument, which can range from voluntary agreements to compulsory measures.

15 Not all of the abstract design features found in the literature concern instruments only, but also include aspects relevant for policy making and implementation, such as continuous improvement (Kivimaa and Mickwitz, 2006) and enforcement (Kemp, 1997), as well as for the overall policy mix, such as credibility (Kemp and Pontoglio, 2011).

16 In the innovation policy literature this feature is also referred to as the "specificity of a policy measure" which serves as indicator as to whether an instrument "quite precisely describes the research target or whether this is rather open" (Cantner and Pyka, 2001, p. 764).

The interwoven nature of design features requires them to be mutually balanced (Kemp, 2007). For example, empirical studies recommend a gradual tightening of the stringency in a predictable manner, while at the same time providing enough flexibility to allow for the exploration of new technological developments (Kivimaa, 2007).

3.1.3. Instrument mix

Moving from single instruments to their combination brings us to the instrument mix, which we conceptualize as being only a part of the overarching policy mix. This calls for a distinction between instrument mix and policy mix, with the latter encompassing the former. Regarding the instruments in this mix it may be useful to distinguish between core (or cornerstone) instruments and complementary (or supplementary) instruments of an instrument mix (IEA, 2011b; Matthes, 2010; Schmidt et al., 2012b). For the example of the instrument mix for renewable energies in Germany, the core instrument would be the EEG with its feed-in tariffs, which is complemented by other instruments such as the KfW renewable energy program.

At the heart of the concept of instrument mixes are *interactions* between the instruments, which signify "that the influence of one policy instrument is modified by the co-existence of other [instruments]" (Nauwelaers et al., 2009). This influence originates from the direct or indirect effect that the operation or outcomes of instruments have on each other (Oikonomou and Jepma, 2008; Sorrell et al., 2003). Clearly, these interdependencies of instruments largely influence the combined effect of the instrument mix and thus the achievement of policy objectives (Flanagan et al., 2011). It is for this reason that interactions of policy instruments represent a central component of any policy mix concept.

However, as pointed out by Gunningham and Grabosky (1998), without considering the particular context in which interactions occur, only tentative conclusions on instrument interactions can be reached, thus calling for empirical analyses. Such analyses ought to understand the mechanisms and consequences of policy interactions, which requires considering a number of aspects, including the scope of the interacting instruments, the nature of their goals, their timing, and operation and implementation processes (Sorrell et al., 2003). This suggests that interaction outcomes are not only determined by the instrument mix but also shaped by the overarching policy mix.

Thus far, interactions have been predominantly dealt with in the environmental domain, particularly on climate and energy issues (del Río González 2009a; Gunningham and Grabosky, 1998; Sorrell et al., 2003). More recently, innovation studies have also started to highlight interactions (Flanagan et al., 2011; Guerzoni and Raiteri, 2015; Nauwelaers et al., 2009). For example, Flanagan et al., 2011 differentiate between four types of interactions, including interactions between the same instruments across different dimensions (see Section 3.4), and similarly between different instruments either targeting the same or different actors/groups involved in the same process, or targeting different processes in a broader system. These studies acknowledge the need to avoid negative interactions and to strive for positive or complementary interaction outcomes.

3.2. Building block 2: policy processes

Rather than looking only at the content of the policy strategy and instrument mix with its interacting instruments, we now turn our attention to the policy making process, or *policy process* for short (Dunn, 2004; Dye, 2008). It is these processes that determine the elements of the policy mix and thus how both the strategy and corresponding instruments change over time. In addition, policy processes may also impact technological change by shaping policy mix characteristics. Given their importance these processes constitute another building block of the proposed policy mix concept (Howlett and Rayner, 2007; Kay, 2006; Majone, 1976).

Since there is no uniform definition of the policy making process, we build on Howlett et al. (2009) and Sabatier and Weible (2014) and refer to it as political problem-solving process among constrained social actors in the search for solutions to societal problems – with the government as primary agent taking conscious, deliberate, authoritative and often interrelated decisions. As such, these interactive and continuous reconciliation processes with various feedback loops involve power, agency and politics. Clearly, this is of high relevance in the context of sustainability transitions with their complex and messy policy processes with a plethora of involved actors and their conflicting interests and ideas (Meadowcroft, 2009; Stirling, 2014). Finally, policy processes are shaped by socio-economic conditions, infrastructure and biophysical conditions, but also by culture and institutions (Sabatier and Weible, 2014), and can thus differ significantly across space and time.

Policy processes cover all stages of the policy cycle, including problem identification, agenda setting, policy formulation, legitimization and adoption, implementation, evaluation or assessment, policy adaptation, succession and termination (Dunn, 2004; Dye, 2008; Schubert and Bandelow, 2009). As such, the policy making process can be seen "as a cycle of problem-solving attempts, which result in *'policy learning'* through the repeated analysis of problems and experimentation with solutions" (Howlett et al., 2009, p. 3). This ongoing and reactive nature of policy processes both shapes the setting and adjustment of the policy strategy as well as the (re)design of instruments in the mix.

Because of the fundamental importance of policy implementation in determining the effectiveness and efficiency of a policy instrument, we follow others in differentiating policy processes into policy making and policy implementation (Richardson, 1982). Regarding *policy making*, we stress two aspects: First, due to the dynamic, multifaceted and uncertain nature of technological change and sustainability transitions, policy adaptation and thus policy learning is a crucial feature of policy making processes (Allen et al., 2011; Bennett and Howlett, 1992; Boekholt, 2010; Kemp et al., 2007; Loorbach, 2007). To facilitate such interactive processes, the monitoring and evaluation of the impacts of policy mixes are of fundamental importance (Kemp, 2011). Also, participatory processes of envisioning, negotiating, learning and experimenting can strengthen policy learning (Frantzeskaki et al., 2012). Second, policy making is a highly political process characterized by resistance to change, particularly from actors with vested interests (Unruh, 2002). In that sense, the adoption of a policy strategy with clear objectives but without the simultaneous adoption of a set of instruments can be understood as an attempt of setting the agenda for upcoming changes in the instrument mix. However, given the political nature of policy making processes it may remain difficult to radically adjust the instrument mix even if new policy objectives are in place. This may be one reason why new instruments supporting niches may be added to those supporting existing regimes instead of replacing them (Kern and Howlett, 2009).[17] By *policy implementation* we mean "the arrangements by authorities and other actors for putting policy instruments into action" (Nilsson et al., 2012; Fig. 1), that is, for executing and enforcing them (Sabatier and Mazmanian, 1981), implying that policy implementation is particularly relevant to the instrument mix. Complex and insufficient implementation structures but also political resistance at sub-ordinate governance levels may lead to implementation difficulties such that ultimately a policy instrument may not tap

[17] Arguably, policy making may often be more affected by such politics than policy implementation.

Table 3
Broad overview of key policy processes describing the evolution of the German policy mix for renewable energies (until 2004).

Time	Involved actors	Policy processes
Aftermath of oil crises and Chernobyl	Renewables advocacy groups, parliament	Promotion of initial support programs for wind and solar power, e.g. 1000 roofs program
Late 1980s to 1990	Renewables advocacy associations	Proposal of Feed-in Law (StrEG), predecessor of Renewable Energy Act (EEG)
1990	Ministry of Economic Affairs, big utilities	Opposition to StrEG
	German Bundestag	Adoption of StrEG in all-party consensus
Mid 1990s	German Länder, municipal utilities	Support for renewables through specific local programs
2000	German Bundestag	Accelerating the fast adoption of the first EEG
2000 to 2004	Government opposition, utilities, associations, interest groups	Different degrees of disagreement on drafting first EEG amendment

Source: Own compilation (based on Jacobsson and Lauber, 2006; Wüstenhagen and Bilharz, 2006).

its full potential. Such difficulties may partly be overcome by an appropriate crafting of policy instruments (May, 2003; Mazmanian and Sabatier, 1981), including the provision of sufficient funding and staff for implementation, thereby illustrating the close link between policy making and implementation.

Table 3 illustrates the evolution of the German policy mix for renewable power generation technologies by linking actors and policy-making processes, ranging from the promotion of initial support programs by advocacy groups and the parliament to the adoption and first amendments of the German Renewable Energy Act (EEG).

Finally, we highlight the role of the *style* of policy processes. More precisely, we refer to the policy making and implementation style, i.e. the “standard operating procedures for making and implementing policies” (Richardson 1982, p.2). The policy style captures, for example, the typical kind of goal setting or flexibility in instrument application (Blazejczak et al., 1999; Jänicke et al., 2000). It may directly and indirectly influence the policy mix, e.g. regarding its credibility or the design and implementation of policy instruments and thus may play an important role in how the overall policy mix affects innovation.

3.3. Building block 3: characteristics

3.3.1. Consistency of elements

We suggest that *consistency* captures how well the elements of the policy mix are aligned with each over, thereby contributing to the achievement of policy objectives. It may range from the absence of contradictions to the existence of synergies within and between the elements of the policy mix.

We highlight two key features of this consistency definition. First, it focuses on the *state of the elements* of the policy mix at any given point in time, i.e. its content. In this regard, the development of the alignment of the elements of the policy mix over time is captured by the term temporal consistency. Second, it may be most useful to understand consistency in relative terms, i.e. differentiating between the degree of consistency and its variation across dimensions, such as time, geography or governance level. A consistent policy mix at a minimum needs to be free of contradictions or conflicts (Forster and Stokke, 1999), as this may impair the achievement of objectives (Ashoff, 2005; Hoebink, 2004; McLean Hilker, 2004). If on top of such weak consistency complementarities, mutual support and synergies exist we refer to this as strong consistency.

We distinguish between consistency of the policy strategy, consistency of the instrument mix, and consistency of the instrument mix with the policy strategy. First, consistency of the *policy strategy* incorporates the alignment of policy objectives (Mickwitz et al., 2009a; OECD, 2003a), which suggests that these can be achieved simultaneously without any significant trade-offs. This is important since conflicting objectives are a major source of tension between the instruments in a policy mix (Flanagan et al., 2011). Examples are whether climate targets are consistent with energy security or competitiveness targets, or whether interim targets are consistent with long-term targets. In addition, it captures whether principal plans, i.e. framework conventions, guidelines, strategic action plans and roadmaps, are free of contradictions or mutually supportive. This first level of consistency also captures whether these plans are consistent with policy objectives. An example of this is the German Energy Concept’s (2010) confirmation of the German 40% GHG emissions reduction target by 2020 as originally specified in 2002.

The second level of consistency concerns the *instrument mix* and can be assessed through interaction analysis. The instruments in an instrument mix are consistent when they reinforce rather than undermine each other in the pursuit of policy objectives (Howlett and Rayner, 2013). “They are inconsistent when they work against each other and are counterproductive” (Kern and Howlett, 2009, p. 396). Therefore, strong instrument mix consistency is associated with positive interactions, weak instrument mix consistency is characterized by neutral interactions, while instrument mix inconsistency is captured by negative interactions (del Río González, 2009a, 2010; IEA, 2011b; Sorrell et al., 2003).

Finally, third level policy mix consistency addresses the *interplay of the instrument mix and the policy strategy*. This overall policy mix consistency is characterized by the ability of the policy strategy and the instrument mix to work together in a unidirectional or mutually supportive fashion (Howlett and Rayner, 2013), thereby contributing to the achievement of policy objectives. Thus, a higher degree of first- and second-level consistency positively influences the degree of third-level consistency. This implies that a consistent policy strategy is implemented by a consistent instrument mix encompassing instruments with design features capable of reaching the objectives. For example, the instrument mix operationalizing the German Energiewende is currently perceived as inconsistent with its ambitious targets (ARD, 2013; WDR, 2013). Ultimately, consistency at these three levels may be one determinant of the performance of a policy mix, particularly regarding its effectiveness and efficiency.

3.3.2. Coherence of processes

To characterize policy processes we use the term *coherence*, thereby following studies that focus on the process dimension (Den Hertog and Stroß, 2011, 2002; OECD, 2001, 2003a,b). Building on Jones (2002) we suggest defining policy coherence as referring to synergistic and systematic policy making and implementation processes contributing – either directly or indirectly – towards the achievement of policy objectives. Such more synergistic and systematic policy processes may be achieved through a number of structural and procedural mechanisms, such as strategic planning, coordinating structures and communication networks (Ashoff, 2005; den Hertog et al., 2004; OECD, 1996, 2001).

We highlight three key features of this definition. First, it addresses the coherence of policy processes *across different policy fields and governance levels*. These processes shape all elements of the policy mix, thereby underlining that neither the policy strategy nor instruments are seen as given. Second, it points to the need of systematic capabilities of policy makers (Jacobsson and Bergek, 2011). That is, coherence of policy making and implementation requires advanced organizational capacities, including, for example, the ability to assemble related knowledge from diverse sources, to build networks with all relevant actors, or to engage with multiple stakeholders (Quitzow, 2011, 2015a). Third, we differentiate between a *direct and indirect effect* of coherence. Its direct effect refers to how coherence influences the behavior of actors and thus the performance of a policy mix, as measured by standard assessment criteria. For example, we propose a positive direct link between coherence and the effectiveness of a policy mix. In contrast, the indirect effect addresses how coherence contributes to shaping the policy mix elements and their consistency, thereby indirectly affecting the performance of a policy mix. For this we presume a positive link, meaning that greater coherence is expected to be associated with greater consistency.

Two major tools for improving policy coherence are *policy integration* (OECD, 2003a; Underdal, 1980) and *coordination* (Bouckaert et al., 2010; Magro et al., 2015; OECD, 1996).[18] The former can improve policy coherence by enabling a more holistic thinking across different policy sectors, at the same time involving more holistic processes. In contrast, the latter can strengthen coherence by aligning the tasks and efforts of public sector organizations (Bouckaert et al., 2010), e.g. in enhancing information flows through formal mechanisms (OECD, 1996). For example, the establishment of an integrated energy and climate policy department, as accomplished in the UK and Denmark, seems to be a promising approach of structural coordination for overcoming the recurring conflict of jurisdictions between the German Federal Departments for the Environment (BMU) and Economics (BMWi), which may have hampered the realization of the German Energiewende (Rave et al., 2013).

In conclusion, we want to stress that it may be impossible to actually achieve complete coherence and consistency (Carbone, 2008; Hoebink, 2004; McLean Hilker, 2004). Reasons for this may include the complexity of the systems and associated sustainability challenges we are faced with, including path dependence and lock-in, resistance of regime actors, conflicting interests and tensions, and fragmentation of policy making (Meadowcroft, 2007; Unruh, 2002). Therefore, "the aim is to make progress towards maximum coherence within the limited resources available" (McLean Hilker, 2004), thereby also striving to maximize policy mix consistency. Yet, ultimately neither coherence nor consistency should be seen as goal in itself but rather as means for improving the performance of a policy mix regarding the standard assessment criteria, particularly effectiveness and efficiency.

3.3.3. Credibility

In addition to consistency and coherence, credibility may also be relevant for describing the nature of policy mixes for sustainability transitions. Such policy credibility is rooted in macroeconomics and monetary policy and refers to the challenges that short time horizons (electoral cycles) pose for policy makers' credibility (Kydland and Prescott, 1977). However, while the term appears frequently in current debates on climate policy, its underlying meaning remains rather vague. Therefore, we define credibility as the extent to which the policy mix is believable and reliable (Newell and Goldsmith, 2001), both overall and regarding its elements and processes.

Credibility may be influenced by a range of factors, such as the commitment from political leadership, the operationalization of targets by a consistent instrument mix or the delegation of competencies to independent agencies. For example, for the case of solar PV in Germany a content analysis of the industry journal Photon (1996–2012) suggests that the most relevant determinants of the perceived degree of credibility were the stability and temporal consistency of the policy mix, and the commitment from political leadership, followed by the consistency of the instrument mix and the support level of policy instruments (Bödeker and Rogge, 2014).

We argue that the credibility of the policy mix may play an important role in the achievement of policy objectives and thus in determining the effectiveness of the mix (Gilardi, 2002; Majone, 1997).

3.3.4. Comprehensiveness

The *comprehensiveness* of the policy mix captures how extensive and exhaustive its elements are and the degree to which its processes are based on extensive decision-making (Atuahene-Gima and Murray, 2004; Miller, 2008).

That is, comprehensiveness of the elements of the policy mix implies that the policy mix is constituted of both a policy strategy with its objectives and principal plans and at least one instrument in the instrument mix operationalizing the policy strategy. The comprehensiveness of this instrument mix is determined by the degree to which the instrument mix addresses all market, system and institutional failures, including barriers and bottlenecks (Lehmann, 2012; Sorrell, 2004; Sovacool, 2009; Weber and Rohracher, 2012). As such, a comprehensive instrument mix may address all three instrument purposes of technology-push, demand-pull and systemic concerns.

By contrast, the comprehensiveness of policy processes can be influenced by their structure, rigor and thoroughness (Atuahene-Gima and Murray, 2004). As with the other characteristics, the comprehensiveness of a policy mix may impact its performance regarding standard assessment criteria.

3.4. Dimensions

All three building blocks of the policy mix concept can be specified along a number of dimensions, including the policy field, governance level, geography, and time. These dimensions capture the space in which interactions can occur (Flanagan et al., 2011) by pointing to the origin of the different components of the policy mix.

The first dimension *policy field* refers to the policy domain, such as energy, environmental, climate, innovation, technology, science, industrial and transition policy (van den Bergh et al., 2007). For instance, a policy strategy aiming at the promotion of renewable power generation technologies does not have to originate from the field of climate or energy policy but instead could be based on industrial policy, e.g. depending on the national circumstances. Analyzing policy mixes across policy fields matters because internal and external inconsistencies and incoherencies within and across policy fields could render these mixes ineffective (Huttunen et al., 2014).

For the second dimension *governance level* we focus on the distinction between vertical and horizontal governance, a distinction typically made in studies on policy coherence and consistency (Carbone, 2008; den Hertog et al., 2004; Pal, 2006). The vertical level differentiates, for example, between the EU and its member states as well as between international, federal or local levels. It further distinguishes between government departments and implement-

[18] While some studies view coherence as equivalent to integration and coordination (Duraiappah and Bhardwaj, 2007; Geerlings and Stead, 2003), we follow others in seeing them as distinct formalized tools for improving policy coherence (Carbone 2008; Di Francesco 2001; McLean Hilker 2004; OECD, 2003a).

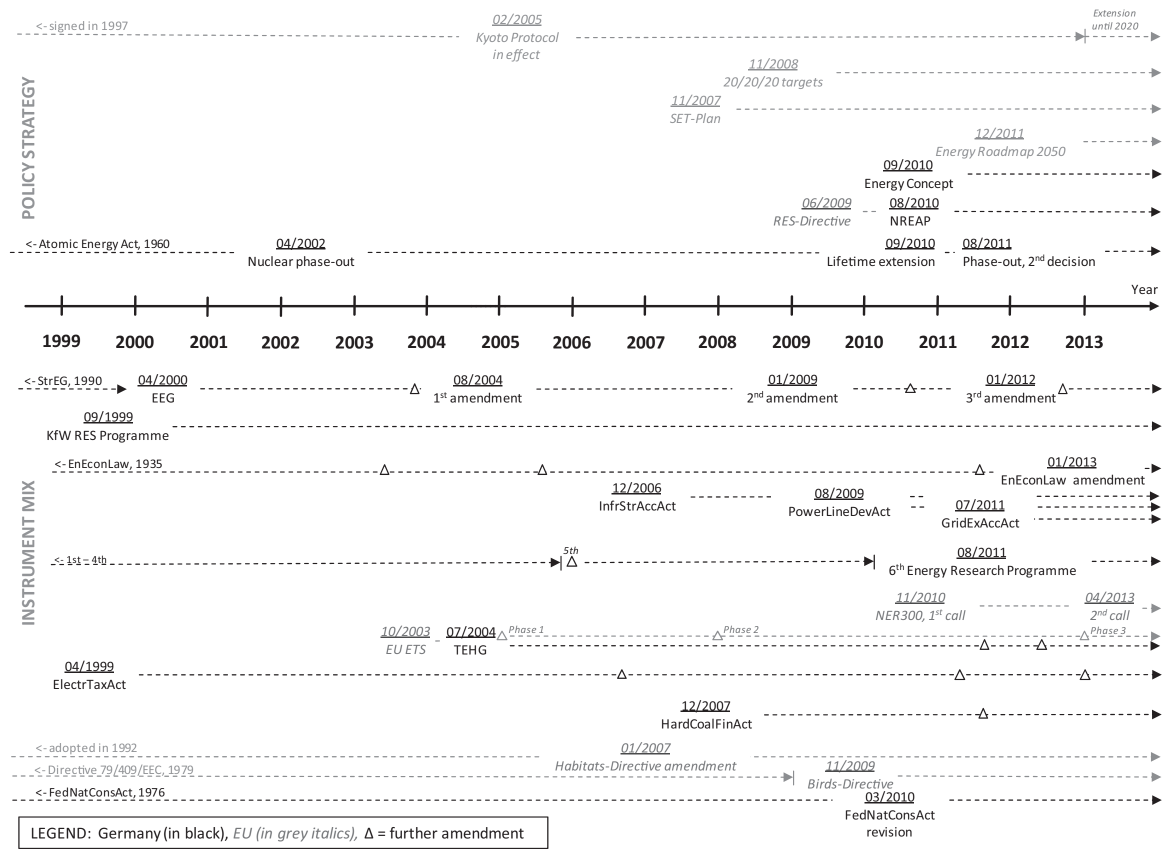

Fig. 1. Development of the elements of the policy mix for renewable energies in Germany over time.

ing agencies. For example, in the first and second EU ETS trading phase, policy making has occurred both at the level of the EU and the member states, while its implementation has predominantly taken place at the member state level. In contrast, the horizontal level allows for differentiating between different political or administrative entities at the same vertical governance level, such as federal departments of different policy fields. An example is the German Energiewende, in which six federal departments have been involved.

Third, closely related to this abstract space of governance level is the *geography* dimension, constituting the space from which the policy mix originates. The inclusion of this dimension is in line with the increasing attention to the geographical perspective in transition studies (Coenen et al., 2012; Raven et al., 2012; Späth and Rohracher, 2012). An example of this is a regional policy strategy and instruments targeted towards a certain geographical region (Navarro et al., 2014), such as funding initiatives of specific cities or regions aiming at promoting green industrial clusters.

Finally, *time* is another crucial dimension in the policy mix concept, capturing its dynamic nature. That is, a policy mix develops over time in terms of its elements, processes and characteristics. First, the *elements* of the policy mix change over time, which we illustrate using the example of the evolution of the elements of the German policy mix for renewable energies from 2000 to 2013. As can be seen in Fig. 1, particularly the instrument mix has changed over the years, with new instruments having been added, existing ones amended but only few ones terminated. Policy instruments may not only change in terms of their contents, ideally resulting in continuous improvement (Kivimaa, 2007), but also in terms of their effects as they are interpreted against changing rationales (Flanagan et al., 2011) and changing contexts. Similarly and resulting from changing instruments, interactions are not stable over time either, which may cause the instrument mix to drift out of alignment (IEA, 2011b; Sorrell et al., 2003). Second, policy *processes* may also change over time (Flanagan et al., 2011). For example, adaptive policy making allows for adjusting the policy mix as "the world changes and new information becomes available" (Walker et al., 2001; p. 283)., thereby enabling policy learning for transitions (Loorbach, 2007; Rotmans et al., 2001). Finally, *characteristics* can change over time. For example, the adherence to long-term targets beyond electoral cycles and thus the stability of targets may be one factor influencing policy mix credibility. Also, large unexpected changes in policy instruments may lead to temporal inconsistency of the instrument mix and thus to a loss of credibility (White et al., 2013). Another example concerns increases of coherence due to a move away from unscheduled ad-hoc changes to advanced planning, prior announcements and stakeholder participation in the light of envisaged changes to the policy mix.

3.5. Synopsis

Having introduced the three building blocks and the dimensions, we now integrate them into an extended policy mix concept (see Fig. 2).

First, the *elements (E)* are at the core of the policy mix concept and refer to the content of the policy mix, including (i) the instrument mix – with interacting policy instruments characterized by their goals, type and design features – and (ii) the policy strategy – with its objectives (including long-term targets) and principal plans (Section 3.1).

Second, in incorporating the *policy processes (P)* of policy making and implementation the concept includes political problem-solving processes among constrained social actors in the search for

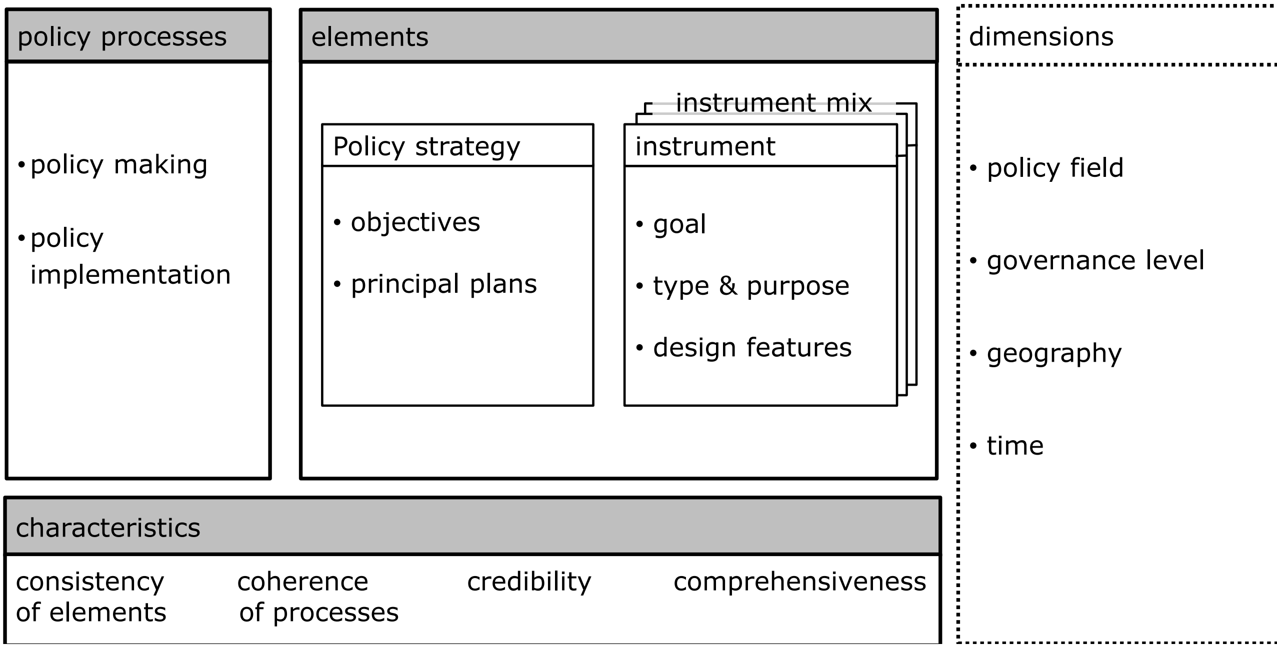

Fig. 2. Building blocks of the extended policy mix concept.

solutions to societal problems (Section 3.2). These policy processes determine the policy mix elements.

Third, overarching *characteristics (C)* describe the policy mix. While consistency refers to the alignment of the elements of the policy mix, the term coherence relates to synergic and systematic policy processes. In addition, credibility captures the extent to which the policy mix is believable and reliable, while comprehensiveness describes how extensive and exhaustive it is. These policy mix characteristics may be important determinants for the performance of the policy mix regarding standard assessment criteria, such as its effectiveness.

Finally, the *dimensions (D)* can serve to specify the elements, processes and characteristics of a policy mix. For example, a study could consider the temporal consistency of the policy mix *(D: time)* or its horizontal coherence *(D: governance level).*

4. Application of the policy mix concept

4.1. Towards an analytical framework for evaluating policy mixes

The main intention of this paper is to derive a policy mix concept that serves as interdisciplinary analytical framework for studying the link between policy and technological change in the context of sustainability transitions. In the following we therefore outline how the three building blocks of the policy mix concept relate to each other and, based on this, derive key implications for how the concept can be used for evaluating policy mix impacts on technological change. Fig. 3 illustrates these linkages with numbered arrows.

For redirecting and accelerating technological change towards sustainability objectives not only the instrument mix with its interacting instruments (1) but also the policy strategy (2) is important to consider. That is, their impact on technological change is likely to be a joint one due to the combined effect of the elements of a policy mix (3). While the policy strategy, such as the EU 2020 climate and energy targets, may provide some long-term orientation it is how such targets are translated into concrete instruments – at potentially different governance levels – which may ultimately help to explain the redirection and acceleration of technological change (Reichardt and Rogge, 2016).

In addition, policy mix analysis should go beyond analyzing how these elements of the policy mix come about and why they change (4) but should also investigate how the resulting strategies and/or instruments impact technological change (4 + 3). Such a combined analysis of policy processes and elements enables highlighting the impact of politics and power not only on targets and instruments but also on innovation. By considering the political realities such an integrated impact analysis may also enable more realistic policy recommendations.

A closer look at the processes of policy making and implementation may even reveal a direct link between such policy processes and technological change (5). We indicate the bi-directionality of this link between technological change and policy making using a double-sided arrow. That is, the innovation impact of policy mixes can have repercussions for the evolution of the policy mix as it may have to be adjusted due to technological developments (Hoppmann et al., 2014). Such patterns of the co-evolution of the policy mix and technological change can only be revealed through dynamic analyses, for example regarding the joint development of technological innovation systems and policy mixes for emerging green technologies (Reichardt et al., 2016).

Finally, policy mix characteristics may be crucial for assessing the effectiveness of policy mixes in redirecting and accelerating technological change. The extent to which the proposed characteristics are relevant in this regard needs to be uncovered (6). Such an analysis requires a detailed understanding of policy mix elements (7) and policy processes (8) as these may determine policy mix characteristics. For example, a stable and ambitious policy strategy backed up by attractive demand-pull instruments may signal a strong political will and hence lead to high credibility. Similarly, controversial public debates and political discussions may lower such credibility. In this context research should also investigate the interplay between different characteristics, such as between the consistency of the policy mix and its credibility.

In conclusion, such extended policy mix analysis may significantly enhance our understanding of the complex link between policy and technological change and their co-evolution (9). For this, studies can attempt to capture the complex interplay in a comprehensive manner (Bödeker and Rogge, 2014), but can also

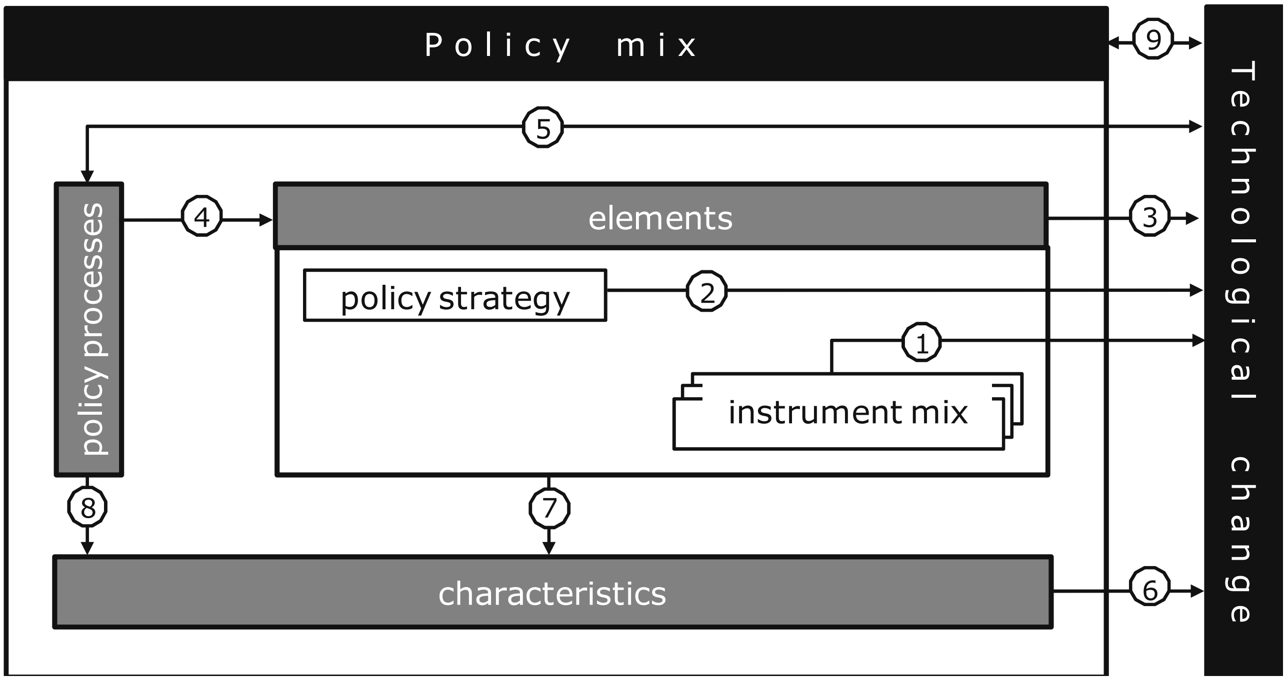

Fig. 3. Framework for analyzing the link between the policy mix and technological change.

reduce the complexity by focusing on just some of the linkages. Meta-studies can then utilize the policy mix concept as integrating analytical framework to synthesize these partial contributions to further advance our understanding of how technological change can be redirected and accelerated towards sustainability objectives. Thereby, this line of policy mix research – which includes but also goes well beyond the analysis of instrument interactions – may generate an improved basis for more nuanced policy recommendations aimed at redirecting and accelerating technological change as key requirement of sustainability transitions.

4.2. Challenges of empirical policy mix analyses

Applying the extended policy mix concept as analytical framework for investigating the link between real-world policy mixes and technological change poses several practical challenges for policy analysts. In the following we discuss two key challenges, namely boundary setting (Section 4.2.1) and operationalization (Section 4.2.2).

4.2.1. Boundary setting

One key challenge of any policy mix study concerns the task of setting its boundaries, thereby determining the complexity of the studied policy mix as well as its observable impact. As usual, such boundary setting is dependent on the concrete research question and research case, and therefore the boundaries of different policy mix studies can vary substantially. In the following we will discuss boundary setting in terms of the policy mix to be studied – its scope – and in terms of the analysis of the impact of the policy mix – the study's unit of analysis.

Regarding the *scope of the policy mix* analysts have to decide whether it is sufficient to focus on the policy mix creating the protected space for an emerging sustainable technology or whether they also need to pay attention to the policy mix of the encompassing regime, including, for example, subsidies for competing technologies.[19] In line with Kivimaa and Kern (2016) we suggest that research on policy mixes for sustainability transitions should include the latter, thereby calling for greater attention to policies (de)stabilizing unsustainable regimes, such as, for example the existence and stringency of political carbon constraints. In addition, researchers need to decide whether they only provide a static snapshot of a policy mix at a given point in time, or offer a dynamic perspective by capturing its development over time (see below).

Of course, the specification of the system boundaries in terms of the scope of the policy mix to be studied also determines the alleged feasibility of achieving policy mix consistency and coherence. For example, a study of the policy mix regarding renewable energies could focus on the niche for one specific technology (e.g. wind), widen its scope to all renewable energy technologies or assume a holistic energy sector perspective. Given conflicting interests and tensions between niches (e.g. onshore wind vs. offshore wind vs. solar PV) and regimes (e.g. renewable energies vs. fossil fuels), the wider the boundaries are set and thus the greater the scope of the policy mix, the greater the challenges for consistency and coherence, as indicated by the arrow in Fig. 4. However, widening the system boundaries may allow for a more holistic perspective of the problem – both in terms of policies and politics – and may thereby enable a better achievement of policy objectives.[20]

Apart from the scope of the policy mix to be studied researchers also need to decide on the appropriate boundaries for the analysis of the impact of the policy mix on technological change, i.e. on the *unit of analysis*. Such a decision should be based on a detailed understanding of the relevant innovation system for the technology or sector in question, including, among others, its past development and the current techno-economic maturity of the technology, the sectoral pattern of innovation and the relevant actors and networks (Hekkert et al., 2007; Malerba, 2004; Pavitt, 1984). For example, a

[19] For example, Quitzow (2015a) analyses the technology-specific policy mix for solar PV in India.

[20] For example, a recent study on aligning policies for a low-carbon economy included, among others, not only climate and innovation policies but also tax and trade policies (OECD/IEA/NEA/ITF, 2015).

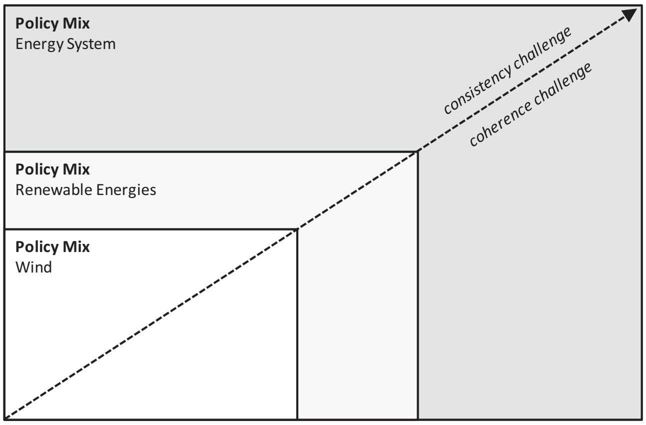

Fig. 4. Link between policy mix boundaries and consistency/coherence.

study on the policy mix for renewable power generation technologies should expect a supplier-dominated pattern of innovation and thus include technology providers and their innovation activities in the analysis (Rogge et al., 2011c). Another example concerns the relevant actors (e.g. authorities, companies, consumers) and their networks (e.g. industry associations and non-governmental organizations) to be included in the analysis of policy processes (Markard et al., 2015). One possible criterion for their inclusion or exclusion may be their degree of influence and power in decision making. Similarly, researchers need to decide on the geographical confines of the impact analysis. For the example of the German energy transition and the policy mix promoting solar PV the increasingly global innovation system would imply to not only investigate innovation effects within Germany, but also the interplay with the resulting technological and structural change in foreign countries, such as in China (Quitzow, 2015b). A final example concerns the timing of the impact, with today's policy mix determining tomorrow's technological change, which in turn may have repercussions for future changes in the policy mix. This co-evolution of impacts and policy mix can only be unpacked by a dynamic analysis covering decades rather than years, while a static analysis of a certain year provides in-depth insights into the current link between the policy mix and technological change.

To conclude, boundary setting is by no means a straightforward exercise, and the initially set boundaries may change as the analysis proceeds. Given its analytical consequences, boundary setting should be seen as an important iterative task, which requires continuous attention.

4.2.2. Operationalizing the policy mix

After an initial delineation of the scope of the policy mix under study a second key challenge concerns the capturing of the relevant real-world policy mix.

The operationalization of the *instrument mix* requires the identification of key instruments and their design features. As starting point research can draw on data bases of policy instruments, such as the IEA policies and measures data bases for renewable energies or energy efficiency (IEA, 2012). Analysts may also refer to the original laws, acts, governmental strategies and other public documents, particularly for extracting information on the design features of selected instruments. One example is the German Renewable Energy Sources Act (EEG) as core instrument of the *Energiewende*, which, among others, established technology-specific feed-in tariffs. These provide one proxy for the level of support, which – due to several regular and irregular amendments – have changed over time. Another example concerns the EU Emission Trading System (EU ETS) whose stringency can be operationalized, for example, by tracking carbon prices published by the relevant stock exchanges.[21] Often, however, the specification of design features will not be as straightforward but require further analysis, as these cannot always be directly derived from publicly available documents and data bases. Further analysis may also be needed for identifying instrument interactions. For example, in order to study interactions between technology push and systemic instruments public R&D funding needs to be separated into these two categories, as done by Cantner et al. (2016) for the case of public R&D funding for wind and solar PV in Germany.

Apart from capturing the relevant instrument mix our extended policy mix concept points to the need to also consider the *policy strategy*, and thus long-term targets and principal plans. Targets can be operationalized based on figures included in strategic policy documents. For example, in terms of the German energy transition these data could be extracted from the German Monitoring reports published on a yearly basis (BMWi, 2015). Such quantitative targets could then, for example, be integrated in a policy mix index, as was done by Hess and Mai (2014) who developed a policy mix index including not only feed-in tariffs and emissions trading but also renewable electricity targets as part of Asian countries' policy strategies. Of course, dynamic analysis will need to pay attention to changes in long-term targets over time, such as an increase or decrease in ambition levels. In contrast to the fairly straightforward measurement of long-term targets, the details typically included in the associated principal plans are likely more difficult to be operationalized and made comparable across countries, and may thus require more sophisticated analysis but also major simplifications. One avenue may be obtaining expert judgments on the quality of a given principal plan, e.g. in terms of its credibility or comprehensiveness (see below).

For the analysis of *policy processes* researchers can draw on the standard methods and variables for operationalizing these processes used within the study of public policy (Howlett et al., 2009; Sabatier and Weible, 2014). Operationalizing them could, among others, draw on a content analysis of media coverage and could be further supplemented by interviews with involved policy makers and other stakeholders. By doing so, analysts could track, for example, the debate about the suggested retrospective adjustment of previously guaranteed feed-in tariffs received by plant operators in Germany initiated by the Federal Minister of the Environment at the beginning of 2013 (Spiegel Online, 2013a). This would allow for analyzing, among others, whether this heavily debated and later withdrawn suggestion had a detrimental effect on innovation, e.g. by casting doubt on the predictability of the EEG and the credibility of the policy strategy (Spiegel Online, 2013b), thereby enabling insights on the direct link between policy processes and technological change.

This leads us to the need for operationalizing policy mix *characteristics*, such as the above mentioned credibility, which may pose one of the greatest analytical challenge as official databases or documents typically do not capture such characteristics. Rather, their operationalization may require original data collection and interpretation. Two main routes for capturing policy mix characteristics may exist: the first one is the derivation of these characteristics from the analysis of policy mix elements; the second one pursues the collection of perceptions of innovators or other stakeholders regarding these characteristics. An example for the former is the observation of renewable energies having come under the auspices of the German environmental department in October 2002 (BMU, 2013). This structural change could be interpreted as increase of the coherence of policy making as it may, for example, have eased

[21] Botta and Kozluk (2014) provide an example of available options and difficulties for operationalizing the stringency of environmental policy across OECD countries.

the integrated consideration of demand-pull, technology-push and some of the systemic concerns relevant for the transition to renewable energies. An example for the latter is the conduction of a survey asking companies about their judgment on the credibility of the *Energiewende* policy mix.[22] Such direct questions appear particularly suitable for eliciting innovators' perceptions on the current level of credibility, whereas changes of these perceptions over time may be more difficult to capture, unless such surveys are regularly repeated.

Overall, this implies that studies applying the extended policy mix concept are likely to require the development, testing and further refinement of novel ways of operationalizing relevant policy mix components. Only then will future policy mix research be able to provide answers to the questions raised by the analytical framework proposed in this paper (see Section 4.1).

5. Conclusion

This paper on policy mixes for sustainability transitions contributes to the literature on the link between policy and technological change in two major ways. First, it advocates an *extended concept* of the policy mix that takes into account the complexity and dynamics of real-world policy mixes and provides a uniform terminology applicable across academic disciplines, thereby enabling interdisciplinary research. Specifically, the concept stresses that a policy mix goes beyond the combination of interacting instruments – the instrument mix – but also includes a policy strategy, policy processes and characteristics. Second, the paper provides an *integrating analytical framework* which may aid empirical research by pointing to previously neglected aspects to be considered in empirical policy mix studies. Such studies are faced with multiple analytical challenges, among them the setting of the boundaries for the considered policy mix and its impact, for which the paper proposes some analytical guidelines. Thereby, the paper aims to pave the way for increasing our insights on the role of policy mixes for sustainability transitions.[23]

We derive three main policy implications. First, the paper underlines the importance of *thinking in terms of policy mixes* for redirecting and accelerating technological change towards sustainability objectives, and it provides an analytical framework helpful in assuming such a broader and systematic perspective. More precisely, it highlights the need for policy makers to consider instrument mixes and instrument interactions along with the policy strategy with its long-term orientation as equally important elements of a policy mix. It also stresses that policy processes may directly influence innovation and emphasizes the relevance of characteristics such as credibility.

Second, policy makers are advised to work on *improving both the consistency of the elements of the policy mix and the coherence of policy processes*. Of course, and particularly in times of fundamental societal transitions, a certain degree of inconsistencies and incoherence may be expected due to the complexities involved in addressing sustainability challenges, conflicting objectives and mutually exclusive interests, for example between niche and regime actors. Yet, given the relevance of consistency and coherence for the performance of policy mixes in terms of assessment criteria, such as its effectiveness in redirecting innovation, policy makers are advised to intentionally and continuously strive for their enhancement.

Third, the paper stresses the necessity to assume a *system perspective in policy making*. For example, an instrument mix should not only address demand pull or technology push instruments but should cover all concerns, including systemic ones. In addition, policy makers should also scan the existing instrument mix for instruments inconsistent with a given policy strategy, including from different policy fields, which therefore may have to be adjusted or phased out. Such an analysis requires systemic capabilities, which could be supported through coherent policy processes and further developed through policy learning.

We see two main limitations of the policy mix concept proposed in this paper. First, since it has been developed for technological change, it may not be directly applicable to non-technological innovations. Second, some of the components of the concept lack well-established indicators, which may complicate their investigation in empirical studies.

In conclusion, this paper calls for unpacking the link between policy mixes and technological change in the context of sustainability transitions, for which we envisage four main areas of future research. First, empirical studies should analyze the interplay within and between the three building blocks of the policy mix and how such interplay affects the effectiveness of policy mixes in redirecting and accelerating innovation towards sustainability objectives. In doing so, studies will need to find new or improved ways of operationalizing the policy mix. Second, the nature of policy processes – including the underlying politics – and their direct and indirect influence on the performance of policy mixes regarding innovation and sustainability transitions should be explored in more depth. Third, empirical research should investigate the determinants and relevance of policy mix characteristics, such as credibility, for innovation. Finally, the integration of the policy mix concept with other research approaches, such as the technological innovation system approach, may further sharpen the analytical clarity and policy advice of such approaches in the context of sustainability challenges.

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[22] A possible question for the case of the German *Energiewende* could, for example, ask respondents for their opinion regarding a number of statements on the policy mix for renewable energies in Germany, such as regarding the existence of a broad consensus across all political parties, the clarity of the political vision, the stability of the political will or the unambiguity of political signals – measured, e.g. with a Likert scale ranging from "very low" to "very high".

[23] Besides the importance of analyzing policy mixes and their impacts, detailed policy instrument evaluations remain indispensable as well.

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