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Going beyond instrument interactions: towards a more comprehensive policy mix conceptualization for environmental technological change

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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. Several studies of policies supporting environmental technological change 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 and the underlying politics of (re)designing them. In this paper we take a first step towards a more comprehensive, interdisciplinary policy mix concept for environmental technological change 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, processes and characteristics, which can be delineated by several dimensions. Throughout the paper, we illustrate the concept using the example of the policy mix for fostering the transition of the German energy system to renewable power generation technologies. We argue that the proposed concept provides an integrating analytical framework for empirical studies analyzing the impact of the policy mix on environmental technological change and sustainability transitions more broadly. Finally, we derive policy implications and suggest avenues for future research.

Keywords: Policy mix, policy strategy, instrument mix, policy making and implementation, consistency, coherence, credibility, comprehensiveness, environmental technological change, eco-innovation, sustainability transitions

JEL: L38, L52, L94, O13, O14, O38, P48, Q01, Q28, Q48, Q54, Q55, Q58

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). [1] One important requirement for such a transition is the redirection and acceleration of technological change towards sustainability objectives. However, this environmental 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, Rohracher 2012). Responding to this challenge, in recent years several 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, Rayner 2007). Furthermore, the terminology applied in these studies is often ambiguous, particularly regarding the desired characteristics of a policy mix.[2]

This limited scope and ambiguous terminology of existing policy mix studies have two major consequences. First, the narrow scope of policy mix concepts may cause researchers to neglect important policy mix elements or processes in their analyses of environmental technological change. This may lead to an insufficient understanding of the role of policy mixes for such technological change, potentially resulting in fragmentary and oversimplified policy recommendations on how to redirect and accelerate technological change towards pressing environmental objectives. 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 eco-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 environmental technological change, thereby heeding Flanagan et al.'s (2011) call for a reconceptualization of the pol-

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1 This paper presents an updated version of earlier work by the authors (Rogge, Reichardt 2013).

2 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.

icy 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 a more comprehensive 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 in the field of environmental technological change. 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 a more comprehensive 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), processes (section 3.2) and characteristics (section 3.3), while in section 4 we introduce relevant dimensions for delineating policy mixes. Finally, in section 5 we first synthesize the proposed policy mix concept (section 5.1), then illustrate this analytical framework (section 5.2) and discuss its application in empirical studies (section 5.3), using the example of the German "Energiewende". Section 6 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.[3] 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

[3] 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).

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).[4] 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, 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, 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, Schröter-Schlaack 2011) and "developed incrementally over many years" (Kern, 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).

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."

Yet, a comprehensive policy mix concept needs to go beyond this narrow scope – interacting instruments aimed at achieving objectives in a dynamic setting – at least in three

4 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, Schröter-Schlaack 2011).

respects. First, aside from capturing its dynamic nature, a comprehensive concept of the policy mix should consider more of its *complexity*, 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, Pearson 2007; 2008). Third, a comprehensive policy mix concept 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; 2011c; Schmidt et al. 2012b).

2.2 Characteristics of policy mixes

The literature differentiates between policy mix characteristics and assessment criteria to describe the desired nature and performance of policy mixes (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, stability or comprehensiveness (Foxon, Pearson 2008; Howlett, Rayner 2007; Kern, 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, 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.[5] In contrast, the latter distinguishes consistency and coherence as different characteristics (Howlett, 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, Stroß 2011; Gauttier 2004), while coherence calls for an achievement of synergy or positive connections (Missiroli 2001; Tietje 1997).[6]

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, Bhardwaj 2007; Fukasaku, 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, Stroß 2011; Forster, 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[7] and integration[8] (Mickwitz et al. 2009a; Van Bommel, 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, Pierre-Antoine 2003), climate policy (Kern, Howlett 2009; Mickwitz et al. 2009b) and eco-innovation policy (Reid, Miedzinski 2008; Ruud, Larsen 2004).

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5 While some base their definition on the absence of contradictions and non-conflicting signals (Forster, Stokke 1999; Van Bommel, 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, Hirata 1995; Picciotto 2005).

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

7 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. 9). Subsets of policy coordination are cooperation and collaboration (Bouckaert et al. 2010).

8 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, Hovden 2003, p. 9).

To better deal with such diversity in meaning and the resulting difficulties in integrating findings across studies, a comprehensive 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, a more comprehensive policy mix concept 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 c*haracteristics* of policy mixes. In capturing this complexity of actual policy mixes it should also pay attention to the dynamic nature of policy mixes. 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 making *processes.* Both elements and processes can be described by their *characteristics*, including the consistency of elements, the coherence of processes, credibility and comprehensiveness. Finally, the policy mix can be delineated by several dimensions, including policy field, governance level, geography, sector, technology, value chain position, innovation phase, actor and time.

3.1 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, Pearson 2008; Quitzow 2015; Weber, 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, 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. 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, Rotmans 2005).[9] [10] 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).[11] In addition to environmental objectives, the policy strategy may also include social and economic issues (Daly, 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).

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. In communicating not only the ends but also the 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 Tech-

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9 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."

10 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).

11 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).

nology (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, 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 long-term climate targets in steering R&D activities of companies in the power sector (Rogge et al. 2011b; 2011c; 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, 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, 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, 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) 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 3x3 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, Kuhlmann 2004, 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 to environmental technological change.

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

PRIMARY TYPE	PRIMARY PURPOSE: Technology push	PRIMARY PURPOSE: Demand pull	PRIMARY PURPOSE: 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

* RD&D = Research, development and demonstration

Source: Own elaboration (based on del Río González 2009a; Edler, Georghiou 2007; Hemmelskamp 1999; Hufnagl 2010; IEA 2011b; Mowery 1995; Rammer 2009; Rennings et al. 2008; Smits, Kuhlmann 2004; Sterner 2000; Wieczorek, Hekkert 2012)

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

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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.

the instrument type (Kemp, 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, Pontoglio 2011)[15], but there is no universally accepted list. In the context of environmental technological change, 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. 2011c; 2011a; 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, 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

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, Mickwitz 2006) and enforcement (Kemp 1997), as well as for the overall policy mix, such as credibility (Kemp, Pontoglio 2011).

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, 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, 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).

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 relevant for environmental technological change, which we conceptualize as being only a part of the overarching policy mix. This calls for a distinction between instrument mix and policy mix. Also, 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, p.4). This influence originates

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, Pyka 2001, p. 764).

from the direct or indirect effect that the operation or outcomes of instruments have on each other (Oikonomou, 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, Grabosky 1998; Sorrell et al. 2003). More recently, innovation studies have also started to highlight interactions (Flanagan et al. 2011; Guerzoni, Raiteri 2015; Nauwelaers et al. 2009). These studies recognize the importance of interactions among instruments as central to dealing with policy mixes. They also acknowledge the need to avoid negative interactions and to strive for positive or complementary interaction outcomes.

3.2 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 environmental technological change by shaping policy mix characteristics. Given their importance these processes constitute another building block of the proposed policy mix concept (Howlett, Rayner 2007; Kay 2006; Majone 1976).

Given that 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, 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, 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 problem and experimentation with solutions" (Howlett et al. 2009, p. 3).

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 environmental technological change and sustainability transitions, policy adaptation and thus policy learning ought to feature prominently within policy making processes (Allen et al. 2011; Bennett, Howlett 1992; Kemp et al. 2007; Loorbach 2007). This includes strengthening participatory processes of envisioning, negotiating, learning and experimenting (Frantzeskaki et al. 2012) and the systemic capabilities of policy makers (Jacobsson, Bergek 2011). Second, policy making is a highly political process characterized by resistance to change, particularly from actors with vested interests (Unruh 2002), rendering it more 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, 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, figure 1), that is, for executing and enforcing them (Sabatier, 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 its full potential. Such difficulties may partly be overcome by an appropriate crafting of policy instruments (May 2003; Mazmanian, 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 promo-

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

tion of initial support programs by advocacy groups and the parliament to the adoption and first amendments of the German Renewable Energy Act (EEG).

Table 3: Selected 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. 1,000 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, Lauber 2006; Wüstenhagen, Bilharz 2006)

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 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. As such, consistency can be analyzed at three levels: (1) consistency of the policy strategy, (2) consistency of the instrument mix, and (3) consistency of the instrument mix with the policy strategy.

We highlight three 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, 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. Third, *three main levels of policy mix consistency* can be distinguished.

The first level of policy mix consistency addresses the *policy strategy*, since conflicting objectives are a major source of tension between the instruments in a policy mix (Flanagan et al. 2011). Consistency of the policy strategy comprises three sub-levels. First, consistency of objectives (Mickwitz et al. 2009a; OECD 2003a) suggests that they can be achieved simultaneously without any significant trade-offs. Examples are whether climate targets are consistent with energy security or competitiveness targets, or whether interim targets are consistent with long-term targets. Second, principal plans, i.e. framework conventions, guidelines, strategic action plans and roadmaps, ought to be free of contradictions or mutually supportive. Third, principal plans should be 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 concerns consistency of the *instrument mix*, which 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, Rayner 2013). "They are inconsistent when they work against each other and are counterproductive" (Kern, 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, 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, Stroß 2011; 2002; OECD 2001; 2003a; 2003b). Building on Jones (2002) we suggest defining policy coherence as referring to synergic and systematic policy making and implementation processes contributing – either directly or indirectly – towards the achievement of policy objectives. Such more synergic 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 two 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, 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 challeng-

18 While some studies view coherence as equivalent to integration and coordination (Duraiappah, Bhardwaj 2007; Geerlings, 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).

es 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 a policy mix for environmental technological change. 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, 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, Goldsmith 2001), both at an overall level and at the level of 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, 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, 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, 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, Murray 2004). As with the other characteristics, the comprehensiveness of a policy mix may impact its performance regarding standard assessment criteria.

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, sector, technology, value chain position, innovation phase, actor and time. That is, the dimensions can serve as a guideline for setting the system boundaries of a policy mix study and thereby determine its scope, as illustrated by Table 4 for the example of renewable energies in Germany. Of course, such boundary setting should be guided by the research question and is a challenging but necessary empirical exercise in attempting to reduce the complexity of actual policy mixes. For example, when analyzing green niche innovations, such as onshore wind, studies can focus on the policy mix creating the protected space for the emerging green technology, but at the same time may need to pay attention to the policy mix of the regime, such as the existence of subsidies for fossil fuels or the lack of stringent carbon control instruments.

Table 4: Selected choices for setting the boundaries of the policy mix for renewable energies in Germany

Dimension	**Application to policy mix for renewable energies in Germany** *(exemplary)*
Policy field	Climate, energy, innovation, environmental, industrial policy
Geography	Germany,regions, cities
Governance level	International, EU, national,federal, local; departments, implementing agencies
Sector	Power
Technology	Emerging renewable power generation technologies (e.g. wind, PV), competing against established fossil and nuclear power generation technologies
Innovation phase	Invention, innovation, diffusion
Actor	Policy makers (e.g. EU commission, German government), target actors (e.g. private investors, grid operators, households), consumers, interest groups
Value chain	Manufacturing, project development, installation, power generation, operation & maintenance
Time	Static (point-in-time, e.g. 2014) vs dynamic analysis (development over time, e.g. 1990-today)

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, 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 implementing 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 in which the policy mix plays out. This implies a focus on the place where the impact of a policy mix is intended and underlines the increasing attention to the geographical perspective in transition studies (Coenen et al. 2012; Raven et al. 2012; Späth, Rohracher 2012). An example of this is a policy strategy and instruments targeted towards a certain geographical region (Navarro et al. 2014), such as a funding initiative for specific cities or green industrial clusters.

The fourth and fifth dimensions of the policy mix are the *sector* and the *technology.* They allow, for example, delineating policy mixes within sectoral or technological innovation systems (Hekkert et al. 2007; Malerba 2004), such as the policy mix relevant for energy storage technologies. In addition, a policy instrument can target specific sectors or technologies. An example of the former is the EU ETS, which initially covered larger installations within the energy and industry sectors only, while an example of the latter is the European Energy Program for Recovery (EEPR), which only addresses selected low-carbon power generation technologies.

Sixth, closely related to the technology dimension is the dimension of *innovation phase*, as technologies run through various – not necessarily linear – innovation phases, a simple example being the distinction between invention, innovation and diffusion (Schumpeter 1942). More sophisticated typologies differentiate between invention, euphoria, disillusionment, reorientation and rise (Jochem 2009), or between R&D, prototypes, demonstration, pre-commercial and early commercial niche technologies to mature technologies, with early adoptions potentially followed by mass application of regime technologies (Ekins 2010; Foxon et al. 2005). These differences in the innovation phase may be reflected in the functioning of the corresponding innovation systems, calling for an adjustment of policy mixes based on changing needs (Foxon et al. 2005).

Seventh, an essential dimension for studying the evolution and effects of policy mixes is the *actor*, that is, more or less powerful decision-making entities (e.g. authorities, companies, consumers) and their networks (e.g. industry associations and non-governmental organizations). One straightforward differentiation is that between public actors involved in policy making and implementation, on the one hand, and target actors, i.e. those affected by the resulting policy mix, on the other (Mickwitz 2003).[19] Of course, target actors may not be a homogeneous group, justifying a tailoring of the policy mix to better address such heterogeneity (Schmidt et al. 2012a). It may be also useful to distinguish between the strategies of incumbents and new entrants, or regime and niche actors (Farla et al. 2012).

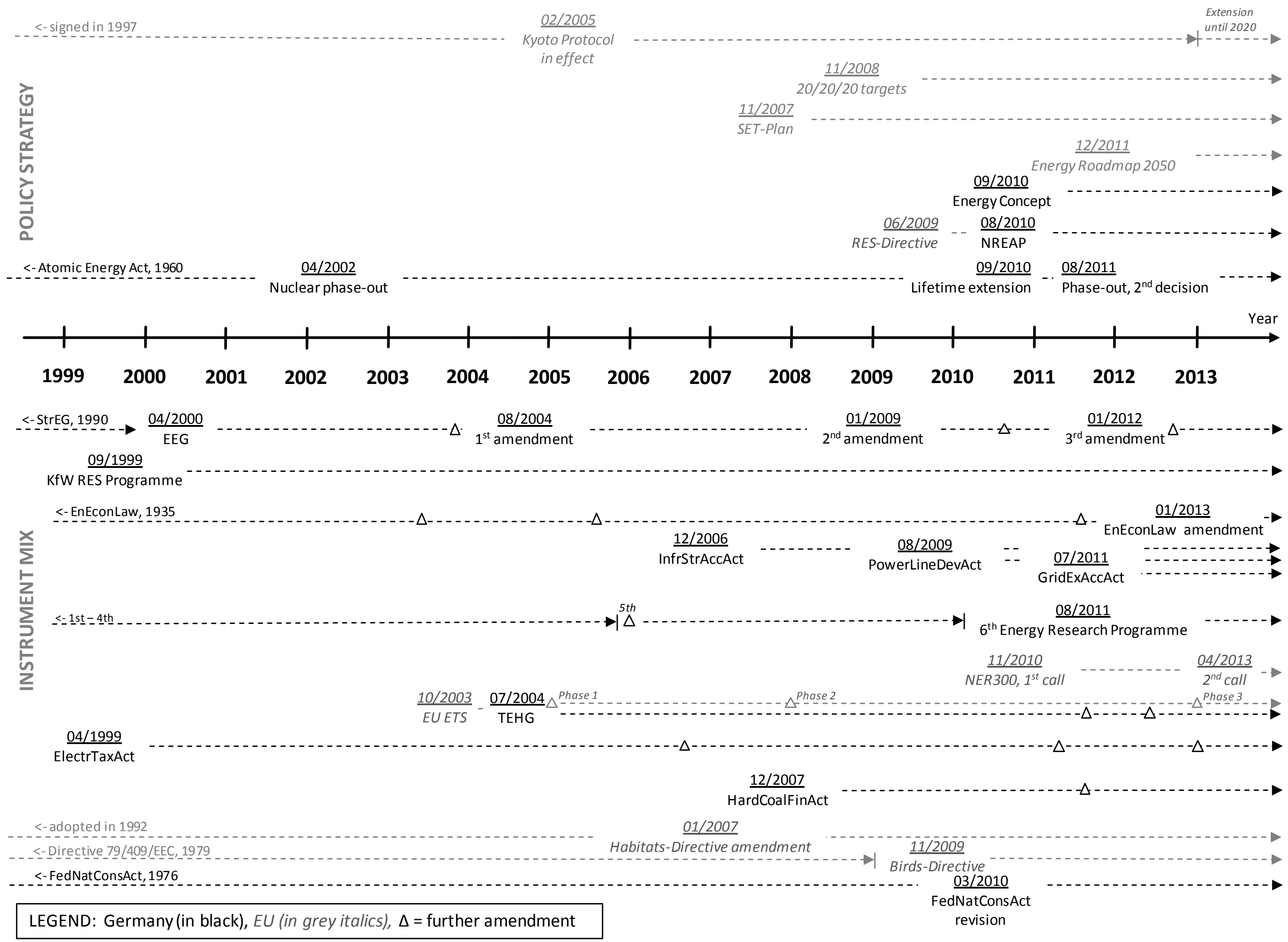
Eighth, the *value chain position* indicates the location of a firm within the market (Cox, Lamming 1997) and captures "the physically and technologically distinct activities a firm performs" to create a product (Porter 1985, p. 33). For example, the location of a firm within such a value chain was shown to be important for explaining innovation effects of the policy mix in the power sector, e.g. by identifying trickle down effects of the EU ETS (Rogge et al. 2011c). Clearly, a link exists between this dimension and the technology dimension, as value chains typically differ across technologies.

Finally, *time* is another crucial dimension in the policy mix concept, capturing its dynamic nature. That is, studies can provide a static snapshot of a policy mix at a given point in time, or a dynamic perspective capturing its development 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 2000-2013. As can be seen in Figure 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

19 Of course, the latter may also be involved in policy making, for example through interest groups.

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.

Figure 1: Development of the elements of the policy mix for renewable energies in Germany over time

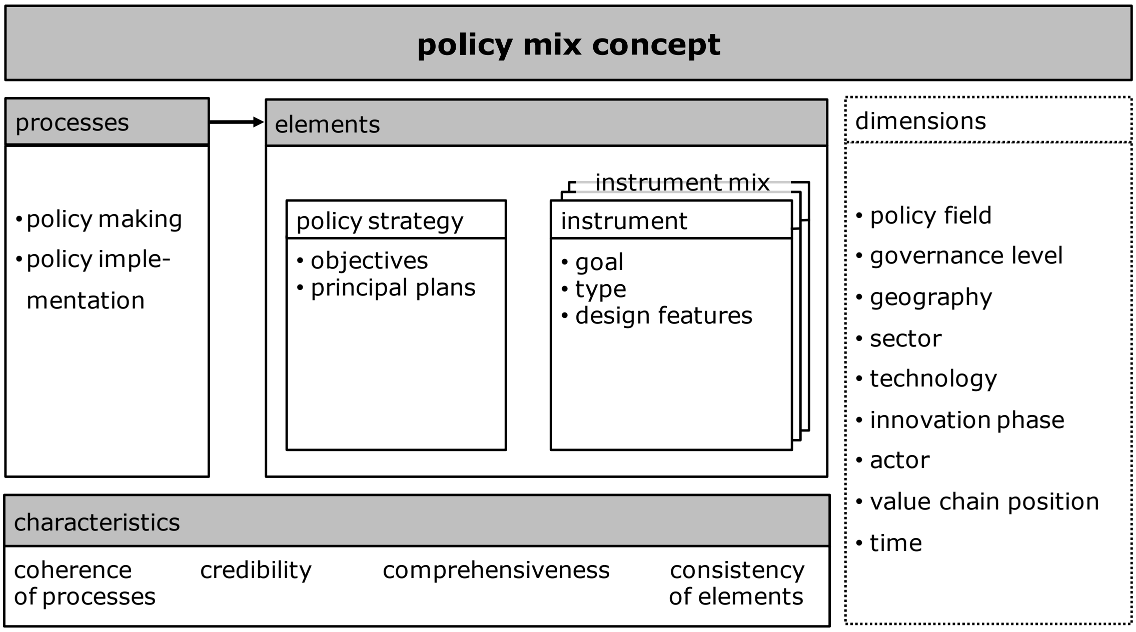


5 Discussion

5.1 Synopsis

Having introduced the three building blocks and the dimensions, we now integrate them into a more comprehensive policy mix concept (see Figure 2).

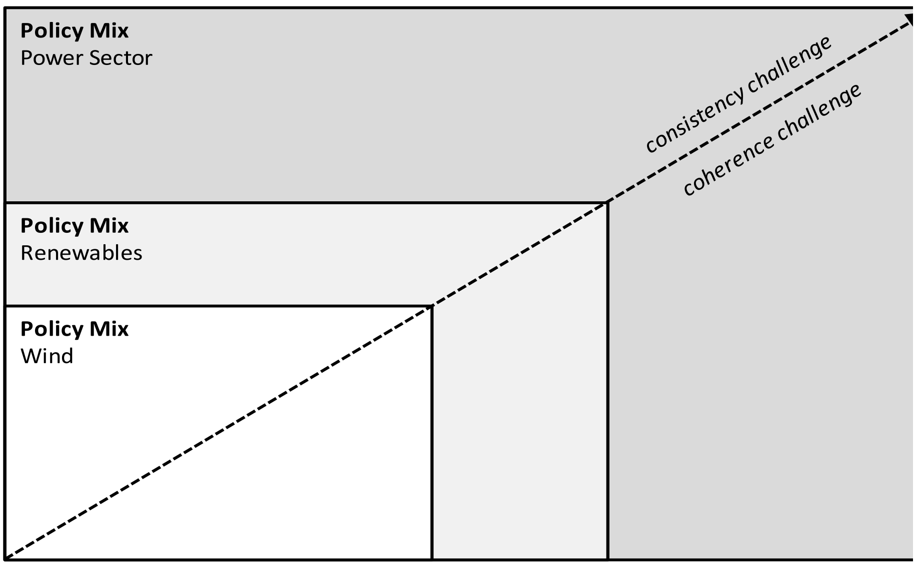
Figure 2: The policy mix concept



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 *processes (P)* of policy making and implementation the concept includes political problem-solving processes among constrained social actors in the search for solutions to societal problems (section 3.2). These policy processes determine the policy mix elements (as indicated by the arrow in Figure 2). 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.

The *dimensions (D)* can serve to specify elements, processes and characteristics of a policy mix and thereby assist in setting the boundaries of a policy mix. For example, a study could analyze the temporal consistency of the policy mix *(D: time)*, its horizontal coherence *(D: governance level)*, the policy mix promoting a specific technology *(D: technology)*[20], or the most influential actors in the policy making process for a new policy instrument *(D: actor)*.

Figure 3: Link between policy mix boundaries and consistency/coherence, exemplified using the dimensions technology and sector



The specification of the dimensions determines not only the scope of the policy mix but also 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 technologies or assume a holistic energy sector perspective. Given conflicting interests and tensions between niches and regimes, the wider the boundaries are set and thus the greater the scope of the policy mix the greater the challenges for consistency and coherance, as indicated by the arrow in Figure 3. However, widening the system

20 Quitzow (2015) analyzes such a technology-specific policy mix for solar PV in India.

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.

5.2 Illustration of the concept

In this section we illustrate how the building blocks of elements *(E)*, processes *(P)* and characteristics *(C)* – specified by the dimensions *(D)* – assist in a more systematic understanding of real-world policy mixes. Taking the example of the German "Energiewende" we discuss some key policy mix challenges and relate these to the relevant policy mix terminology (indicated in italics).

In 2014, German policy makers and other stakeholders were preoccupied with reforming the EEG with its feed-in tariffs, the core instrument of the German policy mix for renewables *(E: instrument),* while neglecting other policy fields and interacting policy instruments, such as energy efficiency *(D: policy field)* or the EU ETS with its low carbon prices *(E: instrument – design feature)* (FAZ 2013; Germanwatch 2013)[21]. A key reason for these EEG reform efforts lies in the effectiveness of the EEG in (over)achieving its goals for the diffusion of renewables in Germany *(E: instrument – goal)* and resulting high costs (Ragwitz et al. 2012).[22] So far, this has been addressed by changing the EEG, e.g. adjusting goals upwards and tariffs downwards, which serves as example of adaptive policy making *(E: instrument – goal, design features, P: policy making)*.

Yet, due to the magnitude and sustained increase of the EEG costs, policy makers' attention has shifted to further modifications aiming at market integration and system optimization *(E: instrument – type, design feature, P: policy making, D: time)* (Agora Energiewende 2013; Spiegel Online 2013b). For example, future demand-pull instruments may include spatial specifications for priority areas for capacity additions that recognize the trade-off between physical potential, such as wind or sun, and the distance to demand centers and thus grid requirements *(D: geography)* (Agora Energiewende 2013).

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21 EUA prices have dropped from ca. 22 € in the second half of 2008, to ca. 12 € in December 2010 and 6 € in December 2012 *(D: time)* and – with the interim failure to adopt "backloading" by the EU parliament on April 16, 2013 *(P: policy making)* – went further down to ca. 3-4 € / EUA (EEX 2013).

22 The so-called 'EEG-Umlage' increased from initially 0.19 ct/kWh in 2000 to 3.59 ct/kWh in 2012, thereby representing a share of electricity costs of nearly 14 % for households (BMU 2013b).

A related example is the debate about a retrospective adjustment of previously guaranteed feed-in tariffs received by plant operators, initiated by federal minister of the environment Peter Altmaier at the beginning of 2013 *(P: policy making, E: instruments – design features, D: actor)* (Spiegel Online 2013a). His suggestion, which was later withdrawn *(D: time)*, shook the core beliefs of investors by questioning the right of continuance (the so-called 'Bestandsschutz'). ‚Merely raising the question may have had a detrimental effect on innovation by casting doubt on the predictability of the EEG and the credibility of the policy strategy *(C: credibility)* (Spiegel Online 2013c).

Yet, in general the German government aims at improving policy coherence *(C: coherence)*. For example, renewable energies have been under the auspices of the German environmental department since October 2002 (BMU 2013a), a structural change which may have eased the integrated consideration of demand-pull and technology-push and some of the systemic concerns of a transition to renewable energies *(P: policy making, E: instrument – type, instrument mix, D: policy field, time).*[23] More recently, the problematic developments regarding ever-increasing EEG costs and other concerns have been addressed by enhancing procedural coordination and thus policy coherence by means of formalized public debates (e.g. "EEG-Dialog") and working groups *(P: policy making, coherence, D: time).*[24] Yet, considering the highly ambitious policy strategy associated with the "Energiewende", these and other current political discussions and actions appear not systemic enough and too fragmented between different policy fields and governance levels. [25]

5.3 Application of the policy mix concept

We foresee several avenues for applying our interdisciplinary policy mix concept in empirical studies investigating the role of actual policy mixes for environmental technological change. One main avenue comprises analyses on the role of specific components of the proposed policy mix concept, which have so far largely been neglected – including elements, processes and characteristics.

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23 This structural coordination may have contributed to the successful development of the German technological innovation systems for renewable energies (Walz, Ragwitz 2011).

24 A prime example for the latter is the renewable energy platform which was established on April 25, 2012, uniting federal and state-level policy makers from various departments as well as non-governmental stakeholders *(D: actor, value chain, governance level)* to jointly develop solutions to identified transition challenges (BMU 2012).

25 This is exemplified by the attention given to reforming the EEG while neglecting the reform of the EU ETS despite both instruments' interactions (del Río González 2006) *(C: second level consistency)*.

That is, studies can further unpack the link between the *elements* of a policy mix and environmental technological change. One option regarding the instrument mix is to build upon the proposed type-purpose instrument typology and instrument design features to increase our understanding of the role and interactions of demand pull, technology push and systemic instruments. For example, for inventor networks in wind power and PV in Germany, Cantner et al. (2014) find that these instruments complement each other and form a consistent instrument mix to increase inventive activity and inventor interaction. Another option is the specific consideration of the policy strategy together with the associated instrument mix. For example, Rogge et al. (2011c) find that long-term climate and renewable energy policy targets for 2020 have been key for corporate vision changes towards low-carbon technologies, with demand pull instruments further contributing to such redirection of companies' visions.

In addition, studies should investigate in more detail the link between policy *processes* and environmental technological change. An example in this regard is the study by Hoppmann et al. (2014) which analyzes the dynamic nature of the policy making process for the German feed-in tariffs for solar PV. They find that many of the changes in the design of these feed-in tariffs became necessary due to policy-induced technological developments, highlighting the complex interplay between policy mix and technological change. In addition, based on company case studies on offshore wind in Germany Reichardt and Rogge (2014) find evidence that high-level policy debates about the potential reduction of feed-in tariffs were detrimental to innovation, even though the design features of this instrument were eventually left unchanged. They also find that a cooperative policy style and adaptive policy making can reinforce technological change.

Finally, more analysis is also needed to increase our limited understanding on the link between policy mix *characteristics* and environmental technological change. Clearly, policy mix consistency can count as prime area of such investigations. An example is the overachievement of Germany's expansion targets set for renewable power generation technologies. For this, Wiebe and Lutz (2014) show that the resulting adaptive instrument design of the EEG enables a predictable phase-out of the feed-in tariffs for solar PV while ensuring third-level consistency with the 35% expansion target set for 2020. This indicates the usefulness of implementing targets, instruments and their consistency in macro-economic modeling. Another area of investigation is the role of policy mix credibility for environmental technological change, but also the interplay of policy mix characteristics. For example, research on offshore wind in Germany suggests that high policy mix credibility can alleviate negative effects of an inconsistent and incomprehensive instrument mix (Reichardt, Rogge 2014).

The second main avenue we foresee for policy mix research is to analyze the link between the *overarching policy mix* and environmental technological change, thereby also considering the interplay of the different building blocks of the policy mix. An example of a first step in this regard is the work by Bödeker and Rogge (2014) for solar PV and wind in Germany. Based on a novel policy mix indicator capturing changes in the overarching policy mix from the early 1990s until 2012, their analysis reveals that patent applications for wind closely follow changes in the perception of the overarching policy mix. However, the positive sign of this link changes for PV, where the perceived deterioration of the policy mix is associated with an increase in inventive activities, confirming the need for technology-specific policy mixes and evaluations.

In conclusion, studies adopting a more comprehensive policy mix concept promise to significantly enhance our understanding of the link between policy and environmental technological change, by going well beyond the analysis of instrument interactions. Such an enhanced understanding can be further advanced by synthesizing the findings of different studies, applying the policy mix concept as integrating analytical framework. Thereby, this line of research may generate an improved basis for more nuanced policy recommendations aimed at redirecting and accelerating environmental technological change as key requirement of sustainability transitions.

6 Conclusion

This paper contributes to the literature on the link between policy and environmental technological change in two major ways. First, it advocates a more *comprehensive concept* of the policy mix that takes into account the complexity and dynamics of real 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 in at least two ways. On the one hand, the three building blocks of elements, processes and characteristics may point to previously neglected aspects of actual policy mixes to be considered in empirical studies. On the other hand, the dimensions provide a systematic yet flexible way of setting the boundaries of a policy mix under study, and thus assist in concretizing its scope and depth, bearing in mind the tradeoffs between the two. Thereby, the proposed policy mix concept could pave the way for increasing our insights on the role of policy mixes for environmental technological change.

We derive three main policy implications. First, the paper underlines the importance of *thinking in terms of policy mixes* for environmental technological change, 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 need to work on *improving both the consistency of the elements of the policy mix and the coherence of policy processes*. Of course, in times of fundamental societal transitions a certain degree of inconsistencies and incoherence may be expected due to conflicting 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 effectiveness and efficiency, 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 but 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, 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: since it has been developed for environmental technological change, it may not be directly applicable to non-technological innovations. In addition, some of the components of the concept lack well-established indicators, which may complicate their investigation in empirical studies.

In conclusion, we envisage three main areas for future research. First, future 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 doing so, studies will need to find new or improved ways in 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 should be explored in more depth. 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.

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