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An evolving risk perspective for policy instrument choice in sustainability transitions

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Research Highlights

- We apply financial risk, transaction cost, innovation and social welfare considerations to sustainability transitions
- We analyze optimal choice between price and quantity instruments for support of emerging technologies
- The dynamic nature of risk implies changes in optimal instrument choice during sustainability transition process
- Price instruments seem optimal at first, then quantity control could take over with flattening marginal costs
- Solar PV in Germany as case, where auctions (a form of quantity control) succeeded feed-in tariffs (price instrument)

Abstract

We develop the concept of evolving risk to demonstrate that the optimal policy choice between price and quantity instruments may change over time. Drawing from system innovation, evolutionary concepts and modern financial and transaction cost economics, we analyze dynamic cost and welfare impacts of instrument choice under uncertainty. In early market deployment of niche technologies, economic and system-innovation arguments suggest price instruments can stabilize revenues and decrease market risks for investors. This accelerates deployment without necessarily compromising economic efficiency. Protective policies that work well for niche technologies should, however, be used cautiously during market upscaling and diffusion, due to the changing nature of risks. We use theoretic arguments and a case to demonstrate that a gradual shift towards quantity control may become preferable for welfare maximization under certain circumstances. Solar photovoltaics in Germany serves as illustrative case, where auctions (a form of quantity control) succeeded feed-in tariffs (a price instrument).

Keywords: dynamic risk; sustainability transformation; instrument choice; innovation systems; feed-in tariff; time-consistent policy

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1 Introduction

A grand challenge of our age is to transform our global society to ensure its sustainability. Sustainability transitions are transformative changes of entire socio-technical systems that depend greatly on public policy intervention, not least in the early stages (Geels, 2002). Until recently, economics, particularly neo-classical economics, has been the predominant discipline informing policymaking related to socio-technical systems (Bolton and Foxon, 2015). Whether this reflects the discipline's tradition of analytical rigor, or represents the imposition of an abstract and unrealistic normative worldview remains fiercely controversial (MacKenzie et al., 2007). In light of the technological complexity and socially contested nature of sustainability transitions, a wide range of inter-, multi- and transdisciplinary approaches have emerged to inform policy decisions. Research into sustainability transitions and transformations proposes that public policy should reflect the complex and multi-faceted nature of sustainability transitions, requiring a multiplicity of policy instruments to pursue a wide range of goals (Rogge et al., 2017). Some dismiss economics altogether as a viable basis for transformational policy (see Bolton and Foxon, 2015). At the same time, while the economics discipline itself has moved on from many of its classical and neo-classical assumptions (see e.g. Hoff and Stiglitz, 2001; Dasgupta, 2002; Joskow, 2004), some economists dismiss policies advocated by sustainability transition scholars as inefficient and costly. The creation of protected spaces for technology innovation and shielding from market pressures is a common policy prescription emerging from the transition perspective that is cast in a particularly dim light by some economists (see e.g. Frondel et al., 2010). These apparently contradictory

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policy conclusions appear to betray a troubling disconnect between what is perceived as mainstream economic thought, and a 'systems innovation' or 'evolutionary' approach, here broadly labelled as the 'transitions perspective'.

In a spirit of optimism, we start from the observation that, when sustainability transitions are conceived as encompassing multiple domains and parallel journeys, then the economics and the transitions perspectives are not only reconcilable, but complementary (see Grubb et al., 2017; Safarzyńska et al., 2012). By exploring the implications of divergent conceptualizations of risk for policy instrument choice, we seek to bridge the divide between the complexity of societal transition and the narrow specificity of individual policy decisions.

In a multi-disciplinary enquiry, we draw on economics, sustainability transition and transformation studies, and political science to investigate the choice between different options for 'demand pull' instruments for moving technologies towards commercialization and market diffusion. We propose that the economic perspective is most usefully integrated with the sustainability transition perspective in a market setting. Market incentive instruments are also the most commonly used in environmental policymaking in Europe (Bailey, 2003; Hahn, 1989; Neuteleers and Engelen, 2015), with abundant conceptual and empirical material available. Market instruments can broadly be categorized into price and quantity types, i.e. those where policymakers determine a price (e.g. a tax or support level) and those where policymakers determine a quantity (e.g. an emission cap, quota or support budget). In a competitive market with perfect knowledge the two instrument types should theoretically yield the same volume and price outcome, regardless of if policymakers choose to control price or quantity (Cropper and Oates, 1992; Weitzman, 1974). This symmetry dissolves under conditions of uncertainty when price and quantity instruments may lead to significantly different outcomes.

Uncertainty is one of the fundamental issues facing decisions about the future – including those for sustainability policy. The concept of uncertainty, and especially that of its companion risk, reveals key differences in the economic and transition perspectives. Drastically simplifying, economics and finance have traditionally understood risk as a phenomenon that can be quantified and subsequently priced by markets (e.g. Knight, 1921). It is clear that economics is not defined by such a restricted view of risk. We acknowledge the diversity of approaches encompassed by the field, including prospect theory, studying subjective risk perception and its influence over decision making behavior (Kahneman and Tversky, 1979), and analyses related to systemic risk (Acemoglu et al., 2015). Still, in many studies related to understanding and predicting investment patterns, such as in those based on modern portfolio theory, risk is considered primarily as a matter of measurable variability.

The starting point for this paper is that this somewhat narrow, investor-focused view is seemingly in contrast to a complex, multidimensional, systemic consideration of risk adopted in the study of sustainability transitions (Stirling, 2008). In line with work by Grubb et al. (2017) and Williamson (2000), we posit that prudent policy design takes places in different domains and on different levels and inevitably calls for the simultaneous adoption of a narrow, financial view of risk that is required for effective economic instrument selection and design (instrument-level conception) without losing sight of the complex and multifaceted nature of risk (system-level conception) in sustainability transitions. This paper explores how policymakers charged with the challenge of instrument choice can effectively incorporate both seemingly conflicting conceptions in their practice, and suggests that this calls for temporal differentiation.

It is well established in sustainability transition and transformation research that policies need to be 'evolutionary' or 'adaptive' (Nill and Kemp, 2009), and that 'time-strategies' based on an understanding of the relationship between time, innovation, and instrument choice can contribute to a more responsive policy framework (Erdmann et al., 2007; Nill, 2004). The ability of instruments to simultaneously initiate and adapt to systemic change is therefore a vital consideration (Weber and Rohracher, 2012). Uncertainty and its risk implications are inherent (explicitly or implicitly) in many of the theories put forward in the sustainability transitions literature. Some of these theoretical perspectives treat risk straightforwardly as a component of a rational choice approach to strategic decision-making about technology investments by firms (Rugman and Verbeke, 1998), others invoke a broader, more nuanced position. In particular, evolutionary perspectives seek to understand the interaction and co-evolution of society and technology, as well as policies and actors, over time, emphasizing issues such as lock-in to particular pathways as well as attempting to reflect a broader range of social and political risks (Butler et al., 2015; Leach et al., 2010; Markard et al., 2016; Stirling, 2008; Lieu et al., 2018). We observe, however, that the dynamic nature of risk and its practical implications have so far received less explicit attention, and this study aims to go some way in counteracting that omission.

Likewise, economic studies of instrument choice often focus on finding the optimal solution for a selection problem without attending to the changing nature of risk in different environments. Where risk is incorporated in the analysis, it is often considered static. Static 'cost-benefit' considerations based on indicators such as short-term effectiveness and efficiency are, in practice, still often employed to evaluate instrument choices (Gross et al., 2010). This is in spite of significant advancements in economic theory incorporating greater complexity in the analysis of regulation and governance (see e.g. work of Joskow and Tirole, 2007; Laffont and Tirole, 1993; Rothschild and Stiglitz, 1978; Williamson, 1975). There is also a large body of literature addressing the dynamics of environmental policy, including technological development and learning (see Jaffe et al., 2003). Two important studies for our context are Pizer (1999), who investigates the dynamics of a stochastic growth model under uncertainty with risk neutral agents, and Baldursson and von der Fehr (2004), who consider a context of certainty yet allow for risk-averse actors. Furthermore, building on Kydland and Presscott (1977), much of the economic literature on 'dynamic optimization' addresses the potential issue of time-inconsistent environmental policies (see e.g. Biglaiser et al., 1995; Tarui and Polasky, 2005). The key distinction here is between 'discretionary policies' that allow for flexible changes and adjustments, and 'policy rules' or strategies that are fixed over time. While the former, due to its demand for flexibility, allows for possible policy inconsistencies, rules can serve as a commitment device. Which of the two forms of governing is preferable, depends on the degree of uncertainty; under relatively low uncertainty, rules are usually preferable since the need to adjust policies is likely to be less important than credible investment incentives. Under high uncertainty, the opposite holds true and discretionary (flexible) policies may be preferred (Tarui and Polasky, 2005). Surprisingly, all dynamic optimization studies we are aware of analyze instrument choice for a single instrument only. None allow for changes between price and quantity instruments over time.

The example of instrument choice for technologies that use renewable energy sources (RES), important factors in nearly all sustainability transitions, provides ample empirical data to explore the interaction of risk and instrument choice (see e.g. Gross et al., 2010; Klessmann et al., 2008). Therefore, to demonstrate our theoretical argument, we use solar photovoltaics (PV) in Germany as an illustrative case. Support policy for deployment of PV in Germany has undergone a radical transformation starting with the introduction of fixed feed-in tariffs (as a price instument) in 2000[4], followed by gradual changes to instrument configuration (including the introduction of build-out corridors and caps) towards the eventual arrival at an auctioning system in 2015-16 (Leiren and Reimer, 2018) (as a quantity control). Figure 1 shows how PV in Germany evolved from a predevelopment phase during the 1990s to a take-off phase in the 2000s and arguably into a market diffusion phase (see also Lauber and Jacobsson, 2016), reaching 7% market share in 2017 (BMU, 2018). The apparent 'completeness' of Germany's journey from the price-setting principles of feed-in tariffs to the quantity-setting through auctions provides an especially clear and well-documented illustration against which to develop our theoretical argument.

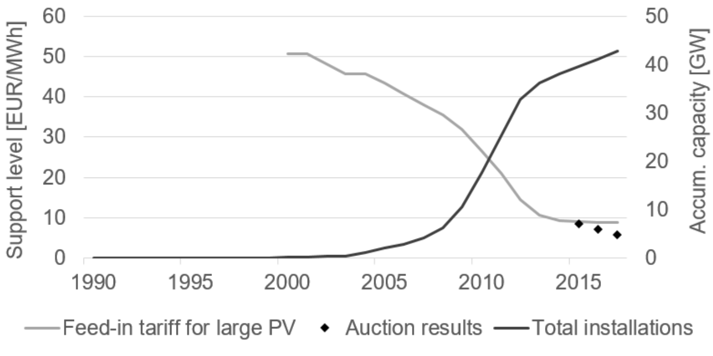

Figure 1: Development of PV installations in Germany, and corresponding average support levels for new large PV installations (>1 MW) (BMU, 2018; BNA, 2018a; BNA, 2018)

This paper proceeds in six sections. Following this introduction, section 2 outlines the key conceptual principles of risk relating to choice of policy instruments in a changing transition environment. Section 3 operationalizes these principles and develops an instrument selection strategy that emphasizes risk mitigation as key success factor for early transition phases. Section 4 explores the change in optimal instrument choice in the face of evolving risk. Section 5 discusses the implications

[4] Prior to that, RES could receive a certain share of the historical average retail price as variable 'feed-in' payment

of the findings, emphasizing the importance of adaptive policy design and consistency across time horizons. Section 6 concludes.

2 Key concepts

2.1 Conceptualizing uncertainty and risk

While the terms are used widely, there are no commonly agreed definitions of uncertainty or risk. Indeed, the fundamental ontologies of different approaches in the sustainability transitions literature lead to wide variations in conceptions of uncertainty and risk (Geels, 2010, see also Stirling, 2008, Stirling, 1998, Nill and Kemp, 2009). Uncertainty in its broadest understanding can be seen as a lack of perfect information about the future, stemming from flawed, incomplete or absent knowledge (Stirling, 1998: 102). In economic settings, especially financial theory, the terms are often used in the narrow context of variability of returns. Uncertainty here manifests as 'risk' with exposure to loss or gain related to the possible outcomes of an investment made. For example, the future value of company shares is uncertain. The variability of the share value becomes a risk for an investor once she has purchased those shares. As company shares may equally yield high or low returns, the risk includes both the possibility of undesirable (negative) outcomes and the option to benefit from positive outcomes. In the sustainability transitions literature, risk is similarly distinguished from uncertainty, although risk here typically relates to the possibility of negative outcomes only, and also encompasses the broader implications of courses of action or inaction (Renn and Schweizer, 2009), as also discussed in the Introduction to this Special Issue. From this perspective, a strategy for risk reduction is one that aims at avoiding possible negative outcomes.

Risk can stem from political, social, environmental and economic factors, or may refer to negative impacts on individuals, society, the economy or the environment (see also Hanger et al., 2016). Different sources of risk present different challenges for society. The exposure to market risks, such as exposure to uncertain costs and revenue streams, receive particular attention in the design of policy instruments for the promotion of new technologies. RES can be exposed to different potential markets: (1) power markets (future and spot), (2) balancing markets, and (3) support markets (Klessmann et al., 2008). All markets entail price and volume risk (Mitchell et al., 2006). Moreover, investors must access capital markets to secure finance and are exposed to related risks. Indeed, instrument design is, in large part, a question of who (society-at-large, private firms, etc.) should bear these market risks (see Klessmann et al., 2008).

System-level risks are equally significant, yet harder to measure and allocate. Such risk can be related to technology itself, regulatory and legal issues, and the broader social environment (Michelez et al., 2011). While we do not attempt to cover them all, we do address social risk as potential negative impacts of policy choices on social welfare. We argue that this risk can be proactively targeted and mitigated to increase the success likelihood as well as reduce the cost of a transition process, as discussed below.

A risk-centered approach to policymaking requires an understanding of the nature of risk in a dynamic transition context. We posit that, as new sustainable technologies progress from early commercialization to larger market diffusion, the types of risk associated with them change. This influences the allocation of market risks, which in turn has implications for instrument choice. We therefore view instrument choice through the lens of "evolving risk".

2.2 Risks and policies in a changing transition environment

Sustainability transitions involve many processes interacting across multiple levels. For analytical purposes, three levels may be considered: *niches* in which radical innovation can occur, the *regime* of established rules and practices and the broad socio-technical *landscape* (Geels, 2011, 2004). They may also progress through several distinct phases of technology development, e.g. from predevelopment, take-off, acceleration to stabilization (Rotmans et al., 2001). We refer to early phases of a sustainability transition when immature technologies develop in niches and experience early market commercialization, and to late transition phases, when technologies have been through a take-off phase and reach larger market diffusion, thereby challenging the existing regime.

There is great uncertainty about how the costs of emerging technologies will evolve during their development process. Although the direct cost will likely decrease over time (Jamasb and Köhler, 2007), due to e.g. learning spill-over and scale effects, different technologies will have different cost reduction profiles, both in slope and shape. Systemic cost may actually increase with diffusion, as technologies affect other areas of the system that have not evolved to accommodate them. Systemic marginal 'integration cost' steadily rises with increasing shares of variable RES (Ueckerdt et al., 2013). Although high systemic costs with low immediate benefits may be expected to give way to high benefits at low cost in a reshaped future system, the timing and amount of future societal benefits are uncertain.

Policy goals are by no means constant during such transition processes. Indeed, transition implies that the entire socio-technical environment is in a state of change. Miller et al. (2013) describe how policy objectives will evolve during an energy transition from maximum technology targets in the first phase of technology deployment altering towards more nuanced objectives including the reduction of investment risk, minimization of policy costs and market integration in later phases. Hence, caution must be exercised when using common instrument evaluation criteria such as efficiency and effectiveness – the results of such evaluations may as much be a reflection of the context they are undertaken in as about the evaluated policies themselves.

Effectiveness in its most general understanding is defined as the ability of an instrument to deliver a desired outcome at the desired time (Haas et al., 2011), but the criteria against which it is assessed change with time. In the early stages of the deployment of a new (niche) technology, policy goals are often expressed so that *at least* the targeted amount of deployment shall be realized. Over time, the cost of large volumes of the new technology may drive a redefinition of policy goals, and therefore policy success criteria. An effectiveness criterion may shift from *at least* to *no more than* a particular volume, with more or less deployment equally undesirable. In Germany, a shift in policy goals in 2013 was reflected by a growth corridor and cap when PV had surpassed a market share of 5%, with even higher market shares by other RES (Leiren and Reimer, 2018). At this time, the political salience of RES costs was increasing across Europe (Del Río and Cerdá, 2014; Fitch-Roy and Fairbrass, 2018).

Dynamic thinking is equally essential for evaluating efficiency. The term efficiency is not unanimously defined (see a discussion of different economic approaches in Newman, 2008). The simplified and static evaluation of efficiency, strictly relating to the satisfaction of a societal demand at minimal production cost, is no longer prevalent in modern economics or in multi-disciplinary approaches that increasingly embrace long-term consequences and impact of dynamic processes on optimal outcomes (see Hoff and Stiglitz, 2001; Finon & Menanteau, 2004; Joskow, 2004) . While it was previously often assumed that a unique equilibrium exists, i.e. a single welfare-maximizing point to which society must strive, modern economic theory operates with multiple potential equilibria that are specific to circumstances and time, depending on institutions, history, distributional and behavioral factors (Hoff and Stiglitz, 2001). Indeed, many political actions that have previously been deemed inefficient by economists, can now be theoretically justified as credible attempts to cope with transaction costs (Dixit, 1996). In practice, transaction costs often constitute a considerable part of the costs related to policy choice (del Río and Linares, 2014; Griffin, 1991).

Moreover, policy instruments should not only be assessed by their ability to deliver on explicitly formulated policy goals, such as the low cost deployment of certain technologies, but also by their potential to trigger changes at a larger scale (Weber and Rohracher, 2012). With this dynamic perspective, the question 'which policy is best?' is no longer salient. Instead, the questions become 'what policy specifications and combinations are more likely to achieve which targets, and on what time scale?' (see also Kitzing & Mitchell, 2014). Recently, research has explored the performance and potential of portfolios of policies or 'policy mixes' (Rogge et al., 2017; Rogge and Reichardt, 2016; Lehmann, 2012). We adopt a similar perspective when discussing policy implications of evolving risk.

3 Mitigating early risks for investors to initiate effective transitions

As described above, in the early phase of a transition towards sustainability, policy focus is often on enabling deployment of newly developed technologies. A sub-set of the transitions literature focusses on 'strategic niche management' (e.g. Kemp et al., 1998; Kemp et al., 2001; Jacobsson and Lauber, 2006; Schot and Geels, 2008) and advocates the creation of protected spaces to allow for development, commercialization and large-scale market diffusion of technologies. Stabilizing revenue streams as well as protection from costs and risks of market participation are a major source of protection or 'shielding' afforded to private investors in niches (Finon and Perez, 2007; Smith and Raven, 2012). Economic risk is thereby transferred from innovative firms to other individuals or a wider population. This policy strategy is strongly criticized by some economists, e.g. the creation of a protected space through introduction of feed-in tariffs for PV in Germany was highly debated (see a short account of this discussion in Grubb et al., 2017). We posit that such conflict arises, in part, from contradicting conceptualizations of risk. In a narrow conceptualization of risk implied by single equilibrium models, there is no societal benefit from pooling or socializing of private risk among the broader public. That is, because in the state-preference model, if differences stemming from risk exposure occurred, individuals would trade with each other until such differences are eliminated ('balance of the states'), leading to the social optimum and maximized welfare (Just et al., 2004). Only when accounting for frictions and distortions such as transactions costs or asymmetric and incomplete information, it may be the case that competitive markets cannot converge in the one market price that is required to reach the social optimum. Then, it can be socially beneficial to take risks away from individuals and re-allocate them to other individuals that have better hedging options or spread them among the broader public.

In fact, a number of imperfections exist in markets for technologies relevant to sustainability transitions. Electricity markets are quite incomplete, e.g. forward contracts are traded only for up to 3-6 years into the future in often illiquid markets, long-term agreements and price insurance contracts are still uncommon (Gawel et al., 2017). Constraints in marketing the product, either because of market design (bidding sizes and time blocks) or physical grid infrastructure adds to the experience of incomplete markets for new technologies. In such incomplete markets, volume risks due to uncertain production also become relevant. To hedge these risks, firms seek long-term contracts or vertical integration, resulting in efficiency losses not foreseen by classical welfare economics (Finon and Perez, 2007; Jaraitė and Kažukauskas, 2013).

In imperfect markets, the elimination of economic risks for investors has financial effects (see also Simkins and Simkins, 2013, p. 385f): A firm with lower risk projects can generally achieve greater debt capacity, and lower cost of debt and equity. Thus, providing long-term revenue stability can help facilitate the financing of capital-intensive new technology projects (Weiss and Marin, 2012). Risk of bankruptcy is greater in imperfect markets. Firms may address this by employing mitigation measures such as active liquidity management. Although it had previously been argued in classical economics that active liquidity management and related costs of risks are not relevant for investment considerations of firms (Modigliani and Miller, 1958), it is now generally recognized that bankruptcy does incur irreversible costs (Bris et al., 2006). Empirical studies demonstrate a willingness to pay to avoid bankruptcy (Acharya et al., 2012). To address these issues, policymakers can, next to prudent instrument choice, also adopt 'financing support' measures, such as reimbursable equity or venture capital from governmental institutions, low interest loans, equity guarantees, loan guarantees and securization products (Kitzing et al., 2012).

The cost reducing effect of absolving investors of some market risk is illustrated in Figure 2. Assume that F_1 is a technology learning curve containing a certain amount of risk with decreasing marginal cost over the aggregated quantity of a specific technology deployed over time. Further, assume that this learning curve reaches a marginal cost level of p_1 at time t_x. Then, employing risk mitigating policies for investors decreases the risk element in the cost function and thus may lead to a shift of the learning curve from F_1 to F_2 with $F_2 < F_1$ for $\forall$ t. Since the mitigation policy leads to a vertical shift of the learning curve, it follows necessarily that $p_1 > p_2$ for $\forall$ t. Cost of risk and therewith the risk mitigating impact of policy tends to be highest in the beginning of a technology learning curve and reduced throughout the learning process. Hence, $\frac{\partial}{\partial t}(F_1 - F_2) < 0$. In non-technical language, investors experience lower cost under risk mitigation strategies, the potential impact of which is highest during early transition phases.

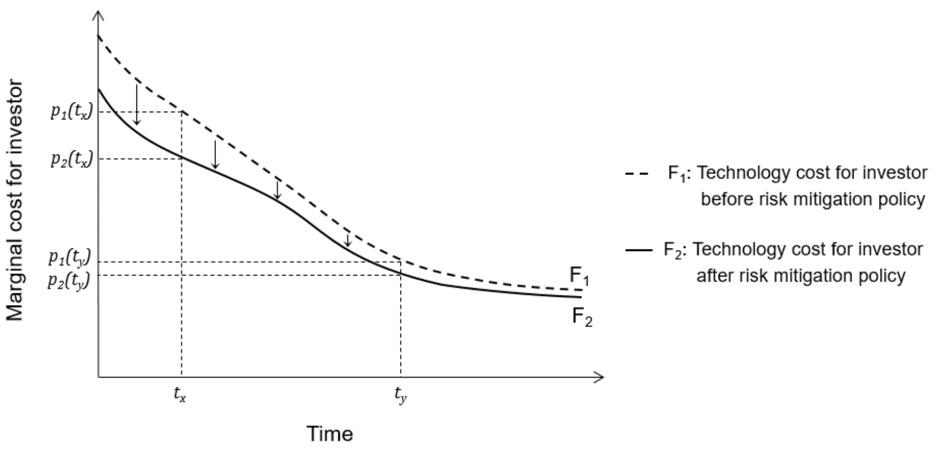

Figure 2: Transfer of market risks from investor to society decreases costs for investors

Note that most market risks do not disappear when reduced for private investors: they are mainly transferred to other actors, e.g. spread out to the wider public (pooling). Thus, the cost for investors is reduced but remains largely the same for society as a whole.

So, how can cost reduction from market risk mitigation be achieved in practice? Protection can be provided to niche technologies in form of shielding from exposure to normal market conditions and the selection pressures of existing regimes (Smith and Raven, 2012). For RES, this is in the early commercialization and take-off phases often done through fixed feed-in tariffs, i.e. providing a guaranteed price and production offtake. This arrangement addresses many of the risks identified above, including stabilization of revenues and protection from the cost and risk of market participation. In fact, the literature on RES support policy often describes price instruments such as feed-in tariffs as low-risk instrument (from an investor's perspective) (see Klessmann et al., 2008). The price stabilizing effect of feed-in tariffs for investors implies that market risk is transferred from individuals to the system operator or an energy utility, who in turn transfers the costs of such risk to consumers or taxpayers.

Price instruments (such as feed-in tariffs) offer clarity and simplicity for transactions between producers and purchasers, because many of the details are defined *ex ante*, thereby reducing risks and transaction costs. They also reduce the costs of activities targeted at avoiding financial and economic distress. Quantity instruments exploit a different lever. Such instruments often take the form of tradeable certificates and related quotas. They do not provide the same price stabilizing effect, yet provide more clarity regarding the targeted environmental outcomes and reduce risk for governments about the total cost of the policy. An additional risk element is introduced (related to the variable price of certificates) for individual firms, while risk may be reduced for other societal agents. Creating a new (certificate) market entails also the risk for additional market imperfections and thus increased distortional effects. This is why using these instruments is sometimes considered a high-risk approach (see Klessmann et al., 2008). In an empirical analysis of European countries, Jaraitė and Kažukauskas (2013) show that quantity instruments are more likely to evoke market imperfections than price instruments because they entail higher investment risks, capital constraints, and transaction costs.

Further implications arise from general risk-averse investor behavior. Exploiting recent advancements in financial theory for investment decisions under uncertainty, both Pineda et al. (2018) and Baldursson and von der Fehr (2004) find that price instruments (and related revenue stabilization) outperform quantity control once it is assumed that investors are primarily risk-averse. Policymakers may prefer to transfer the risk related to uncertainty of environmental outcomes (e.g. emission reduction effects of certain technologies) to investors using quantity instruments. This is, however, only welfare-maximizing if investors are risk-neutral. If they are risk-averse, the risk is better distributed over all of society through price instruments. Building further on these investigations, an interesting, yet unanswered, question is in how far heterogeneity of innovative firms and their level of risk aversion could influence optimal instrument choice.

Another often-neglected factor is that policy choice can also affect the willingness to participate. Especially in early phases of technology development, it is difficult for investors to adequately assess risks. Indeed, risks may be perceived as significantly higher than a purely objective risk assessment would suggest, see for example a study on prohibitive risk perceptions for biomass plants in Malaysia (Hansen and Nygaard, 2013). The perception of risk also varies between investor types with less sophisticated actors tending to overestimate risks compared to more experienced investors, especially risks associated with electricity market participation (Dóci and Gotchev, 2016). Firms and other actors learn through experience how to assess and cope with the risks associated with new technologies (see Ramesohl and Kristof, 2002). This effect can be prohibitive for some and costly for others. Risk reducing policies can help to give a comforting signal to investors and financial partners in times when the risk assessment of new technologies is still in the learning phase, and so enhance participation.

Revenue stabilization can also have a long-term dynamic effect on technological innovation. With long-term and foreseeable price setting, future surplus from cost reductions can be anticipated, enabling the research and development (R&D) investments required for technological innovations (Menanteau et al., 2003). Empirical analyses show that price instruments are favorable for immature technologies, as long as the prices are set close to production costs, while quantity instruments promote innovation in close-to-market technologies (Johnstone et al., 2010; Söderholm and Klaassen, 2006). Quantity instruments, however, tend not to offer the same clarity of future revenues, potentially decreasing R&D incentives (see Menanteau et al., 2003; Finon & Menanteau, 2004).

In summary, we see three risk areas that policymakers can address with the following impacts on overall cost of deploying technology, all of which are connected to pooling of risk: (1) protection from market participation will reduce transaction cost and increase willingness to participate; (2) revenue stabilization through price instruments will reduce transaction cost and increase R&D incentives; (3) financing support measures can increase willingness to participate and reduce financing cost.

Note that the inherent characteristics of price and quantity instruments can be substantially altered by design specifications (e.g. sliding premiums or caps and floors), so each instrument can also be implemented in a 'low risk' or 'high risk' way. Ragwitz et al. (2011) show that key properties in price- and quantity-based policies for RES support are gradually converging in Europe.

Risk mitigation strategies can thus achieve a cost reduction effect for investors when imperfect markets and transaction costs prevail. This cost reduction effect has another significant impact: it can accelerate deployment. Figure 3 illustrates this effect based on a short-term demand-supply diagram. Assume a technology in a relatively early phase of market deployment (t_x). Then, $\hat{F}_1(q)$ is the quantity (q) dependent technology supply curve for short term deployment options without risk mitigation policy and $\hat{F}_2(q)$ with such policy. Then, we have $\hat{F}_2 < \hat{F}_1 \ \forall \ q > 0$, because firms under a regime without risk mitigation policies need to account for higher risk and hence incur higher cost. For $\hat{F}_1(q_1) = \hat{F}_2(q_2) = p^*$, it follows necessarily that $q_1 < q_2$ for $q_1 > 0$ and $q_2 > 0$. At a given support level that allows investors to realize p^*, $\hat{F}_2$ will thus deliver a higher deployment quantity (q_2) than $\hat{F}_1$ (q_1). This finding is supported by empirical studies, which show that policies focusing on reducing risks perform better in achieving high deployment rates in the early phases of an energy transition (Mitchell et al., 2006; Butler and Neuhoff, 2008; Klessmann et al., 2008a; Ragwitz et al., 2006; Haas et al., 2011). Analyses using finance theory, real options approaches, and econometrics conclude the same (Boomsma et al., 2012; Kitzing, 2014; Nicolini and Tavoni, 2017).

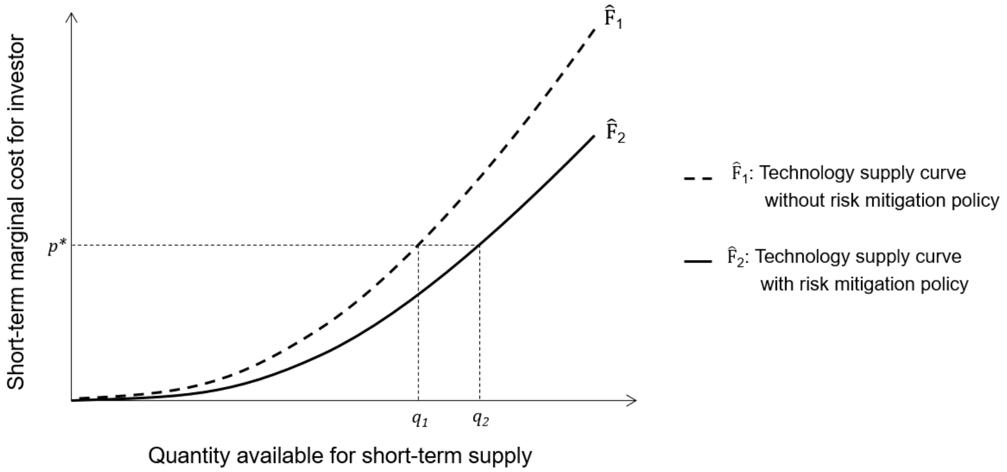

Figure 3: Illustrative marginal direct cost curves for a certain technology under different policies, resulting in different deployment quantities for a given support level

Whether such accelerated deployment is desirable depends on the policy objectives and on the phase of the transition process. If maximum deployment is the policy objective, as is often the case in early transition phases, then a policy strategy of risk pooling and risk reduction for investors can be deemed successful as it leads to maximum deployment at a given support level. In later phases, rapid deployment may not be the goal and risk mitigation becomes less important. Indeed, there are economic limits to risk pooling benefits: risk reduction can entail moral hazard and adverse selection problems, in which the beneficiaries adopt socially adverse behaviors because of their protected situation (Just et al., 2004). This may have considerable system effects when technologies grow into significant market shares. For example, RES producers who are fully protected from market price signals will not decrease their production in situations of negative market prices. This can be suboptimal from a welfare perspective since oversupply may impose additional costs on society (e.g. through need for active reserve management). In Germany, PV installations that operate under the fixed feed-in tariff rather than a sliding premium (as introduced for large installations from 2014) have much less incentive to behave in a 'system-friendly' manner (Winkler et al., 2016). Even if other factors, such as flexibility of incumbent production, also play a role, it is clear that a pooling of risk to the benefit of private investors can only be accepted for a limited time in a controlled niche in order to achieve important policy targets.

We conclude that risk mitigation in the form of shielding and protection from market forces and reduction of investor exposure to economic risk can significantly contribute to overcoming the barriers of early phase technology deployment. However, does this increased effectiveness (in terms of reaching deployment targets) come at the expense of efficiency (in terms of creating social welfare)? In other words, are we, through risk reduction on individual level (for investors in new technologies), imposing a new type risk on societal level related to negative consequences from a suboptimal policy instrument? We explore this in the next section.

4 Addressing policymakers' risks to ensure efficient outcomes

Weitzman (1974) observed that uncertainty changes the nature of the optimization problem between price and quantity instruments. When demand and supply functions (in our case marginal cost of technology and marginal social benefits of deployment) are not perfectly known, policymakers cannot simply maximize social welfare. They need to maximize *expected* social welfare and manage exposure to negative outcomes (also called regulator's regret).

If either marginal costs or marginal benefits are predicted incorrectly at the time of policymaking, price and quantity instruments can both entail suboptimal results implying a relative loss in social welfare. Figure 4 illustrates this for a situation where actual marginal costs (C') are lower than expected (E[C'])[5], reflecting recent experiences with RES cost developments (Edenhofer et al., 2012)[6]. If marginal costs are overestimated (E[C'] > C'), then a price instrument will lead to higher than expected quantities deployed ($\tilde{q} > \hat{q}$), whereas quantity control will lead to lower than expected prices ($\hat{p} < \tilde{p}$). Both effects cause net welfare loss. Depending on the slopes of the curves, the amount of net welfare loss may differ significantly, as illustrated by the shaded areas. For a relatively steep marginal cost curve (on the left), where $|C''| > |B''|$, the incorrectly determined quantity $\hat{q}$ yields a larger welfare loss than an alternatively determined price $\tilde{p}$ (since the shaded area with vertical stripes depicting net welfare loss from quantity control is larger than the area with horizontal stripes for price control). For relatively flat marginal costs (on the right), where $|C''| < |B''|$, the result reverses. Then, quantity control becomes preferable from a welfare perspective.

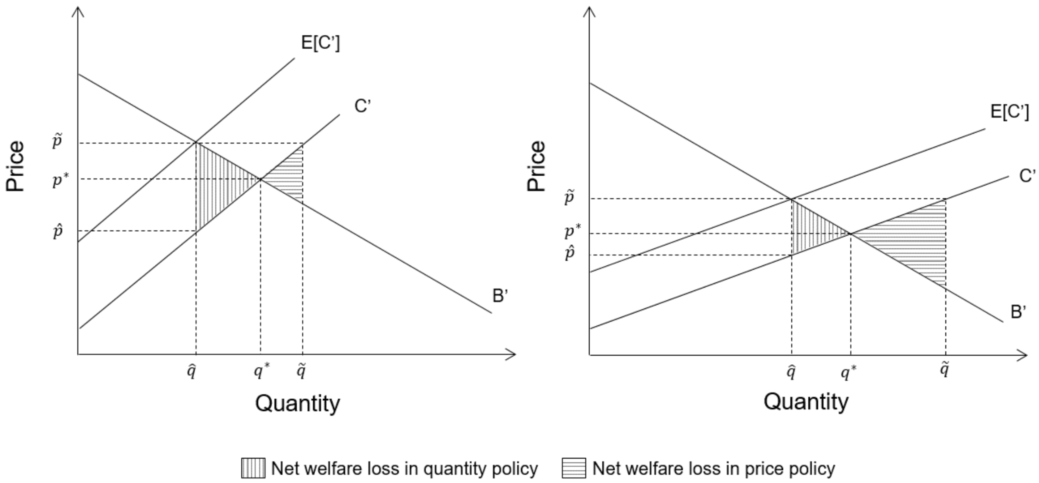

Figure 4: Risk of net welfare loss under lower than expected cost for quantity and price policies, for a marginal cost curve steeper than the benefit curve in an early transition phase (t_x) (on left), and vice versa in a late transition phase (t_y) (on right)

To find the optimal policy instrument and control, it is essential to understand the nature of the curves and their relative positioning towards each other. These are very difficult to estimate. The marginal benefit curve depends essentially on the climate damage function (expected loss in gross domestic productivity or consumption from increased mean temperature.

However, when conducting partial analysis on non-polluting RES in the energy system, it is relevant to consider the societal cost of emission reduction alternatives, also referred to as carbon abatement cost. The marginal benefit curve is often assumed to be rather flat (Cropper and Oates, 1992)), and is subject to high uncertainty (González-Eguino et al., 2016). We do not consider any potential changes of the marginal benefit curve and focus on the relative impact through changes in the steepness of the marginal cost curve. It has earlier been suggested that marginal cost curves of RES are rather flat, and (more importantly) flatter than the marginal benefit curve (at least near the equilibrium where it matters) (Finon and Perez, 2007). This would imply that quantity instruments should be preferred. Stern (2007), on the other hand, assumes a rather steep short-term marginal cost curve. He argues that in the short-term, it becomes progressively more expensive to install additional RES technologies unless it is possible to exploit further cost potentials by R&D or adjust the available technology (both are assumed to be impossible in the short-term). From a long-term perspective, Stern (2007) argues that marginal cost curves are relatively flat allowing for adjustment of technology choice and technological developments. We argue not only that the policymakers perspective matters (short-term or long-term), but also the point in time at which instruments are implemented.

As Newell and Pizer (2003) mention as a side note (p.426), cost declines due to technological improvements may change the slope of the curve and eventually lead to a preference for quantity controls. We are not aware of any in-depth economic

[5] We use linear cost and benefit functions for simplicity. As Weitzman (1974) describes, the conclusions are equally valid for other shapes as long as the area around the intersection is reasonably similar to linear functions.
[6] The insights of our analysis similarly apply to the case where policymakers underestimate the actual marginal costs, as the slopes of the curves are the only relevant factor.

study taking a dynamic view on how the steepness of marginal cost curves may change over time. Here, the conceptual framework of sustainability transitions is helpful for understanding the changing environments in which technologies are deployed.

Emerging technologies face various barriers to introduction; it takes time and an enabling environment to develop the necessary infrastructure and capacity for the technology (Rogge and Reichardt, 2016). This implies that a sector must first evolve before equipment manufacturers and project developers become active and abundant. In the niche phase of technology development, supply capacity is likely limited, both in terms of physical infrastructure and organization. Plant capacities for manufacturing equipment still need to be established and relatively few sites are being developed by relatively few actors. We argue that such limited supply in the short-term is the reason for a comparably steep marginal cost curve in the early market commercialization phase of a technology. It is only during later transition phases, where market diffusion accelerates, that supporting infrastructure develops and interest of a multitude of actors emerges. Then, more manufacturers and investors enter the market, more sites are explored, and knowledge will be shared. This increases the potential supply of PV installations and the marginal cost curve will thus necessarily *become* flatter over time.

In regard to the PV case, we notice that in a cost-effective decarbonization analysis, Timmons et al. (2016) have made the theoretical proposition that the supply curve for PV installations is very elastic, i.e. flat, based on the assumption that component costs are constant in a country, operating costs near zero, and operating performance constant for unshaded sites in a region, implying that a nearly unlimited quantity of solar energy can be provided at a given time. Surprisingly, the availability of empirical data to support the discussion on steepness of cost curves is extremely limited, as most available cost information is either limited to average cost or does not contain information on available quantities (supply potentials) connected to different cost levels. In a simplification to the multiple factors discussed above that can constrain supply options, we have roughly modelled the marginal cost curve for PV in Germany as a function of the technology cost for different application types, from residential rooftop to utility scale green field developments on the one hand, and supply options, restricted by PV manufacturing capacity only, on the other. Table 1 lists the development of global manufacturing capacity and cost development in Germany.

Table 1: Development of global PV manufacturing capacity (Jäger-Waldau, 2017; IEA-PVPS, 2014) and cost development in Germany (Wirth, 2018; Jäger-Waldau, 2017; IEA-PVPS, 2014) from 1990 to 2016; cost ranges estimated based on data for 2006 from Held (2009)

	1990	2000	2006	2016
Annual global PV manufacturing capacity	46 MW	400 MW	2,900 MW	90,000 MW
Average cost of a new rooftop PV installation	14,000 €/kWp	6,700 €/kWp	4,650 €/kWp	1,200 €/kWp
Marginal cost range of all PV installations types	1,300-6,200 €/MWh	650-2,950 €/MWh	300-1,500 €/MWh	150-750 €/MWh

Held (2009) has estimated a technical potential cost curve for the year 2006 by differentiating PV installation cost and supply based on type, site availability and full load hours. Using this cost curve and scaling it according to the data points for price (average installation cost) and quantity (global annual manufacturing capacity) mentioned above, we have roughly estimated marginal cost curves (C') for 2000, 2006 and 2016 as shown in Figure 5 on the left. The transition from steep to flat cost curve becomes apparent. For a relative comparison with the marginal benefit curve, we translate the prices and quantities into carbon effects as shown in Figure 5 on the right. We do this very roughly by estimating avoided emissions with a marginal emission offset of PV in the German electricity system for the respective years, between 676 tCO_2/GWh in 2006, (Marcantonini and Ellerman, 2013) and 531 tCO_2/GWh in 2016 (BMWI, 2017). We approximate the marginal benefit curve (B') in a highly stylized manner from two points of observed willingness to pay for carbon abatement from PV in Germany: 552 EUR/tCO_2 for 1.5 $MtCO_2$ avoided in 2006 (Marcantonini and Ellerman 2013, p. 14) and 423 EUR/tCO2 for 21 MtCO2 avoided in 2016 (results by Marcantonini and Ellerman, 2013, extrapolated to year 2016 based on abatement volume and system carbon intensity from BMWI, 2017). Assuming a constant marginal benefit curve, we fit it to these points, acknowledging the high uncertainty about level, shape and slope. With reference to Newell and Pizer (2003), who in their analysis include slope sensitivities spanning four order of magnitudes, we show a range in which possible marginal benefit curves could lie (grey area). It is possible that the marginal cost curve for PV in Germany has become flatter than the marginal benefit curve between 2006 and 2016.

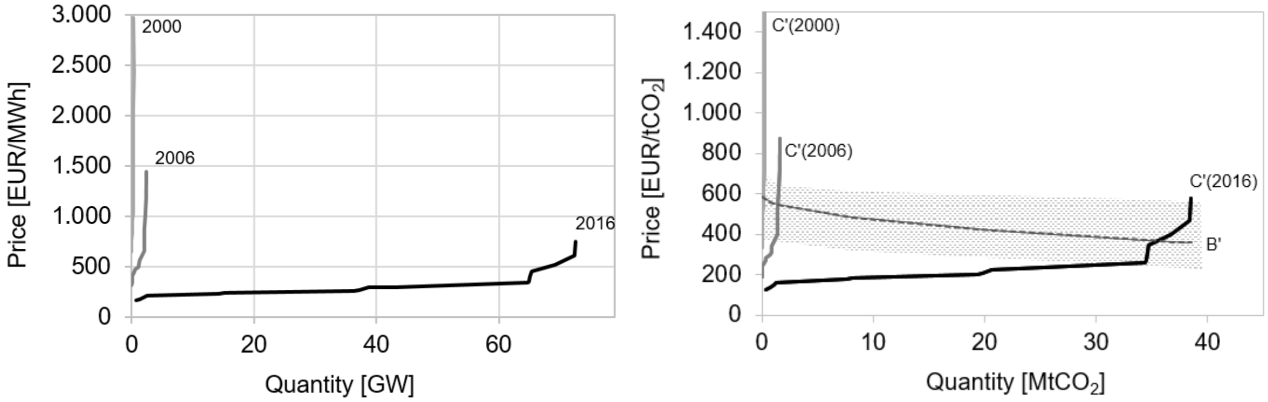

Figure 5: Left: Marginal cost curves for PV in Germany for 2000, 2006 and 2016; Right: Approximated marginal cost and benefit curves for carbon abatement from PV in Germany

Going back to the initial argument of Weitzman (1974), price instruments would therefore be preferable at least in an early phase of a sustainability transition as they minimize the risk of welfare losses. In later phases, the marginal cost function may flatten out so that the relation between the marginal cost and benefit curves could changes. Then, the considerate introduction of quantity controls (e.g. through auctions) may become beneficial.

5 Policy implications: evolving risks require an adaptive policy approach

A significant implication of the changing nature of risk in the course of sustainability transitions is that the instruments used in pursuit of a policy goal should respond to these changes. The insight that different policy instruments are optimal at different stages of the transition process can pose difficulties for policymakers, as it is often not clear in which phase a transition is and for how long. Rapid or unanticipated changes to policy or instruments may create regulatory or policy risks. At some point, one policy instrument must give way, and be replaced with another. While this is not a new observation, it presents two distinct challenges.

First is the question of timing. If we pursue a temporal strategy, in which there is a preferred sequence of instruments, for example, a price instrument to be replaced with a quantity instrument, then the strategy needs to embody an understanding of *when* such a switch is best made. This is easier said than done. Based on the argument outlined above, this decision can be based on the relative slopes of the marginal cost and benefit functions. However, these gradients are unknown *ex ante*, and often disputed *ex post*, meaning the analysis tends to have historical, rather than practical value. Secondly, instrument change tends to be somewhat complex and unpredictable. Rather than items on a menu, instruments are a component in a wider governance system and, as such, they must cohere with the wider political and governance norms and preferences (Howlett, 2009), so that policy consistency can be ensured (Lieu et al., 2018). The range of instrument choice can be constrained by political factors not directly relevant to the economic analysis, such as the historical performance of classes of instruments in other sectors, administrative preferences developed over time, and the "favored sets of ideas and instruments, or 'governance mode' " (ibid, p76). At the same time, instruments can be subject to socialization processes through the community of specialists that hold knowledge about them, which tends to entrench and expand their use (Voß and Simons, 2014). As a result, new instruments can be difficult to establish, and, once in place, just as difficult to replace, creating their own temporal lock-in effects (Nordensvärd and Urban, 2015).

One obvious approach is to progressively alter the specifications of an instrument until it more closely resembles another. This 'morphing' strategy closely aligns to the historical account of PV support in Germany where 'market' elements were progressively layered onto the feed-in tariff, first voluntarily and then compulsorily, while auctions (a form of quantity control) were trialled in parallel with the feed-in programme until the transition from one instrument to the other was completed in 2016 (Leiren and Reimer, 2018). Of course, whether or not this process was a) the result of a long-term strategy or simply reactive, and b) suitably timed, is for debate. Additionally, we stress that the illustration of German PV presented here, while a useful background against which we can develop our theoretical argument, is not a sufficient empirical test of the argument's universal robustness. Indeed, while there is evidence of a global tendency to proceed over time from price instruments to quantity instruments in renewable energy policy, a general link between such trends and policy effectiveness has yet to be definitively established (Winkler et al., 2018). An evolving risk perspective such as the one developed here may contribute to ongoing research in this area. We also note that policy objectives beside economical efficient technology deployment play a role in shaping policy instrument choices, particularly the selection of auctions, including enhancing the capacity of state actors to overcome institutional constraints to use of feed-in tariffs (Eberhard et al., 2017).

Whether, in light of the limits of knowledge, an optimal instrument can be said to exist is debatable. An alternative approach may thus be the use of what has come to be known as 'instrument mix' (Rogge et al., 2017), 'policy mix' (Lehmann, 2012), or 'instrument patching' (Lieu et al., 2018). The emphasis and characteristics of the mix can alter over time to influence the instrument 'balance' (Schmidt and Sewerin, 2018). Specifically, social welfare might be best optimized by using price and quantity instruments in tandem, where each acts as 'safeguard' against the potential pitfalls of the other (Roberts and Spence, 1976; Weitzman, 1978).

Acknowledging that different policy instruments or mixes of instruments may achieve better traction against goals at different points in time, an intuitive response by policymakers could be to adopt a flexible approach to instrument choice, based on continuous or regular evaluation. However, an important lesson from the economic literature on dynamic optimization is that desire for flexibility may result in 'time-inconsistent' instrument choice (Biglaiser et al., 1995; Tarui and Polasky, 2005)[7]. While not necessarily problematic, it may undermine the credibility of decisions or allow strategic investors to lobby for certain instruments that *ex ante* had been deemed undesirable or suboptimal. Time-consistency, instead, implies adopting a policy rule that *a priori* links instrument use and its updating to certain future conditions, so that policymakers can continue to act according to their initially developed plan if and when foreseen changes unfold, entirely independent from investor behavior and strategic considerations[8]. Economic studies investigating such policy rules and discretionary (flexible) policies with regard to optimal instrument use typically only allow for a single instrument (i.e. either price or quantity instrument), which cannot be changed over time. However, a consistent policy is not necessarily defined by the number of instruments employed but rather through instrument use being non-contradicting. That is, if a dynamic policy plan or set of rules prescribes the use of different instruments under different conditions, this may still be a consistent plan as long as it does not allow for ambiguity or wiggle room for discretion. The insights of our analysis, therefore, are not restricted to policy rules or discretionary policy; instead, they are compatible with both forms of governing.

A conflict between the instrument-level and system-level risk perspective also arises from the de-contextualization of economic decision-making that is often necessary for policy application. Instrument selection typically focusses on a particular market or niche. However, technology is always embedded in a larger socio-technical system and there are mutually influencing effects that not only concern long-term consequences, but also current technology costs. Indeed, coordination between niches and 'socio-technical alignment' can decrease overall societal risk and cost (Nill and Kemp, 2009). This coordination and widening of perspective can inform how relationships between niche policies (e.g. support of technologies), sectoral policies (e.g. energy market regulation) and cross-cutting policies (e.g. taxation) are managed; here, the impact is greatest in early transition phases, where 'policy coordination failure' can lead to significantly increased cost (Weber and Rohracher, 2012). Active steering of parallel developments in sectors that are mutually enforcing can reduce barriers. For example, the introduction of smart grid infrastructure and demand-side management technology is beneficial for an improved electricity market operation (Riesz et al., 2013). If additionally timed so that it supports the integration of variable RES, the overall societal cost can be reduced (e.g. through saved investments in grid infrastructure enforcements). It is therefore important to address intertemporal as well as cross-sectoral effects.

6 Conclusions

By analyzing policy choice between price and quantity instruments for deployment of technologies, we highlight some complementarity of innovation economics and system-innovation transition perspectives. The two disciplines do not necessarily lead to contradictory conclusions about instrument choice if we acknowledge that different levels of analysis

[7] As also mentioned in section 1. For the formal argument underlying the reasoning of this literature, see Kydland and Prescott (1977).
[8] It is debatable how the possibility of unforeseen events that we are ignorant about at the time of decision-making (spontaneous radical social or technological innovation, for example) should influence the selection of rules.

require different conceptualizations of risk. The idea of evolving risk helps to distinguish between different temporal phases of sustainability transitions and to accept diverging conclusions about instrument choice, depending on the transition phase. We are not aware of any economic studies that address this temporal aspect and encompass a dynamic perspective with risk as the major factor when analyzing optimal instrument choice. Equally, we are unaware of sustainability transitions research that operationalizes insights from economics about dynamic processes and changing risk environments at the instrument-level with respect to social welfare.

The concept of evolving risk demonstrates that the optimal choice between price and quantity instruments can change over time. Specifically, we have shown that economic and system-innovation arguments both indicate that it can be advantageous in the early market deployment phase of niche technologies to stabilize revenues and decrease market risks for investors, by employing price instruments. This can effectively accelerate deployment without necessarily compromising efficiency. The protective and risk-reducing policies that work well for immature technologies may, however, create undesired incentives in later transition phases with larger market diffusion. In general, price instruments may be preferable for supporting niche technologies with steep marginal cost curves while quantity instruments can be more efficient when technology is more mature and marginal cost curves have flattened.

We have used PV policy in Germany as an illustrative case, where the price instrument of feed-in tariffs was first used to create a protected space in the early years of market deployment, leading to dynamic growth of the niche. With increasing market diffusion, policy drifted towards greater market integration and, eventually, quantity control through auctions. This development seems to be in line with the political as well as the economic rationale laid out in this paper. Further research involving a greater range of empirical examples is necessary to more thoroughly test our proposition.

The dynamic nature of risk requires different policy actions at different points in time. Policy decisions can require seemingly contradictory conceptualizations of risk. However, rather than seeing this as a conflict, we show that by adopting both a narrow instrument-level and a broader system-level perspective, pragmatic policymakers can design effective policy strategies for instrument choice while acknowledging the complex and multifaceted nature of sustainability transitions.

Acting on these findings may pose challenges, as it is not straightforward to determine when and how instruments should be switched. Radical policy changes can be difficult to implement. Progressive alterations such as patching, layering or 'morphing' are an obvious approach. Instruments can also be used in tandem or as hybrids. Research in this area is not sufficiently matured to provide any concluding answers. One insight, however, becomes increasingly evident: The search for the *one* optimal policy instrument is almost certainly fruitless. Sustainability transitions and society as a whole may best benefit from researchers and policymakers who focus on dynamic policy strategies and the question of how and when to change between instruments.

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