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Balancing technology-push and demand-pull policies for fostering innovations and accelerating their diffusion

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ABSTRACT

Technology-push and demand-pull policies have been shown to be important elements of policy mixes for socio-technical transitions. Currently, however, we still lack a sufficient understanding of how to balance these two types of policy instruments to maximize the mix efficiency and effectiveness. In this paper, we use agent-based modelling to simulate how the relative focus on technology-push vs. demand-pull instruments affects the outcome of policy interventions in socio-technical systems. Based on simulations for the solar photovoltaic industry in Germany, we show that whether a focus on technology-push or demand-pull intruments is more effective depends on two important factors: (1) the goals of policy-making and (2) the relative weight policy makers put on present vs. future performance. A focus on technology-push is useful if policy makers pursue industry policy goals and put a stronger weight on future performance. A focus on demand-pull is more effective if policy makers pursue environmental goals and strongly value present performance. Our study contributes to the literature on policy mixes by stressing the importance of weighing and combining alternative policy goals, rather than only instruments. Moreover, by shifting the discussion to policy goals our research helps more closely integrate the literatures on policy mixes and politics.

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1 INTRODUCTION

Pressing societal issues, such as climate change, local air pollution, or resource depletion call for a sustainability transition that decouples economic growth from its negative consequences for natural ecosystems (Markard et al., 2012). Given the urgency of the situation, in recent years policy makers in a large number of countries have introduced policies that aim to speed up the transition and steer economic activities onto more sustainable pathways (Mowery et al., 2010). These policy interventions are usually not limited to the use of single policy instruments but include the introduction of policy mixes, consisting of several instruments that complement each other in their effect (Flanagan et al., 2011; Rogge and Reichardt, 2016). For example, the literature has shown that to foster innovation in environmental technologies, countries often combine so-called technology-push and demand-pull policies (Peters et al., 2012; Rennings, 2000). Technology-push policies seek to enhance the supply of technologies by providing incentives that reduce the costs of their development, e.g., through direct subsidies for research and development (Nemet, 2009). Demand-pull policies, on the other hand, foster technological change in technologies by stimulating their demand, e.g. through regulation, financial incentives, or information campaigns (Peters et al., 2012).

Whereas until 1990 most countries primarily relied on technology-push policies, in recent years countries have strongly raised their use of demand-pull policies to foster socio-technical transitions (Hoppmann, 2015). The fact that demand-pull policies are often connected with considerable social costs has triggered a debate on the optimal level between technology-push and demand-pull in the policy mix (Hoppmann et al., 2013; Nemet, 2009). While some have found demand-pull policies to be very effective in stimulating socio-technical change (Cantner et al., 2016), others have stressed that a stronger focus on technology-push would lead to a more efficient use of public resources (EFI, 2012; Frondel et al., 2010). Currently, however, we know little about how to balance technology-push vs. demand-pull policies to achieve a high effectiveness and efficiency of policy support. Studies show that policy interventions aim to achieve a large number of different goals, including the goal to foster technological innovation, reduce environmental pollution and stimulate the creation of jobs in domestic industries (Hoppmann et al., 2014). Yet the few studies that have investigated the role of the balance between technology-push and demand-pull instruments have usually concentrated on investigating their impact on technology diffusion and innovation as the main outcome variables, not allowing for a comprehensive analysis of their effects (Costantini, Crespi and Palma, 2015; Johnstone et al., 2009). Moreover, a limitation in previous studies is that they have usually relied on ex-post regression analysis of historical policy schemes. While important, however, the use of regression analysis does not allow us to study counterfactual development, e.g., whether a stronger or weaker focus on either technology-push or demand-pull policies would have led to a higher effectiveness of policy interventions.

Amid these shortcomings in the literature, in this paper we use an agent-based modelling approach to study *how the balance of technology-push and demand-pull policies influences socio-technical transitions*. Toward this end, we develop a detailed model of the socio-technical system for solar photovoltaic (PV) technologies in Germany between 1990 and 2014. We chose this empirical setting since Germany has made strong use of policy support to foster sustainable technologies, particularly PV. However, the fact that Germany put a strong emphasis on demand-pull policies compared to technology-push policies has raised concerns about whether a stronger focus on technology-push would have led to better outcomes. Using agent-based modelling we test several scenarios that include a stronger emphasis on technology push to show the impact of the balance between technology-push and demand-pull on several key outcome variables, such as emission reduction or job creation. The fact that the German case has been extensively studied and data is abundant, allowed us to build a model that captures the complex dynamics of interaction between different actors along the value chain in the German PV sector and also includes spillovers across national boundaries.

Our study makes three key contributions to the literature. First, we contribute to the debate on technology-push vs. demand-pull policies by showing that the optimal balance between the two depends on policy goals. Previous studies primarily focused on diffusion and innovation and posited that a balance between technology-push and demand-pull will yield the best outcome. We demonstrate that when considering temporal preferences and additional outcome dimensions, such as industry policy and environmental policy, policy makers may rather focus more strongly on either technology-push or demand-pull policies.

Second, we contribute to the literature on policy mixes by pointing to the importance that weighing alternative policy goals plays for effective policy-making. Previous studies on policy mixes have predominantly focused on finding the right mix between instruments to maximize the impact of policy on one specific outcome parameter, often innovation (Costantini, Crespi and Palma, 2015). Our analysis suggests that besides a mix in means, policy makers also need to think about the mix in ends. The mix in ends, however, is by definition a question of political preferences and value judgments. Therefore, we consider our work an important step toward further integrating the literature on policy mixes with the one on politics.

Third, we introduce a methodology for ex-ante evaluation of policy mixes. Previous studies have primarily relied on historical data when analyzing policy mixes designed to foster socio-technical transitions. By combining agent-based modelling with real-world data, we provide a systematic procedure that allows policy-makers to simulate the impact of alternative policy mix configurations on various outcomes. Such policy evaluation, in turn, will be useful both when introducing new policies and adapting existing ones to new geographic contexts.

The rest of the paper is structured as follows. Section 2 provides an overview of the relevant literature on policy mixes as well as technology-push and demand-pull policies. Section 3 describes the agent-based modelling approach we employed as well as the research setting. Section 4 describes the results of our model simulations before section 5 discusses their implications for the literature. Section 6 concludes.

2 THEORETICAL BACKGROUND

2.1 The role of policy mixes in socio-technical transitions

A core concern in the literature has been the question how societies can foster large-scale changes in socio-technical systems so as to steer economic systems onto more sustainable pathways (Markard et al., 2012). While it has been recognized that such change requires altered behaviour of a large number of different actors, there is a strong consensus that public policies play an important part in speeding up and facilitating large-scale socio-technical transitions (Horbach et al., 2012; Mowery et al., 2010). Scholars in both, neo-classical and evolutionary traditions, have pointed out that policies are important for sustainability as they help internalize market externalities and break path dependencies and lock-ins that prevent large-scale change (Jaffe et al., 2005; Nill and Kemp, 2009; Rennings, 2000).

Given the high importance that policy can play in fostering socio-technical transitions, it is not surprising that the recent years have seen a larger number of studies that investigate the effectiveness and efficiency of different policy instruments. In this context, early studies particularly focused on testing and comparing the effect of different policy instruments, particularly with regard to their impact on the diffusion of and innovation in technologies (Jaffe et al., 2002; Jänicke and Lindemann, 2010). Classical debates for example revolved around the questions whether policy makers should make use of market-based vs. command-and-control instruments and whether quantity-setting or price-setting instruments would provide the best outcome (Jänicke and Lindemann, 2010).

More recently, the focus of analyses has shifted away from testing the impact of individual instruments toward analysing the effect of policy mixes, which Kern and Howlett (2009) defined as “complex arrangements of multiple goals and means which, in many cases, have developed incrementally over many years” (p. 395). The concept of policy mix suggests that to achieve the policy objectives, single policy instruments are rarely sufficient (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016). Instead, policy makers need to combine different policy instruments that each have their own merits and thus complement each other in their effects. Moreover, it has been suggested that a policy mix consists of more than instruments. As Rogge and Reichhardt (2016) point out, policy mixes comprise the broader policy strategy as well as policy processes. Whereas the policy strategy describes the longer-term objectives policy-makers seek to achieve by implementing policies, policy processes describe the ways in which policies are developed and implemented (Howlett and Rayner, 2007; Quitzow, 2015a).

2.2 Technology-push and demand-pull policies

While policy mixes have been investigated from a variety of different perspectives, one core question in this literature is how to balance technology-push and demand-pull policies as two important types of instruments policy-makers have used to support socio-technical change (Costantini, Crespi, Martini, et al., 2015; Peters et al., 2012; Rennings, 2000). *Technology-push* policies aim to foster socio-technical change by reducing the private cost of research and development (Nemet, 2009). Typical technology-push policy instruments include public R&D

funding or tax reductions for R&D investments, and financial support for pilot projects (Nemet, 2009). *Demand-pull* policies aim to stimulate socio-technical change by supporting the use of technologies on the demand side (Edler and Georghiou, 2007). Demand-pull policies typically include subsidies or tax credits for end consumers, standard-setting instruments (e.g., performance standards or the protection of intellectual property), information campaigns, or federal procurement programs (Jaffe et al., 2002; Peters et al., 2012; Crespi, Guarascio, 2018).

Both technology-push and demand-pull policies have been extensively used by policy-makers to induce socio-technical changes, e.g., in the form of support for renewable energy technologies in the energy sector (Hoppmann, 2015). In early years of policy support, governments strongly focused on technology-push instruments. Particularly since the 1990s, however, governments all over the world have started to make increasing use of demand-pull policies, such that in many countries the funding for these policies by far exceeds the one of technology-push policies. For example, in Germany, demand-pull policy funding for PV technologies under the feed-in tariff regime exceeded the funding for public R&D by a factor of 40 (Hoppmann et al., 2013).

The considerable public funds that have been dedicated to demand-pull policies in recent years have spurred a debate about the optimal balance between technology-push and demand-pull policy funding in the policy mix (Hoppmann et al., 2013). Scholars agree that both types of policies are important in driving socio-technical change (Cantner et al., 2016; Costantini, Crespi, Martini, et al., 2015; Rogge and Reichardt, 2016). Yet, it currently remains unclear which balance countries should choose to achieve the highest policy effectiveness and efficiency. In fact, several scholars have argued that demand-pull policies in their current form represent unsustainable subsidies and that a stronger focus on technology-push policies would lead to better outcomes (Frondel et al., 2010). Others have suggested that a stronger focus on technology-push policies is unlikely to induce changes at the pace necessary to meet the urgent challenges faced by today's society.

2.3 Balancing technology-push and demand-pull policies

While the question of how to balance technology-push and demand-pull policies is important from both an academic and practical perspective, the extant literature provides quite limited insights into how policy-makers should distribute funds between the two policy types. In particular, the literature suffers from two main shortcomings that prevent us from deriving detailed policy recommendations: First, previous studies have focused on a rather limited set of outcome indicators when measuring the impact of technology-push and demand-pull policies. Almost all studies focus on investigating their effect on either the diffusion of or innovation in technologies (Cantner et al., 2016; Costantini, Crespi and Palma, 2015; Johnstone et al., 2009). While this focus is understandable, it neglects that the motivation to implement such policies often goes beyond inducing innovation or diffusion of technologies. For example, the explanatory memorandum of the German feed-in tariff scheme states Act 2000 lists, among others, the reduction of carbon emissions, the improvement of technologies, and the creation of industries and jobs as important policy goals (IWR, 2016). The idea that policies can include multiple goals is very much in line with the literature on policy mixes and sustainability transitions, that have acknowledged the complex interplay of multiple means and ends (Rogge and Reichardt, 2016). So far, however, the idea of multiple ends has found insufficient consideration in empirical studies on policy mixes that usually regress one specific outcome on technology-push policies, demand-pull policies and an interaction of the two (Costantini, Crespi and Palma, 2015). Particularly if one assumes that different policy instruments may contribute differently to different goals—as is one of the core assumptions in the literature on policy mixes—analyzing policies only with regard to one outcome variable does not allow assessing the effectiveness of the policy mix as a whole.

Second, a limitation of the many studies that have tested the impact of technology-push and demand-pull policies lies in the fact that they have strongly relied on ex-post policy evaluation using regression analysis. By retrospectively analysing policies, scholars are able to test *whether* policies individually and jointly have had an effect on specific outcome variables, such as innovation, in a set of countries during a specific period of time (Albrecht et al., 2015). Such ex post analyses based on historical data by definition, however, cannot test the counterfactual, i.e., whether a weaker or stronger focus on either technology-push or demand-pull policies would have resulted in better outcomes. This is because ex post analyses can draw inferences about the optimal policy mix only by comparing the effectiveness of policies across different countries or time. Yet countries differ considerably in their context, which may make direct comparisons difficult (Del Río González, 2009). Moreover, comparisons across different years may prove problematic as the optimal balance of technology-push and demand-pull policies itself is likely to change over time.

Given the aforementioned shortcomings in the literature, in this paper we address the question of how alternative balances between technology-push and demand-pull policies affect socio-technical transitions. In contrast to previous research, we use simulation to directly compare the impact of alternative policy mixes on a number of important performance indicators, beyond innovation and diffusion. The insights we generate this way shed new light on the optimal balance between technology-push and demand-pull policies and bear important implications for the role that policy goals play for policy mixes.

3 METHOD

3.1 Research approach and setting

To address our research question, we use agent-based modelling and apply it to the socio-technical system for solar photovoltaic (PV) power in Germany. Agent-based models have previously been applied in a range of disciplines such as ecology (Grimm and Railsback, 2005), ecosystem management (Janssen, 2002), and economics (Tesfatsion and Judd, 2006). They build on the idea that to understand the dynamics of socio-technical systems one needs to understand the decisions, behavior, and interaction of the actors that are part of it (Miller and Page, 2007). Instead of modelling system behavior at the aggregated level, agent-based modelling opens the black box of socio-technical systems to understand how system behavior emerges from the complex interplay of heterogeneous and learning agents (Gunderson and Holling, 2002). As a result, agent-based modelling is well suited to capture the non-linear dynamics of complex, adaptive systems at multiple scales and how they are influenced by policy interventions of different sort (Levin et al., 2013).

We selected PV as a technology as it bears considerable potential for decarbonizing the electricity sector; it has been subject to considerable policy support in the past, and shares key features with emerging technologies such as electricity storage (e.g., mass-production, modularity and strong learning effects). Moreover, we chose Germany as the geographic setting since Germany has been particularly active in supporting PV technologies and in 2018 still is the country with most installed PV capacity per capita (IEA PVPS, 2019). The fact that Germany has a long history in supporting PV implies that data for accurately modelling the socio-technical system in this country is readily available. Moreover, Germany put a strong emphasis on demand-pull policies compared to technology-push policies, which led to a controversial debate about whether a stronger focus on technology-push would have produced better outcomes. While some have found the German policy mix to be very effective in stimulating socio-technical change (Cantner et al., 2016), others have stressed that a stronger focus on technology-push would lead more efficient use of public resources (EFI, 2012; Frondel et al., 2010). Using agent-based modelling we test several scenarios that include a stronger emphasis on technology push to show the impact of the balance between technology-push and demand-pull on several key outcome variables, such as emission reduction or job creation.

3.2 Model description

Figure 1 shows the basic concept of the model, including input, model, and output. In building our model, we closely followed the ODD (i.e. overview, design principles, details) protocol (Grimm et al., 2006; Grimm et al., 2010), which ensures a systematic model development. In the following, we briefly outline the main structure and content of our model. A more detailed model description is available from the authors upon request.

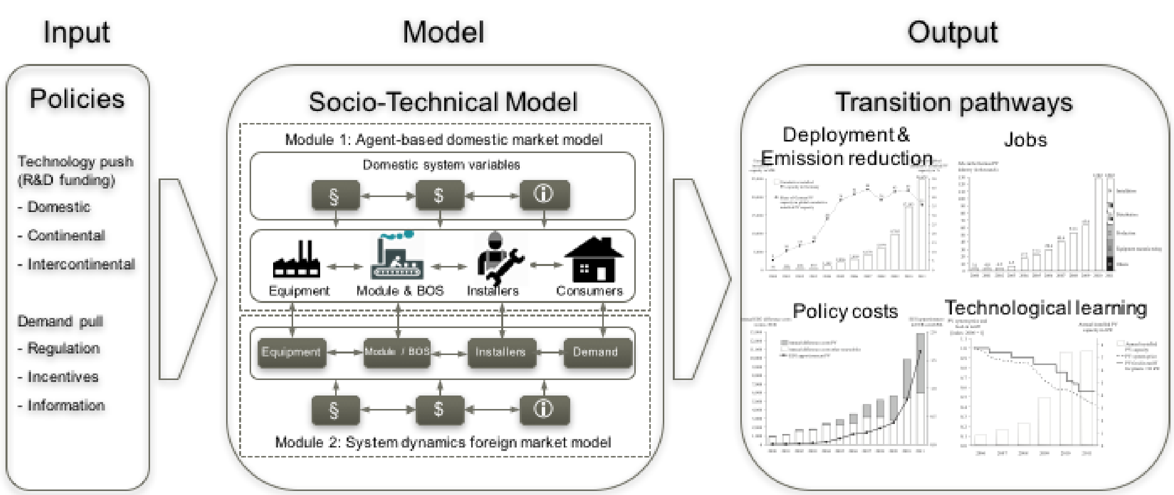

Figure 1: Conceptual model representation

3.2.1 *Model logic*

The *model* consists of two main modules: (i) an agent-based domestic market module representing the German PV market, and (ii) a system-dynamics foreign market module representing the "rest-of-the-world" (ROW) or foreign PV market. The *domestic market module* simulates the decisions and behavior of the domestic actors of the German socio-technical system for PV, namely the consumers (i.e. homeowners and larger-scale actors), and producers (i.e. installers, module, balance of system (BOS) and manufacturing equipment producers). Consumers are sub-divided into households, farmers and industrial consumers according to the type and size of PV system they demand (4-10 kWp rooftop, 10-40 kWp rooftop, and > 40 kWp ground mounted systems, respectively). In the model, they purchase PV systems from installers, which in turn buy the system components from module and BOS producers. Moreover, module producers purchase manufacturing equipment (ME) from ME producers (see Figure 3 for the structure of the PV value chain).

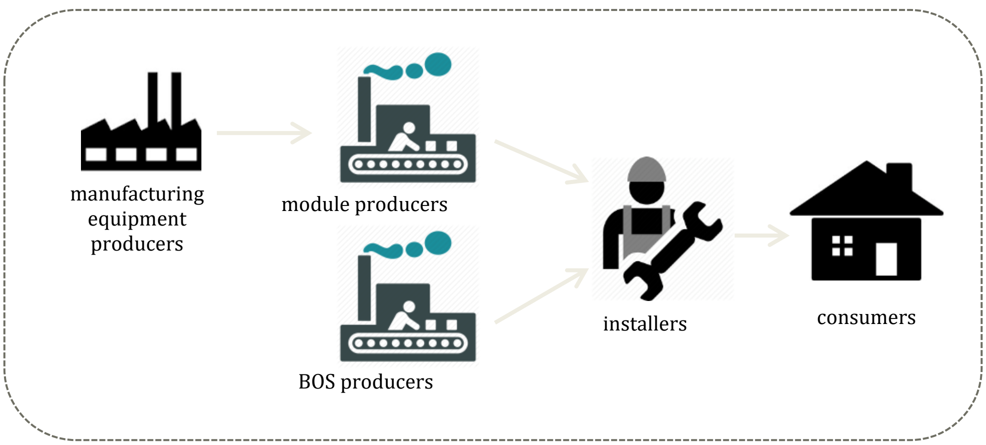

Figure 2: PV supply chain implemented

Each one of the producing agents carries a range of product variables (i.e. sales and price), a range of business variables (i.e. number of employees, production capacity, experience, R&D expenditure, business radius, and expected profits), accounting variables (i.e. production, fix and variable costs, monthly and annual profit) and strategic variables (i.e. profitability and extension threshold). In the model, producers review their strategy every month and potentially adjust it, depending on their performance. Moreover, new producers may enter the market if demand exceeds supply. In this early model version, only sales, production-capacity and employees are implemented based on the photovoltaic factsheets from the German Trade & Invest Gmbh (GTAI).

In contrast to the domestic market module, the *foreign market module* does not model individual agents in foreign countries. Instead, the dynamics in foreign markets are modelled using stock and flow logic by using a small number of agents, each of which represents the average behavior of one world region. In particular, the model distinguishes two general regions: countries with high labor costs (e.g. USA, Japan, other EU countries) and PV production countries with comparably low labor costs (e.g. China and the ROW). Such separation and simplistic representation of the foreign market, allows for a deep dive into the German context without neither an overly complex model nor ignoring international impacts and dynamics. In this early model version, only one “rest-of-the-world” region (i.e. excluding Germany) is implemented through an international demand variable (i.e. annual installed capacity), and by allowing module, BOS, and manufacturing equipment imports.

3.2.2 Model output

We chose the output measures of the model to reflect the goals stated in the German Renewable Energy Act (EEG). Correspondingly, the key outputs we track are (1) deployment, i.e. the installed PV capacity, (2) emission savings, i.e. avoided emissions from fossil power plants, (3) jobs in the German PV industry, and (4) technology improvement (e.g., PV panel price reduction and conversion efficiency increases). Moreover, to be able to evaluate the efficiency of different policy mix configurations, we monitor the total costs of policy measures.

3.2.3 Model input

Our model includes input parameters related to policy, technology, and economic dimensions. Technological and economic variables include PV efficiency and operational life expectancy, and bank loan interest rates, which are assumed exogenous and time-variant. However, since we focus on simulating the impact of the policy mix on socio-technical transitions, the main *input* parameters to our model are the intensity and instruments part of technology-push and demand-pull policies. On the demand-pull side, our model consists of four main policy instruments: (i) information campaigns that increase the probability of consumers thinking about installing a PV system, (ii) lump-sum subsidies that reduce investment costs, (iii) low-interest loan programs, and (iv) feed-in-tariff incentives. On the technology-push side, our model includes (i) direct R&D funding to the industry that increase their search process-efficiency, (ii) R&D funding to universities that boost the general knowledge about the technology, and (iii) production capacity subsidies to the industry. In addition, (iv) trade barrier settings allow more or less international interaction and, consequently, spillover effects. The R&D inputs are not implemented yet in the present model version.

Investigating how a change in the relative focus on demand-pull and technology-push policies influences policy outcomes required us to systematically vary our input variables. All demand-pull and technology-push levers can be adjusted regarding their timing as well as their intensity. As exploiting this entire parameter space would lead to an unmanageable number of scenarios to model, in this paper, we focus on four key scenarios. Moreover, we only consider scenarios for increased technology-push support, reduced demand-pull support, and a combination of both. This is because the German demand-pull policies have been criticized as too high and technology-push policies as too low, such that scenarios lowering demand-pull and raising technology-push funding were considered most realistic. Table 1 displays the resulting scenario matrix.

The first scenario "HISTORY" simply replicates the historical development of policies and their outcomes in Germany and is used to calibrate our model. The second scenario, "PUSH INCREASE" simulates policy outcomes for the case that technology-push policies (i.e., industry support) would have been 100% higher than historical values, while leaving demand-pull policies at historical levels. The third scenario, "PULL REDUCTION", tests the impact on the socio-technical system if all technology-push policies are left at historical levels and demand-pull policies (i.e., all FIT and lump-sum subsidies) are reduced by 30%. Finally, the fourth scenario "PUSH FOCUS" investigates how simultaneously raising technology-push intensity by 100% and reducing demand-pull levels by 30% affects the simulation outputs.

Table 1: Scenario matrix for different demand-pull and technology-push settings.

		Demand-pull	
		History	Reduced
Technology-push	History	**HISTORY**	**PULL REDUCTION**
	Increased	**PUSH INCREASE**	**PUSH FOCUS**

3.3 Model scale and resolution

Ideally, every actor in reality would be represented by exactly one agent in the model. However due to computational power constraints this is often not advisable, especially not for representing large-scale system like the German PV market. Therefore, the model is developed with a "resize-population" scaling parameter for a consistent scaling and faster model development and simulation phase. This resize parameter is set to 0.001, meaning every 1,000th actor is represented in the model.

Customers are distributed in the states (Bundesländer) according to the number of residential buildings. Patches are the spatial grid units representing a geographical area of 100 km^2. Besides their coordinates, patches carry a variable indicating the state and irradiation data as (kWh/m^2*year as global horizontal irradiation (GHI)). Producers are randomly distributed around the country in this preliminary version of the model.

As the shortest time-period between two FIT adjustments was one month and industry is not expected to adjust their strategy on shorter intervals than annually, one time-step in the model refers to one month in reality. The model starts with the first PV policy measures at the beginning of 1991, and runs until the end of 2015.

3.4 Model calibration

To accurately represent the dynamics in the German system, we calibrated the model against the historical trends of the cumulative installed PV capacity and policy costs on the demand side, and number of jobs in PV industry, PV system costs, and PV efficiency for the supply side. The basic algorithms of the model were derived based on theory, empirical data from previous studies and expert interviews. The model is calibrated against these patterns thanks to the large amount of historical data available. This procedure can be referred to as “pattern oriented modelling” (c.f. Grimm et al., 2005). Figure 6 shows the model behaviour against the historic data for the development of cumulative installations, policy costs, and the development of jobs in the German socio-technical system for PV. As can be seen, our model quite accurately captures the historical developments. It should be noted, however, that currently the model is still under development and that the developments shown only provide a first idea of the model outputs.

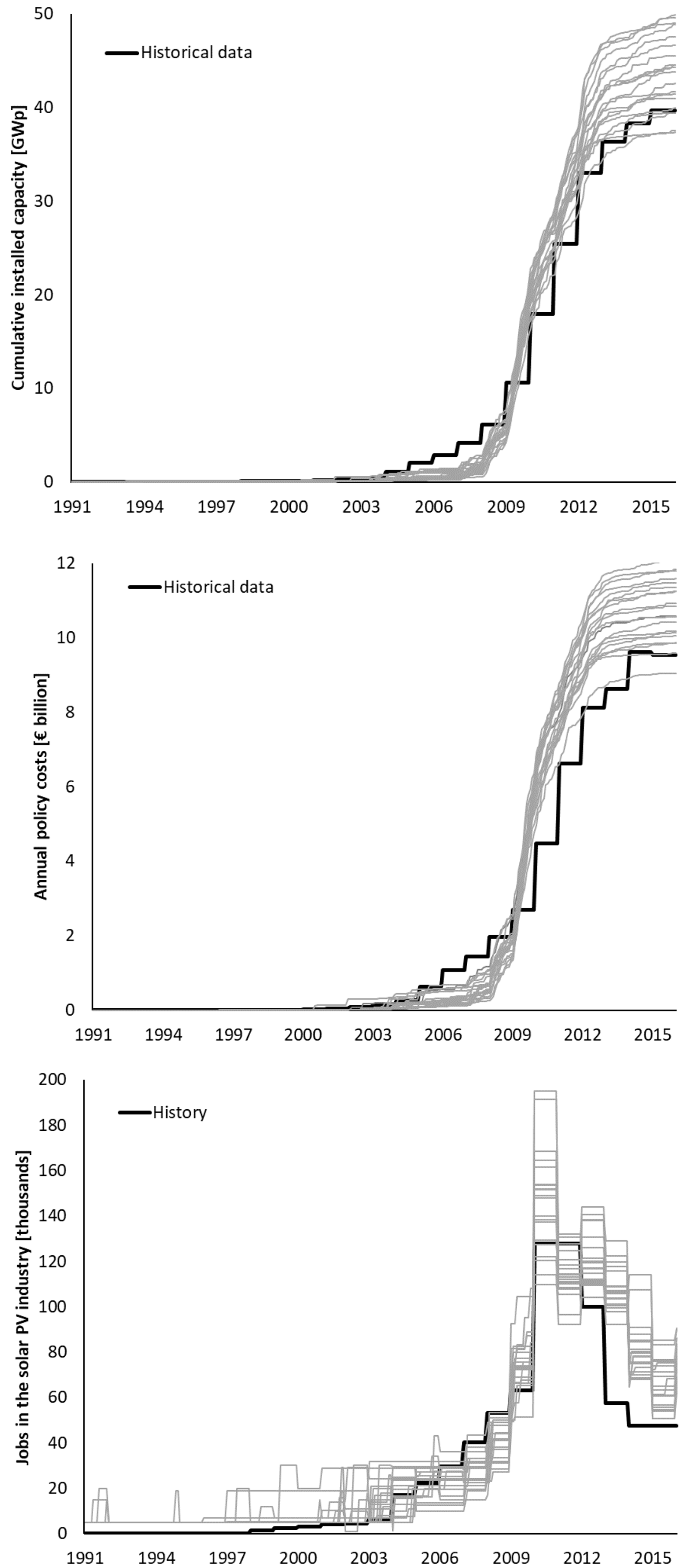

Figure 3: Robustness test for cumulative installed capacity [GWp,] (top), annual policy costs [€ billion], and employment in the German PV industry [thousands] (bottom) for 20 simulation runs (grey) against the historical trend (black).

4 PRELIMINARY RESULTS

In the following, we present the preliminary results for the four scenarios (i.e. HISTORY, PULL REDUCTION, PUSH INCREASE, and PUSH FOCUS) we used to test the influence of different policy mixes on socio-technical transitions. For each scenario, we ran the model 20 times and calculated the mean values of the output variables over time. Calculating the mean is necessary since the model is based on the behavior of individual agents, which do not behave in a deterministic way. As a result, each model run produces a slightly different output, implying that model results need to be interpreted stochastically. Figure 8 shows the development of cumulative installed capacity, employment in the PV industry as well as the amount of emissions saved.

The mean values of the HISTORY simulation runs show where and how well the historic data could be reproduced. The demand is slightly underestimated in the pre tack-off years (2006-09) and again in the last two years, while in the early years up to 2005 and during the boom (2010-13) the model produces a reasonably good fit on average. Regarding the number of jobs created, the average fit is acceptable in the late years (post 2009). To improve the model fit pre 2009, the model will be further refined in the future.

Reducing the amount of demand-pull funding under the “PULL REDUCTION” scenario also reduces the amount of PV deployed. Since this deployment is directly coupled to emission savings, short-term savings are lower in the “PULL REDUCTION” scenario. At the same time, reducing demand-pull funding without raising the amount of funding for technology-push policies leads to a considerable reduction in the amount of jobs generated. Despite reducing the incentive levels by 30%, cumulative policy costs in the “PULL-REDUCTION” scenario were 75% below the HISTORY-SIM scenario (not shown).

Doubling the amount of technology-push funding without changing the amount of demand-pull funding under the PUSH INCREASE scenario leads to a deployment of PV that is very similar to the one of the HISTORY scenario. This is because the deployment of PV is primarily determined by demand-pull funding. At the same time, however, the increase in technology-push funding leads to an increase in the competitiveness of the domestic industry, such that the number of domestic jobs under the PUSH INCREASE scenario rises significantly. Cumulative policy costs are very similar to the HISTORY scenario, as well.

Finally, raising technology-push policy funding while simultaneously lowering demand-pull policy funding under the PUSH FOCUS scenario leads to deployment of PV and emission savings that are similar to the one under the PULL REDUCTION scenario. This indicates that to a reduced focus on demand-pull policies necessarily goes along with a reduced potential for saving emissions in the short run. Due to the increase in technology-push funding, however, jobs under the PUSH FOCUS are not as strongly reduced as under the PULL REDUCTION scenario. Instead, the number of jobs added is similar as under the HISTORY scenario, indicating that technology-push policy funding can be used to compensate for a reduction in demand-pull policy funding with regard to this output variable. Interestingly, however, under the HISTORY scenario, the number of jobs created in earlier years is higher than in the PUSH FOCUS scenario but also drops more quickly in later years. This suggests that a stronger focus on technology-push may be better suited if one is interested in generating jobs in the longer run. Cumulative policy costs are almost the same as the PULL REDUCTION scenario (not shown).

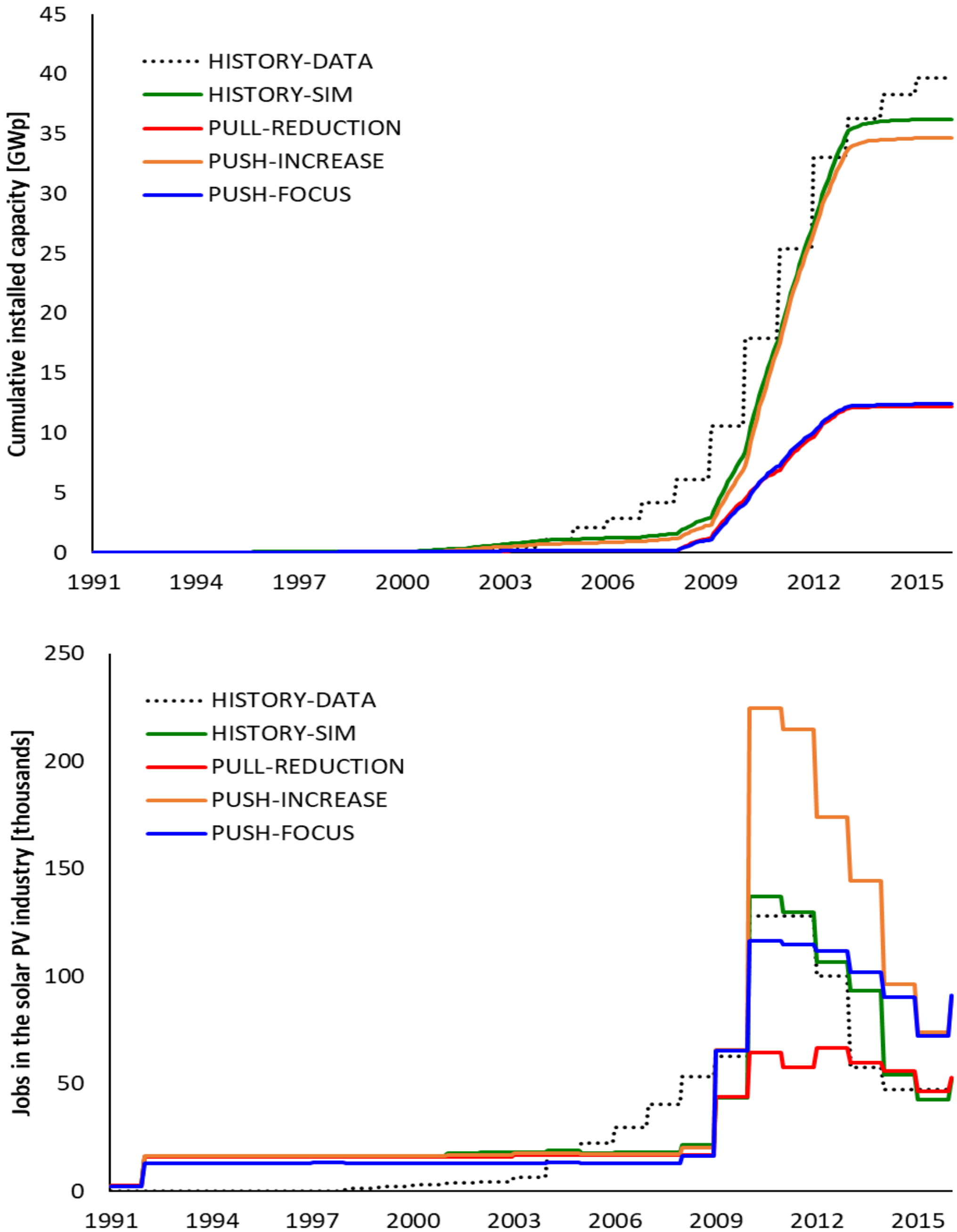

Figure 4: Evolution of cumulative installed capacity [GWp] (top) and employment in the German solar PV industry [thousands] (bottom) for the different scenarios (mean of 20 simulation runs) against the historic data (black, dotted line).

5 DISCUSSION

Our study makes several contributions to the literature streams on technology-push and demand-pull policies and policy mixes as outlined below. In addition, we elaborate on the methodological contributions to ex-ante evaluation of policy mixes with agent-based modelling and discuss limitations of the research approach.

5.1 Balance between technology-push and demand-pull policies

First, our study contributes to the literature on technology-push and demand-pull policies. Prior literature on this field has investigated the impact that these two types of policy instruments have on socio-technical change. However, so far, studies have primarily concentrated on investigating the impact of technology-push and demand-pull policies on technology diffusion and innovation, and provide limited insights into the optimal balance between the policies (Peters et al., 2012). In contrast, we show how the balance technology-push and demand-pull policies influences a broader set of outcomes, including emissions savings, job creation, and electricity costs (i.e. through policy costs). In doing so, our study suggests that the optimal balance between technology-push and demand-pull policies strongly depends on policy makers' goals and temporal preferences. Both types of instruments could be used to pursue a variety of different goals including technology policy, industry policy, environmental policy, climate policy, development policy, and social policy goals. We show that technology-push policies are more effective when policy makers pursue industry policy goals and have a stronger preference for future performance. Demand-pull policies on the other hand, are more effective when policy makers pursue environmental goals and focus on present performance. This is because, in contrast to technology-push policies, demand-pull policies directly lead to emission reductions and international spillovers, which contribute to the achievement of environmental goals not only domestically but also abroad.

5.2 Policy mixes, policy goals, and temporal preferences

Second, our study also makes several contributions to the literature on policy mixes. Prior literature on policy mixes has strongly focused on investigating how the mix in policy instruments affects overall policy effectiveness (Rogge and Reichardt, 2016). Our findings suggest that besides focusing on instruments, it is important to consider the mix in alternative policy goals as well as temporal preferences in policy-making.

We show that the consideration of *multiple, potentially conflicting goals* can considerably alter the evaluation of policies. As a result, our study helps reconcile divergent views in the literature on whether specific policy schemes are effective or not. The German feed-in tariff, for example, has been praised as very effective by some and very ineffective by others (Cantner et al., 2016; Frondel et al., 2010). To a large extent, the reason for the strong differences in the evaluation are due to divergent views on what the feed-in tariff system was supposed to accomplish. When evaluating the scheme from a technology and development policy perspective, the effectiveness can be considered quite high as it helped significantly increase the diffusion and reduce the costs for renewable energy technologies, at least in the short run (Hoppmann et al., 2014). When evaluating the same policy from an industrial and environmental policy perspective, however, the policy has not been as successful because it primarily stimulated job creation in foreign countries and direct emission savings were quite limited (de la Tour et al., 2011; Quitzow, 2015b). Policy makers therefore need to consider carefully the relative importance of ends before choosing the mix in means. In the German case, different actors often attached different ends to the feed-in tariff, resulting in very different evaluation of the policy scheme. A more explicit discussion of the relative importance of alternative goals might have enabled a more tailored policy design.

Similarly, we argue that a more explicit consideration of *temporal preferences* in policy evaluation could help close the current divide between policy evaluations in the neo-classical and evolutionary traditions. Our findings show that to evaluate the effectiveness of policies it is important to specify whether one is interested in the short- or the long-run impact. Extent policy analyses, however, rarely differentiate in this dimension, which can lead to very different evaluations of policy instruments. Environmental economists in the neo-classical tradition, usually advocate the use of market-based instruments, such as carbon prices (Jaffe et al., 2005). The main reason for this is that such instruments have been shown to be most effective in inducing short-term emission savings by allowing the market to identify the most cost-effective saving opportunities. Scholars in the evolutionary tradition, in contrast, usually advocate policies that create niches for new technologies that are deliberately shielded of from the markets (Kemp et al., 1998; Nill and Kemp, 2009). The reasoning behind this is that such policies have been shown to induce innovation and break socio-technical lock-ins. In principle, both types of policies—neo-classical and evolutionary—are suited to steering economic activity onto more sustainable pathways. We argue that the main difference, however, lies in the temporal preference for emission savings. The neo-classical approach more strongly values the present as it leads to emissions savings in the short-term but is connected to limited innovative activity, thereby potentially lower emission savings in the long-term. The evolutionary approach, on the contrary, more strongly values the future as it leads to limited emission savings in the short-term but potentially higher emission savings later on as new technologies enter the market. This example shows that both policy-makers and scholars are well advised to be explicit about their temporal preferences when designing and evaluating policy mixes.

5.3 Policy mix and politics

Third, by pointing to the importance that weighing different policy goals and temporal preferences plays for effective policy mixes, our study also contributes to a closer integration of the literature streams on policy mixes and politics. The extant literature stresses that policy processes of policy development and implementation are an important component on policy mixes (Howlett and Rayner, 2007). We suggest that an important part of this process lies in the definition of policy goals and temporal preferences. We argue that even more so than the question of which instruments to implement, the development of policy goals is a highly political process as it involves finding a consensus among different actors on how to weigh alternative ends. As pointed out above, policy-makers usually implement policies to achieve a number of different, often partially conflicting goals. At the same time, different societal and political actors assign very different weights to the goals and possess diverging preferences for future versus present performance. Bringing the different goals and preferences together requires a process of negotiation among various actors that can be expected to involve power plays and framing. By pointing to the importance of policy goals and temporal preferences in policy mixes, our study emphasizes the important role of politics in the development of policy mixes.

5.4 Using Models for Ex-Ante Evaluation of Policy Mixes

Finally, a contribution of our work lies in developing a systematic methodology for the ex-ante evaluation of policy mixes. The previous literature so far strongly relied on ex post analyses to evaluate the effectiveness of policy instruments and their interaction. The main shortcoming of such analyses, however, is that they do not directly allow for testing counterfactual policy developments and require historical data that can only be obtained after the policy has been implemented for a considerable amount of time. By drawing on agent-based modelling and real-world data, we provide a systematic method for simulating alternative policy mix configurations. In this sense, our work is of direct value to policy makers who can use such models to compare different policy mixes before their implementation.

5.5 Limitations

Our study has several limitations that offer avenues for future research. First, our model is necessarily limited in the detail at which it captures the dynamics of the socio-technical system for PV in Germany. For example, while there is a large number of actors that have influenced socio-technical dynamics, we concentrate on the ones that we deemed most important for simulating different policy effects, namely users and producers of PV technology. Future models might include additional actors, such as research institutes and financing bodies, as these actors may also be influenced by and affect the results of policy.

Second, our study is limited in its technological, geographic and temporal scope. To be able to accurately model socio-technical transitions, we focused on the case of the German system for solar photovoltaic power from 1990 to 2015. Foreign markets in our model are represented in a more aggregated fashion than dynamics within Germany. Future research should develop more detailed models of other countries and technologies to test whether our findings are robust across alternative geographies and technologies with different characteristics.

6 CONCLUSION

In this study, we investigated how the balance between technology-push and demand-pull policies influence socio-technical transitions. Drawing on agent-based modelling of the socio-technical system for solar PV in Germany, we showed that whether a focus on technology-push or demand-pull policies is more effective depends on both the goals of policy-makers as well as their preference for present vs. future performance. Technology-push policies are seen as more effective when policy-makers pursue industry policy goals and focus on future performance. This is because technology-push policies can be used for improving the competitive position of domestic firms in the long-term. Demand-pull policies, on the other hand, are regarded as more effective if policy makers pursue environmental goals and focus on present performance. This is because, in contrast to technology-push, demand-pull policies directly lead to emission reductions in the short run.

Our findings have important implications for the literatures on technology-push and demand-pull policies, and policy mixes. Moreover, we make a methodological contribution by providing a systematic methodology that can be used for ex-ante evaluation of policy mixes. We argue that thinking more closely about the ends, rather than only about the means, of policies is a critical step toward improving the effectiveness of public policies, which may also help resolve existing controversies in the academic literature. We consider this study a first step to better understanding how thinking about multiple goals can considerably change the evaluation of policies. Future research should build upon our study to investigate how different policy instruments and mixes fare with regard to alternative goals and time horizons. Moreover, we see much potential for research that combines the literature on policy mixes with the one on politics to study how alternative goals are weighed and combined in the policy-making process.

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