Energy Policy 165 (2022) 112948

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Does green growth foster green policies? Value chain upgrading and feedback mechanisms on renewable energy policies

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ARTICLE INFO

Keywords:
Energy transition
Renewable energy
Value chain
Public policy
Policy feedback theory
Innovation

ABSTRACT

The expansion of renewable energies not only lowers carbon emissions, it also redistributes resources among actors. This article argues that green industrialization – specifically, manufacturing and the development of renewable energy technologies — creates economic gains that impact political processes and increase renewable energy policy ambition. Building on a combined framework of policy feedback and global value chain literature, we see domestic value creation as a key determinant of coalition strength and learning effects for policymakers. We analyze the relationship of value chain involvement to policy ambition using panel data on countries' manufacturing and innovation activities in the wind and solar industry from 2010 to 2018. The results show a positive technology policy feedback mechanism, implying that higher local value creation leads to more ambitious renewable energy policies. These first large-N findings support previous case studies on the importance of green growth for raising policy ambition; it implies that transformative policies fostering value creation could create a virtuous cycle for policy ambition. We further propose an interdisciplinary research agenda to shed light on the role of value chain dynamics for policy feedback mechanisms across different political economies.

1. Introduction

The decarbonization of the energy sector is key for reaching the Paris Agreement's goal to limit global warming to 1.5 °C. Public policies and technological innovation are both seen as accelerators for a transition towards renewables. Yet, further research is needed to gain a more detailed understanding of the interactions between technological changes and policy processes for an effective and transformative policy design (Schmidt and Sewerin, 2017).

A large body of research investigates how policies can foster technological change. Some policies aim to scale up investments in renewable energies (Deleidi et al., 2020; Mazzucato, 2015). Others focus on upgrading in clean energy value chains, that is, promoting the involvement of domestic industries in value segments with higher returns, especially manufacturing and research and development (Chen and Lees, 2016; Lewis and Wiser, 2007; Mazzucato, 2018). Less is known about the co-evolution of technological change and policies (Schmidt and Sewerin, 2017). The objective of this paper is to shed light on the ways in which technological changes may influence policy. More precisely, we address the following research question: does a stronger domestic renewable energy industry result in more ambitious renewable energy policies?

To answer this question, we bring together two separate strands of literature, one on policy feedback mechanisms and one on global value chains. The key argument of the paper is that value chain position matters: manufacturing and innovation activities have strong resource and interpretive effects that impact policy ambition. We test the association between value chain position and policy change using panel data analysis, drawing on a unique dataset of 78 countries' manufacturing and innovation activities over 10 years. The data allow us to track changes in wind and solar industries, and to model the relationship between industry size and clean energy policies. We focus on wind and solar because they have experienced the strongest growth of all renewable energy sources, and are expected to form the backbone of the clean energy system (IRENA, 2018). The findings suggest that involvement in manufacturing and innovation correlates with increased policy ambition in the following years. Interestingly, the effects of manufacturing gains are more short-lived, whereas innovation-based effects are longer-term; this suggests that R&D, as the highest value-added segment, establishes different policy feedback dynamics.

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https://doi.org/10.1016/j.enpol.2022.112948
Received 17 December 2021; Received in revised form 23 March 2022; Accepted 25 March 2022
Available online 9 April 2022
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Our findings contribute to the literature in three ways. First, we address the still under-researched relationship of technological change and policy ambition in an exploratory, theory testing study. Second, we complement the policy feedback literature, which is largely case study-based, by adding quantitative evidence with a first large-N study to explore policy feedbacks in relation to changes in renewable energy value chains. Third, we add a new perspective to these debates by combining literature on global value chains for clean energy with policy feedback literature, and lay out a research agenda to further explore those linkages.

The paper is structured as follows: the next Section 2 reviews the literature on policy feedbacks in the renewable energy transition with a focus on value chains. We draw on two strands of literature in our framework and present our methodological approach in Section 3. Section 4 discusses the findings in the light of current debates on the importance of local value creation and risks arising from uneven transition patterns for policy ambition. Following this discussion, it outlines a research agenda to further explore policy-technology linkages with a focus on value creation and distribution, differences in political economies, and methodological plurality which can be improved by open data. Section 5 concludes and highlights policy implications.

2. Literature review and framework

How politics influence the emergence, stability, design, and success of policies has been a key concern of public policy research for decades and has recently seen increased interest from scholars working on climate and energy topics. Policy feedback theory added insights on the concrete mechanisms of how politics influence policies and vice versa. It evolved from the observation by historical institutionalists like Schattschneider (1935) and Lowi (1972) that policies change politics, and that this may affect future policy decisions in multiple ways. Pierson (1993) elaborated on the two main mechanisms of policy feedback: some policies create *resource effects* by redistributing resources. Such policies strengthen or weaken certain societal interest groups in the political process, which in turn, influence future policies. Other policies create *interpretive effects* when new information leads to policy learning[1] and influences decisionmakers.

Whereas earlier works tended to focus on so-called positive feedback effects that reinforce policies, creating persistence and lock-in, recent studies highlighted the importance of negative policy feedbacks that can undermine policies and might lead to instability, policy change or termination (Campbell, 2012; Jacobs and Weaver, 2015; Patashnik and Zelizer, 2013; Weaver, 2010). These positive and negative feedback effects can even interact simultaneously (Jacobs and Weaver, 2015).

Policy feedback effects have largely been studied in social policy research, but lately feedback theory has been applied in new fields such as health, climate, and energy (Jordan and Moore, 2020; Lockwood et al., 2017). Recent feedback literature focuses on the co-evolution of policy and technology, wherein energy transitions create major shifts in socio-techno-economic systems. These changes, especially from fossil fuels towards cleaner technologies, can generate wins and losses for different groups (Schmidt and Sewerin, 2017). This technological change is expected to effect the relationship between governments and firms, with implications for politics (Meckling and Hughes, 2018a).

Such policy feedback dynamics have largely been explored in case studies of western countries with an advanced clean energy sector. For example, a study on Australian policy feedbacks showed that policies that increased the local benefits from renewable energy installment also increased resources for actors in the renewable energy sector (White et al., 2021). Job creation in the renewable energy sector is generally an important element of subsequent policy feedback effects, as it is associated with increased popular support in the UK and US (Lockwood, 2013; Stokes and Warshaw, 2017). Shifts in labor markets may expand coalitions of “interest groups that lobby to maintain or extend policies” (Meckling and Hughes, 2018a, pp.480). These dynamics have been investigated in detail in Germany (Schmid et al., 2020), where the wind industry created alliances with farmers and regional policymakers to successfully lobby for supportive policies and subsidies in the 1990s (Michaelowa, 2005); trade unions also played a key role in these political conflicts, challenged by fossil fuel industries’ interest groups (Jacobsson and Johnson, 2000). Industry also plays an important role in the United States, where authors have observed Californian solar industry actors pushing for RE policies (Stokes, 2015), and more advanced policy instruments and updates (Smith, 2020). Other studies have identified relevant actors challenging (fossil) incumbents such as independent power producers in the US (Lee, 2020) and local governments in China (Tan et al., 2021). But despite new resources from the energy transition, feedback effects are not always enough to overcome incumbent opposition and national political economy structures. Incumbents can also succeed in blocking reforms (see Mori, 2018 for the case of China), or dismantling RE policies altogether (see Gürtler et al., 2019 on the case of Spain and the Czech Republic; or Prontera, 2021 for the case of Italy). Successful change may depend on the distribution of resource effects: Lockwood (2015) argues that Germany’s largely positive policy feedback is due to the broader distribution of resource gains and therefore support, whereas in the UK benefits are captured by larger clean energy firms, resulting in stronger negative feedback.

Additionally, interpretive effects in the form of learning by policymakers have been observed. This can take the form of an iterative process, where policies encourage local benefits, which result in further recalibrations over time as authors observe in Australia (White et al., 2021). Policy learning is also identified as playing a role in Polish climate and energy policy, where positive implementation experiences (or the absence of negative experiences) led to support or acceptance for more ambitious EU policy (Skjærseth, 2018). In Germany, Meckling (2019) finds that policymakers continued to strengthen the 1990 feed-in tariff because of learning effects from industry development and job creation in renewables. In another instance of policy learning, Meckling points out that institutions to promote global renewable energy policy like IRENA grew from policymakers learning that their “ecological industrial policy” could be promoted globally, creating new export markets abroad (2019, pp. 11–12).

In sum, existing works suggest that resource and interpretive effects have impacted policy in certain countries. Building on these works, we posit that green growth leads to higher renewable energy policy ambition across cases and time. We also bring in an additional element based on the value chains literature: value chain position. So far, most studies look at feedback effects of renewable energy installment on policy expansion and stability (Rosenbloom et al., 2019; Schmidt et al., 2017; Sewerin et al., 2020). Focusing primarily on installment is a limitation because this does not take into account what we know from the global value chains literature: there are differences in value-added for different activities in value chains. We therefore argue that upgrading to manufacturing and innovation activities in particular has important policy feedback effects.

First, the overall magnitude of value creation and subsequent resource effects depends on the value chain segments involved. The difference in value-added between different activities in globalized industries is addressed by the body of work on global value chains (GVCs). This work is rooted in Marxist thought, following Hopkins and Wallerstein (1994) who argue that higher value-added activities are often retained in the core while lower value-added activities are outsourced to

[1] The concept of policy learning is not very clearly established in policy science, which often leads to ambiguities as the concept is described as having different qualities and logics depending on the institutional policy contexts they are embedded in (Dunlop and Radaelli, 2020). In this paper we draw on the definition of policy learning provided by Dunlop and Radaelli (2020:257) as “the updating of beliefs based on lived or witnessed experiences, analysis or social interaction”, which is “acted upon by policy actors”.

Fig. 1. The relationship between RE value chain changes and policy feedbacks.

the 'periphery'. In general, the least profitable part of the value chain is resource extraction, manufacturing ranges in the middle and the most valuable is research and innovation, product development and design (see for example Pipkin and Fuentes (2017); Gereffi and Lee (2012)).[2] In less hierarchical value chains, it is possible for countries or firms to 'upgrade' - that is, to improve their value chain position and "move from low-value to relatively high-value activities in global production networks" (Gereffi, 2005, pp. 171), thereby allowing them to gain more profits and knowledge. This can also be observed in the clean energy industry, where manufacturing and innovation have become very profitable activities. Firms that enter these segments can add more long-term, well-paid jobs and gain important skills or technologies allowing them to innovate (IEA, 2021; IRENA, 2020b). Manufacturing in particular has especially high employment effects (Llera et al., 2013), while rents from innovation are generally higher (Lachapelle et al., 2017). Firms that are active in these segments may therefore increase their resources, and influence policy processes. While not directly connected to the policy feedbacks literature, we see evidence of resource effects in the success of manufacturers promoting solar PV industry protection in the EU and US (Hughes and Meckling, 2017; Meckling and Hughes, 2018b) as well as in India (Behuria, 2020). In some cases, renewable energy industry actors were even able to push for new policies to be established: in China, Liu and Goldstein (2013) argue, specific policy support for solar was only introduced after manufacturing became an important export sector.

Second, there are important interpretive effects associated with the move to higher value-added activities, and the ensuing technological spillovers and development this upgrading can spur. The GVCs literature suggests that involvement in manufacturing and innovation activities can enable upgrading through technological advancements, and bring further development benefits (Amendolagine et al., 2019). Also in smaller developing countries, states aim to promote upgrading by offering support for key industries (Pipkin and Fuentes, 2017). This view of value chain involvement as reducing poverty and promoting development has been embraced by international institutions (Gereffi and Lee, 2012; and for a recent example, see Swinnen and Kuijpers, 2020). Similar narratives have emerged around renewable energy, which is seen as creating local value and development benefits; this may in turn encourage policymakers to increase their climate ambition (Lachapelle et al., 2017) and governments to act as 'green developmental states' (Meckling, 2018). Authors have noted that Schumpeterian framings of climate policies as jump-starting a "low-carbon industrial revolution" which should "create jobs, strengthen competitiveness and realize green growth" (Meckling and Allan, 2020, p. 436) often focus explicitly on upgrading strategies such as research and development subsidies. Changes in interpretative framings might be fostered by resource effects mentioned above that benefit the state budget, such as employment creation in "green jobs" or increases in a country's exports, and the economic and development potential of transitions (Gallagher, 2013; Schmidt and Sewerin, 2017). Here, governments appear more likely to support renewable energy policies if they see them as an economic opportunity (Gallagher, 2013). Put differently, policymakers' interpretations appear to result in policy change. This is also observed in the transport sector: as Meckling and Nahm (2019) argue, countries that see electric transportation as an opportunity to promote exports and industrial renewal introduce green industrial policies. Here it is important to note that, although certain actors may lobby for additional specific policies (R&D subsidies, support for electric vehicle infrastructure), they have in common that they benefit from overall increases in RE policy ambition.

In sum, we argue that upgrading in value chains has important resource and interpretive effects. Higher profits for industry allow them to organize and lobby for policy change; new and higher value-added jobs are created; these developments, combined with green growth framings, have interpretive effects. Therefore, we test the hypothesis that increased value chain involvement in the renewable energy industry leads to more ambitious RE policy.

While our econometric approach assesses only the relation between the beginning and the end of the outlined causal chain (see Fig. 1), the outlined theoretical framework offers a plausible causal pathway for policy feedback to occur based on the combined impact of resource and interpretive effects. In the following section, we present data and the methodology to test this hypothesis.

3. Methodology

We apply statistical reasoning to analyze the effect of value chain changes in the renewable energy sector on renewable energy policies. We control for factors that have been described in the literature as influencing both variables of interest. The section below describes the rationale for their inclusion and the data sources. Descriptive statistics of the variables can be found in the Supplementary Material to this article.

Value chain involvement is measured by manufacturing output in megawatts from 2008 to 2018 (BNEF, 2020) and R&D is measured by the number of new patents filed from 2008 to 2017 (IRENA, 2020a). The manufacturing data covers central components of solar and wind energy technologies; we used the nameplate capacity of nacelles in the wind sector and the aggregate production capacity of various solar cell components, covering crystalline silicon cells and modules, mono- and multi-crystalline silicon ingots, thin film (non) silicon modules and wafers.[3] Patent filing data is a common proxy for a country's activity in research and development (Dechezleprêtre et al., 2011; Lachapelle et al., 2017). For a better comparability across countries, we normalized the value chain data by taking the natural logarithm divided by the country's total population (World Bank, 2021).[4]

[2] It is beyond the scope of this paper to describe the breadth and depth of value chains research which has split into different schools emphasizing different parts of the puzzle of how global industries are organized (see also global supply chains, global production networks); and looks at many different industries – for an overview of the topic and an in-depth look at upgrading see for example Pipkin and Fuentes (2017).

[3] The manufacturing data covers less components in the wind than in the solar sector, which is why we might not be able to capture all the dynamics in the wind sector in this segment. This is also a reason why we abstained from a more granular comparative analysis of dynamics in both sectors. However, the dataset is the most complete renewable energy value chain data over multiple years and countries available; the aggregated data still provides a good overview of countries' changes in the production of the components covered; the general dynamics of upgrading depicted are in accordance with country and firm case studies describing more granular changes (Bazilian et al., 2020).

[4] As a robustness check, tests are run with both GDP-normalized and population-normalized variables; we found no significant differences between these measures.

Renewable energy policies are measured by the country score for renewable energy on the World Bank's Regulatory Indicators for Sustainable Energy (RISE) index (RISE, 2020). (e.g. Sy and Sow, 2019). Scores range from 0 to 100, where higher scores refer to more ambitious renewable energy policies. This proxy for renewable energy policy is made up of seven equally-weighted sub-indicators: legal frameworks for renewable energy, planning for renewable energy expansion, incentives and regulatory support for renewable energy, attributes of financial and regulatory incentives, network connection and use, counterparty risk, and carbon pricing and monitoring. Each sub-indicator is based on a series of detailed questions assessing policy and action.[5] While we acknowledge that this indicator has its limits – it does not capture every potential policy that could support renewables – it provides a measure of national policy ambition for a broad sample of 136 countries for the years 2010–2019, and has been used in other analyses of clean energy governance (e.g. Sy and Sow, 2019). As noted above, overall policy ambition is expected to be supported by coalitions who may have additional and more detailed policy goals.

Control Variables. To eliminate potential estimation biases in the analysis, we control for confounding variables that might affect both variables of interest: past renewable energy policies and fossil fuel rents. Controlling for previous renewable energy policies is important because of their potential impact on value chain position (see section 2), as well as path-dependency and policy stickiness (Kay, 2012; Rosenbloom et al., 2019). Fossil fuel rents are included as a control because they can strengthen the influence of incumbents who oppose more ambitious policies (Mori, 2018; Tørstad et al., 2020), and because economies depending on resource rents have lower industrial and R&D output generally (Williams, 2011). They are measured by the combined percentage of coal and oil rents of a country's GDP [6] (World Bank, 2021).

Country sample. Of the countries for which RISE data are available, 78 participated in manufacturing or patenting for multiple years. More countries were involved in R&D than in manufacturing (see Supplementary Material for categorization and full sample). Comparing countries which participate in value chains with those that do not, we find that countries that were not involved in manufacturing and patenting had significantly lower mean RISE scores (using the Welch two-sample T-test, $p = 0.0099$ and $p = 0.0000$ respectively). Given that these groups differ significantly, and we aim to understand the effect of change in position on policy, countries without any involvement in the studied timeframe are excluded from the sample. We observe that countries involved in manufacturing and R&D tend to be high-income, with some upper-middle income and lower-middle income countries as well. As described in the literature, more countries are involved in solar PV value chains than wind value chains.

Dynamic panel data analysis. We use the System General Method of Moments (GMM) estimator (Arellano and Bover, 1995; Blundell and Bond, 1998) to investigate the potential impact of value chain upgrading on renewable energy policies. This model is appropriate when there is a linear relationship between the variables of interest, which is the case for our data (see Supplementary Material Figs. 1 and 2). The GMM estimator is well suited for samples with a large number of countries and a few years, and has a lower bias and higher precision than OLS, static panel models or first-difference GMM estimators (Soto, 2009). It is useful for cross-country comparison because it allows for individual heterogeneity by including individual fixed effects, therefore eliminating time-constant unobserved effects such as cultural differences and particular structural characteristics of countries' economies. We also control for time fixed effects that affect all countries simultaneously. The system GMM model allows the dependent variable, renewable energy policies, to be dynamic and to depend on its own past realizations.

The estimation is based on the following equation:

$$Y_{it} = \beta_1 Y_{it-1} + \beta_2 Y_{it-2} + \beta_3 Y_{it-3} + \beta_4 X_{it-2} + \beta_5 C_{it-2} + u_i + d_t + \varepsilon_{it} \tag{1}$$

Y_{it} refers to renewable energy policies in country i in year t. X refers to renewable energy value chain involvement in country i in year t-2. C includes control variables while u_i refers to country fixed effects and d_t to time fixed effects; εi, is the error term. A significant positive coefficient β_2 indicates that a country's increased involvement in manufacturing or innovation would lead to more renewable energy policies, with a time lag of 2 years.

This time lag is based on theoretical expectations, as new resources from manufacturing or innovation take time to translate into lobbying actions and political decisions. This is confirmed by the correlations between lagged upgrading variables and renewable energy policies (Supplementary Material Figs. 3 and 4). Based on these tests, we chose a lag of two years in the manufacturing value chain segment and a lag of two, three and five years in the R&D segment. We adjusted the time lag for controls to the same year as the main variable of interest, with the exemption of previous RE policy levels, which always include the year prior to the reference year.

$Y_{it-(1-3)}$ is endogenous, implying that first differencing the above equation, to eliminate static, country-specific effects, yields the problem that the new error term is correlated with the lagged dependent variable. The difference and the system GMM estimator address this by introducing additional moment conditions. The system GMM estimator further adds instruments of variables in levels with lags of their first differences, based on the assumption that the differences of these variables and unobserved country specific effects are not correlated.

The system GMM estimator allows for autocorrelation within countries but not across them. The Arellano–Bond test for serial correlation

Table 1
System GMM results of the effect of changing value chain involvement on renewable energy policies.

Model	(1) Manufacturing	(2) Manufacturing	(3) R&D	(4) R&D
RE Policy (t-1)	0.886***	0.893***	0.930***	0.941***
	(0.101)	(0.109)	(0.068)	(0.069)
RE Policy (t-2)	−0.032	−0.035	−0.080	−0.077
	(0.074)	(0.075)	(0.068)	(0.069)
RE Policy (t-3)	−0.089	−0.084	−0.069	−0.072
	(0.064)	(0.064)	(0.045)	(0.045)
Manufacturing/ R&D output per capita (t-2) (log)	0.328** (0.142)	0.336** (0.151)	0.291*** (0.106)	0.295*** (0.106)
Fossil fuel rents (log)		−0.003 (0.007)		0.003 (0.003)
Constant	21.64***	21.94**	20.93***	19.38***
	(7.213)	(8.516)	(4.546)	(5.017)
Number of Observations	258	258	348	348
F Statistic	1342.08	1214.22	5526.93	5723.52
Groups/ Instruments	43/17	43/18	58/17	58/18
Hansen Statistic	0.364	0.323	0.742	0.68
AR (2)	0.607	0.603	0.524	0.552

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; year dummies included; Windmeijer corrected, robust standard errors in parentheses; p-values reported for AR(2) and Hansen test.

[5] For further information, see https://rise.esmap.org/indicators#pillar-renewable-energy.

[6] GDP itself is not included in our model because it is an integral part of what we aim to measure (how resource and interpretive effects shape policies). We acknowledge that GDP might foster industrial and R&D output by higher internal demand and influencing policy ambition as more resources for public policies are available (Tørstad et al., 2020). However, it is not included in our model as it is a mediator of the analyzed technology policy feedback effect: increased resources for industries based on increased manufacturing output in the renewable energy sector would also be depicted in a higher GDP and subsequent higher tax revenues might be a starting point for policy learning.

confirmed the absence of second order autocorrelation, and the Hansen test confirms the use of valid instruments (see Table 1). To avoid overfitting the model by too many instruments in the equation, which can result in biased results (Roodman, 2009), we limit the instrument for each variable and lag distance. Furthermore, we introduced robust standard errors to control for heteroskedasticity, after a likelihood ratio test.

4. Results and discussion

The model results indicate a significant positive effect of increased involvement in manufacturing and innovation in renewable energy value chains on renewable energy policy ambition with a time lag of at least 2 years. The effect of changes in the manufacturing value chain segment is larger than for changes in the R&D segment. These findings hold after additional robustness checks, such as adding control variables to the model, changing time lags, and rerunning the model with the independent variable of value chain participation normalized by GDP rather than population (see Supplementary Material Tables 3 and 4).

The table shows the results of four models of the relationship of value chain involvement to policy ambition. The regression coefficients represent the change in policy score associated with a given variable. Ceteris paribus, a 1% increase in manufacturing output is associated with a 0.0034 increase in the renewable energy policy score, while a 1% increase in patents is only associated with a 0.0029 increase (see Table 1, model 2 and 5). However, the latter coefficient increases if we consider a longer time difference between R&D growth and policy feedbacks: with a time lag of 5 years, a 1% increase in patents is associated with a 0.00415 increase in renewable energy policy scores (see Supplementary Material, Table 6).

The mean policy score rose in the period between 2010 and 2018 by 34.9 points. Based on the mean increases in the manufacturing and R&D sector between 2008 and 2016, this observed policy feedback effect explains 2.4% of the average policy change. As our dataset did not cover the full extent of value chain involvement in manufacturing and innovation (for example, further data on wind manufacturing beyond nacelles, or innovation activities not captured by patenting), and we did not analyze other value chain segments, such as the installment, maintenance and operation of renewable energy plants, the aggregated effect of involvement in all renewable energy value chain segments on policy ambition might be even larger.

Our results confirm the hypothesis that countries' increased involvement in higher-value segments of the clean energy industry (manufacturing and innovation) are associated with more ambitious clean energy policies. Out of the other factors that we control for, the previous year's policy was significant and positive, indicating that these pathways may be somewhat sticky; yet fossil fuel rents were not significant.

We additionally find that technology policy feedback effects differ based on the value chain segments involved. After two years, changes in manufacturing are associated with stronger feedback effects than changes for R&D. This could potentially be explained by higher employment effects associated with increases in the manufacturing value chain segment (Llera et al., 2013). Building on policy feedback theory, the group of actors benefiting from employment-based resource effects might be larger in this value chain segment, increasing their bargaining power in political processes. In practice, changes in the manufacturing sector have played a larger role for policy feedbacks, because the manufacturing sector has experienced stronger growth over the studied time (202,46%) than the R&D sector (46,87%). This makes growth from manufacturing more visible to policymakers and citizens and increases the interpretive feedback effects that 'green growth' brings. However, further research is needed to explain the longer time frames associated with policy feedbacks in the R&D sector.

These findings are consistent with previous case studies which highlight how growing renewable energy industries can use newly gained resources to strengthen their voice in political processes and achieve more ambitious renewable energy policies (e.g. see Michaelowa, 2005; Stokes, 2015). As the first large-N study on this matter, our findings point to feedback mechanisms being a more general pattern across countries. We add to the policy feedback literature by differentiating between resource and feedback effects that can occur from involvement in different value chain segments, with a particular focus on upgrading dynamics. Moreover, we are among the first to quantify the degree to which policy change can be explained by technology policy feedback mechanisms, highlighting the need for greater methodological plurality in this research field.

Our results have further implications for policy design. If policies manage to increase domestic value creation, this positive feedback mechanism could initiate a reinforcing cycle, as research on policy sequencing in climate policy suggests (Meckling et al., 2017; Pahle et al., 2018). The literature on upgrading highlights China's success as a key example. Its market size and stability made it an attractive location to produce both wind and solar energy technology; local firms with innovative capacities took advantage of knowledge spillovers to upgrade to new and profitable value chain segments (see Binz and Truffer, 2017). The advanced manufacturing sector for other products and relatively low labor costs for high skilled workers allowed for economies of scale to quickly develop for solar PV in particular (Lachapelle et al., 2017). This upgrading was not only due to firm capacities, but also to different forms of government support. The wind sector was directly supported in the form of creating domestic markets for installation, combined with local content requirements and pursuit of joint ventures; the solar industry received less direct support but nevertheless benefitted from general policies to encourage manufacturing (see Chen and Lees, 2016; Nahm and Steinfeld, 2014).[7] Following the growth of the clean tech industry and its importance for the export sector, authors have observed increased policy ambition (Liu and Goldstein, 2013) and even green industrial policy competition in new sectors such as electric transportation (Meckling and Nahm, 2019).

Yet China is arguably an outlier in terms of its market size and innovation capacities (see for example Steffen et al. (2018) - other countries that have aimed to gain local value through upgrading from manufacturing to R&D were less successful, for example South Africa (Baker et al., 2014; Bazilian et al., 2020). Therefore, this cycle might not be replicable in every country context, as upgrading in green industries is a complex puzzle involving enabling factors beyond policy support. Low-income countries are largely absent from the innovation and production of renewable energy technologies (Goldthau et al., 2020), which we also see in our data. The observed dynamic could thus increase an already existing gap between energy transition frontrunners and laggards (Quitzow et al., 2021). Additionally, negative feedback cycles, lowering the competitiveness of countries lagging behind a global energy transition might make it harder for countries to catch up and upgrade (Eicke and Goldthau, 2021). These dynamics highlight the importance of the distribution of gains and losses in the energy transition process on a national as well as on an international level for a just transition.

Our study its limited in that it only depicts the significant correlation between the beginning and end of the causal chain: technological changes and policies. Because variables can be correlated by chance, we take two commonly used criteria to establish causality: establishing a temporal sequence, and controlling for potential confounding variables (Oppewal, 2010). The study accounts for temporal sequence by adding lagged values of our value chain upgrading variables, and controls for

[7] Simplified for clarity – research on GVCs for wind and the interactions between Danish and Chinese firms suggest that while lead firms were often successful in protecting technologies from being transferred, their component suppliers were a link for tech transmission and upgrading (Haakonsson and Slepniov, 2018).

potential confounding variables by adding country and time fixed effects to our model design. These measures might have reduced potential sources of misinterpretation. However, the limitation remains that we cannot assess steps in between the beginning and the end of our causal chain in the same manner. Given that the RISE index is only a proxy for overall ambition, we also cannot explore in detail the ways in which changes in value chain involvement might result in more specific policy changes such as targeted support for manufacturers or research. Hence, our methodology is not able to prove resource or interpretive feedback effects. Yet, based on our theoretical framework, we offer a plausible causal interpretation for the effects observed in the global value chain literature and previous case studies of policy feedbacks.

Building on this analysis, further research combining policy feedback and global value chains literature could advance scientific knowledge on policy-technology interactions. We present three avenues for a future research agenda along these lines:

1) *Differences in feedback mechanisms based on value chain structure and position.* This study explored a relatively short time horizon in the life of a rapidly changing industry, and we cannot rule out that technology policy feedbacks weaken over time if resource effects also change. Given that certain value chain segments like manufacturing have lost importance in terms of value added in other industries (Driffield and Munday, 1998; Wolfe and Asch, 1992), we suggest future research to compare technology policy feedbacks associated with changes in different value chain segments across different sectors. This could include analyses of whether upgrading dynamics in the manufacturing sector results in different policy instruments that are tailored towards involved actors' specific interests, such as local content requirements.
2) *Differences of policy feedback mechanisms across different political economies.* Most studies exploring policy feedback dynamics focus on western democracies. Although our large N cross-country analysis and single case studies on policy feedback effects suggest that policy feedbacks occur across different political and economic systems, they might operate along different logics and trigger different dynamics. In certain contexts, policy makers may be less responsive to public opinion, but still influenced by changing coalitions especially in industries relevant for export growth. Comparative case studies should take into account institutional differences between countries (e.g. Lockwood, 2015), which we do not consider in our study's fixed effects model design. Such approaches could reveal additional country-specific dynamics but also shine light on potential similarities across countries along the lines of political economy contexts, for example in a varieties of capitalism framework.
3) *More interdisciplinarity and methodological plurality.* Further research on the mechanisms of value chain upgrading and policy feedbacks would benefit from interdisciplinary perspectives involving political science, economics, innovation and technology scholars as well as from plural methodological approaches. These approaches could include process tracing of concrete technology policy feedbacks to enhance understanding of the causal mechanisms at work or stakeholder interviews with actors from industry, government, and civil society involved in the process. Research on technology policy interactions would further benefit from more use of currently underrepresented quantitative approaches, which would benefit from grater data availability and transparency. Such approaches could include expert surveys among actors involved in these mechanisms, or further large N panel data studies, identifying significant drivers and patterns of policy technology feedbacks and quantifying their relative importance across sectors.

5. Conclusion and policy implications

Our exploratory and theory-testing study suggests that value chain dynamics in the renewable energy sector have implications for political processes and contributes a research framework combining literature streams on policy feedbacks and global value chains. We find that growth in manufacturing and R&D is associated with a higher ambition in renewable energy policies in subsequent years. We explain this by resource and interpretive policy feedback effects: actors benefiting economically from changes in value chain involvement invest these resources in political processes to foster favorable policies, and policymakers and civil society see renewable energy technologies as an opportunity for growth. These technology policy feedback effects differ based on the value chain segments involved. At least in the short term, growth in manufacturing is associated with relatively stronger policy feedbacks than growth in R&D, potentially due to larger employment effects. Also in absolute terms, growth in wind and solar energy manufacturing has been a more important driver of policy feedback effects than R&D.

Adding support to the previous empirical methods resting on case studies, we show that this dynamic is observable across countries. Our study is also the first to quantify this effect in a first large-N panel data analysis of technology policy feedbacks, covering 78 countries that manufacture and patent solar and wind technologies. Assuming the observed correlation can be attributed to policy feedback effects, this could explain 2.4 percent of the average policy change. With this, the study contributes to the scholarly understanding of the relationships between technological change and public policy and puts forward an interdisciplinary future research agenda.

The relationship between value chain involvement and renewable energy policies is relevant for policymakers as the world aims to slow emissions and avoid a climate catastrophe. Many stakeholders hope that the benefits of clean energy, especially local jobs and income, will increase support for renewables and for more ambitious climate policy in general (Helgenberger et al., 2017). Our study results confirm the importance of local value creation in energy transition processes, which can be fostered by a wide range of further policy instruments beyond those measured by the RISE index, such as the creation of joint ventures or local content requirements to increase local manufacturing (Chen and Lees, 2016; Nahm and Steinfeld, 2014). Accordingly, policymakers can enhance innovative capacity via public financing to scale up innovations, special research and training programs or international technology transfer and partnerships (Mazzucato, 2018). Given the right circumstances and preconditions for value chain upgrading, such policies could even foster the emergence of a reinforcing cycle of policy feedbacks, raising ambition in a sequence of policies. All in all, governments would be well advised to address the distribution of risks and benefits of the energy transition in their policy design, as local value creation can be a key component for promoting more ambitious policies in line with the Paris Agreement's 1.5 °C goal.

Funding statement

The research is funded by the 'Investigating the Systemic Impacts of the Global Energy Transition' (ISIGET) project under the "Make our Planet Great Again - German Research Initiative", grant number 57429628, which is financed by the Federal Ministry of Education and Research (BMBF) and implemented by the German Academic Exchange Service (DAAD).

Data availability

Data on value chain position were gathered from BNEF (2020) and IRENA (2020a) and are not publicly available. All other data used are publicly available, including RISE Indicators (2020) and World Development Indicators (World Bank, 2021).

CRediT authorship contribution statement

Laima Eicke: Conceptualization, Literature, Data curation, Visualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Silvia Weko:** Literature, Data curation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Sherry Towers, Andreas Goldthau, Jeffrey Verhey and Sebastian Kripfganz as well as the participants of an ECPR Joint Session on 'The Co-Evolution of Policy and Technology: Integrating a Technology Perspective into Feedback Theory' held between 24–26 May 2021 and the International Studies Association's General Conference 2021 for useful comments at previous stages of the research process.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2022.112948.

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