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Economic Impacts of Renewable Power Generation Technologies and the Role of Endogenous Technological Change

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Abstract

This paper brings together the debate on economic impacts of renewable energy (RE) deployment and the discussion on modelling endogenous technological change on the global markets for the different renewable power generation technologies. Economic impacts of RE deployment are still mostly discussed on national level, where different effects have been identified. Recent research for Germany shows positive effects on the macro level and different distributional impacts. High investment in solar photovoltaics (PV) from 2010 to 2012 and induced increases in the RE surcharge are the main drivers. At the same time, cost reductions for wind and solar PV take place on global markets, with global learning curves explaining the cost reductions very well. This calls for better including the international dimension into the modelling. The complex feedback loops between global cost curves and national policies, which react to global learning with some time lags, are not yet integrated into complex economic models. These models have to capture different RE technologies, different industries, either delivering the RE technologies or strongly depending on electricity prices, which are influenced by national support policies and macroeconomic development. As a first step to better understand the role of international markets, assumptions on RE exports based on global scenarios can be used. Results show the importance of global markets at least for the German RE industries. If the international dimension is taken into account, mainly positive economic impacts of further RE deployment can be observed.

Keywords

Renewable Power Generation Technologies, Economic Impacts, Global Markets, Learning Curves

1. Introduction

Renewable energy (RE) deployment is growing rapidly on a global scale. Non-hydro renewable power capacity

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has increased by a factor of seven in the past decade, with PV increasing by more than a factor of 50 and wind power with a factor of about 6.6 [1]. China, Germany, Spain and the US are among the countries with highest installed capacity of renewables. Regional shares of deployment have shifted from Europe towards Asia and America, with new players such as Japan in the installation top lists. In many countries, for instance in Germany, the large growth in renewable power generation capacities in the past has been mainly due to demand supporting policy measures such as feed-in-tariffs (demand-pull). In the future, increasing deployment will be accelerated by strongly decreasing costs of these technologies and by narrowing the gap to fossil fuel generation. Deployment, *vice versa*, leads to cost decreases via scale effects and learning curves capture this interdependence. Using this concept it is possible to—at least partly—endogenize technological change more precisely regarding renewable energy technologies in economic models. So far, technological change is either set exogenously (autonomous energy improving technological change), as for example in [2] or [3], or price-induced in economic models, see [4] for a review of modelling technological change in energy-environment-economy models.

Economic impacts of renewable power generation technologies (RPGT) deployment are often analyzed on a national level. International trade effects can be (some of) the most important drivers. Introducing or at least partly taking into account endogenous technological change is necessary to adequately analyze not only direct effects of technological change, but also the impacts on important macroeconomic indicators such as growth, employment, welfare and trade as well as their feedback to the electricity sector. This paper brings together two strands of research: the debate on economic impacts of renewable energy deployment and the discussion on modelling endogenous technological change. Section 2 describes economic impacts of renewable power generation technology deployment on a national level. Some general effects are discussed and recent research for Germany is summarized. Section 3 focuses on the global dimension and its application in modelling. Macroeconomic results are reported for scenarios with different assumptions of German RE exports showing the important role of the international dimension for the German case. In Section 4, some conclusions are drawn and further research needs are identified. The inclusion of global markets with export opportunities and cost decrease via global learning curves are important to fully understand the macroeconomic impacts of RPGT deployment. Different phases for renewable energy deployment have been identified. Future research will have to deal with specific technologies, their interaction with the electricity system, global deployment and learning curves, and the role of national support systems, taking the national share of fluctuating renewables into account, *i.e.* the specific phase of RE deployment and market integration.

2. Economic Impacts of RPGT Deployment: National Perspective

Economic impacts of an expansion of renewable power generation technologies are currently often discussed and modelled in a national perspective. Deployment of renewable energy in the electricity sector is associated with several effects, positive and negative, on the economy. Firstly, an increase in investment in new power generation technologies such as wind onshore and offshore or solar photovoltaics (PV) can be observed. On the grid level, an increase in volatile energy sources requires extension and adjustment on different levels. Part of the necessary investment into an enhanced grid has to be attributed to renewables. RPGT investment in many countries including Germany is supported by a feed-in-tariff, which is financed by a RE surcharge, paid by electricity consumers as part of the electricity bill. The RE surcharge (EEG) has increased substantially to more than 6 €Cent per kWh in Germany in 2015, about 20% of the household price for electricity.

Increasing shares of renewables in power generation and stagnating electricity demand lead to less generation from conventional power plants. The higher the variable costs of existing plants, the more likely they are mothballed and new investment is postponed. In the short run, flexible (fuel) costs in conventional power generation are reduced. Owners of conventional power plants face overcapacity, depreciation and economic loss. If additional investment in RE (and in grids and storage) is higher than reduced investment in conventional power plants, the (short-term) investment impulse will be positive. In the long term RE surcharge and electricity prices will increase. Early shut-down of existing power plants will reduce profits of their owners. **Figure 1** gives an overview of different impacts on the national level.

The national model PANTA RHEI, a macro-econometric model for Germany, has been applied to simulate the economic indicators for two scenarios: an energy transition (Energiewende EW) scenario, which shows what has been reached in the process thus far and what will be realized in the near future, and a counterfactual scenario (CF) to compare with. PANTA RHEI is an environmentally extended version of the econometric simulation and forecasting model INFORGE. A detailed description of the economic part of the model is presented in

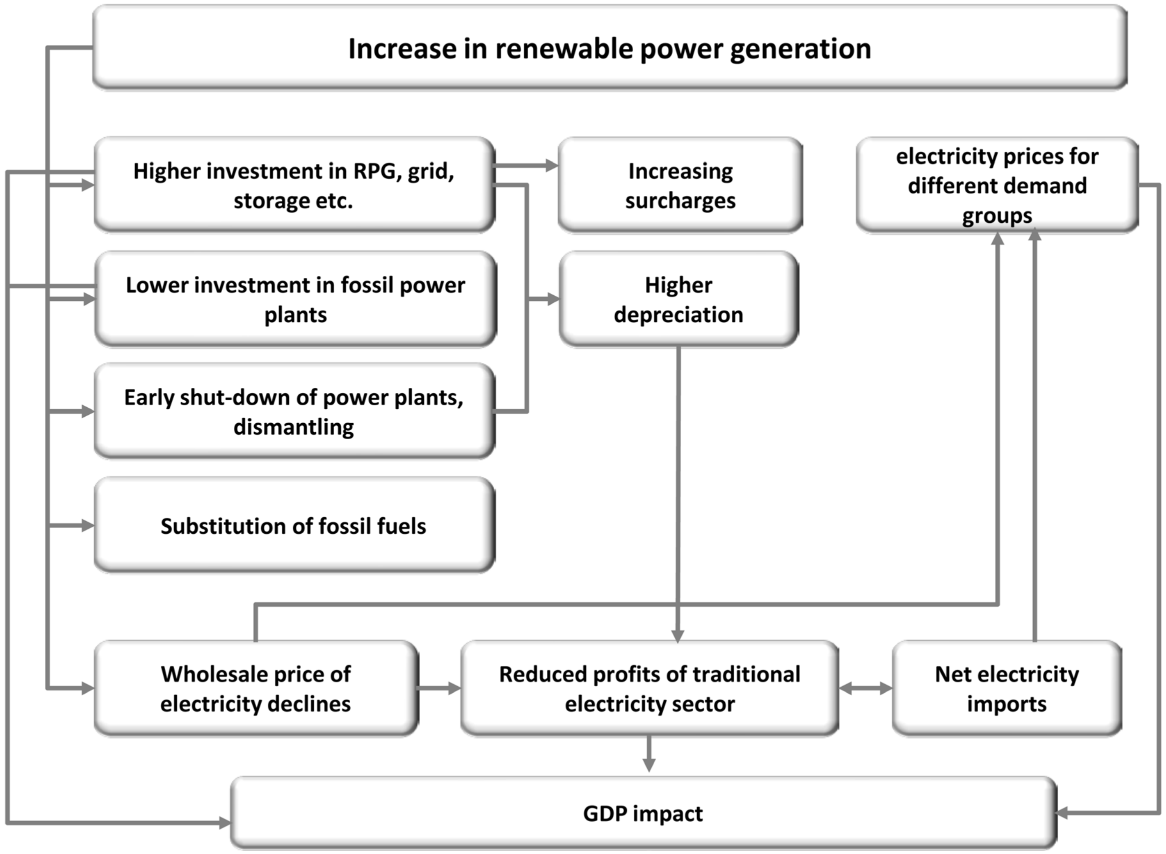

Figure 1. Macroeconomic effects of an increase in renewable power generation [5].

[6]. For more details of the extended model, see [7]. PANTA RHEI has been used to answer several questions on the economic effects of environmental policy instruments. In 2010, economic effects of different energy scenarios were compared to each other, which were the basis for the German energy concept [8], [9]. Recent applications include employment effects of the increase of renewable energy [10], and economic evaluation of climate protection measures in Germany [11]. In a recent overview [12] the model is classified as "input-output", but it is rather "econometric" plus "input-output", as parameters are econometrically estimated and input-output structures are flexible [13]. The overall approach is based on the INFORUM philosophy [14].

Table 1 shows economic impacts of current and expected domestic RPGT expansion and some energy efficiency measures (see [5] for more detail).The different stimuli in the two scenarios are reflected in the macroeconomic differences. Two phases can be observed. Ex post, until the year 2012, the expansion of RPGT dominates, driven by the expansion of PV. Ex ante from about 2015 onwards, energy efficiency measures as well as increased electricity prices primarily drive the macroeconomic effects in the EW scenario.

Especially through the significant investments made in the renewable energy sector from 2010 to 2012, the effects on GDP are markedly positive. Nevertheless, long-term financing via the RE surcharge leads to increased electricity prices in subsequent years for all consumer groups, except for the electricity-intensive industries. They are partly exempt from the RE surcharge and able to slightly benefit from the reduction of wholesale prices. The consumer price index rises significantly up to 2014 because of higher electricity prices. Production prices are also higher in the EW scenario than in the CF scenario. High deployment of RE induces additional employment from installation and production of the respective systems. Therefore, total (net) employment from 2010 to 2012 is higher than in the counterfactual scenario. In the EW scenario additional employment reaches 0.28% compared to the CF scenario, which translates into more than 100,000 additional jobs in 2011. However, increasing prices, rising wages and decreasing investment dynamics slow down the employment effects over time. Investments in the building sector create additional demand for construction activities and play an important role for the macroeconomic effects. In addition, the commercial sector contributes significantly with addi-

Table 1. Differences between selected macroeconomic variables in the EW scenario and the CF scenario, 2010-2020, in absolute terms [5].

	Absolute differences between "Energiewende" scenario and counterfactual scenario										
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	Ex post				Ex ante						
Components of priceadjusted GDP (differences in billion €)											
Gross domestic product	10.7	14.7	10.9	4.0	3.0	2.7	3.0	1.8	1.1	1.8	2.7
Private consumption	0.0	2.7	1.9	0.4	−1.2	−2.0	−2.5	−3.4	−4.4	−5.1	−5.3
Government consumption	0.0	−0.3	−0.1	0.0	−0.1	−0.1	−0.1	−0.1	−0.1	0.0	0.0
Machinery and equipment	9.5	10.1	6.8	1.8	0.7	0.6	0.3	−0.8	−1.2	−0.5	0.2
Buildings	4.5	6.2	5.6	2.8	3.7	3.9	4.7	4.4	4.4	4.8	5.1
Exports	0.4	0.1	−0.5	−0.9	−1.0	−1.0	−1.0	−0.9	−0.8	−0.6	−0.2
Imports	3.2	3.5	2.3	−0.5	−1.7	−2.1	−2.4	−3.3	−4.0	−4.1	−3.6
Price indices (differences in percentage points)											
Consumer price index	0.00	0.01	0.16	0.29	0.35	0.38	0.38	0.39	0.39	0.40	0.29
Production price index	0.01	0.05	0.23	0.34	0.39	0.40	0.39	0.38	0.36	0.34	0.23
Import price index	−0.03	−0.11	−0.10	−0.06	−0.09	−0.10	−0.12	−0.15	−0.18	−0.21	−0.27
Labor market (differences in 1.000)											
Employment	85.1	108.8	61.9	21.6	13.6	9.5	15.2	5.5	3.5	9.8	22.2
Unemployed persons	−54.4	−65.8	−36.8	−12.0	−7.0	−4.5	−8.0	−2.0	−0.8	−4.7	−12.3

tional investments in efficiency measures-especially in the building sector. Again, this supports the construction sector and leads to noticeable (cumulated) effects in subsequent years in the form of lower energy costs.

Private consumption is lower in the EW than in the CF scenario, mainly because expenditures for the increase of energy efficiency in buildings crowd out private consumption. Investment in construction increases in this scenario and consumption of other goods is reduced. However, no full crowding out is assumed, because energy efficiency investment is supported with the respective governmental programs. Not only investment in buildings is larger in the EW scenario, also investment in RE is slightly higher. This is counterbalanced by lower investment in conventional power plants, reflected in the row titled "Machinery and Equipment". GDP is higher in the EW scenario than in the CF scenario. The overall price level, which reacts delayed due to the design of the RE surcharge, remains consistently higher in the EW scenario than in the CF scenario because of the higher RE surcharge. The effects on the international competitiveness of German companies and on their exports are very low because of exemptions from the RE surcharge for electricity-intensive industries. Higher energy efficiency and ambitious renewable energy expansion lead to a smaller demand for fossil fuel imports. Employment is particularly higher in the early years of the energy transition as the expost analysis shows. This is mainly due to the increases in renewable energy, notably in PV. PV installations to a large extend are rooftop installed and thus rather labour intensive. Unemployment does not decrease by the same amount as employment increase. This is mainly for statistical reasons: not all additional employment is recruited from unemployed workforce and employment also includes the self-employed, which are not eligible for unemployment benefit and thus not included in the data on unemployment.

3. Economic Impacts of RPGT Deployment: International Dimension

In macro models the treatment of technological change is still a major source of cost differences of climate change mitigation [15], despite various research efforts in the last years. Most models compared in a study [16] set technological progress exogenously by assumption. Examination of the effects of public policies on innovation in the area of renewable energy in a cross-section of OECD countries over the period 1978-2003 finds that the empirical results indicate a strong influence of policies on innovation in renewable energy technologies [17]. A comparison of two CGE models with regard to the modelling of technical change (endogenous/exogenous) and the resulting effects on the impacts of carbon taxes on different industries is presented in [18]. The main finding is that endogenizing technical change using "gains from specialization" reveals dynamic growth patterns that cannot be reproduced in a model with exogenous technical change. Overviews on modelling technical change in growth theoretic models as well as large-scale econometric models can be found in [19] and in [4].

Most recent efforts to endogenize technological change in economic models of climate change mitigation abstract from specific technologies. Environmentally directed technological change in a simple one-good-two-sector growth model with environmental constraints is discussed in [20]. According to their analysis substitutability of clean and dirty inputs is very important to avoid growth losses. Optimal environmental policy includes carbon taxes and research subsidies. One major conclusion is that (p. 28) "it would be useful to develop a multi-country model with endogenous technology and environmental constraints," to discuss global policy coordination and to deploy the link between environmental and trade policy. In another paper researchers differentiate between price-induced, Research & Development (R&D)-induced and learning-induced technological change to be included in aggregate energy-environment models [21]. They identify a need for future research in the areas of modelling of policy instruments that are closer to the real world policy mix, progress on learning curve and directed R&D modeling. Directed technological change is additionally considered in [22], e.g. the support of clean technologies. Another author [23] distinguishes between four different types of learning (learning-by-doing, learning-by-researching, learning-by-using, learning-by-interacting) and economies of scale.

In the Gretchen project endogenous technological change for different RE technologies has been explicitly introduced in the global GINFORS_E model [24]. More detail about the model can be found in [25] and [26]. The renewable power generation module (RPGM) includes global learning curves for wind onshore and solar PV. Econometric estimations confirm the strong influence of global capacity development on technology costs. Specific investment costs on country level depend on public R&D and capacity development on national level. National capacity additions in turn depend on global prices, specific investment costs and national policies and economic development. While demand-pull policies enhance capacity installations, technology-push policies do not seem to have a significant direct influence.

In [24] a RPGT module for the INFORUM type econometric input-output models [27] such as GINFORS [26] or PANTA RHEI [10] is developed. The selected technologies are wind onshore and solar PV. Their costs follow global learning curves. These are estimated using data on specific costs, capacity installed and R&D. Both one factor and two factor learning curves are tested and compared to results of existing studies, see e.g. [28] for an overview. The learning curves reflect learning-by-doing, indicated by capacity installed, and both learning-by-doing and learning-by-searching, indicated by R&D spending (in case of one factor learning curves).

Technological change in RPGT occurs at different stages of the production chain and affects invention, innovation and diffusion. The learning concepts used in the analysis deal with the diffusion of the final RPGT at the macroeconomic level. The approach is a first step to endogenously determine the deployment of RPGT in macroeconomic energy-environment-economy models, additionally including the effects of policy measures. The theoretical construction of the renewable power generation module RPGM and its links to the energy module and the macroeconomic core model is explained in [24]. The empirical results presented in [29] only apply the RPGM for Germany. Using projected global capacity development and corresponding cost reductions the results confirm the overshooting of PV installations in Germany without additional policy measures adopted in 2014. They also suggest that the deployment of wind power capacity will be much more moderate. Explicitly including different elements of the policy mix in the model makes it possible to analyze the effect of policy instruments on RPGT deployment.

Quickly emerging RPGT also drive structural change in the economy. There is increasing investment in these technologies, while capacity utilization of conventional power plants is reduced. New, partly international, production chains develop. To adequately account for these changes, input-output structures for the RPGT have been implemented in the model, based on a comprehensive industry survey and earlier work [10]. This kind of enlarged macro model with an input-output core is able to take these changes towards renewable power generation into account. In addition to the obvious, and in the short term positive investment effect of increased RPGT installation and additional operation and maintenance during its lifetime, economic structures change towards the new technologies and industries such as machinery and electrical machinery, delivering major components for PV and wind turbines. In a macroeconomic perspective this is especially important, if import and export relations change. This international trade effect can be a major source of positive or negative impacts. It does not only include the installations itself, but also the reduced need of fossil fuels has to be accounted for. Negative effects mainly stem from price increases, often due to renewable energy surcharges to bring the RPGT into the market. Investment in conventional power plants will also be lower.

Developing a fully endogenized global model with country and technology details remains an enormous challenge, however. National RE support policies interact with global technology deployment. This process is by far more complex to understand and to model than global learning curves alone. National policies adjust support schemes to cost changes with some time lags. Modelling these discrete feedback mechanisms by technology at least for the most important countries will be an enormous challenge beyond the scope of the Gretchen project.

To further improve modelling of net economic impacts of an increase in renewable power generation, it is important to understand how strongly different drivers are related to endogenized technological change. Assumptions on future development of exports of RPGT are the most important driver for future economic net impacts in national studies [10], [30]. They depend on new installations in foreign markets, which are driven by global learning and national support policies.

Figure 2 describes three different development paths for German exports of RPGT. They are derived from a detailed analysis and forecast of global RPGT market developments [30]. Obviously, a broad corridor for future export opportunities for German companies is assumed. Scenario A is based on an update of the Energy [R]evolution Scenario for the global deployment of RPGT [31]. German trade shares for RPGT are set constant in the future to their levels of 2012, however, trade volumes in the markets drop significantly. This is due to a regional shift of installations from Europe to Asian and North American countries. Regarding the wind turbine or the PV module, production will follow the regions of largest deployment in the long run. However, production of more complex components and production machinery will still largely remain in Germany and be exported. For a more elaborated view on export opportunities along the value chain, see [32]. In the optimistic scenario A German RPGT exports more than double between 2010 and 2020 from 10.3 to 25.4 billion €. They reach their maximum in 2040 with more than 30 billion €. Scenario B builds on scenario A, but is less optimistic about German world market shares. German export shares are 30% lower compared to scenario A. Total RPGT exports will increase to 16.8 billion € in 2020 and remain stable at this level until 2050, with a peak in 2040 with 20.1 billion €. Scenario C is based on the Current Policies Scenario (CPS) of the [33] World Energy Outlook, which assumes a limited deployment of RPGT. German exports will drop to only 5 billion € in 2020 (from 10.1 billion € in 2010) and remain below historic levels throughout the projection period until 2050.

To describe the range of possible future scenarios for German RPGT exports and their macroeconomic impacts, **Figure 3** shows net employment effects of additional exports in the three different scenarios against a baseline scenario with very low RPGT exports. For understanding the economic effects it is important, that in-

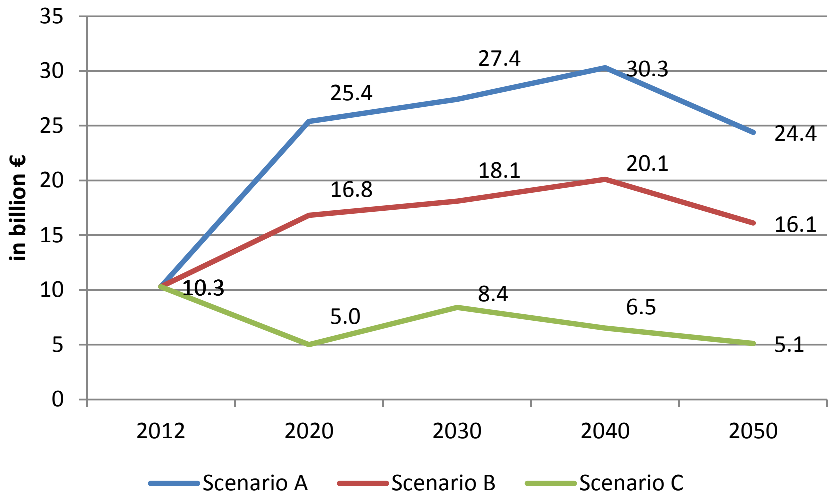

Figure 2. German RPGT exports in the three scenarios in billion € [30].

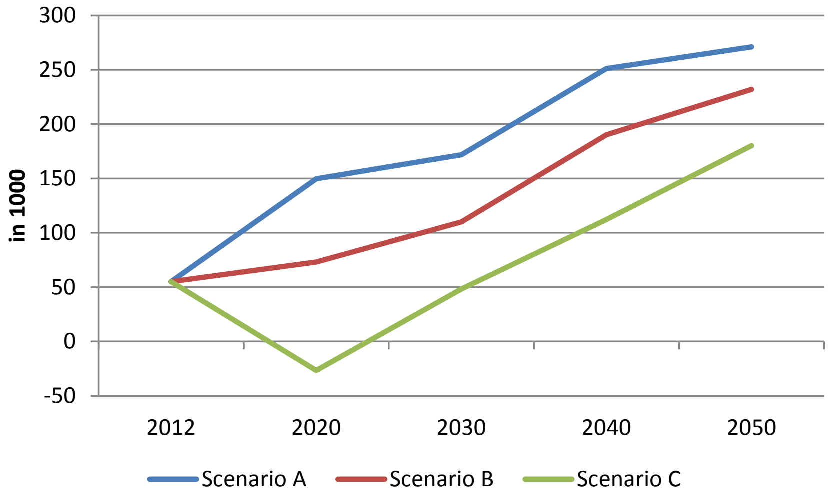

Figure 3. Net employment effetcs of different export scenarios in 1000 [30].

stallations abroad are not linked with costs for the German electricity system. Additional exports will increase demand in the short term, and, in contrast to domestic installations, do not have cost and price effects—or continuous demand effects through maintenance—in the long run. In scenario C with limited increase in global RPGT installations according to [33] Current Policies Scenario, economic impacts will be negative in the short term, but again positive from 2030 onwards. Higher prices for electricity until 2030 and job losses in the conventional power industry outweigh additional exports and related new jobs in the RPGT delivering industries at first. Scenarios A and B with higher export activity have positive effects on the German economy in the near future already. Additional exports more than balance negative cost effects. In 2030 and later, when the costs for the RE surcharge drop significantly, net employment of additional RPGT deployment is considerably positive in all scenarios.

4. Conclusions and Outlook

Economic impacts of an expansion of renewable power generation are mostly still discussed and modelled in a national perspective. Economic impacts of RE deployment are then dominated by investment shifts from conventional power plants to renewables in the short term. In the longer term, they depend on differences in electricity prices, the design of the support mechanisms and global fossil fuel prices. Costs for solar PV have been high a few years ago and dropped strongly, due to scale effects from large deployment and overcapacity from anticipated larger deployment. Onshore wind is already competitive to fossil electricity production in many high wind speed areas, while other technologies such as wind offshore are still rather expensive. Impacts of an RE increase are diverse with various distributional implications.

It is important to take the international dimension into account. In the Gretchen project, endogenous technological change has been explicitly introduced in the global GINFORS_E model. The renewable power generation module includes global learning curves for wind onshore and solar PV. Econometric estimations confirm the strong influence of global capacity development on technology prices. Specific investment costs on country level depend on public R&D and capacity development on national level. National capacity additions in turn depend on global prices, specific investment costs and national policies and economic development. While demand-pull policies enhance capacity installations, technology-push policies do not seem to have a significant direct influence.

Developing a fully endogenized global model with country details remains an enormous challenge. National RE support policies interact with global technology deployment. These feedbacks between global learning and discrete national policy adjustments are very complex and vary between different technologies. They also depend on different phases of RE deployment. Assumptions for global market development are a means to partly describe these processes in a simplified way, until more complex feedbacks will be understood and adequate modelling will be available for different technologies.

Based on assumptions on three different development paths for German exports of RPGT, modelling results show positive macroeconomic effects of German RE deployment in the long term. In the near future, cost increases due to the RE surcharge may outweigh positive investment and export effects in the case of a weak global RE deployment. The IEA highlights the different phases of wind and solar PV deployment, which require specific policy design on the national level according to the stage of RE deployment [34]. According to their analysis, Germany is on the way from policy-driven deployment to integrated frameworks, where a coherent and comprehensive policy approach is needed. The inclusion of storage technologies will be important.

Including global markets with export opportunities and cost decrease via global learning curves is important to fully understand the macroeconomic impacts of RPGT deployment, especially for the later stages of policy-driven deployment and market integration. Future research will have to deal with specific technologies, their interaction with the electricity system, global deployment and learning curves and the role of national support systems. The markets will have to be adjusted and closely monitored to support full market integration of renewables and to sustain the positive macroeconomic effects of their deployment.

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