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Can Technology-Specific Deployment Policies Be Cost-Effective? The Case of Renewable Energy Support Schemes

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Abstract: While there is relatively limited disagreement on the general need for supporting the deployment of renewable energy sources for electricity generation (RES-E), there are diverging views on whether the granted support levels should be technology-neutral or technology-specific. In this paper we question the frequently stressed argument that technology-neutral schemes will promote RES-E deployment cost-effectively. A simple partial equilibrium model of the electricity sector with one representative investor is developed to illustrate how the cost-effective support levels to different RES-E technologies will be influenced when selected market failures are introduced. We address market failures associated with technological development, long-term risk taking, path dependencies as well as various external costs, all of which drive a wedge between the private and the social costs of RES-E deployment. Based on these analytical findings and a review of empirical literature, we conclude that the relevance of these market failures is typically heterogeneous across different RES-E technologies. The paper ends by discussing a number of possible caveats to implementing cost-effective technology-specific support schemes in practice, including the role of various information and political economy constraints. While these considerations involve important challenges, neither of them suggests an unambiguous plea for technology-neutral RES support policies either.

Keywords: Technology deployment; renewable energy sources; support schemes; cost-effectiveness.

JEL Codes: H23, O33, Q42.

1 Introduction

To facilitate a transition towards sustainable modes of economic development, green technologies are needed. Compared to conventional technologies, green technologies allow attaining a certain level of economic development at a reduced level of resource use and environmental impacts. It is a major concern of environmental and energy policies to safeguard that investments in green technologies occur at an appropriate level. In this respect, a decisive question faced by policy-makers is whether to implement technology-neutral or technology-specific policy approaches to spur the development and deployment of green technologies (Aghion et al. 2009; Rodrik 2014). Technology-neutral policies may refer, inter alia, to policy options pricing environmental externalities (e.g. by emissions taxes or emissions trading schemes) or generic subsidies to research and development (R&D) and/or technology deployment. In contrast, technology-specific policy approaches promote selected technological fields, sectors or even projects based on differentiated support levels (e.g., feed-in tariff schemes, specific R&D subsidies etc.). In this paper, we aim to shed light on this policy issue by making reference to the case of promoting electricity generation from renewable energy sources (RES-E).

Virtually all EU Member States have implemented RES-E support schemes. Most of these schemes grant technology-specific subsidies (e.g., Kitzing et al. 2012). That is, they differentiate subsidies (per MWh) to RES-E plants on the basis of the energy source used, the technology employed, the size of the plant, or the location of the plant (or a combination of these considerations). However, technology-specific RES-E support has faced increasing critique. Several studies argue that such a policy approach makes the attainment of RES-E deployment targets more costly (Fürsch et al. 2010; Frontier Economics 2012; Frontier Economics and r2b 2013; Jägemann et al. 2013; Frontier Economics 2014; Jägemann 2014). In turn, technology-neutral approaches to RES-E support, which thus abstain from differentiating the support based on technology, have been praised for their cost-effectiveness as they promote the deployment of the least costly technologies first. The recommendation to switch from technology-specific to technology-neutral support to increase the cost-effectiveness of RES-E support has also entered the guidance documents of the European Commission (European Commission 2013c; European Commission 2013b; European Commission 2013a) as well as of national advisory councils (for Germany, see e.g., Monopolkommission 2011; Monopolkommission 2013; SVR 2014). In this paper we aim to provide a critical examination of this policy recommendation, and more specifically scrutinize a number of potential rationales for relying on technology-specific policy approaches to increase the cost-effectiveness of RES-E deployment.

The promotion of technology-neutral RES-E support schemes rests on two important assumptions: (a) market failures associated with the development and diffusion of RES-E technologies are absent, or are properly addressed by other policies; and (b) the costs of renewables deployment beyond the private generation costs – e.g., system integration costs and environmental costs – are irrelevant for RES-E policy design because they are either homogenous across RES-E technologies or properly internalized by other policies. Consequently, under these assumptions RES-E technologies can be expected to compete among each other efficiently on the basis of their total social generation costs, and there would be no need for differentiating the support across these technologies in order to attain a certain RES-E target. Our analysis essentially addresses the question of how the cost-effective choice between technology-specific and technology-neutral RES-E policies can be affected once these assumptions are relaxed.

To guide and illustrate our analysis, we develop and employ a simple partial equilibrium model of the electric power sector with one representative RES-E investor. In the benchmark case, i.e., in the absence of any market or policy failures, this model replicates the finding that technology-neutral support provides a cost-effective deployment of RES-E generation. Subsequently, however, as selected market and policy distortions are introduced, the model analysis reveals that technology-specific support may perform better in terms of cost-effectiveness. We focus on different types of market failures. First, RES-E technology development and diffusion may be hampered by: (a) the knowledge spillovers related to technological learning; (b) investment uncertainties combined with risk aversion, capital market failures and regulatory constraints, and (c) path dependencies biasing innovation and development activities towards the dominating energy sources. Our modelling of these market failures is in part inspired by qualitative insights from the innovation system literature. This research emphasizes the role of RES-E policies for promoting technological development, and it often endorses the use of technology-specific policies given that different technologies tend to face unique learning processes, bottlenecks etc. (Aghion et al. 2009; Azar and Sandén 2011; Jacobsson and Bergek 2011). Moreover, RES-E investments may also be distorted by the presence of external environmental and system integration benefits and costs, whose magnitudes will often differ across technologies.

For each of the above market failures we also briefly comment on some of the existing empirical evidence to verify whether or not the preconditions for technology-specific support are likely to be satisfied in practice or not. This requires both an assessment of the importance of each of the above market failures, as well as of the extent to which existing policies have been able to address each of these. Finally, the paper ends by discussing a number of potential caveats to the implementation of technology-specific support that may arise in practice. For instance, policy decisions on technology differentiation may be distorted by imperfect information as well as politico-economic constraints related to, among other things, distributional impacts and associated lobbying efforts of interest groups. Eventually, regulators therefore face the challenge of picking (wrong) winners.

Our paper is in part related to the ongoing debate on whether climate policies, such as carbon taxes or emissions trading, should be complemented by RES-E policies and targets. This is in fact also a discussion about technology-neutral (e.g., carbon trading) versus technology-specific (e.g., RES-E support) policies, and about the extent to which these two policy approaches should be substitutes or complements (Sijm 2005; e.g., Bennear and Stavins 2007; Söderholm and Klaassen 2007; Fischer and Preonas 2010; Lehmann 2012; Lehmann and Gawel 2013). The research on this issue suggests that carbon pricing needs to be complemented with public R&D and technology deployment policies. RES-E support schemes may often constitute an important component of this policy mix, but we go beyond these analyses by asking whether these schemes should in turn differentiate across various RES-E technologies to promote a cost-effective deployment path over time.[1] Indeed, our analysis

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[1] The choice between a generic (technology-neutral) and a more specific innovation policy is discussed also in Aalbers et al. (2013) and Nordhaus (2011), but in both these cases with a focus on the diversification of public R&D support.

illustrates that the potential benefits of technology-specific RES-E support schemes are in many cases directly related to the economic rationales for implementing RES-E deployment policies and targets in the first place.

The remainder of our paper is organized as follows: Section 2 introduces the analytical model and discusses the benchmark case in which a technology-neutral RES-E support is found to stimulate a cost-effective deployment of these energy sources. Section 3 then uses this model to illustrate some potential benefits of technology-specific RES-E support that arise once selected market and policy failures are taken into account. Section 4 discusses possible caveats to getting a technology-specific policy design right in practice, while section 5 concludes the paper.

2 Analytical Model and Benchmark Case

In order to illustrate RES-E generation decisions and the corresponding policy implications for cost-effective RES-E support design, we develop a simple partial equilibrium model with a representative firm in the renewable electricity sector. The model has two periods $t = (1,2)$. Power generation from renewable energy sources occurs in both periods. There is discounting at the rate $\delta = (1+r)^{-1}$, with $\delta \in [0,1]$, between the two periods.

In both periods the representative firm may generate renewable electricity x_t^i, where superscript i denotes available types of RES-E technologies. For illustrative reasons, we assume that there are only two RES-E technologies available, i.e., $i = (w, p)$, representing wind power (w) and solar photovoltaics (PV) (p). Generation costs in period 1, i.e. $c_1^i(x_1^i)$, are simply a function of the respective levels of electricity generation x_1^i (e.g., in MWh). RES-E generation costs in period 2 are a function of both the generation in the same period and electricity generation in period 1: $c_2^i(x_2^i, x_1^i)$. The costs of generating RES electricity in one period are increasing and convex in generation of the same period, i.e., $\partial c_t^i / \partial x_t^i > 0$ and $\partial^2 c_t^i / \partial x_t^{i2} > 0$. The inter-temporal effect is incorporated to account for the possibility that RES-E generation in period 1 generates learning effects, i.e., tacit knowledge acquired through manufacturing and/or improvements in the technology as a result of feedback from user experiences. We therefore assume that the generation costs in period 2 are decreasing and convex in the generation of period 1, i.e. $\partial c_2^i / \partial x_1^i < 0$ and $\partial^2 c_2^i / \partial x_1^{i2} > 0$. We further assume the existence of a social planner, which aims to attain a certain RES-E target $\bar{Z}$ in period 2 at least total cost, C. The social planner's optimization problem can thus be expressed as:

$$\min C = \sum_i c_1^i(x_1^i) + \delta \sum_i c_2^i(x_2^i, x_1^i) \qquad (1)$$

subject to:

$$\bar{Z} = \sum_i x_2^i \qquad (2)$$

This optimization problem can be rewritten using the Lagrangian approach:

$$\min \Lambda = \sum_i c_1^i\left(x_1^i\right) + \delta \sum_i c_2^i\left(x_2^i, x_1^i\right) + \lambda \cdot \left(\bar{Z} - \sum_i x_2^i\right) \qquad (3)$$

The corresponding first-order conditions for minimizing total costs of attaining the second-period RES target are:

$$\frac{dc_1^i}{dx_1^i} = -\delta\frac{\partial c_2^i}{\partial x_1^i} \tag{4}$$

$$\delta\frac{\partial c_2^i}{\partial x_2^i} = \lambda \tag{5}$$

Thus, in order to ensure that the RES target is met, the regulator introduces subsidies to both types of RES generation, $s_t^w$and s_t^p (per MWh) in both periods. For simplicity, we assume that this subsidy is a fixed feed-in tariff introduced not in addition to but instead of the market remuneration, an approach that exists in many EU Member States (Kitzing et al. 2012).[2] The resulting optimization problem for the representative firm in the RES-E sector maximizing its profit π is:

$$\max \pi = \sum_i s_1^i x_1^i - \sum_i c_1^i\left(x_1^i\right) + \delta\left[\sum_i s_2^i x_2^i - c_2 \sum_i\left(x_2^i, x_1^i\right)\right] \tag{6}$$

The corresponding first-order conditions for maximizing the firm's profit are then:

$$\frac{dc_1^i}{dx_1^i} = s_1^i - \delta\frac{\partial c_2^i}{\partial x_1^i} \tag{7}$$

$$\frac{\partial c_2^i}{\partial x_2^i} = s_2^i \tag{8}$$

Substituting eqs. (7) and (8) into (4) and (5) reveals that in a cost-effective setting (a) no subsidies should be paid in period 1, i.e., $s_1^w = s_1^p = 0$; and (b) the subsidy paid in period 2 should be technology-neutral equaling the compounded shadow price on the RES target, i.e., $s_2^w = s_2^p = \lambda/\delta$. In this setting, firms properly account for (differences in) inter-period learning effects because they are perfectly aware of these effects and can fully appropriate the corresponding cost decrease in terms of a profit increase in period 2.

Figure 1 illustrates the cost-effectiveness of technology-neutral RES-E support, and the excess cost of technology-specific support under the above assumptions. Technology-neutral RES-E support attains the RES-E target $\bar{Z}$ in period 2 by an optimal allocation of wind power and solar PV deployment (x_2^{w*},x_2^{p*}), this since it ensures that the marginal generation costs are equalized. The same target $\bar{Z}$ could of course also be reached through the use of technology-specific RES-E subsidies. Following the graphical example In Figure 1, the specific subsidy to wind ($s_2^{w}{}'$) could be set below and the subsidy to solar PV ($s_2^{p}{}'$) could be set above the technology-neutral rate. This is an option of technology differentiation existing in many EU Member States (Kitzing et al. 2012). In this specific case wind power deployment ($x_2^{w}{}'$) would be lower and solar PV deployment ($x_2^{p}{}'$) higher than in the technology-neutral case. The marginal generation costs of these deployment levels would then vary across RES-E technologies, and in Figure 1 the resulting excess cost of technology-specific RES-E support is highlighted by the grey-shaded triangle.

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[2] Discussing a premium tariff paid in addition to the market electricity price instead of a fixed feed-in tariff would only partly affect our analysis. In this case, most of the arguments discussed in the following would similarly imply a differentiation of the premium. Yet, making the market electricity price part of the remuneration received by RES-E operator may internalize some of the system integration costs discussed in Section 3.4, to the extent these are reflected in market prices.

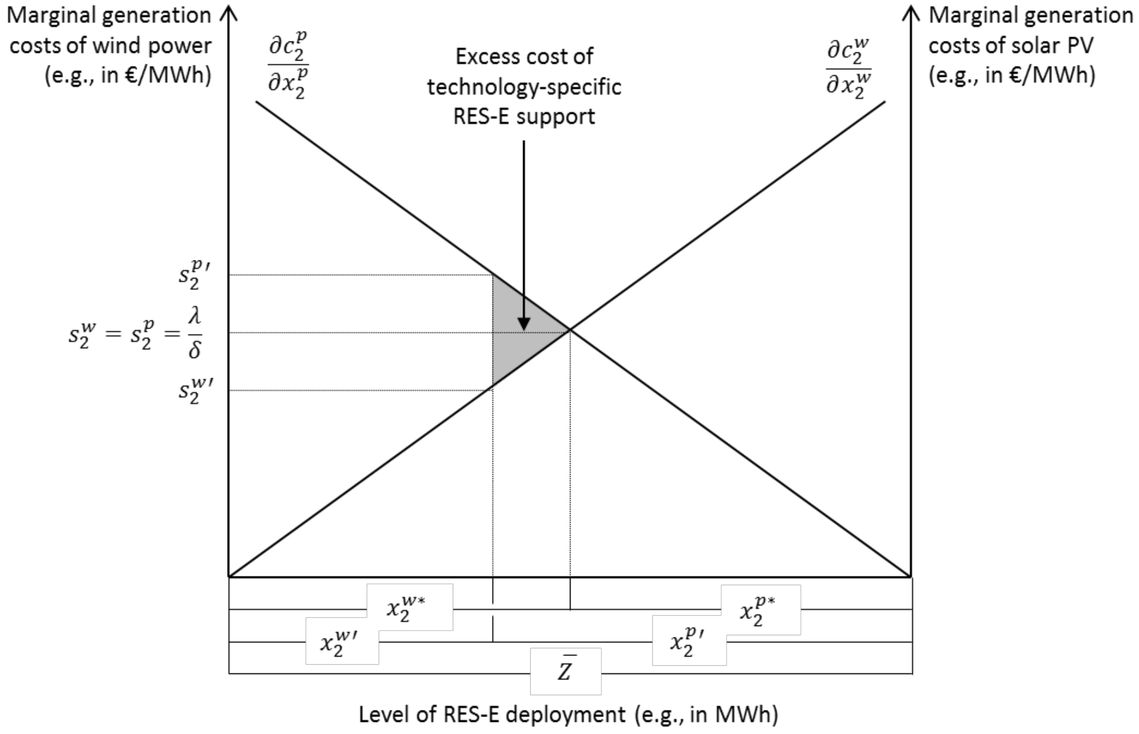

Figure 1: Excess cost of technology-specific RES-E support in period 2: benchmark case

3 Benefits of Technology-Specific RES-E Support

This section discusses the possible benefits of technology-specific RES-E support from a cost-effectiveness point of view. These benefits will need to be compared to the excess costs of technology-specific support outlined in the previous section to decide whether or not technology differentiation may actually increase the cost-effectiveness of RES-E support.

3.1 Knowledge Spillovers Related to Technology Learning

In the basic model, it is assumed that the benefits of learning in terms of generation cost reductions in period 2 are purely private, i.e., they can in their entirety be appropriated by the single RES-E generator. However, at least a part of the new knowledge created through learning may also spill over to other generators, which can appropriate this knowledge at a low (or even zero) cost. Such learning-generated knowledge spillovers can arise due to, for instance, personnel movements and communication between firms, joint participation in meetings and conferences, or so-called ‘‘reverse engineering’’ (Argote and Epple 1990; Irwin and Klenow 1994). Certainly, patents protecting intellectual property rights (IPRs) may be considered a first-best approach to address the presence of knowledge spillovers. However, the patent system is often subject to important limitations. For instance, RES-E technologies typically “consist of a large set of components and require the expertise of several companies to improve the system. A consortium will face difficulties in sharing the costs of ‘learning investment’, as it is difficult to negotiate and fix the allocation of future profits,” (Neuhoff 2005, , p. 98). Moreover, IPR policies may even slow down the deployment of some RES-E technologies by creating a bias towards the development of close-to-commercial technologies.[3] Under these circumstances, it may be worthwhile to consider policy options that rely on differentiated RES-E support schemes.

Following Fischer and Newell (2008), knowledge spillovers related to learning can be incorporated into our model through a spillover rate ρ^i, with $\rho^i \in [0,1]$, which represents the reduction in period-2 generation costs that can actually be appropriated by the firm generating the learning effect. This rate is allowed to be technology-specific. Correspondingly, the period-1 first-order condition (7) for the representative firm can now be rewritten as follows:

$$\frac{dc_1^i}{dx_1^i} = s_1^i - \delta\rho^i \frac{\partial c_2^i}{\partial x_1^i} \tag{9}$$

Substituting eq. (9) into (4) gives following the cost-effective subsidy in period 1 in the presence of knowledge spillovers related to learning:

$$s_1^i = -\delta\left(1-\rho^i\right)\frac{\partial c_2^i}{\partial x_1^i} \tag{10}$$

Eq. (10) illustrates that now the RES-E subsidy in period 1 is positive, reflecting the share of period-2 generation cost reductions that cannot be appropriated by the firm generating the learning effect. Moreover, this subsidy needs to be technology-specific if the RES-E technologies are heterogeneous in terms of: (a) the degree of learning, i.e., if $\partial c_2^w / \partial x_1^w \neq \partial c_2^p / \partial x_1^p$; and/or (b) the degree of learning spillovers, i.e. if $\rho^w \neq \rho^p$.[4]

These preconditions for technology-specific RES-E schemes – variations in the significance of both learning and knowledge spillovers – are likely to be met in practice. In fact, previous studies suggest that the innovation systems surrounding RES-E technologies tend to be technology-specific. The different technologies are exposed to fairly unique and multi-dimensional growth processes, e.g., in terms of bottlenecks, learning processes, the dynamics of the capital goods industries etc. (Jacobsson and Bergek 2011; Hoppmann et al. 2014). For instance, the technological progress of wind power has mostly been driven by turbine manufactures and the existence of strong home markets, while equipment suppliers and manufacturers that produce their own equipment have dominated solar PV development. This is, for instance, likely to have created different conditions for producer-user interactions and feedbacks, in turn influencing the presence and the magnitude of learning spillovers.

The heterogeneity of RES-E technologies in terms of the rate of learning has also been confirmed in quantitative empirical work. Even though the actual level of learning rates is debatable (Nordhaus 2014),[5] there is overwhelming evidence that these rates are positive and varying across technologies

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[3] One potential reason for this is put forward by Budish et al. (2015). These authors note that while patents award innovating firms a certain period of market exclusitivity, the effective term may be considerably shorter since some firms choose to file patents at the time of discovery rather than at first sale. This implies that the patent system may provide meager incentives for firms to engage in learning about technologies that have a long time between invention and commercialization.

[4] Kverndokk and Rosendahl (2007) and Lehmann (2013) also confirm this finding in more complex modelling settings.

[5] Empirically it remains very difficult to separate learning-by-doing from exogenous technological change and economies of scale (see also, Söderholm and Sundqvist 2007). For instance, significant advances in solar PV

(for overviews, see IEA 2000; McDonald and Schrattenholzer 2001; Rubin et al. 2015). Table 1 summarizes the results from a recent literature review of empirical estimates of RES-E learning rates, which indicate how much the generation costs decline in percentage terms with every doubling of cumulative production or capacity installed. Although these figures illustrate considerable uncertainties concerning the magnitude of the respective learning rates, they also show evidence of important differences across, for instance, wind power and solar PV.

	Range of learning rates
Wind (onshore)	-11% - 32%
Solar PV	10% - 53%
Biomass	
• Biomass production	20% - 45%
• Biomass power generation	0% - 24%
Hydropower	0% - 21%

Table 1: Range of learning rates reported in empirical studies. Source: Rubin et al. (2015).

There is less empirical work, though, examining the knowledge spillovers relating specifically to learning with RES-E technologies – even though *s*uch spillovers have been found to be significant for non-renewable energy technologies (Zimmerman 1982; Lester and McCabe 1993) and manufacturing in general (Argote and Epple 1990; Irwin and Klenow 1994). However, knowledge spillovers have been affirmed to exist and be technology-specific in the case of research and development (R&D) in RES technologies (Popp 2002; Braun et al. 2010; Noailly and Shestalova 2013).

Noailly and Shestalova (2013) find that RES technologies do not only differ in the level of spillovers but also in the type of knowledge spillovers. They measure knowledge spillovers by counting citations of patents by other successive patents, assuming that more frequently cited patents have a higher value to society.[6] This approach can be used to pick up spillovers emanating both from R&D and different learning processes. The authors distinguish between: (a) intra-technology spillovers (patents cited by other patents in the same specific RES-E technology field, e.g., wind power); (b) inter-technology spillovers (patents cited by patents in other renewable and non-renewable power technology fields); and (c) external-technology spillovers (patents cited by patents in other technology fields not related to electric power technologies). Our analytical model addresses the first of these categories.

Table 2 provides an overview of the results presented in Noailly and Shestalova (2013). The values illustrate how much more or less likely a patent related to a specific RES-E technology is to be cited compared to an average fossil-fuel technology patent. For instance, wind power patents are 86% more likely to be cited in general than patents for fossil-fuel technologies. Bringing these pieces of

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technology have resulted as a result of investments made outside the RES-E sector, such as in the semi-conductor industry (Nemet 2006).

[6] Certainly, not all successive patent citations are external to innovating firms. In this sense, the actual market failure is less profound than suggested by the results reported in Noailly and Shestalova (2013). This notwithstanding, the figures presented clearly illustrate the heterogeneity in terms of spillovers.

evidence together, it seems fair to assume that knowledge spillovers may be significant with respect to RES-E technologies and they tend to vary across technologies.

	Total citations	Intra-technology citations	Inter-technology citations	External-technology citations
Wind	1.86	2.79	n.s.	0.68
Solar PV	1.36	1.54	0.34	1.19
Biomass	n.s.	n.s.	1.89	n.s.
Geothermal	1.23	0.74	0.04	0,45
Hydropower	0.55	0.42	2.09	0.61

Table 2: Likelihood of RES-E technology patents cited by successive patents compared to an average fossil-fuel technology patent, organized by renewable energy technology and type of citation (n.s. = not statistically significant). Source: Noailly and Shestalova (2013).

Finally, since RES-E technology development takes place at a global level, learning spillovers will also transcend across country borders. Peters et al. (2012) show that the international learning spillovers from solar PV production support schemes have tended to be more prevalent than the corresponding spillovers from public R&D. For a single country this raises the question to what extent the domestic economy can appropriate the learning benefits emanating from the implementation of national RES-E support schemes. Still, while these considerations may render difficult choices and trade-offs in the design of domestic policies, neither of them do suggest a strong emphasis on technology-neutral RES-E support. For instance, some RES-E technologies (e.g., wind power) tend to be more dependent on the presence of a home market than others, e.g., making possible important interaction between basic knowledge generation and learning-by-using etc.

3.2 Capital Market Failures and Other Obstacles to Long-term Risk Taking

So far, we have assumed that there is perfect foresight regarding the future benefits of investments in RES-E deployment in the first period. However, these benefits are a priori unclear to investors for a variety of uncertainties related to (Yeh and Rubin 2012; Aalbers et al. 2013; Purkus et al. 2015):

- the degree of technological learning (also visible by the large ranges provided in Table 1),
- the development of resource costs and energy prices, and
- the trajectories of climate and energy policies, e.g., the CO_2 allowance price emerging from the EU Emissions Trading Scheme and the remunerations paid under RES-E support schemes.

If capital and insurance markets worked perfectly, private RES-E investors would be able to hedge against the risks resulting from these uncertainties and behave risk-neutrally – just as a public investor who can spread the risk across numerous tax payers (Arrow and Lind 1970). In such a case, an investor would be indifferent between two types of RES-E investments with different risk profiles as long as the expected return on investment is equal. Arrow and Lind (1970) argue, however, that this condition is unlikely to hold in practice because capital and insurance market failures are ubiquitous. Inter alia this may be due to problems of moral hazard and/or significant transaction costs (the latter likely to be particularly prevalent in the case of small-scale RES-E plants). Consequently, private RES-E investors are typically risk-averse, inducing them to charge a risk premium on their capital. Moreover, the capital markets may also face difficulties in providing risk-management instruments for immature RES-E technologies, in part due to the lack of historical data to assess risk.

Again, of course, a first-best approach would directly correct the failures of capital and insurance markets. The feasibility of such responses may be doubtful, though. For example, the risks RES-E generators face could be eliminated in principle through the use of long-term contracts between final consumers and the owners of the power plants, but in liberalized electricity markets such practices are prevented due to regulations aiming at fostering retail competition (Neuhoff and De Vries 2004). Given such restrictions, it may make sense to consider modifications in RES-E support schemes to correct for these failures.

Risk aversion has two important implications in the context of our model: First, a risk-averse private investor will discount future benefits of RES-E investments more strongly than a risk-neutral social planner, i.e., $r^f > r^s$ and correspondingly $\delta^f < \delta^s$ (similarly in Torvanger and Meadowcroft 2011), where superscripts f and s denote the discount rates for a private investing firm and the social planner, respectively. This thus provides one reason why private investors may behave excessively myopically from a social perspective.[7] Second, a risk-averse private investor will discount riskier RES-E investments more strongly than less risky ones, i.e., it may turn out that $\delta^{fw} \neq \delta^{fp}$ (see further below).

While the wedge between the private and the social discount rate does not impair firms' decisions in period 2, it will lead to underinvestment of private firms in RES-E deployment in period 1. This has an effect on the cost-effective design of the RES-E subsidy. In this case, the social and private first-order conditions for period 1 given in eqs. (4) and (7) must be rewritten as follows:

$$\frac{dc_1^i}{dx_1^i} = -\delta^s \frac{\partial c_2^i}{\partial x_1^i} \tag{11}$$

$$\frac{dc_1^i}{dx_1^i} = s_1^i - \delta^{fi} \frac{\partial c_2^i}{\partial x_1^i} \tag{12}$$

Substituting eq. (12) into (11) yields the optimal subsidies in period 1 in the presence of myopic firm behavior. We have:

$$s_1^i = \left(\delta^{fi} - \delta^s\right) \frac{\partial c_2^i}{\partial x_1^i} \tag{13}$$

Eq. (13) illustrates that, in the presence of risk aversion, a positive RES-E subsidy is necessary also in period 1 to compensate for the difference between privately and socially discounted future generation costs reductions emanating from learning. This RES-E subsidy needs to be technology-

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[7] Certainly, myopic behavior may also be due to other factors such as the fact that firm managers are only appointed for short periods of time (e.g., 4-5 years). Stein (1989) argues that firms may be acting inefficiently with a bias towards short-term payoffs due to agency problems within the firm, thus suggesting myopic behavior also in the presence of efficient capital markets.

specific if: (a) learning effects differs across the RES-E technologies, i.e. if $\partial c_2/\partial x_1^w \neq \partial c_2/\partial x_1^p$; and/or (b) risks vary across these technologies, i.e. $\delta^{fw} \neq \delta^{fp}$.

We have already shown that RES-E technologies tend to vary with respect to the magnitude of the learning rates. It is also likely that the perceived risks will vary with different types of RES-E technologies; these risks may be a function of:

- Maturity: With more mature (i.e. more commercially viable) technologies, not only the degree but also the variance of possible learning effects declines (e.g., compare the ranges in the learning rates for hydropower and solar PV, respectively, in Table 1).
- Technological complexity: Technologies incorporating a larger amount of technical components or depending on a larger variety of inputs for plant production (e.g., diverse rare earth metals for solar PV) or power generation (in particular biomass) are likely subject to higher overall risks.

Moreover, the eventual impacts of a certain risk on generation costs are also a function of capital intensity: RES-E technologies with a higher share of upfront investment costs per unit of output impose higher risks on the investors (compare, e.g., biomass with wind or solar PV) (see, e.g., Fischer et al. 2012). For the above reasons it is likely that the preconditions for technology-specific RES-E support schemes in the light of uncertainty – heterogeneous learning effects and risks – may hold in practice.

Interestingly, our analytical model result also implies that the necessity of technology-specific policy designs is more profound in the presence of RES-E support schemes that impose higher risks on private investors. Several studies have shown that investment risks increase when switching from fixed feed-in tariffs to premium schemes, tenders or quotas (Rathmann et al. 2011; Klessmann et al. 2013; see, e.g., Kitzing 2014). For instance, while under feed-in tariff systems there is no risk in terms of price fluctuations, RES-E generators face price volatility under a quota system. However, in spite of this and thus in contrast to our above finding, existing quota systems are usually less differentiated technologically than feed-in tariffs.

3.3 Path Dependencies

Investments in RES-E technologies create path dependencies. Path dependencies emerge because technology choices are subsequently reinforced by positive feedback effects in technology systems, e.g., firms often choose to build on accumulated technology-specific knowledge in developing new or better-performing products and processes (Acemoglu et al. 2012). Arthur (1989) points out that technology choices are likely to be particularly self-reinforcing if investments are characterized by high upfront costs and increasing returns from technology adoption, such as scale, learning and network economies and adaptive preferences. Technological path dependencies may be reinforced by an institutional framework, which co-evolves with technologies; this is usually referred to as the techno-institutional complex (Unruh 2000; Geels 2004; Rohracher 2008). These institutions – e.g., legal rules such as permitting procedures and informal codes of conduct – are subject to path dependencies themselves (North 1990).[8]

In the presence of such path dependencies the cost of exploring alternative technology pathways steadily increases. Thus, past investments can be said to generate long-run "switching costs", which will affect the economic viability of future investment decisions (Prado and Trebilcock 2009). As a result, a "lock-in" of incumbent technologies may arise.

Switching costs can be incorporated into our model by assuming first that deployment of wind power in period 1 does not only reduce the generation costs of wind power in period 2 but also produces an increase in the cost of solar PV in period 2, i.e., $c_2^p(x_2^p, x_1^p, x_1^w)$ with $\partial c_2^p / \partial x_1^w > 0$ and $\partial^2 c_2^p / \partial x_1^{w2} > 0$. Obviously, vice versa, solar PV deployment in period 1 may also affect the cost of wind power deployment in period 2 in a corresponding way. Consequently, the social planner's first-order conditions for period 1 given by eq. (4) can then be rewritten as:

$$\frac{\partial c_1^w}{\partial x_1^w} = -\delta \left(\frac{\partial c_2^w}{\partial x_1^w} + \frac{\partial c_2^p}{\partial x_1^w} \right) \tag{14}$$

$$\frac{\partial c_1^p}{\partial x_1^p} = -\delta \left(\frac{\partial c_2^p}{\partial x_1^p} + \frac{\partial c_2^w}{\partial x_1^p} \right) \tag{15}$$

If multiple firms invest in RES-E deployment simultaneously, the path dependencies created by single investment decisions are unlikely to be considered by the investing firm. Thus, the switching costs that arise from technology deployment constitute an external cost; e.g., if the period-1 power generators invest in wind power-specific human, institutional and physical capital, this will lower the pay-off of directing period-2 activities towards solar PV that (at least in part) cannot make use of this capital. Consequently, the private first-order conditions for the RES-E investor in period 1 remain unchanged as in eq. (7). Substituting eqs. (14) and (15) into (7) yields the cost-effective subsidy for each RES-E technology:

$$s_1^w = -\delta \frac{\partial c_2^p}{\partial x_1^w} \tag{16}$$

$$s_1^p = -\delta \frac{\partial c_2^w}{\partial x_1^p} \tag{17}$$

Eqs. (16) and (17) show that the existence of path dependencies requires a negative RES-E subsidy, or a markdown to the subsidy, in period 1 to address the external switching costs generated by investments into specific RES-E technologies. A simple example illustrates that this markdown may vary across RES-E technologies. Assume that: (a) wind power deployment in period 1 is higher than solar PV deployment ($x_1^w > x_1^p$) because the marginal costs of wind power deployment are lower ($dc_1^w / dx_1^w < dc_1^p / dx_1^p$); and (b) the slope of the marginal switching cost curves produced by either

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[8] Differences in terms of ownership and traditions may affect future pathways. For instance, in his assessment of the electricity regimes in the Nordic countries, Thue (1995) notes that while the Danish electricity system has largely been organized in a bottom-up manner with cooperative organizations and municipalities as owners of power stations, the Swedish system has been more hierarchical. The latter led to a relative lack of experience of investment in small-scale plants in Sweden, and instead a focus on large state-supported hydropower and nuclear energy. During the 1990s this contributed to a relative lack of Swedish interest in wind power, while the tradition of local ownership enabled high level of penetration of small-scale wind power in Denmark.

technology in period 2 is equal for both RES-E technologies ($\partial^2 c_2^p / \partial x_1^{w2} = \partial^2 c_2^w / \partial x_1^{p2} > 0$). Under these assumptions, the marginal switching costs produced by wind power deployment and affecting solar PV will be higher than the corresponding effect from solar PV deployment ($\partial c_2^p / \partial x_1^w > \partial c_2^w / \partial x_1^p$). Thus, in this example the markdown to the RES-E subsidy needs to be higher for wind power than for solar PV, thus providing an additional rationale for the use of technology-specific RES-E support.

It is frequently pointed out that the power sector exhibits several characteristics, which are likely to produce strong path dependencies (see, e.g., Grubb 1997; Unruh 2000; Neuhoff 2005; Kalkuhl et al. 2012; Lehmann et al. 2012). Investments in this sector are large-scale, long-term and exhibit increasing returns from technology adoption. Technological path dependencies are aggravated by the fact that power outputs from different types of technologies are almost perfect substitutes. That is, emerging power technologies can only compete on price with incumbent ones, and thus with little scope for product differentiation. Moreover, the power sector is highly regulated, implying that existing technological patterns of power generation are embedded into and enforced by a complex set of institutions (see above).

The empirical significance of these characteristics is likely to differ across RES-E technologies. For instance, investments in new RES-E capacity are generally capital-intensive, and since the investment costs of existing plants are sunk this capacity will compete with new capacity on the basis of their variable costs. The greater the difference between the total cost of a new plant and the variable cost of an existing plant, the greater is the incentive for a more intense use of existing capacity through higher capacity utilization, life time extensions, and incremental capacity additions (e.g., Söderholm 2001). Some new RES-E technologies are likely to be more aligned with existing institutions than others, thus lowering the cost of new plants. For example, spatial planning law may discriminate between different types of RES-E technologies.[9] In addition, for some technologies increases in RES-E generation within existing technologies, e.g., co-firing with biomass in combined heat and power plants, are easier than for others.

As indicated above, path dependencies are not only related to investments into power generation capacity but also to the direction of technological change (Acemoglu et al. 2012; Aghion et al. 2012). Such path dependencies have been used to explain the competitive advantage of fossil-fuel over RES-E technologies (“carbon lock-in”), and to derive a general rationale for implementing RES-E policies in addition to emission policies. Similarly, path dependencies may also distort the allocation of R&D investments across different RES-E technologies (Kverndokk et al. 2004). Some empirical evidence is available for path dependency in the direction of technological change with RES-E technologies. One indication is provided by the results reported in Table 2, which points to the fact that present R&D activities for a specific RES-E technology tend to be strongly driven by past R&D in the same technology field (see also Popp 2002). This appears to be particularly evident for wind power and solar PV. Another piece of evidence is provided by studies comparing the innovation effects for technology-neutral and technology-specific RES-E support schemes, respectively. Using patent counts

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[9] See, for example, §35 of the German Building Code, which privileges the use of wind power and bioenergy; corresponding plants can be installed in areas for which no formal development plan exists, i.e. in areas where other types of developments are ruled out.

data, Johnstone et al. (2010) and Bäckström et al. (2014) show that technology-neutral RES-E policies are more likely to induce technological change for close-to-commercial technologies, such as wind power, which are primarily promoted under such schemes. In contrast, technology-specific RES-E policies are required to induce innovation in the case of more costly, emerging technologies, such as solar PV. This may be understood as an indication of existing path dependencies, even though it may also be attributable to other factors, such as differences in the allocation of risks under the different policies. Overall, it thus seems plausible to assume that path dependencies may also impair choices between RES-E technologies, and should therefore be considered in designing technology-specific RES-E policies.

3.4 External Costs of RES-E Generation

Next to the private generation costs, RES-E deployment may also produce additional costs that may be inadequately internalized through other policy measures (e.g., taxes, standards etc.). First, RES-E plant installation and operation as well as the production of bioenergy crops bring about environmental costs (Abbasi and Abbasi 2000; Sathaye et al. 2011). These costs may be (a) site-specific, regarding impacts on ecosystem services and biodiversity due to habitat destruction and fragmentation, and water and air pollution; and/or (b) related to the distance of a site to human settlements, regarding impacts of landscape changes, air pollution or noise emissions. In addition, the pollution avoided by marginal increases in RES-E generation may also differ across technologies, thus giving rise to heterogeneous marginal external benefits (e.g., Kaffine et al. 2013). Second, additional costs are also associated with the integration of RES-E in-feed to the power system. Hirth et al. (2015) distinguish between three types of system integration costs produced by RES-E deployment: (a) balancing costs (the marginal costs of coping with deviations from day-ahead generation schedules due to forecast errors for intermittent RES-E sources); (b) grid-related costs (marginal costs of transmission constraints and losses due to the location of RES-E generation in the power grid); and (c) profile costs (marginal cost of output adjustments and an overall reduced utilization of convention thermal power plants due to the timing of variable RES-E generation).

These diverse cost categories may at least in part be external to the single firm, i.e., not included in c_t^i. To illustrate this, we incorporate external costs $e_t^i(x_t^i)$ into our model for both periods. We do not here explicitly consider the possible impacts of avoided environmental impacts following any decline in non-RES-E deployment, although much of the general arguments made below will be valid also for this case. The external costs are assumed to be increasing and convex in RES-E generation, i.e. $de_t^i/dx_t^i > 0$ and $d^2e_t^i/dx_t^{i2} > 0$. The first-order conditions for the social optimum in eqs. (4) and (5) are consequently modified as:

$$\frac{dc_1^i}{dx_1^i} = -\delta\frac{\partial c_2^i}{\partial x_1^i} - \frac{de_1^i}{dx_1^i} \tag{18}$$

$$\delta\frac{\partial c_2^i}{\partial x_2^i} = \lambda - \frac{de_2^i}{dx_2^i} \tag{19}$$

Obviously, these external costs could be internalized efficiently by, for instance, a Pigovian tax on emissions. However, such first-best policies may not be available for a variety of reasons (see also below). In this case, modifications in the RES-E subsidy design may be one available means of addressing the externalities of RES-E deployment. Substituting eqs. (7) and (8) into (18) and (19), respectively, gives the following cost-effective RES-E subsidies in the presence of external costs:

$$s_1^i = -\frac{de_1^i}{dx_1^i} \tag{20}$$

$$s_2^i = \frac{1}{\delta}\left(\lambda - \frac{de_2^i}{dx_2^i}\right) \tag{21}$$

Eqs. (20) and (21) illustrate that the cost-effective subsidy is negative, i.e., a tax or a markdown to the subsidy in period 1, and below the shadow price on the RES-E target in period two to compensate for the external costs. Moreover, the subsidy needs to be technology-specific if the external costs vary across technologies, i.e., if $de_t^w/dx_t^w \neq de_t^p/dx_t^p$. Of course, if the external costs of non-RES-E generation is also taken into account this technology differentiation should also reflect the potential heterogeneity in avoided impacts (Novan 2015).

It is obvious that the environmental and system integration costs of RES-E deployment will vary significantly across technologies (by RES-E type) as well as within technologies (by RES-E plant location and design). Table 3 provides illustrative examples. Obviously, any attempt to assess the cost differential between RES-E technologies empirically and in monetary terms faces significant restrictions. It is subject to diverse uncertainties and general limitations of economic valuation and hinges crucially on the technological assumptions for either technology or the cost categories and stages in the life cycle considered. It may also be difficult to determine the extent to which these costs are already internalized.

These limitations notwithstanding, some general indications on external cost differences can be detected. In their survey of the literature estimating the environmental external costs of power generation Söderholm and Sundqvist (2006) report that these costs tend on average to be higher for biomass generation than for both wind power and solar PV, although this review also identifies substantial variance in the cost estimates. Important differences typically exist also in the case of avoided air pollution. For instance, Novan (2015) shows that in the Texas electricity market an increase in wind power generation will offset more carbon dioxide emissions than output from solar PV plants and this difference increases as the installed capacity grows. Turning to the system integration costs this is clearly a more important issue for intermittent RES-E generation, such as wind power or solar PV, as compared to, for instance, biomass (see Table 3).

Obviously, the categories of environmental and system integration costs referred to in Table 3 are not by definition fully external to RES-E investors – and even if they were, technology-specific RES-E support would not be the first-best response to correct for these externalities. Environmental costs can be internalized by direct taxes on environmental harmful activities such as air pollution. They may also be addressed by command-and-control regulations, such as performance standards and/or land use planning. Furthermore, system integration costs are imposed on RES-E investors if: (a) RES-E remuneration reflects market prices, as under a premium tariff; and/or if (b) the temporal and spatial variation of the market value of electric power is properly reflected in spot, future and balance markets (Löschel et al. 2013; Hirth et al. 2015). However, the institutional framework may often fail to internalize these costs properly. For example, the system integration costs of RES-E deployment are currently not fully imposed on investors: fixed feed-in tariffs are used instead of premium tariffs.

Power markets fail to send improper investment signals due to the design and timing of the contracts traded, the absence of locational price signals, regulatory uncertainty or market power (Hirth et al. 2015). Obviously, the correction of these institutional failures would be the first-best response to directly internalize such system integration costs. However, this may not be possible because – and actually institutional failures may be the result of – a lacking political will and/or significant administrative costs and legal hurdles (Löschel et al. 2013), or simply because some costs may be produced outside the administrative area under consideration. Under these conditions, the differentiation of support schemes across (as well as within) different RES-E technologies may be a politically feasible option.

	Environmental costs	System integration costs
RES type	• Different relevant categories of costs, e.g. biomass-specific impacts of growing, transporting and burning energy crops (Miyake et al. 2012) • Different levels of costs, e.g., landscape impacts higher for wind power than for solar PV and biomass (Dobers et al. 2015)	• Generally, higher for intermittent RES-E technologies (i.e., wind, solar PV) • Profile costs higher for solar PV than for wind power because daily solar radiation is concentrated in few hours (Hirth 2013) • Balancing costs lower for solar PV than for wind power due to fewer forecast errors (Hirth 2013) • Depending on RES-E mix, e.g., aggregated profile costs lower with equal shares of wind power and solar PV (Tafarte et al. 2014)
RES plant location	• Increasing with higher ecological sensitivity of the site (Drechsler et al. 2010) • Landscape impacts increasing with declining distance to human settlements (Drechsler et al. 2010; Meyerhoff et al. 2010)	• Profile costs lower with a more even spatial distribution of RES-E plants (geographical smoothening of RES-E plants) (Hirth et al. 2015) • Profile costs lower for offshore wind power than for onshore installations (Hirth et al. 2015) • Lower grid-related costs for RES-E plants closer to load centers (Hirth et al. 2015)
RES plant design	• Landscape impacts increasing with height of wind turbines/size of wind parks (Bergmann et al. 2008; Meyerhoff et al. 2010)	• Decreasing with advanced, more system-friendly plant design, e.g. PV modules oriented to east and west, weak-wind turbines (Hirth and Mueller 2015)

Table 3: Heterogeneity in environmental and system integration costs by RES-E type, plant location and plant design.

3.5 Interim Conclusion

Table 4 provides a summary of the cost-effective RES-E subsidy levels derived in the previous sub-sections. For each category of market failure, the subsidy needs to be designed to reflect the wedge that exists between the private marginal generation costs of RES-E deployment and the corresponding social costs.

	Cost-effective RES-E subsidy	
Assumptions	Period 1	Period 2
No market and policy failures (benchmark case)	0	$\frac{\lambda}{\delta}$
Knowledge spillovers	$-\delta\left(1-\rho^i\right)\frac{\partial c_2^i}{\partial x_1^i}$	
Uncertainty, capital market failures, risk aversion	$\left(\delta^{fi}-\delta^s\right)\frac{\partial c_2^i}{\partial x_1^i}$	
Path dependencies	$-\delta\frac{\partial c_2^p}{\partial x_1^w}$ and $-\delta\frac{\partial c_2^w}{\partial x_1^p}$	
External costs	$-\frac{de_1^i}{dx_1^i}$	$\frac{1}{\delta}\left(\lambda-\frac{de_2^i}{dx_2^i}\right)$
Grey-shaded areas highlight potentially necessary technology-specific RES subsidies		

Table 4: Summary of analytical results

This wedge may be negative for some market failures, i.e. the social costs may be lower than the private generation costs. This holds true in the case of positive learning externalities as well as for uncertainty combined with capital market failures (the latter leading to excessive discounting by private investors). The wedge will instead be positive for some other market failures, i.e. the social costs may be above the private generation costs. This is the case in the presence of path dependencies (generating external switching costs) as well as external environmental and system integration costs. Importantly, our discussion of either case of market failure has demonstrated that the size of the wedge is likely to be technology-specific in most cases. Consequently, technology-specific RES-E subsidy rates are needed to address the relevant market failures.

The policy implications of the wedge driven between private and social costs of RES-E deployment by the diverse market failures are also illustrated in Figure 2, which extends upon the benchmark case displayed in Figure 1. For the sake of generality, we represent this wedge as Δ^i and abstain from using the time subscript (given the fact that the wedge may be produced within one time period as well as between periods). Next to private generation costs Figure 2 also depicts the social costs, i.e. the sum of generation costs plus a wedge ($\partial c^i/\partial x^i+\Delta^i$, the dashed lines).

In this example, we assume that the wedge is positive and lower for wind power than for solar PV deployment. This may hold true, for example, for external environmental costs. In this case, the cost-effective allocation of deployment to attain a given RES-E target (x^{w*},x^{p*}) deviates from that in the benchmark case with generation costs only ($x^{w\prime}$,$x^{p\prime}$). The cost-effective level of wind power (solar PV) deployment is higher (lower) than in the benchmark case because it exhibits a smaller (larger) positive wedge than solar PV (wind power). If the RES-E support scheme is to correct for the wedge, these cost-effective deployment levels can only be attained through the use of technology-specific RES-E subsidy rates (s^w,s^p). A technology-neutral RES-E subsidy ($s^{w\prime}=s^{p\prime}$), as in the benchmark case, would produce an excess cost (see the grey-shaded triangle in Figure 2). Notably, Figure 2 illustrates that the technology-specific subsidy to wind power is higher than in the benchmark case – even though a positive wedge would imply a markdown to the subsidy rate (see, e.g., eq. (21)). This is because the shadow price λ of the RES-E target $\bar{Z}$ is higher than in the benchmark case if the social costs of RES-E deployment exceed private generation costs.

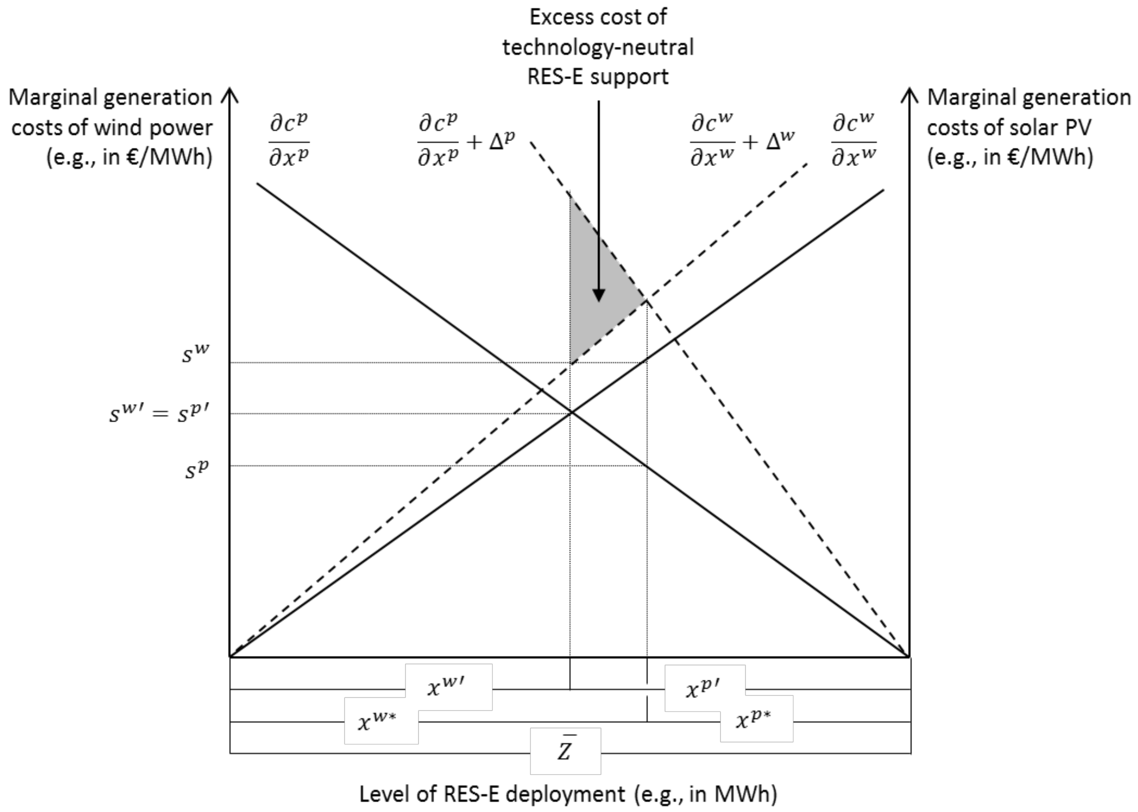

Figure 2: Excess cost of technology-neutral RES-E support with external costs in period 2.

By the discussion of benefits of technology-specific RES-E support schemes so far we do not mean to suggest that designing and implementing such schemes cost-effectively is a straightforward exercise. To the contrary, we have shown that the actual size of the wedge will be uncertain. Moreover, the arguments we have so far discussed in isolation need to be merged to provide an aggregate assessment of cost-effective technology differentiation. In this context, potential trade-offs between addressing different rationales for technology differentiation have to be considered. For example, some rationales may point to a relatively high level of support to solar PV (e.g., knowledge spillovers, uncertainty etc.) while others may call for a lower level (e.g., system integration costs). What is more, the different rationales for technology-specific RES-E support may also interact. For example, the welfare loss from imperfectly addressed learning spillovers or external costs as well as capital market failures may be aggravated in the presence of technological and institutional path dependencies. These challenges lead over to potential practical caveats to implementing technology-specific RES-E support cost-effectively.

4 Potential Caveats to Technology-Specific RES-E Support

So far, we have discussed the potential benefits of technology-specific RES-E support schemes. Certainly, technology differentiation may also give rise to government failures. Notably, the proper design and implementation of technology-specific policies may be impaired because regulators face significant information constraints, and/or because their decisions may also be driven by politico-economic considerations (Rodrik 2014). Given the fact that investment decisions in the power sector tend to be strongly path dependent, such distortions may result in governments "picking the wrong winners" by relying on technology differentiation. These challenges will be discussed critically in the following.

4.1 Regulation under Asymmetric Information

The design of technology-specific support schemes is quite demanding in terms of information – with respect to both the relevance of individual rationales as well as their aggregation. As the theoretical analysis has demonstrated, a proper design requires information on current technology costs, technology learning rates and any related knowledge spillovers, investment risks, path dependencies as well as environmental and system externalities, and suitable technological responses to address these.

At least some of the needed information may be more easily accessible to private investors than to a central regulator, e.g., information on current and future technology costs and/or suitable pollution abatement technology. Due to these information asymmetries, a regulator may fail to design technology-specific schemes properly – a critique that has been raised with respect to RES-E support in particular (Frontier Economics and r2b 2013; Monopolkommission 2013; del Rio and Cerdá 2014; Frontier Economics 2014; SVR 2014) and government intervention in general (Lerner 2009). In this respect, technology-neutral schemes may be superior because they require fewer policy design decisions (in theory, only the determination of one uniform price or quota for all RES-E generation sources). Thus, one would eventually have to balance the potential benefits from technology differentiation against the potential welfare losses from implementing policies that are sub-optimally designed because of information constraints.

Notably, however, technology-specific RES-E support schemes can also be designed to reveal private information by including auctions. Certainly, auctions only make sense for moderate degrees of technology differentiation (e.g., across but not within RES technologies) because they require a certain quantity of bidders (del Rio and Linares 2014). In addition, asymmetric information can be addressed by facilitating policy learning over time, e.g., by installing a preset monitoring and revision process for RES-E support schemes that allow for policy reforms once new information becomes available to the regulator (Foxon and Pearson 2008; Rodrik 2014). Eventually, asymmetric information may therefore not question technology-specific support in general but rather call for a careful assessment of the feasible depth and temporal flexibility of technology differentiation.

Moreover, it is important to emphasize that information constraints faced by a regulator may also be due to general uncertainties, regarding for example the expected degree of technological learning for different technologies. These constraints will also impair private investors' decision, and cannot serve as an argument against technology differentiation. The main implication is rather that governments should avoid supporting "single winners", and instead provide support schemes for several emerging technologies (that are not perfect substitutes) to reduce uncertainties (Azar and Sandén 2011; Aalbers et al. 2013). However, such a portfolio approach to RES-E support does not in any way preclude technology differentiation. In the light of the uncertainties about the future prospects for RES-E generation some technologies sometimes labeled backstop technologies may deserve preferential treatment (Fischer et al. 2012). A true backstop technology is available in more or less unlimited quantities at some given cost, and for this reason it may assist in putting a cap on the cost of reaching strict emission reduction targets, i.e., it represents an insurance against high costs. Some RES-E technologies are more likely to exhibit important backstop characteristics than other; e.g., compared to biomass the scarcity constraints are likely to be less prevalent in the case of solar PV since the flow of solar energy to earth is abundant and solar panels can be placed on roofs. Technology-specific support schemes that can bring down the cost of solar PV can therefore have an added insurance value.

4.2 Political Economy of Regulation

A second caveat to technology-specific RES support (and indeed regulation in general) is that political decisions concerning the degree of technology differentiation may not only be driven by cost-effectiveness motivations but also by other policy criteria as well as by the self-interests of political actors and key stakeholders (for an overview, see Strunz et al. 2015).

One important motivation behind implementing technology-specific RES-E support schemes may be distributional concerns. In particular, surcharges on electricity prices to fund RES-E subsidies may impose a substantial financial burden on electricity consumers. It is shown in the literature that technology-specific RES-E support schemes may decrease final consumer costs (i.e., the sum of generation costs and producer rents) basically because price discrimination across technologies with different costs may help to reap producer rents (e.g., Jacobsson et al. 2009; Bergek and Jacobsson 2010; del Rio and Cerdá 2014; Held et al. 2014; Hitaj et al. 2014; Resch et al. 2014). From a politico-economic perspective this redistribution of income from power producers to consumers may be motivated by political concerns about the public acceptance of RES-E deployment and potentially lost votes for upcoming elections.

Moreover, it is often argued that technology-specific policies are more prone to regulatory capture by different political interest groups than technology-neutral ones (Lerner 2009; Aalbers et al. 2013; SVR 2014). According to Helm (2010), technology differentiation opens up avenues for a “renewable pork barrel”, i.e., lobbyists of different RES-E technologies may be able to simultaneously satisfy their potentially heterogeneous interests and maximize their individual rents by promoting technology-specific subsidy rates. Lobbyists may also be more able to seek rents under technology differentiation because their information advantage increases. There is clear empirical evidence, for example, that the technology-specific rates under the German feed-in tariffs have been driven by interventions from business groups as well as from the subnational administrations of the German *Länder* (Hoppmann et al. 2014; Sühlsen and Hisschemöller 2014; Vossler 2014; Strunz et al. 2015).

Against this backdrop, Helm (2010) argues that there is a “premium to simplicity”. Technology-neutral policies should, the argument goes, be preferred over technology-specific ones as they are harder to capture. However, this recommendation may hardly be instructive for practical policy-making. As Strunz et al. (2015) point out, all types of policies are likely to be eroded by the influence of political interest groups – even those which are meant to be technology-neutral in the first place. This has become obvious for carbon emissions trading in the EU ETS where the alleged textbook simplicity has in part vanished during the implementation process (see, e.g., Anger et al. 2008;

Rudolph 2009; Spash 2010). This insight is eventually also confirmed by Helm (2010), who reports that due to lobbying efforts technology-specific bands were introduced for the originally technology-neutral concept of UK's renewable obligation certificates.

4.3 Hazards of Picking Winners

In the presence of asymmetric information and politico-economic constraints, it is sometimes argued that technology-specific RES-E support runs the risk of picking the wrong winners (e.g., Monopolkommission 2013). This concern is based on the assumption that specific support for a selected set of RES-E technologies will create path dependencies and impair the development and production of other technological options, which may be emerging but are not yet known to or accepted by regulators (Kverndokk et al. 2004, , see also Section 3.3). This effect is aggravated by the fact that (technology-specific) RES-E policies may not be easy to revise, modify or abolish even if new information about new emerging technologies becomes available to the regulator. Reasons include institutional path dependencies and politico-economic barriers (Strunz et al. 2015). Nordensvärd and Urban (2015) testify a feed-in tariff lock-in for the German wind power sector, and Kverndokk and Rosendahl (2007) show that the cost of picking the wrong winners among RES-E technologies may be substantial.

These insights raise questions about whether and to what extent the alternatives to technology-specific RES-E support reduce the hazards of picking winners. In this respect, Aghion et al. (2009) emphasize that "[i]n a fundamental sense these hazards are inescapable" (p. 689) – and also that there is remarkably little evidence on whether governments are better or worse than firms at picking winners. Technology-neutral RES-E support schemes leave the technology choices to the market. However, this tends to create a situation where the currently most competitive technologies are adopted, such as onshore wind power. However, this is not necessarily cost-effective in the long run as the cost advantages of established RES-E technologies may at least partly be due to unexploited learning effects for the emerging technologies as well as path dependencies. These distortions risk being perpetuated into the future under technology-neutral support schemes. In Section 3.3, we showed that in this case technology-specific support schemes may in fact be warranted to avoid only the close-to-commercial RES-E technologies to be picked.

In the face of the ambiguities as to how to design RES-E support, one might be tempted to abstain from RES-E subsidies at all – and rather rely on the even more technology-neutral policy tool of carbon trading only. However, Kverndokk and Rosendahl (2007) demonstrate that this is not a dominant strategy either: without explicit subsidies to clean technologies existing market failures next to the carbon externality cannot be addressed cost-effectively (see also, Fischer and Newell 2008). Technology development and deployment would be distorted in favor of established non-renewable technologies – and even more so if the carbon trading scheme is improperly designed and the external costs of non-renewable generation are not fully internalized. The resulting excess cost may more than outweigh the potential risk of picking the wrong technologies by a technology subsidy.

Consequently, the real issue in designing RES-E support schemes is not how to avoid picking winners – as this is likely to happen under any scheme – but "to be picky on your picks" when designing technology-specific subsidies (Grubler et al. 2012, , p. 1708). In addition, and as was noted above, decision-making under uncertainty also implies a portfolio approach to RES-E support rather than an extreme picking-the-winner policy – but with technology-specific support levels.

5 Conclusion

Technology-specific RES-E support schemes, which differentiate subsidy rates between RES-E technologies, are ubiquitous in the EU and beyond. A frequent critique of this kind of policy is that compared to a technology-neutral RES-E support scheme it generates an excess cost of reaching a given RES-E deployment target. In this paper, we have addressed the conditions under which technology-specific RES-E support schemes may nevertheless provide benefits in terms of cost-effectiveness. Rationales may be related to market failures associated with technological development as well as additional external costs, both of which drive a wedge between private and social costs of RES-E deployment. The degree and the empirical relevance of these market failures are typically heterogeneous across different RES-E technologies. Technological differentiation of RES-E support schemes may be a regulatory response to this heterogeneity. Certainly, this policy approach will be only second-best in most cases – but it may be a reasonable policy pathway if other (first-best) policy solutions need to be ruled out.

Of course, we are not arguing that technology-specific RES-E support increases cost-effectiveness by definition. Assessing cost-effective technology-specific RES-E subsidy rates is a challenging task as an aggregated assessment of all potential rationales is necessary and corresponding trade-offs need to be considered (such assessment would be beyond the scope of our analysis). Moreover, policy-makers may fail to design technology-specific RES-E subsidies properly if they lack information and/or are driven by politico-economic considerations.

These constraints notwithstanding, it is the main message of our paper that an unambiguous plea for technology-neutral RES-E policies cannot be justified on economic grounds either. In the presence of uncorrected market failures, this approach may distort technology choices and impair the cost-effectiveness of attaining in particular long-term RES-E deployment targets. This is even more so as technology-neutral RES-E support schemes may be subject to government failure as are technology-specific approaches. Our analysis thus suggests that there are no simple answers to the question how to design RES-E support schemes, or technology policies in general, in a cost-effective manner.

In the end the discussion on the cost-effectiveness of technology-neutral versus technology-specific RES-E support schemes is related to the debate on economic rationales for supporting RES-E in the first place. This boils down to the notion that a RES-E target cannot be a desirable goal in itself; it must be logically derivable by analysis of more basic motives and of the relevant costs and constraints. Our key point is that almost regardless of which these motives are, there is generally a stronger case to be made for technology differentiation compared to technology neutrality.

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