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Climate Policies with Pollution Externalities and Learning Spillovers

Abstract:

Economic theory suggests that with a pollution externality and learning spillovers related to renewable energy technologies, the optimal climate policy mix includes an emissions policy and an output subsidy to the learning industry. Instead of output subsidies, feed-in tariffs are often implemented in addition to emissions policies. This paper reveals that this policy mix may theoretically provide for a first-best outcome as well. However, its efficient design may be cumbersome for regulators. An emissions tax must be below the Pigovian level and differentiate between fossil fuels. Moreover, both tax and feed-in tariff must be adapted continuously.

Keywords: Emissions tax, feed-in tariffs, policy mix, spillovers, learning by doing

JEL Codes: D62, Q48, Q54, Q58

1 Introduction

Government strategies to cope with greenhouse gas emissions from energy generation are based on a policy mix in many countries. On the one hand, regulators implement market-based policies such as permit trading schemes or taxes to price greenhouse gas emissions. On the other hand, support schemes have been implemented to promote renewable energy sources and an alternative to fossil-fueled electricity generation. The most common approach has been the so-called feed-in tariff (Madlener and Stagl 2005). Operators of renewable energy plants are paid a fixed price – or an output subsidy – per unit of electricity produced, which is independent of the electricity price. Unlike conventional subsidies, this fixed price is not funded by the government but by a uniform add-on to the electricity price. Thus, electricity consumers pay eventually for renewable energy support. Feed-in tariffs have a remarkable track record throughout Europe (Menanteau et al. 2003). Installed capacity of renewable energy plants has experienced two-digit annual growth rates in countries such as Germany, Denmark and Spain. However, it has remained out of focus whether feed-in tariffs interact with emission policies existing in parallel. Can emissions still be reduced at least cost under market-based emissions policies if feed-in tariffs are in place in addition?

Theoretical literature suggests that a combination of emissions policies and policies for technology support can be justified in the presence of two types of market failures: a pollution externality and spillovers related to technological learning-by-doing (for an overview see Lehmann 2008). Learning-by-doing implies that the unit cost of a product decreases as its cumulative production increases (Argote and Epple 1990). Learning-by-doing has resulted in remarkable cost decreases for renewable energy technologies (see, e.g., Isoard and Soria 2001; Junginger et al. 2005; Neij 1997; 1999; Söderholm and Klaassen 2007). However, learning-by-doing also generates spillovers to other market participants than the one adopting the technology (Arrow 1962). Spillovers may occur, for example, due to personnel movements and communication between firms, participation in meetings and conferences or "reverse engineering" (Argote and Epple 1990). Thereby, competitors may benefit from experiences made during the adoption process without incurring learning costs themselves and without compensating the adopter. Thus, the learning firm cannot appropriate the entire social benefits of learning-by-doing, and will invest too little in the learning process from an economic point of view. Empirical studies have confirmed spillovers of learning-by-doing in the manufacturing sector in general (Argote and Epple 1990; Irwin and Klenow 1994; Lieberman 1984; Lloyd 1979) as well as in the renewable energy industry (Hansen et al. 2003; Junginger et al. 2005; Neij 1999).

Two studies provide an in-depth analysis of the combination of emissions policies and policies supporting renewables. Fischer and Newell (2008) assume a partial equilibrium model of the energy sector with fossil-fueled energy generators and operators of renewable energy installations. The renewable operators experience learning-by-doing. Fischer and Newell show that an emissions price imposed on fossil-fueled generators and an output subsidy to renewable energy generators achieves a first-best outcome. Bläsi and Requate (2007) adopt a more differentiated model of an energy sector with free entry. They distinguish between fossil-fueled generators, operators of renewable energy plants and producers of renewable energy technologies. They find that an optimal policy mix includes an emissions policy as well as an output subsidy and an entry premium for producers (not operators) of renewable energy technologies. When discussing the policy mix, both studies assume a subsidy paid in addition to the market price (of electricity or the renewable technology). Thus, they do not incorporate the efficiency effects of a feed-in tariff paid irrespectively of the market price. Moreover, they do not consider distortions arising from the add-on which funds the feed-in tariff.

It is therefore the aim of this paper to take these characteristics of instrument design into account and to provide a more applied analysis of the policy. For this purpose, the model used by Fischer and Newell (2008) is advanced. Their assumption of a simple output subsidy is substituted by that of a feed-in tariff with more complex characteristics. Thus, the paper evaluates the efficiency of an emissions policy combined with a revenue-neutral feed-in tariff rather than with a pure output subsidy. It is assumed that the emissions price is fixed – as under an emission tax but unlike under emissions trading schemes. The paper argues that a revenue-neutral feed-in tariff can be interpreted as an output tax for the fossil-fueled energy generators. It is therefore one of main results of the paper that the optimal emissions tax is below the marginal damage, i.e. below the Pigovian level of taxation. What is more, the emissions tax has to be differentiated between fossil-fueled generators with different emission factors. Low-emission generators should pay a lower emissions price. In addition, the optimal tax level in the presence of a feed-in tariff depends on the maturity and the number of adopters of renewable energy technologies as well as the share of renewable energy sources in electricity generation. The optimal output subsidy is similarly determined by the maturity and the number of adopters of renewable energy technologies, but also on the electricity price. Consequently, policy makers are obliged to adapt both policies continuously as the corresponding variables change.

The paper is structures as follows. Section two introduces the model. Section three highlights the conditions of the social optimum. Section four outlines the optimal regulatory approach. Section five analyses the combination of an emissions tax with a feed-in tariff. Section six concludes.

2 Model

The analysis is based on a stylized partial equilibrium model of the electricity sector as it is found in Fischer and Newell (2008). The electricity sector encompasses two subsectors. One sector uses fossil fuels to generate electricity and produces emissions of carbon dioxide. The other sector employs renewable energy sources, such as wind or solar, which are carbon-free. Both sectors are perfectly competitive and produce an identical output, electricity. Any electricity generated from renewable energy sources substitutes marginal fossil-fuel production.[1]

The model has two periods. Electricity generation, consumption and emission occur in both periods. Firms take the electricity price as given not only in the first period but also in the second period. Moreover, they are assumed to have perfect foresight regarding the price in period two. There is discounting at rate δ between periods, but not within each period. Social and private discounting rates are assumed to be identical.

The fossil-fuel sector may choose between a technology using a carbon-intensive fossil fuel x, e.g. coal, and a technology using a low-carbon fuel y, such as natural gas. The former technology supplies base-load while the latter is the marginal technology producing peak-load electricity. The total output of electricity produced in the emitting sector in period t is $f_t = x_t + y_t$. Emissions with each technology i are assumed to be fixed at rate μ_i. This assumption reflects that fuel switching is the major means to reduce emissions in the emitting sector. Other measures, such as improvements in generation efficiency or carbon capture and sequestration, are of minor importance at the moment because they have limited emission reduction potentials or are in very early stages of technological development. Total emissions from the emitting sector in period t are $E_t = \mu_x x_t + \mu_y y_t$. Production costs C_i^t of each technology in each period are assumed to be increasing in output and strictly convex, i.e. $C_i'^t > 0$ and $C_i''^t > 0$.

The renewable sector consists of n identical firms, each of which produces an electricity output q_t in period t.[2] The production costs are given as in Bläsi and Requate (2005; 2007). Production

[1] This model abstracts from nuclear and hydro as important further energy sources currently used. However, these sources are carbon-free and employed to generate base load electricity. Their output can be assumed to be fixed in the presence of emission policies and support schemes for renewable energy sources. Thus, integrating them into the model would not change the analytical results.

[2] The number of firms in the renewable sector is assumed to be constant in this model. Bläsi and Requate (2005; 2007) allow for firm entry and show that with learning-by-doing spillovers an additional policy is necessary to attain a

cost in period one is $G^1(q_1)$. Production cost in period two is a function of output in period two and the total level of learning (or experience) L in period one, i.e. $G^2(q_2,L)$.[3] Total learning depends on the output of the firm under consideration (private learning) and the output of all other identical firms in the sector (learning spillovers): $L = q_1 + \rho(n-1)q_1$. The spillover rate ρ indicates to which extent a firm can benefit from the experience made by other firms. Production costs in each period are increasing and convex in output, i.e. $G^t_{q_t} > 0$ and $G^t_{q_t q_t} > 0$. Production cost in period two is declining and convex in learning: $G^2_L < 0$ and $G^2_{LL} > 0$. Learning also reduces marginal production cost in period two, i.e. $G^2_{q_2 L} < 0$. Moreover, production cost in period two is assumed to be convex overall, which requires that $G^2_{LL}G^2_{q_2 q_2} - \left(G^2_{q_2 L}\right)^2 > 0$. Subscripts q_t and L denote partial derivatives with respect to the subscripted variable. Notably, as in Fischer and Newell (2008), learning-by-doing is assumed for the relatively immature renewable energy technologies but not for the relatively mature fossil-fuel technologies.[4]

Total output of the electricity sector in period t is the sum of electricity generated in the fossil-fuel sector and the renewables sector: $Q_t = f_t + nq_t$. In equilibrium, electricity output equals

socially optimal outcome. When deciding about market entry, firms do not consider that their entry produces a benefit to other market participants in terms of learning by doing. Market entry will be suboptimal in the absence of regulation and needs to be stimulated by an entry premium.

[3] In reality, the renewables sector exhibits a vertical industry structure consisting of producers and operators. Producers supply renewable energy technology to operators. Operators use this technology to generate electricity. Learning-by-doing effects are more likely to be realized by the producers. In this case, however, the extent of learning-by-doing depends on the number of technology units produced rather than on the amount of electricity produced by them. For this analysis, it is assumed however that a higher production of electricity from renewables brings about a higher production of renewable energy technologies. That is, operators have to install more units of a technology to produce a higher level of electricity (instead of replacing a smaller unit by a unit with more capacity). In this sense, learning-by-doing in technology production may indeed depend on the amount of electricity generated. For a model differentiating between producers and operators of renewable energy technologies see Bläsi and Requate (2005; 2007).

[4] Learning-by-doing effects (and related spillovers) in the fossil-fuel sector are neglected because they are relatively less important and would unnecessarily complicate the analysis. In fact, such enhanced analysis would reveal that an additional policy is needed to promote learning-by-doing in the presence of spillovers in the fossil-fuel sector. Such policy may be required in particular once new promising but immature technologies – such as carbon capture and sequestration – are to be adopted in the fossil fuel sector.

electricity demand. The inverse demand function can then be given by $p_t = P_t(Q_t)$, where p_t is the market price for electricity in period t. This function is downward sloping, i.e. $P_t'(Q_t) < 0$.

Carbon dioxide emitted by the fossil-fuel sector in period t produces damage to society, which depends on the overall level of emissions: $D_t(E_t)$. Damage is assumed to be increasing and convex in emissions, i.e. $D_t' > 0$ and $D_t'' \geq 0$.

Social welfare W over the two periods under consideration is given by:

$$W = \int_0^{Q_1} P_1(Q)dQ - C_x^1(x_1) - C_y^1(y_1) - nG^1(q_1) - D_1(E_1)$$

$$+\delta\left[\int_0^{Q_2} P_2(Q)dQ - C_x^2(x_2) - C_y^2(y_2) - nG^2(q_2,L) - D_2(E_2)\right] \tag{1}$$

Thus, social welfare computes as the sum of consumer surplus and firm profits net of production costs with coal, natural gas and renewable energy sources and environmental damage from emissions in the first-period and the same values discounted for period two.

3 The Social Optimum

The social planner maximizes welfare with respect to electricity generation from coal, natural gas and renewable energy sources in both periods, x_t, y_t and q_t. The resulting first-order conditions are:

$$P_1(Q_1) = C_x'^1(x_1) + D_1'(E_1)\mu_x \tag{2}$$

$$P_2(Q_2) = C_x'^2(x_2) + D_2'(E_2)\mu_x \tag{3}$$

$$P_1(Q_1) = C_y'^1(y_1) + D_1'(E_1)\mu_y \tag{4}$$

$$P_2(Q_2) = C_y'^2(y_2) + D_2'(E_2)\mu_y \tag{5}$$

$$P_1(Q_1) = G_{q_1}^1(q_1) + \delta\left[G_L^2(q_2,L) + G_L^2(q_2,L)\rho(n-1)\right] \tag{6}$$

$$P_2(Q_2) = G_{q_2}^2(q_2,L) \tag{7}$$

These equations represent the conditions for a socially optimal allocation of resources. Conditions (2) to (5) require that the emitting fossil-fuel sector generate electricity from coal and natural gas in period one and two until the sum of marginal production cost and marginal environmental damage of either technology equals the willingness to pay for another unit of electricity (represented by the market price). Thus, when deciding about its output, the fossil-fuel sector should consider the private and social costs of its electricity generation. Condition (6) implies that firms in the renewable sector should produce electricity in period one until the marginal willingness to pay equals the sum of marginal production costs in period one and the discounted marginal reduction of production costs in period two due to learning experienced by all firms in period one. Thus, when deciding about their output in period one, firms in the renewable sector should not only consider learning at the private level but also learning spillovers. Finally, condition (7) highlights that firms in the renewable sector should produce electricity in period two until their marginal production costs equals the marginal willingness to pay.

4 Emissions Tax and Output Subsidy: The Optimal Policy Mix

In the presence of two externalities – environmental pollution and learning spillovers – two policies are necessary to attain socially optimal levels of output by the fossil-fuel and renewable sectors in a decentralized economy: a tax on emissions and a subsidy to output of the renewables sector. This argument is also brought forward by Bläsi and Requate (2007) and Fischer and Newell (2008).

Given the emitting fossil-fuel sector is subject to a tax per unit of emissions at rate τ_t, it faces the following maximization problem:

$$\max_{x_t, y_t} \pi^F = p_1(x_1 + y_1) - C_x^1(x_1) - C_y^1(y_1) - \tau_1(\mu_x x_1 + \mu_y y_1)$$
$$+ \delta\left[p_2(x_2 + y_2) - C_x^2(x_2) - C_y^2(y_2) - \tau_2(\mu_x x_2 + \mu_y y_2)\right] \qquad (8)$$

Superscript F denotes the fossil-fuel sector. The resulting first-order conditions for optimal electricity generation from coal and natural gas in period one and two are:

$$p_1 = C_x'^1(x_1) + \tau_1\mu_x \qquad (9)$$

$$p_2 = C_x'^2(x_2) + \tau_2\mu_x \qquad (10)$$

$$p_1 = C_y'^1(y_1) + \tau_1\mu_y \qquad (11)$$

$$p_2 = C_y'^2(y_2) + \tau_2\mu_y \qquad (12)$$

Conditions (9) and (10) can be interpreted as the inverse supply curves for electricity from the fossil-fuel sector. It will produce electricity from coal and natural gas until the sum of marginal production costs and marginal emissions costs with either technology is equal to the market price of electricity. As in Fischer and Newell (2008, 146), an interior solution is assumed, i.e. no fuel is completely driven out of the market. In the absence of an emissions policy, an increased electricity supply from renewable energy sources reduces the electricity production from coal and natural gas according to the respective supply curves. An increase in the stringency of the emissions policy will result in a larger reduction of production from the emission-intensive coal generation than from the low-emission natural gas generation.

Firms in the non-emitting renewables sector receive a subsidy s per unit of output to foster learning-by-doing. Thus, they get remuneration per unit of output which consists of a variable component (the electricity price) and a fixed component (the output subsidy). Their maximization problem writes as follows:

$$\max_{q_t} \pi^R = (p_1 + s_1)q_1 - G^1(q_1) + \delta\left[(p_2 + s_2)q_2 - G^2(q_2, L)\right] \tag{13}$$

Superscript R denotes the renewable sector. Note that, by assumption, firms only consider the effect of private learning on production costs in period two but not that of learning spillovers to other firms, i.e. $L = q_1$ at the private level (Bläsi and Requate 2005, 8). The resulting first-order conditions for firms in the renewables sector are:

$$G^1_{q_1}(q_1) = p_1 + s_1 - \delta G^2_L(q_2, L) \tag{14}$$

$$G^2_{q_2}(q_2, L) = p_2 + s_2 \tag{15}$$

Condition (12) implies that firms produce electricity from renewable energy sources in period one until the marginal production cost in period one is equal to the marginal benefits of production to the firm. These include the market price for electricity, the output subsidy and the discounted reduction of production cost in period two which can be appropriated by the firm (note that term $-\delta G^2_L(q_2, L)$ is overall positive). In period two, there are no learning effects by assumption. Thus, firms produce until marginal production cost in period two equal the sum of the electricity price and the output subsidy (condition (13)).

The optimal policy levels can be obtained by comparing the first-order conditions for maximum social welfare with those for maximum firm profits. Equating conditions (2) and (4) with conditions (9) and (11) yields the optimal emissions tax rate in period one:

$$\tau_1 = D_1'(E_1) \tag{16}$$

The optimal tax rate has to be set equal to marginal damage from emission, i.e. at the Pigovian level. Similarly, equating conditions (3) and (5) with conditions (10) and (12) gives the optimal emission tax rate in period two:

$$\tau_2 = D_2'(E_2) \tag{17}$$

Given that marginal environmental damages from emission are constant, the tax rate has to be set uniformly over time. Equating conditions (6) and (14) gives the optimal output subsidy to electricity produced in the renewables sector:

$$s_1 = -\delta G_L^2(q_2, L)\rho(n-1) \tag{18}$$

Thus, the subsidy equals the gains from learning not considered by the firms in the renewable sector. This means in turn that if learning is purely private, an output subsidy in period one cannot be justified on efficiency grounds. Comparing conditions (7) and (15) reveals that no subsidy to the output of the renewable sector is needed in period two, i.e. $s_2 = 0$. This is straightforward since no learning and, consequently, no learning spillovers are assumed to occur in the model in period two.

5 Emissions Tax and Feed-in Tariff

The design of feed-in tariffs typically deviates from that of a traditional subsidy modelled in section 5. Producers of electricity receive a fixed feed-in tariff σ_1 per unit of electricity produced in period one irrespective of the electricity price.[5] This is in contrast to the analysis in the previous section where an output subsidy was paid to renewable electricity generators in addition to the electricity price. The feed-in tariff includes an implicit subsidy which amounts to the difference between the feed-in tariff and the electricity price. Unlike traditional output subsidies, this implicit subsidy is not exogenously funded by the government – or general tax revenues. Instead, grid operators buying renewable electricity are allowed to spread the difference between the feed-in tariffs paid and the electricity price across all electricity customers. This results in a uniform add-on φ_1 to the electricity price in period one. Thus, within the partial-equilibrium model of the electricity market, the feed-in tariff is revenue-neutral. Revenues from raising the add-on always have to equal the expenditures on tariffs paid for electricity from renewable energy sources net of the prevailing electricity price, i.e. $\varphi_1 Q_1 = (\sigma_1 - p_1) n q_1$. Thus, the add-on to the electricity price computes as the difference of the feed-in tariff and the electricity price times the share of renewable electricity in total electricity supply:

$$\varphi_1 = (\sigma_1 - p_1)\frac{nq_1}{Q_1} \tag{19}$$

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[5] Recall that since no learning occurs in period two, no promotion of renewable electricity is required in period two.

In a competitive market, electricity producers are assumed to take this add-on as given (similarly to an output tax). However, the add-on only affects production choices of fossil-fuel generators. This is because renewable generators benefits from the obligation of grid operators to purchase renewable electricity preferentially. This implies that any reductions in demand for electricity resulting from a price increase induced by the add-on have to be borne by fossil-fuel generators only. In period two, electricity from renewable energy sources is assumed to compete with electricity from fossil-fuels at the market price.

The profit maximization problem for firms in the fossil-fuel sector can then be rewritten:

$$\max_{x_t, y_t} \pi^F = p_1(x_1 + y_1) - C_x^1(x_1) - C_y^1(y_1) - \varphi_1(x_1 + y_1) - \tau_1(\mu_x x_1 + \mu_y y_1)$$

$$+ \delta\left[p_2(x_2 + y_2) - C_x^2(x_2) - C_y^2(y_2) - \tau_2(\mu_x x_2 + \mu_y y_2)\right] \tag{20}$$

The resulting first-order conditions for optimal electricity generation from coal and natural gas in both periods are:

$$p_1 = C_x'^1(x_1) + \varphi_1 + \tau_1\mu_x \tag{21}$$

$$p_2 = C_x'^2(x_2) + \tau_2\mu_x \tag{22}$$

$$p_1 = C_y'^1(y_1) + \varphi_1 + \tau_1\mu_y \tag{23}$$

$$p_2 = C_y'^2(y_2) + \tau_2\mu_y \tag{24}$$

Thus, when deciding about its output in period one, the fossil-fuel sector now produces until the sum of marginal production costs, the add-on per unit of output produced and the emission costs per unit of output equal the market price of electricity (conditions (21) and (23)). Conditions (22) and (24) for optimal output in period two are identical to those derived above.

The profit maximization problem for firms in the renewables sector is:

$$\max_{q_t} \pi^R = \sigma_1 q_1 - G^1(q_1) + \delta\left[p_2 q_2 - G^2(q_2, L)\right] \tag{25}$$

The corresponding first-order conditions for optimal output in the renewables sector are:

$$G_{q_1}^1(q_1) = \sigma_1 - \delta G_L^2(q_2, L) \tag{26}$$

$$G_{q_2}^2(q_2, L) = p_2 \tag{27}$$

In period one, firms in the renewables sector produce until their marginal costs of electricity generation equal the sum of the feed-in tariff and the discounted reduction in production costs in period two due to private learning. Optimal production in period two is only determined by the market price of electricity.

Comparing the above first-order conditions with those providing optimal social welfare reveals the optimal policy design. Comparing conditions (21) to (24) with conditions (2) to (5) gives the optimal set of taxes:

$$\tau_{1x} = D_1' - \frac{\varphi_1}{\mu_x} \tag{28}$$

$$\tau_{1y} = D_1' - \frac{\varphi_1}{\mu_y} \tag{29}$$

$$\tau_2 = D_2' \tag{30}$$

The optimal emissions tax in period two is again a Pigovian tax since no additional policy affects the behaviour of the fossil-fuel sector in that period. However, the optimal emissions tax rate in period one is below the marginal damage of emissions. What is more, it has to differentiate between fossil fuels. Emissions from electricity generation with an emission-intensive fuel (coal) have to be taxed at a higher rate than emissions from combusting a low-emission fuel (natural gas). The explanation is as follows: The add-on to the electricity price results in a reduction of electricity consumption and production. Consequently, emissions from electricity generation are reduced as well. This implies that the emissions tax that is required to attain the optimal level must be lower than in the absence of the add-on. Emission taxation has to be differentiated because the add-on reduces electricity output from fossil fuels irrespectively of the emissions related to different types of fuels. It incorporates a higher implicit emissions tax, φ_1/μ_i, on low-emission fuels than on emission-intensive fuels. Consequently, the optimal emissions tax in the presence of the add-on has to be lower for the low-emission fuel than for the emission-intensive fuel. This result implies that any emissions tax imposed uniformly on all fuels (even if it is reduced below the marginal damage from emissions) in the presence of the add-on will bring about inefficiency in the fossil-fuel sector in period one. Electricity generation from the low-emission fuel will be below the optimal level, while that from emission-intensive fuels will be higher than optimal.

The optimal feed-in tariff in period one can be derived by equating conditions (26) and (6):

$$\sigma_1 = p_1 - \delta G_L^2(q_2, L)\rho(n-1) \tag{31}$$

The optimal feed-in tariff has to be set equal to the sum of the market price for electricity and the discounted marginal gains from period-one learning spillovers in period two. The market price of electricity is a function of a variety of variables that are exogenous to the partial equilibrium model, such as the prices of crude oil and coal. Variations in these exogenous variables require adaptations of the feed-in tariff. A fixed feed-in tariff that is set with respect to the current electricity price may therefore bring about an inefficient level of output in the renewable sector. If the electricity price increases (decreases), electricity generation from renewable energy sources will be too low (high). Equation (31) also reveals that if renewable technologies differ with respect to marginal gains from learning in period two in absolute terms, $G_L^2(q_2, L)$, and/or the spillover rate, ρ , or the number of adopting firms, $n-1$, a differentiation of feed-in tariffs can be justified on efficiency grounds.

Substituting equation (31) into (28) using (19), the optimal tax rate can be rewritten:

$$\tau_{1x} = D_1' - \frac{\left[\delta G_L^2(q_2, L)\rho(n-1)\right]\frac{nq_1}{Q_1}}{\mu_x} \tag{32}$$

The optimal tax rate in period one for fossil-fueled electricity generators with low emissions, τ_{1y}, writes accordingly. Equation (32) reveals that the optimal tax rate has to be reduced as renewable energy technologies become more mature, i.e. the marginal cost reduction effect of learning declines. It also demonstrates that the optimal tax rate decreases as the number of adopters increases, i.e. the total level of spillovers from learning-by-doing becomes more important. Moreover, the optimal tax rate also decreases as the share of renewable energies in total electricity supply increases. In contrast to the optimal feed-in tariff, however, the tax rate does not depend on the electricity price. A price increase results in a higher feed-in tariff and in a lower add-on. Both effects cancel out. These findings imply that regulators do not only have to choose a tax which is below the Pigovian level and differentiated according to the emissions rate. They also have to adapt the emissions tax rate continuously as the maturity and the number of adopters of renewable energy technologies and the market share of renewable energy sources increases.

6 Conclusion

The implementation of a revenue-neutral feed-in tariff to promote electricity from renewable energy sources deteriorates the efficiency properties of a Pigovian emissions tax. Energy producers using fossil fuels will abate too much. This distortion will be worse for low-emitting generators than for high-emitting ones. The optimal level of the tax is therefore below the Pigovian one. The tax has to be differentiated with respect to the emissions rate of each generator. Low-emission generators should pay a lower tax rate. Apart from the emissions rate, the optimal tax level depends on the maturity and the number of adopters of renewable energy technologies and the share of renewable energy sources in the electricity market. This implies that the tax rate has to be adapted continuously as these variables change. Likewise the optimal feed-in tariff has to be modified continuously – as the maturity and the number of adopters of renewable energy technologies increases and as the electricity price varies. However, these requirements may pose a formidable challenge for regulators. Typically, changes of environmental policies cannot be realized ad hoc but rather have to be approved in tedious political process. If policy makers aim at implementing efficient environmental policies that are easy to administer, they should choose a relatively simple policy mix of an emissions policy and an output subsidy for renewable energy technologies. However, a final judgement on the efficiency of this policy mix would also have to consider possible distortions in a general equilibrium model. These may arise from taxes which are raised to fund the output subsidy.

Several research questions remain unanswered in this paper and may provide avenues for further research. First of all, the paper has analyzed the policy mix from the perspective of the first-best. It may be worthwhile to analyze whether a policy mix of an emissions tax and a feed-in tariff does better than a single emissions tax in the presence of two market failures – even though the policy mix is not designed optimally. These would help to reveal whether implementing a feed-in tariff nevertheless increases efficiency although it does not attain a first-best solution. Moreover, the paper assumed a fixed emissions price. However, given an emissions trading scheme, the emissions price may vary. Feed-in tariffs are likely to result in a rising market share of renewable energy sources in the electricity market and the substitution of fossil fuels for electricity generation. Consequently, less emission permits are demanded by the electricity sector and the permit price decreases. Other participants of the emissions trading scheme may benefit from lower permit prices and increase their emissions. These distortions may raise overall costs of emission abatement and should also be considered in the evaluation of the policy mix.

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