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# Subsidies for Learning in Renewable Energy Technologies under Market Power and Emission Trading

Thure Traber[1] and Claudia Kemfert

**JEL Classification:** L13,L94,O33,Q42

**Keywords:** energy policy; renewable energy; learning by doing; imperfect competition; emission trading

**Abstract**

Under perfect competition on the output market, first best technology subsidies in the presence of learning by doing are justified by knowledge spill overs that are not accounted for by individual companies. First best output subsidies are thus depending directly on the learning effects and are, if applicable, positive. Considering electricity markets, a setting of imperfect competition is more appropriate. We show that the second best output subsidy for learning by doing in renewable energies takes the market distortion due to imperfect competition into account and is of ambiguous sign. Based on simulations with a European electricity market model, we find that second best renewable energy subsidies are positive and only insignificantly impacted by market power. By contrast, the welfare gains from an optimal subsidy are considerably higher compared to a hypothetical situation of perfect competition.

## 1 Introduction

Three major sources of market imperfections are frequently attributed to liberalized electricity markets. First, emissions of fossil fuel combustion give rise to environmental externalities. Second, market dominance of incumbent firms induces strategic market behavior and under production. Third, incomplete property rights provide inappropriate incentives to create knowledge and learning in inexperienced industries. The trio is of particular relevance for the optimal structure of renewable energy support. Since renewables are relatively inexperienced technologies on the electricity market, all three market failures may apply. However, in case of the European electricity market environmental damages from fossil fuel emissions are addressed by the European emission trading system which caps the amount of possible emissions, thereby isolating damage reductions induced by the use of non-emitting renewable energy sources for electricity generation.

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Following the work of Pigou (1938) who proposed an emission tax equal to the marginal damage in presence of environmental externalities, the theoretical literature focused on the optimal policy in presence of a tandem of environmental externalities with only one additional market failure. Barnett (1980) investigated the combination of environmental externalities and monopolistic market behavior and derived the second best optimal emission tax which falls short of the Pigouvian tax level due to monopolistic underprovision of output. Ebert (1992) extended the analysis to the case of an oligopolistic structured output market with symmetric firms and finds that the second best emission tax is adjusted by a term including the oligopolistic mark-up and falls short of the Pigouvian level. Simpson (1996) introduces asymmetric firms and concludes that the optimal tax level might fall short of or exceed the marginal damage depending on the different costs of the duopolists. Comparing subsidies for investments in relatively clean technologies with emission taxes, Carraro and Soubeyran (1996) apply an oligopolistic multi-stage game and find no clear ranking of policies in terms of welfare effects. However, if the resources for production with the clean technology are large, it is likely that the subsidy is preferable to the emission tax policy.

Combining renewable energy support with an emission market with fixed caps - as currently practised in Europe - increases the costs of compliance if production costs are static (Böhringer and Rosendahl 2009, Traber and Kemfert 2009). However, particularly in the context of a problem with a long term nature like climate change, static cost assumptions may lead to inappropriate estimations of future costs. Empirical findings illustrate that environmental policies can have a strong positive feedback on innovation and may induce beneficial economic outcomes (Popp 2001, 2002). This has been demonstrated also by a wide range of model simulations. An important part of this literature uses applied models to simulate not only the impacts of climate change on the economy but also the economic consequences of global long-term climate policy, which can be distinguished by the policy targets under consideration.

One literature stream investigates costs of compliance with given emission reductions. Castelnuovo et al. (2005) investigate the effect of learning by doing (LbD) and R&D on compliance costs and find a reduction due to LbD by five percent and due to R&D by 12 percent. Similar results are found by Edenhofer et al. (2005). They apply an integrated assessment model and demonstrate that due to induced technological change, ambitious policy goals are feasible without significant welfare losses. Kemfert (2005) finds in a global integrated assessment model with R&D in energy efficiency and knowledge spill overs that technological change circumvents welfare drops which would be experienced when emission reductions have to be predominantly achieved by production contractions. Hence, technological change reduces emission abatement costs considerably.

Another literature stream is focussing on optimal taxing polcies and the time profile of optimal taxes. Goulder and Mathai (2000) explore the optimal time path of carbon taxes given a single abatement technology and derive a lower time profile of optimal taxes induced by learning by doing or R&D compared to static technology assumptions. Another central result is that when knowledge is induced by R&D it is beneficial to postpone some emission reductions until more cost effective technology is available, while knowledge accumulation through LbD has ambiguos effects on initial abatement. As in the literature mentioned in the previous paragraph, they find that endogenizing technological change lowers abatement costs significantly by about 30 percent. In regard to LbD policy, the ambiguity of initial optimal abatement is resolved by work that employs experience curves explicitly and finds that there is a need for up-front investment in technologies to make them earlier available at low costs (van der Zwaan et al. 2002; Kverndokk and Rosendahl 2007). Similar results are found by Bramoulle and Olson (2005) for two abatement technologies. In addition, they develop the importance of policy differentiation across technologies if the future cost savings due to learning are not homogeneous.

Gerlagh et al. (2009) use an optimal control framework with R&D induced technological change as in Goulder and Mathai (2000), but introduce a richer structure of the R&D process. Three imperfections are considered: too little production of abatement equipment due to monopolistic competition, positive spillovers of the earlier period innovation stock on new innovations, and negative spillovers of total research effort on new innovations. Their results suggest to fix the emission tax above the pigouvian level if it is the only available policy instrument. In a setting similar to the paper presented here, Fischer et al (2008) analytically derive optimal subsidies for learning and R&D in the presence of learning spill overs and optimal emission prices in a perfect competitive setting. They demonstrate with a numerical example of the US electricity sector how an optimal portfolio of emission prices, R&D subsidies and renewables subsidies can achieve emission reductions at significantly lower cost than using emission prices alone.

The combination of imperfect competition on the output market and knowledge externalities has received only little attention in the context of environmental policy. A notable exception is provided by Katsoulacos and Xepapadeas (1996) who investigate policies in a duopolistic structured output market. They find that in the case of emission and knowledge externalities first best outcomes may be achieved by a combination of R&D subsidies and emission taxes. In this setting the optimal emission tax is smaller than the pigouvian tax, supporting the findings of Barnett (1980), and Ebert (1992). Moreover, the accordingly adjusted emission tax would trigger only insufficient research incentives and should be supplemented by a R&D subsidy, which also depends on the amount of technological spill overs, i.e. the greater the spill overs the higher the optimal subsidy. Finally, the subsidy has to account for strategic over investments in R&D which reduce optimal subsidies. Another example is provided by Traber and Kemfert (2011) who investigate effects of a recycling of proceeds from emission trading to support renewable energy under oligopolistic market structures with the quantitative European electricity market model EMELIE. They find a pronounced impact of market power on welfare effects and the share of proceeds that should be recycled. In contrast, in the present paper we study fixed subsidies to renewable energies and apply analytical and quantitative methods. After deriving analytical ambiguity, we apply the EMELIE model which closely reassembles the situation on the European electricity market. In this framework large and potentially dominant conventional electricity suppliers face an increasingly tight emission budget induced by the European emission trading system (ETS), and a renewable energy sector that gains experience through learning by doing.

The paper proceeds as follows. In section two we present an analytical imperfect competition model with emission trading and derive an analytic expression for the second best subsidy for renewable energies that are experiencing learning by doing and knowledge spill overs. Furthermore, we show the ambiguity of the sign of the second best subsidy. In section three we summarize main features of the model EMELIE, describe the scenarios, and present our quantitative results. Section four summarizes annd concludes.

# 2 Analytical model

We consider a market with two time periods denoted $t \in \{1, 2\}$, and two types of technology which are related to market behavior. The conventional industry consists of $n$ symmetric oligopolists denoted $i$ producing output $x_t^i$ and emissions $e_t^i$ with costs $C^i(x_t^i, e_t^i)$. Marginal costs of conventional production are positive and increasing in output, i.e. $C_x > 0$, $C_{xx} > 0$. Furthermore, costs and marginal costs are decreasing in emissions so that $C_e < 0$, $C_{xe} < 0$. Total emissions of each period, $E_t = \sum_{i=1}^{n} e_t^i$, are restricted by exogenously given emission caps $\bar{E}_t$. The perfectly competitive renewable energy sector is represented by costs $C^1(y), C^2(z, y)$, producing $y$ in period 1 and $z$ in period 2. While periodic marginal costs of renewable energy are positive and increasing in respective periods output, $C_y^1 > 0, C_z^2 > 0$, $C_{yy}^1 > 0$, $C_{zz}^2 > 0$, second period costs and marginal production costs are decreasing in first period output, i.e. $C_y^2 < 0$, $C_{zy}^2 < 0$, representing learning by doing. Conventional and renewable production in each period sum up to total production: $Q_1 = \sum_{i=1}^{n} x_1^i + y$ and $Q_2 = \sum_{i=1}^{n} x_2^i + z$. Demand is represented by inverse demand $P_t(Q_t)$, with slope $P_t'(Q_t) < 0$. Moreover, inverse demand is assumed to satisfy the following condition in regard to its shape: $-P_t'(Q_t) > P_t''t(Q_t)Q_t$, with $'$ and $''$ denoting the first and second order derivatives.

The welfare problem is described as:

$$\begin{aligned} W &= \int_0^{Q_1} P_1(Q_1)dQ - \sum_{i=1}^{n} C^i(x_1^i, e_1^i) - C^1(y) - \sigma_1(\sum_{i=1}^{n} e_1^i - \bar{E}_1) \\ &+\delta[\int_0^{Q_2} P_2(Q_2)dQ - C^i(x_2^i, e_2^i) - C^2(z, y) - \sigma_2(\sum_{i=1}^{n} e_2^i - \bar{E}_2)] \quad (1) \end{aligned}$$

where $\delta$ denotes the discount factor and where exhaustion of the emission caps under emission allowance prices in period one and two, $\sigma_1$, $\sigma_2$, is assumed.

## 2.1 Social optimum

The first order conditions for a social optimum with regard to production and emission in both technologies and both periods can be summarized as follows:

$$P_1(Q_1) = C_x^i(x_1^i, e_1^i), \quad (2)$$

$$-C_e^i(x_1^i, e_1^i) = \sigma_1, \quad (3)$$

$$P_2(Q_2) = C_x^i(x_2^i, e_2^i), \quad (4)$$

$$-C_e^i(x_2^i, e_2^i) = \sigma_2, \quad (5)$$

$$P_1(Q_1) = C_y^1(y) + \delta[C_y^2(z, y)], \quad (6)$$

$$P_2(Q_2) = -C_z^2(z, y). \quad (7)$$

Equations (2), (4), and (7) say that in the social optimum and in regard to conventional production in both periods and renewable energy production in the second period marginal costs have to be equal to the output price. Equations (3), (5) demand equalization of the marginal costs of abatement with the allowance price in both periods. In addition, equation (6) states that the discounted cost reduction in the second period induced by learning has to be deducted from first periods marginal cost to determine optimal initial renewable energy production.

## 2.2 Conventional firms

Conventional firms are producing with non-renewable energy inputs and are represented by oligopolistic firm $i$. The firm maximizes the following profit function by choosing optimal output, i.e. as a Cournot player, and behaving as a price taker on the emission allowance market[2]:

$$\pi(x_1, x_2, e_1, e_2) = P_1(Q_1)x_1 - C^i(x_1^i, e_1^i) - \sigma_1 e_1^i$$
$$+\delta[P_2(Q_2)x_2 - C^i(x_2^i, e_2^i) - \sigma_2 e_2^i]. \quad (8)$$

Differentiating yields four first order conditions. After rearranging, we get two equations that describe the Nash output equilibria:

$$P_1(Q_1)(1 - \frac{\vartheta}{\epsilon}) = C_x^i(x_1^i, e_1^i), \quad (9)$$

and

$$P_2(Q_2)(1 - \frac{\vartheta}{\epsilon}) = C_x^i(x_2^i, e_2^i), \quad (10)$$

where $\vartheta$ is the market share of the oligopolist and $\epsilon$ denotes the value of the demand elasticity. These equations state that the oligopolists charge the mark up $P\frac{\vartheta}{\epsilon}$ on top of marginal costs. Thus, since marginal costs are increasing in output, production is too small compared to the welfare optimal production described by equations (2) and (4).

Furthermore, we get two equations describing first and second period emission abatement activity:

$$-C_e^i(x_1^i, e_1^i) = \sigma_1, \quad (11)$$

and

$$-C_e^i(x_2^i, e_2^i) = \sigma_2, \quad (12)$$

showing no deviation from socially optimal behavior.

## 2.3 Renewable energy supply with production subsidy

The second production sector is sourced from renewable energies and its costs depend on previous period's cumulated production. The representative firm can only appropriate a fraction $\rho$ of the learning effects induced by its first period output decision. To incentivize firms to create positive external effects from learning, we introduce a subsidy $s$ that supports renewable energy in the initial period.

The profit function of the representative renewable energy firm writes:

$$\pi(y, z) = P_1(Q_1)y - C^1(y) + sy + \delta[P(Q_2)z - C^2(z, y)]. \quad (13)$$

[2]While conventional firms have high market shares and considerable market power on their national output markets, it is appropriate to assume a competitive emission market due to comparatively small market shares on the regionally broader emission market. For an alternative assessment see Hintermann (forthcoming), who addresses market power also on the permit market and effects of free allowance allocation.

Profit maximizing behavior is guided by two first order conditions. After rearranging, they can be formulated as:

$$P_1(Q_1) + s = C_y^1(y) + \delta\rho C_y^2(z, y), \tag{14}$$

and

$$P_2(Q_2) = C_z^2(z, y). \tag{15}$$

Deducting (6) from (14), one finds that in the absence of market distortions in the conventional sector, the optimal subsidy would be equal to the not appropriable discounted cost savings in the second period due to learning induced by additional production in the first period: $s = -\delta(1-\rho)C_y^2(z, y)$. However, a second best subsidy policy has to consider market distortion due to strategic output behavior in the conventional sector.

## 2.4 Second best optimal subsidy

To derive the second best optimal subsidy, we interpret welfare as function of the endogenous variables and the subsidy, and differentiate (1) with respect to the subsidy to get the first order condition for a welfare optimum. Inserting the first order conditions of the firms, we get the following expression for the second best optimal renewable energy subsidy:

$$s = -\delta(1-\rho)C_y^2(z, y) + \frac{P_1(Q_1)\frac{\vartheta}{\epsilon}n\frac{\partial x_1}{\partial s} + \delta P_2(Q_2)\frac{\vartheta}{\epsilon}n\frac{\partial x_2}{\partial s}}{\frac{\partial y}{\partial s}}. \tag{16}$$

Equation (16) shows that the second best optimal subsidy depends on two terms. The first unambiguous term which is determined by the non appropriable part of the cost reduction induced by the learning effect and gives rise to a positive subsidy. The second term depends on the ratio of the sum of discounted comparative static effects of conventional output ($\frac{\partial x_1}{\partial s}$, $\frac{\partial x_2}{\partial s}$) weighted with the respective mark up to the comparative static effect of the subsidy on the production of renewable energy in the first period ($\frac{\partial y}{\partial s}$).

The comparative statics of an increase of the subsidy in the case of complete non appropriability are derived in appendix A. They are summarized in the following proposition.

**Proposition 1** *If the system described by equations (9), (10),(14), and (15) has an interior solution, and under non appropriabilty ($\rho = 0$) of learning effects, increasing the subsidy to renewable energies reduces output of conventional technologies in both periods, and increases production of renewable energies in both periods, i.e. :* $\frac{\partial x_1}{\partial s} < 0$, $\frac{\partial x_2}{\partial s} < 0$ *and* $\frac{\partial y}{\partial s} > 0$, $\frac{\partial z}{\partial s} > 0$.

Thus, we find for the extreme case of complete non appropriability that the second term in equation (16) is unambiguously negative. Hence, the sign of the second best subsidy is ambiguous. Moreover, the effect of market power on the optimal subsidy is ambiguous. On the one hand, market power induces a negative effect on the subsidy according to the second term of equation (16). On the other hand, the renewable energy production is higher in both periods due to higher output prices. This induces relatively high learning in the first period even without subsidy, and relatively high gains from learning in the second period.

# 3 Quantitative Model

To study the analytically ambiguous effects of market power on renewable energy subsides, we apply the computable partial equilibrium model EMELIE (Electricity MarkEt Liberalization In Europe) documented in Traber and Kemfert (2009), and Traber and Kemfert (2011), which contains also a detailed description of the model and its inputs[3]. Three time steps 2010, 2030, and 2030 are simulated. In the reference case (scenario A), the model includes the following features and assumptions:

1. 27 European electricity markets linked through limited crossborder transmission capacities,
2. Electricity generation is represented by 26 technological specifications based on nine primary fuel carriers and different vintages,
3. Learning-by-doing reduces the production costs in the following period at a progress ratio of 0.9 for each doubling of cumulated production,
4. Future costs and rents are discounted at a social discount rate of three percent,
5. The dynamic production capacity development is based on depreciation of existing plants and investments in new capacities,
6. Increasing fossil fuel prices[4],
7. The European emission market increasingly restricted by caps on emission allowances that linearly reach emission reductions of 80 percent by 2050,

[3]See Appendix B for the algebraic representation of the model adaptation to a renewable energy subsidy.

[4]Hard coal prices rise from 0.72 in 2010 to 0.9 in 2030 reaching 1.0 eurocent per kWh by 2050, while natural gas prices are currently 2.17 and rise to 3.17 by 2030 and to 3.53 by 2050. Similar increases are expected for fuel oil prices: 1.72, 2.41 and 2.81 eurocent per kWh in the first, second, and third period.

8. 58 firms behave in regard to output and investments either strategically *à la* Cournot or as price takers in case of minor fringe firms,

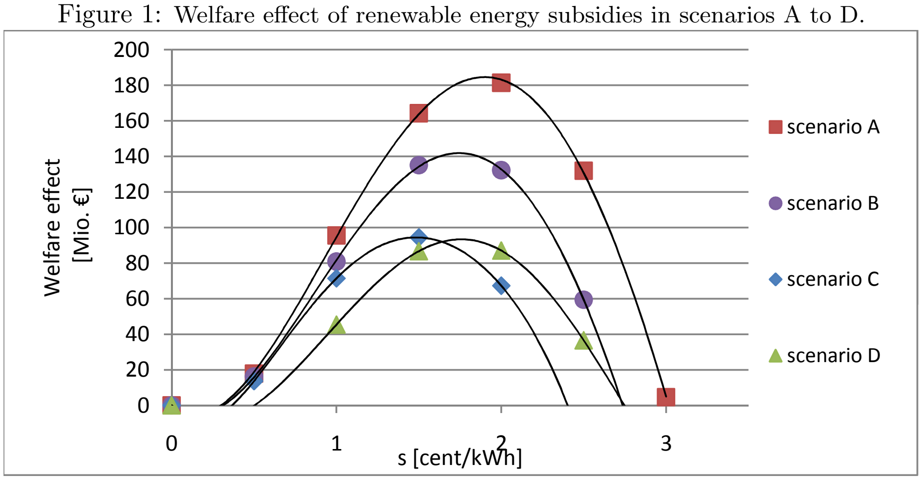
9. Iso-elastic electricity reference demand with elasticity $-0.4$ is increasing linearly by twenty percent by 2050 .

To elaborate the effects of market power and the reference case assumptions, we alter at most two assumptions in regard to features 6 to 9 for each scenario. In order to isolate the model against any imperfect foresight and lock-in effects in the fossil fuel sector, in scenario B existing production capacity and fuel prices are fixed to the base period 2010. Scenario B also reassembles the analytical model most closely. Scenario C introduces a non decreasing emission allowance supply fixed at the current level. For scenario D, we assume price taking behavior of all firms. Finally, for scenarios E1 and E2, we set the demand elasticity to $-0.3$ (E1), and to $-0.5$ (E2), in order to elaborate the impact of different demand settings and to check the sensitivity of the model.

### 3.1 Quantitative results

The results of the quantitative model are derived by applying subsidies to the production of renewable energy in the first model period varying between 0 and 2.5 cent per kilo watt hour for each of the scenarios. Figure 1 presents the welfare effects induced by renewable energy subsidies for scenarios A to D.

Figure 1: Welfare effect of renewable energy subsidies in scenarios A to D.

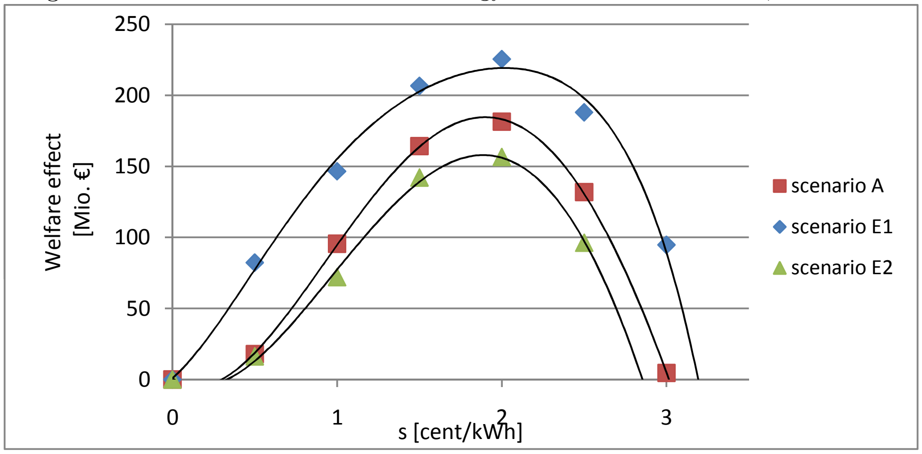



We find that in the reference case (scenario A) the welfare effect is maximized at a subsidy of about two cent per kilo watt hour, yielding a discounted welfare improvement in the three representative years of more than 180 million euro.

Switching to the model that matches the analytical model most closely and abstracts from capital accumulation and depreciation as well as fossil fuel price increases, yields less pronounced results (scenario B). In this scenario a welfare improvement compared to the laissez faire case of at most 140 million euro can be achieved at a optimal subsidy of about 1.75 cent. Scenario C demonstrates the great importance of the climate policy targets implemented by emission trading. Keeping the emission constraint at current level greatly reduces the welfare improvements achievable by the optimal renewable energy subsidy to 95 million euro, while the optimal subsidy is also reduced half a cent compared to the reference scenario. Similar results are obtained when the impact of market power is neglected, as demonstrated by scenario D. In this case maximum welfare improvements are around the level of scenario C. However, the optimal subsidy appears comparatively robust against varying the behavioral assumption to perfect competition, indicated by an insignificant reduction compared to the reference scenario.

Figure 2 below shows the induced welfare effects compared to the case of no renewable energy subsidy in the three scenarios concerning the demand elasticity A, E1, and E2. We find that subsidies of up to 2.8 cent per kilo watt hour increase welfare in all scenarios. Highest welfare improvements are induced by a subsidy of 2 cent per kilo watt hour irrespective of the elasticity scenario, indicating a robustness of our result against changes in the demand elasticities. However, compared to the reference case, higher welfare improvements are induced when the value of elasticity is lower (E1), yielding 226 million euro discounted welfare improvement. By contrast, maximum welfare improvements are lower when the value of the elasticity is comparatively high (E2), i.e. 157 million euro.

Figure 2: Welfare effect of renewable energy subsidies in scenarios A, E1 and E2.



# 4 Summary and Conclusion

We analyized the impact of market power on subsidies for electricity from renewable energy. While under perfect competition the optimal learning-by-doing subsidy is solely determined by the non appropriable part of cost reductions induced by learning effects, oligopolistic competition requires to take into account market distortions on the output market. With an analytical model we derived second best optimal renewable energy subsidies in the presence of learning-by-doing spill overs and oligopolistic market structure in the conventional power sector. Analytically, we find that oligopolistic market power gives rise to a term that reduces the optimal subsidy compared to the situation of perfect competition. However, oligopolistic competition also effects the market driven use of renewable energies through higher prices. Hence, the overall effect of market power on the optimal subsidy to internalize learning externalities is ambiguous.

Applying the European electricity market model EMELIE, we shed some light on the influence of market power on renewable energy subsidies in a quantitative framework. The results show that market power is likely to increase the welfare gains of optimal renewable energy subsidies in the presence of learning-by-doing externalities. However, the optimal subsidy itself - around 2 cent per kilo watt hour - is comparatively robust when we compare strategic behavior and price taking behavior of conventional firms on the output market. Only a slight increase of the subsidy due to imperfect competiton might be justified. The findings can be explained by two intertemporally distinct effects. In the first model period imperfect competiton triggers a wider diffusion of renewable energies, and, hence, a more pronounced learning effect, which in turn reduces the requirement for a subsidy. In subsequent model periods the application of renewable energies is larger when prices are high due to imperfect competition, which leads to pronounced cost savings by experience effects and a justification of higher subsidies in the first period. If the discounted effect in the second period dominates the effect in the first period, market power gives additional justification for renewable energy support. Moreover, similar to the impact of market power, a change of demand elasticities influences the maximum welfare gains more pronounced than the corresponding optimal subsidies. Simulations with three different elasticities show that the model results are fairly robust.

Notably, our scenarios suggest that the climate policy targets implemented by the emission trading system have the most important effect on the size of optimal subsidies. Compared to a less ambitious climate policy which fixes emission caps at the current level, the gradually tightened emission caps of the European emission trading system demand higher renewable energy subsidies. Moreover, it emerges that they generate about twice as much welfare gains compared to a hypothetical situation of intertemporally fixed emission caps. Also, only a minor effect can be attributed to the effects of long lived capital stocks and rising fossil fuel prices which might give rise to technological lock in. In general our results confim earlier findings of the literature in regard to the global and the american examples for the European case, i.e. climate policy targets can be reached at significantly lower costs when emission trading is complemented by subsidies to inexperienced renewable energy technologies.

In the application of our results for policy recommendation, two caveats to our assessment have to be mentioned. First, our results rest on the assumption of an renewable energy industry that supplies perfectly competitive. This assumption is justified by very low short run variable costs and problems to excercise market power with highly dispersed small scale units as wind and solar power plants. However, private learning effects may cause scale effects and a concentrated market structure at least in the up-stream industry that manufactures these plants (Bläsi and Requate 2005, Reichenbach and Requate 2011). Future research should therefore adress the question whether market power in the manufacturing of renewable energy plants is a problem or international competition is sufficient to induce competitive pricing. Second, we assume the absence of policies that might promote technological progress more effecticely, e.g. R&D subsidies. Applying a tailored policy which more directly adresses the source of knowledge creation might be superior to a subsidy to output. Unfortunately, the sources of knowledge creation and their private components are hard to assign to LbD or R&D. Thus, following Pizer and Popp (2008), we emphasize to empirically disentangle R&D and LbD effects, and to explore the relative contributions of public and private R&D.

Finally, in our study a uniform experience effect in terms of the progress ratio for different renewable energy technologies has been analyzed. Empirical studies find significant differences in the speed of progress of different technologies (McDonald and Schrattenholzer 2002, Uyterlinde et al. 2007). Hence, the effects of the differentiation of support to technologies with different progress ratios that is applied in many electricity markets in Europe could be a fruitful subject for subsequent research.

# Appendix A

We demonstrate the comparative static effects claimed in proposition 1 for the case where the firms cannot appropriate learning effects, i.e. $\rho$ equals zero. Differentiating equations (9)-(12) and (14)-(15), and using the fact that binding emission caps provide $\frac{\partial e_1}{\partial s} = 0$, and $\frac{\partial e_2}{\partial s} = 0$, we get the following system of equations:

$$
\begin{aligned}
&\frac{\partial x_1}{\partial s}(nP_1''x_1+(n+1)P_1'-C_{xx}^1)+\frac{\partial y}{\partial s}(P_1''x_1+P_1')=0\\
&\frac{\partial x_2}{\partial s}(nP_2''x_2+(n+1)P_2'-C_{xx}^2)+\frac{\partial z}{\partial s}(P_2''x_2+P_2')=0\\
&\frac{\partial x_1}{\partial s}(-C_{xe}^1)+\frac{\partial \sigma_1}{\partial s}(-1)=0\\
&\frac{\partial x_2}{\partial s}(-C_{xe}^2)+\frac{\partial \sigma_2}{\partial s}(-1)=0\\
&\frac{\partial x_1}{\partial s}(nP_1')+\frac{\partial y}{\partial s}(P_1'-C_{yy}^1)=0\\
&\frac{\partial x_2}{\partial s}(nP_2')+\frac{\partial y}{\partial s}(-C_{yz}^2)+\frac{\partial z}{\partial s}(P_2'-C_{zz}^2)=0,
\end{aligned}
$$

where firm indeces are suppressed, and cost function of the conventional sector in the first and second period are simplified to $C^1$ and $C^2$.

Solving the system of equations for the comparative static effects yields the following determinant:

$$
\begin{aligned}
A=&(C_{yy}^1(C_{xx}^1-(n+1)P_1'-nP_1''x_1)-P_1'(C_{xx}^1-P_1'))\\
&(C_{zz}^2(C_{xx}^2-(n+1)P_2'-nP_2''x_2)-P_2'(C_{xx}^2-P_1'))
\end{aligned}
$$

which is positive due to the assumptions in regard to demand shape and cost functions.

The comparative static effects can now be expressed as:

$$
\begin{aligned}
\frac{\partial x_1}{\partial s}&=\frac{P_1'+P_1''x_1}{(C_{yy}^1(C_{xx}^1-(n+1)P_1'-nP_1''x_1)-P_1'(C_{xx}^1-P_1'))}\\
\frac{\partial x_2}{\partial s}&=-A^{-1}(P_2'+P_2''x_2)C_{yz}^2(C_{xx}^1-(n+1)P_1'-nP_1''x_1)\\
\frac{\partial y}{\partial s}&=-\frac{(n+1)P_1'+nP_1''x_1-C_{xx}^1}{(C_{yy}^1(C_{xx}^1-(n+1)P_1'-nP_1''x_1)-P_1'(C_{xx}^1-P_1'))}\\
\frac{\partial z}{\partial s}&=-A^{-1}C_{yz}^2(C_{xx}^1-(n+1)P_1'-nP_1''x_1)(C_{xx}^2-(n+1)P_2'-nP_2''x_2)\\
\frac{\partial \sigma_1}{\partial s}&=\frac{-C_{xe}^1(P_1'+P_1''x_1)}{(C_{yy}^1(C_{xx}^1-(n+1)P_1'-nP_1''x_1)-P_1'(C_{xx}^1-P_1'))}\\
\frac{\partial \sigma_2}{\partial s}&=A^{-1}C_{xe}^1(P_2'+P_2''x_2)C_{yz}^2(C_{xx}^1-(n+1)P_1'-nP_1''x_1).
\end{aligned}
$$

Using the assumptions in regard to demand shape and cost functions we find the signs claimed in proposition 1.

# Appendix B

The quantitative model is described in Traber and Kemfert (2011), and for this application extended to the case of renewable energy subsidies.

The problem of firm $i$ in period $t$ can be formulated as the following Lagrangian:

$$\begin{aligned}
\max_{q^{i,t},q^{i,t,n},x^{i,t}} L^{i,t} \quad = \quad & \sum_{r\in R} P^{r,t}(X^{r,t})x^{i,r,t} + s^t \sum_{g\in G} q^{i,t,g} \\
& -C^{i,t}(q^{i,t}) - \sum_{n\in N} Cn^{i,t,n}(q^{i,t,n}) \\
& -\sigma^t(E^{i,t}(q^{i,t}) + \sum_{n\in N} En^{i,t,n}(q^{i,t,n})) \\
& -\kappa^{i,t}(q^{i,t} - \overline{q}^{i,t}) - \sum_{n\in N} \phi^{i,t,n}(q^{i,t,n} - \overline{q}^{i,t,n}) \\
& - \sum_{r^*\neq r} x^{i,r^*,t}\tau^{r,r^*,t}(\sum_{i\in I^r} x^{i,r^*,t} - \overline{x}^{r,r^*}) \\
& -\mu^{i,t}(X^{i,t} - q^{i,t} - \sum_{n\in N} q^{i,t,n}), \qquad (17)
\end{aligned}$$

where the first and second term represents revenues of the firm $i$ in all regions from electricty sales $\sum_{r\in R} P^{r,t}(X^{r,t})x^{i,r,t}$ and subsidies to renewable energy production $s^t \sum_{g\in G} q^{i,t,g}$, the third and forth terms denote production costs and the fifth term represents costs associated with emission price $\sigma^t$. The last four terms in (17) represent the capacity restriction with shadow price $\kappa$, the investment restriction with its shadow price $\phi$, the cross-border electricity flow restriction with shadow price $\tau$ and, finally, the production balance, which requires that total supply is not greater than total production. The details of the notation are summarized in the table below.

## Notation

| | |
|---|---|
| $T$ | Set of time steps, where $t$ denotes a single time step |
| $I$ | Set of companies, where $i$ denotes a single firm |
| $I^r$ | Set of companies in region $r$ |
| $R$ | Set of regions, where r denotes a single region |
| $N$ | Set of investment technologies |
| $G$ | Set of renewable energy investment technologies, subset of $N$ |
| $P^{r,t}$ | Electricity price in region $r$ and period $t$ |
| $\delta$ | social discount factor |
| $\sigma^t$ | Price of carbon emissions in period $t$ |
| $X^{r,t}$ | Total electricity supply in region $r$ and period $t$ |
| $E^t_{el}$ | Total emissions of the electricity sector in period $t$ |
| $E^t_{nel}$ | Total emissions of the non-electricity ETS sector in period $t$ |
| $x^{r,r^*,t}$ | Export from region $r$ to $r^*$ |
| $q^{i,r,t}$ | Electricity production of firm $i$ in region $r$ and period $t$ in installed power plants |
| $q^{i,r,t,n}$ | Electricity production of firm $i$ in region $r$ and period $t$ in newly installed power plants of type $n$ |
| $C(q^{i,t})$ | Variable costs of electricity production of firm $i$ in period $t$ in installed power plants |
| $Cn(q^{i,t,n})$ | Total costs of electricity production of firm $i$ in period $t$ for newly installed power plants of type $n$ |
| $E(q^{i,t})$ | Emissions of electricity production of firm $i$ in period $t$ in installed power plants |
| $En(q^{i,t,n})$ | Emissions of electricity production of firm $i$ in period $t$ in newly installed power plants of type $n$ |
| $\overline{q}^{i,t}$ | Capacity restriction of installed power plants of firm $i$ in period $t$ |
| $\overline{q}^{i,t,n}$ | Capacity expansion restriction of firm $i$ in period $t$ and technology $n$ |
| $\overline{x}^{r,r^*}$ | Transmission restriction from region $r$ to $r^*$ |
| $\kappa^{i,r,t}$ | Shadow price of capacity restriction of installed power plants of firm $i$ in region $r$ and period $t$ |
| $\phi^{i,t,n}$ | Shadow price of capacity expansion restriction of firm $i$ in period $t$ and technology $n$ |
| $\tau^{r,r^*,t}$ | Shadow price of transmission capacity from region $r$ to $r^*$ in period $t$ |
| $\epsilon^{r,t}$ | price elasticity of residual demand in region $r$ in period $t$ |
| $\vartheta^{i,r,t}$ | market share of firm $i$ in the strategic segment of region $r$ in period $t$ |
| $s^t$ | subsidy to renewable energy |

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