

Bläsi, Albrecht; Requate, Till

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# **Subsidies for Wind Power: Surfing down the Learning Curve?**

by Albrecht Bläsi and Till Requate

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Christian-Albrechts-Universität Kiel

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# Subsidies for Wind Power: Surfing down the Learning Curve?

by

ALBRECHT BLÄSI and TILL REQUATE\*

Department of Economics, Kiel University<sup>†</sup>

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## Abstract

We develop a model with two types of electricity producers, fossil fuel utilities generating emissions, and suppliers of electricity from renewable resources such as wind energy. We account for the vertical structure of the wind-energy sector by considering wind-turbine producers engaged in learning by doing and selling their turbines to turbine operators. We show that in the absence of learning spillovers a first-best policy requires Pigouvian taxes only. We also study second-best optimal subsidies on electricity generated by wind power when (optimal) emission taxes are ruled out. We further investigate the impact of subsidies on prices, output, the number of firms, and environmental damage. It turns out that, in the case of purely private learning, second-best optimal subsidies should only account for the environmental damage but are not necessary to spur learning.

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<sup>†</sup>Olshausenstrasse 40, 24098 Kiel, Germany, Phone: (++49) 431 – 8804424,  
Email: albrechtblaesi@gmx.de, requate@economics.uni-kiel.de

# 1 Introduction

The governments of most OECD countries encourage the use of renewable energy resources in one way or another. Notably electricity generated by wind power is or has been subsidized by means of different instruments in Australia, Austria, Denmark, Germany, Greece, India, Ireland, Italy, Spain, The Netherlands, and the US, to mention only the larger markets.<sup>1</sup> Without those subsidies, or without an appropriate Pigouvian tax on emissions, electricity from renewable resources such as wind and solar power would hardly be able to compete with fossil fuel utilities. In political debate it has often been argued that subsidizing the use of renewable energy is necessary especially in their inventory phase in order to spur learning effects and thus to cause the producers of wind power to move downwards on their learning curves. It is further argued that those subsidies should be reduced once learning has occurred and costs have decreased.<sup>2</sup> In this paper we scrutinize this claim by setting up a two-period model with two types of electricity producers, (a) a mature fossil fuel utility sector generating emissions, and (b) an emission-free sector generating electricity from renewable energy, such as wind or solar power. In the remainder of the paper we concentrate on the example of wind energy.

When developing our model we had in mind countries that subsidize (or used to subsidize) the use of wind power and at the same time host a domestic turbine

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<sup>1</sup>The “Global Renewable Energy Policies and Measures Database” of the International Energy Agency (2006) provides detailed information about regulatory policies in over 100 countries. See also the survey by BTM-Consult (2007) for details such as market shares of companies in different countries, etc. A survey of Danish policy in this quarter is given by Morthorst (1999) and the Danish Energy Authority (1999) for the period up to 1999.

<sup>2</sup>In particular, the International Energy Agency (2000) argues that countries should subsidize renewable energy because of the learning effects. Among other governments the German Federal government justifies its high feed-in tariffs for solar power with the objective of eventually making those technologies competitive (BMU 2004).

producer sector. This is especially true of Denmark, Germany, Spain, and the USA, also for the small but fast-growing Indian market. In those five markets we observe a strong bias among turbine operators to buy the turbines from domestic producers (see BTM Consult 2007).

Although conventional energy markets are characterized by a relatively high degree of market power and other institutional and technical particularities, we make some simplifying assumptions in our model. In particular, we assume that power-plant operators sell their output directly to consumers in a competitive market, thus also abstracting from the possible market power of grid connectors. We further simplify things by assuming that only one conventional power-generation technology exists that emits a single homogeneous pollutant. We also assume perfect competition on the market for wind turbines.<sup>3</sup> Since a typical feature of wind-power production is dependence on locations (e.g., at coastal sites wind blows more steadily and strongly than at inland sites) we assume that wind-power operators are heterogeneous. Apart from its realism, this assumption induces a nicely downward-sloping demand curve for wind turbines.

The wind-turbine operators, referred to as downstream firms, buy their turbines from upstream turbine producers that incur decreasing costs in the second period of production through learning. We distinguish between purely private learning and learning spillovers. Private learning means that cost reductions in the second period depend only on each firm's own level of output in the first period, while with learning spillovers firms benefit also from other firms' first-period output. For the main part of the paper we follow the model proposed by Petrakis et al. (1997), focusing only on private learning and having the number of firms determined endogenously by free

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<sup>3</sup>We have also worked out a richer version of our model including imperfect competition on both the conventional electricity market and on the market for turbine producers. Due to the 2-period model this feature induces further strategic effects, which makes the model rather complicated and may distract attention from the essentials we are mainly interested in. Therefore we have decided to submit the simpler version with competitive markets.

entry.

We show that if the regulator can charge a Pigouvian tax on emissions that internalizes all damage from pollution and if learning is purely private, then no subsidies are necessary to spur sufficient learning. This is in line with the findings by Petrakis et al. (1997), who show that private learning in competitive markets does not induce insufficient learning. If, however, an emission tax is not feasible, or if an exogenously given tax falls short of the Pigouvian level, a second-best optimal subsidy policy implies positive subsidy rates on electricity generated by wind power. We obtain the neat result that in this case the subsidy rate exactly makes up for the difference between sub-optimal emission tax and marginal damage. Moreover, we find that, if the subsidy is increased in the first period, prices for wind-turbines will rise in the same period but fall in the second period. We further show that, if no taxes on emissions exist, total and fossil-fuel electricity output is higher than optimal. Accordingly, environmental damage is greater than at the first-best allocation. Furthermore, we find that the second-best optimal subsidy rate is constant over time if we assume constant marginal damage from emissions and identical damage functions over time. The bottom line is that if we assume that learning is mainly private, the “learning push” argument put forward in the political debate is obsolete. But if learning spillovers exist, a subsidy can be a corrective for insufficient learning.

There is a major strand of empirical literature claiming the existence of learning and learning spillovers in the sector of wind-turbine production.<sup>4</sup> From Bläsi and Requate (2005) we know that in the presence of learning spillovers one needs two types of subsidies for the learning industry to reach a first-best allocation: an output subsidy and an entry premium or investment subsidy. So, in the case of electricity markets with

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<sup>4</sup>Hansen, et al.(2003) and also Neij (1997,1999) find learning effects in the Danish market. Junginger et al. (2003) analyze a data set on Spanish and British wind farms. Isoard and Soria (2001) analyze learning effects of different renewable energies, Neij et al. (2003) compare learning effects observed in different countries.

pollution, we need an emission tax, an output subsidy on wind-turbine production, and an entry premium for wind-turbine producers. For the case of learning spillovers we also derive the second-best optimal subsidy rule when the only instrument available to the regulator is a subsidy on electricity generated from wind power.

The paper is organized as follows: In Section 2 we set up the model. In Section 3 we characterize the socially optimal allocations. In Section 4 we study the optimal policy of the regulator in a decentralized economy with and without learning spillovers. In Section 5 we investigate second-best optimal subsidy policies for the wind-power sector when a first-best optimal policy is not feasible for both private learning and learning spillovers. We also study comparative static effects with respect to that subsidy and carry out some comparisons between first-best and second-best allocations. In Section 6 we summarize the results and draw some policy conclusions.

## 2 The Model

We consider a vertical industry structure with  $n$  wind-turbine producers (upstream firms) selling their turbines to wind-turbine operators (downstream firms). These operators produce electricity and compete with conventional utilities employing fossil fuels.

The technologies of both sectors are represented by their cost functions,  $\Gamma(\cdot)$  for producers of wind turbines and  $C(\cdot)$  for wind-turbine operators, while conventional utilities produce at constant marginal costs  $\xi$  and emit a pollutant, notably  $CO_2$ , proportional to output.

Since we are focusing on learning-by-doing effects in the upstream sector producing wind turbines, we have to consider at least two periods  $t = 1, 2$ . Let  $y_t$  denote the output of a typical (symmetric) turbine producer in period  $t$ . Then  $\Gamma^1(y_1)$  denotes the production cost in period 1 (without experience) and  $\Gamma^2(y_2; L)$  the production cost in

period 2, where  $L = y_1 + \epsilon(n-1)\tilde{y}_1$  denotes total learning or experience. This is the sum of a typical firm's own output and the output  $\tilde{y}_1$  of all other  $(n-1)$  firms in the first period, where  $\epsilon$  with  $0 \leq \epsilon \leq 1$  is the spillover coefficient. For  $\epsilon = 0$  we have only private learning and for  $\epsilon = 1$  we have complete spillovers. In the latter case, it does not matter for a firm's cost reduction whether some of the output is produced in the firm itself or by some other firm. In the main part of Section 5 we will assume that  $\epsilon = 0$ , i.e. that learning is purely private.

We assume that the cost function  $\Gamma$  satisfies the following properties:  $\Gamma_{y_t}^t > 0$  and  $\Gamma_{y_t y_t}^t > 0$ , i.e. we have positive and increasing marginal costs in each period. Moreover,  $\Gamma_L^2 < 0$  and  $\Gamma_{y_2 L}^2 < 0$ , i.e. experience (own or by other firms) in period 1 decreases both cost and marginal cost in period 2. Furthermore we assume  $\Gamma_{LL}^2 > 0$ , i.e. the marginal effect of learning is decreasing. Finally, we assume overall convexity of  $\Gamma^2$ , implying  $\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - [\Gamma_{y_2 L}^2]^2 > 0$ . To allow for free entry we also assume - deviating from Petrakis, et al. (1997) - that there is a fixed cost  $F$  that the firms incur only once. This implies that firms will either produce or stay out of the market in both periods, as indicated in Bläsi and Requate (2005).

A producer of electricity using wind power (a downstream firm) generates  $q_t$  units of output in period  $t$ . We assume that there is a continuum of downstream firms represented by the interval  $[0, \infty]$ . Thus  $\tilde{x} \in [0, \infty]$  can be interpreted either as a particular firm or as a firm-specific parameter, e.g. location. This parameter has an impact on the cost: the larger  $\tilde{x}$  is, the higher both total cost and the marginal cost of production become. The idea is that wind turbines closer to the shore are more productive than those further inland. So the smaller  $\tilde{x}$  is, the better the location of the wind turbine must be. Hence we write the downstream firms' cost as  $C^t(q_t, \tilde{x})$  with  $C_{q_t}^t > 0$ ,  $C_{q_t q_t}^t > 0$ ,  $C_{\tilde{x}}^t > 0$ ,  $C_{q_t \tilde{x}}^t > 0$ , i.e. we have positive and increasing marginal costs in output and in the location parameter  $x$ . Again we assume overall convexity of



the cost function implying  $C_{\tilde{x}\tilde{x}}^t > 0$  and  $C_{q_t q_t}^t C_{\tilde{x}\tilde{x}}^t - [C_{q_t \tilde{x}}^t]^2 > 0$ .<sup>5</sup>

Each downstream firm buys only one wind turbine. We use  $x_t$  to denote the marginal downstream firm still producing in period  $t = 1, 2$ .<sup>6</sup> By virtue of  $C_{\tilde{x}}^t > 0$  and  $C_{q_t \tilde{x}}^t > 0$ , it is efficient for all firms  $\tilde{x} < x_t$  to produce if firm  $x_t$  produces. This structure also holds for a decentralized economy: If it pays for firm  $x_t$  to produce, then it willn pay for any  $\tilde{x} < x_t$  to produce. Hence

$$x_t = ny_t \tag{1}$$

is the total wind-turbine output by the upstream firms and the total capacity installed in period  $t$ . Since the downstream firms are asymmetric, we write  $q_t(\tilde{x})$  as the output by firm  $\tilde{x}$ . The technical reason why we introduce asymmetry into the electricity production sector based on wind power is the following: If either with or without regulation the firms of that sector were symmetric, the minimum average costs of all the turbine operators would be either lower or higher than the unit costs of the conventional electricity utilities. This would imply that, except for special parameters, either the wind sector or the fossil fuel sector would serve the whole market and no continuous comparative static effects could emerge.

The total output of electricity in period  $t$  is thus given by

$$Q_t = \int_0^{x_t} q_t(\tilde{x}) d\tilde{x} + k_t \quad , \tag{2}$$

where  $k_t$  is the total output of the fossil fuel utilities.

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<sup>5</sup>One might object that the supply of wind is given exogenously and thus is  $q_t$ . Maintenance of wind turbines, however, requires effort and induces variable costs. Inefficiently maintained wind turbines generate no output. Therefore we consider  $q_t$  as a choice variable.

<sup>6</sup>Note that the wind-turbine operators have to buy a new wind turbine in each period. It might seem more realistic to allow for wind-turbine operators producing with the same wind turbine in periods 1 and 2. However, this merely makes the computations more involved and the qualitative results do not change if we allow for two-period operators. Accordingly, we restrict the analysis to the case where a turbine only lives for one period.

Demand for electricity is given by a downward sloping inverse demand function

$$p_t = P_t(Q_t), \quad (3)$$

i.e.  $P'_t(Q_t) < 0$ . Moreover, there is damage to society from pollution generated by output  $k_t$  of the fossil fuel utilities and evaluated by a damage function  $D_t(k_t)$  with  $D'_t(k_t) > 0$  and  $D''_t(k_t) \geq 0$ . We are now ready to define welfare  $W$  by

$$\begin{aligned} W = & \int_0^{Q_1} P_1(Q) dQ - \int_0^{x_1} C^1(q_1, x) dx - n\Gamma^1(y_1) - nF - \xi k_1 - D_1(k_1) \\ & + \delta \left[ \int_0^{Q_2} P_2(Q) dQ - \int_0^{x_2} C^2(q_2, x) dx - n\Gamma^2(y_2; L) - \xi k_2 - D_2(k_2) \right], \end{aligned} \quad (4)$$

where  $\delta$  represents both the social and private discount factor.<sup>7</sup>

### 3 The Social Optimum

The social planner maximizes welfare  $W$  with respect to  $q_t, k_t, y_t$ , and the optimal number of upstream firms  $n$ . The first-order conditions for welfare maximum are given by the following equations, where  $W_{q_1} = \partial W / \partial q_1$  etc. denote partial derivatives:

$$W_{q_1} = P_1(Q_1) - C^1_{q_1}(q_1, \tilde{x}) = 0 \quad \text{for all } \tilde{x} \leq x_1 \quad (5)$$

$$W_{q_2} = P_2(Q_2) - C^2_{q_2}(q_2, \tilde{x}) = 0 \quad \text{for all } \tilde{x} \leq x_2 \quad (6)$$

$$W_{k_1} = P_1(Q_1) - \xi - D'_1(k_1) = 0 \quad (7)$$

$$W_{k_2} = P_2(Q_2) - \xi - D'_2(k_2) = 0 \quad (8)$$

$$W_{y_1} = P_1(Q_1)q_1(x_1) - C^1(q_1, x_1) - \Gamma^1_{y_1}(y_1) \quad (9)$$

$$-\delta[\Gamma^2_L(y_2; L) + \Gamma^2_L(y_2; L)\epsilon(n-1)] = 0$$

$$W_{y_2} = P_2(Q_2)q_2(x_2) - C^2(q_2, x_2) - \Gamma^2_{y_2}(y_2; L) = 0 \quad (10)$$

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<sup>7</sup>In general, the social and the private discount factor need not coincide. We neglect such differences as they are not important to the focus of this paper.

$$\begin{aligned}
W_n = & [P_1(Q_1)q_1 - C^1(q_1, x_1)]y_1 - \Gamma^1(y_1) - F \\
& -\delta[\Gamma^2(y_2; L) + n\Gamma_L^2(y_2; L)\epsilon y_1] \\
& +\delta[P_2(Q_2)q_2 - C^2(q_2, x_2)]y_2 = 0
\end{aligned} \tag{11}$$

The interpretation is straightforward. (5) and (6) require that the marginal willingness to pay for electricity must be equal to the marginal costs of electricity production by the clean (wind) sector while (7) and (8) require that the marginal willingness to pay must also be equal to the private plus the external marginal costs for the dirty (fossil fuel) electricity sector. (9) and (10) determine the optimal output levels for wind turbines for a single upstream producer, while (11) determines the optimal number of upstream firms. Note that (9), (10), and (11) also determine the optimal number of wind-turbine operators in both periods, as defined by (1).

## 4 The Optimal Regulation in a Decentralized Economy

In this section look at a decentralized economy and ask which policy instruments will be necessary to implement the first-best allocation. We know that, if markets are competitive, a Pigouvian tax usually induces a first-best allocation even if there is free entry of firms (see Spulber 1985). Petrakis et al. [?] have shown that competitive firms incurring private learning effects fully take these effects into account and thus voluntarily incur losses in the first period that they will recover in the second. Hence under free entry, firms enter the market until the optimal number of firms is reached and no governmental intervention is necessary. By contrast, Bläsi and Requate (2005) have shown that if learning spillovers are present, the regulator needs two instruments, an output subsidy and an entry premium, to establish the first-best allocation. The intuitive explanation of why the entry premium is necessary alongside the output subsidy to reach a first-best allocation is as follows: While the output subsidy  $s_{out}$  takes

account of the fact that there is too little output by each firm in the first period, we need the entry premium  $s_{ent}$  to cover the fact that there is also too little market entry and hence not enough sources of learning.

Therefore, with pollution and learning by doing under free entry, we will need three instruments to decentralize the first-best allocation: a Pigouvian tax, an output subsidy for turbines, and an entry premium for turbine producers.

Thus the profit of the fossil fuel utility  $\pi_t^k$  is given by

$$\pi_t^k = p_t k_t - \xi k_t - \tau_t k_t \quad \text{for } t = 1, 2, \quad (12)$$

using  $\tau_t$  to denote the emission tax rate in period  $t$ .

Facing an output subsidy  $s_{out}$  and an entry premium  $s_{ent}$ , the profit of a typical turbine producer (upstream firm) is given by

$$\pi^u = b_1 y_1 - \Gamma^1(y_1) + s_{out} y_1 + s_{ent} - F + \delta[b_2 y_2 - \Gamma^2(y_2; L)] \quad , \quad (13)$$

where  $b_i$  denotes the competitive price for turbines in period  $i$ .

Finally, a typical turbine operator's profit (downstream firm) is given by

$$\pi_t^d = p_t q_t - C^t(q_t, x) - b_t \quad \text{for } t = 1, 2, \text{ and all } \tilde{x} \leq x_t \quad (14)$$

Since all firms are assumed to behave as price-takers, profit maximization leads to the following behavioral equations:

$$p_t = \xi + \tau_t \quad \text{for } t = 1, 2 \quad (15)$$

$$p_t = C_{q_t}^t(q_t, \tilde{x}) \quad \text{for } t = 1, 2, \text{ and all } \tilde{x} \leq x_t \quad (16)$$

$$b_1 = \Gamma_{y_1}^1(y_1) + \delta \Gamma_L^2(y_2; L) - s_{out} \quad (17)$$

$$b_2 = \Gamma_{y_2}^2(y_2; L) \quad (18)$$

Zero profit conditions due to free entry for both turbine producers and operators yield

$$p_t q_t - C^t(q_t, x_t) - b_t = 0 \quad \text{for } t = 1, 2 \quad (19)$$

$$b_1 y_1 - \Gamma^1(y_1) - F + s_{out} y_1 + s_{ent} + \delta[b_2 y_2 - \Gamma^2(y_2; L)] = 0 \quad (20)$$

Note that (19) holds for the marginal turbine operator  $x_t$ , while for all  $\tilde{x}_t < x_t$  the profit is positive. Comparing equations (15) - (20) with the conditions for the social optimum (5) - (11) shows that the optimal levels of  $\tau_t$ ,  $s_{out}$ , and  $s_{ent}$  are given by  $\tau_t = D'_t(k_t^*)$ ,  $s_{out} = -\delta\epsilon(n-1)\Gamma_L^2(y_2^*, L^*)$ , and  $s_{ent} = -\delta\epsilon\Gamma_L^2(y_2^*, L^*)y_1^*$ , where asterix variables denote first-best levels.

We can summarize these results as follows:

**Proposition 1** *In the model with pollution, private and public learning by doing, and market entry as outlined above, the socially optimal allocation can be reached by i) charging a Pigouvian tax (equal to optimal marginal damage)  $\tau_t = D'_t(k_t^*)$  on electricity produced by fossil fuels, ii) paying a first-period output subsidy per turbine  $s_{out} = -\delta\epsilon(n-1)\Gamma_L^2(y_2^*, L^*)$ , and iii) paying an entry premium for wind-turbine producers  $s_{ent} = -\delta\epsilon\Gamma_L^2(y_2^*, L^*)y_1^*$ .*

We observe that with a sufficiently rich toolbox of instruments we do not need any subsidies for electricity generated from renewable energy sources. Instead, the subsidies should be paid directly to where the learning effects occur, i.e. to the turbine producers.

Note that instead of taxing emissions, the regulator could alternatively issue a corresponding number of permits inducing the same (optimal) total level of emissions and leading to a price for emission allowances that is equal to the Pigouvian tax rate.

A second important conclusion from our result is that if the regulator can tax emissions according to the Pigouvian level (or can issue a corresponding number of tradable permits), no subsidies should be paid if the learning effects are purely private, i.e. if  $\epsilon = 0$ .

In the next section we investigate second-best optimal subsidies for wind-turbine operators when both taxes at the Pigouvian level and direct subsidies to turbine producers are ruled out.

## 5 Second-best Optimal Subsidies when Pigouvian Taxes and Direct Subsidies are Ruled Out

Emission taxes at the Pigouvian level are often ruled out for political reasons. Moreover, direct subsidies for wind turbines are also ruled out by WTO rules, especially if the turbines are traded internationally. In several countries, such as Germany, Spain or Denmark, subsidies are camouflaged as so-called feed-in tariffs paid to turbine operators by the conventional power plants. As mentioned in the introduction, these subsidies are justified by arguing that the increased output of today's turbines accelerates learning by doing and thus shifts down the cost curves by sliding along the learning curve. Another argument frequently heard is that for this reason subsidies should be chosen high in the early periods of technology invention and should then decrease as learning proceeds. We investigate this hypothesis by introducing subsidies on “clean electricity” in the decentralized economy. In Subsections 5.1 and 5.2 we assume that there is only private learning, i.e.  $\epsilon = 0$ .

Under this policy setting, profit functions and first-order profit-maximum conditions for the fossil fuel utilities remain unchanged because while we still allow for taxes on fossil fuels, we assume that the tax level is given exogenously and may possibly not be optimal. The only difference in the profit functions and first-order conditions for the upstream turbine producers (17), (18), and (20) is that we drop the subsidies  $s_{out}$  and  $s_{ent}$ . By contrast, the profit function and first-order conditions for the turbine operators now include the output subsidy on wind power  $\sigma_t$ . We neglect the fact that in some countries, such as Denmark and Germany, conventional utilities and not the government pay those subsidies directly to the turbine operators. Since we assume the electricity market to be fully competitive, this does not make any difference. Note that if we included market power on the electricity market, feed-in tariffs according to market shares could induce further strategic behavior by large utilities, because higher market shares would induce higher amounts of feed-in payments to the wind operators.

However, we neglect those complications in this paper.

The operator's profits are therefore given by  $p_t q_t - C^t(q_t, x_t) - b_t + \sigma_t q_t$ , where we use  $\sigma_t$  to denote the subsidy rate for "clean electricity". The turbine operator's first-order condition for profit maximum is therefore given by

$$p_t + \sigma_t = C_{q_t}^t(q_t, \tilde{x}) \quad \text{for } t = 1, 2 \text{ and all } \tilde{x} \leq x_t$$

and zero profits through market entry imply

$$p_t q_t - C^t(q_t, x_t) - b_t + \sigma_t q_t = 0 \quad \text{for } t = 1, 2$$

for the marginal firm  $x_t$ , while for all  $\tilde{x}_t < x_t$  the profits are positive.

## 5.1 Comparative Statics if Learning is Private

Second-best analysis usually requires carrying out some comparative statics exercises. Besides, the results are of some interest in themselves. We therefore investigate the impact of increasing both output subsidies  $\sigma_t$  and tax rates  $\tau_t$  on the firms' choice variables, notably output and also on the number of firms and on energy prices. For this purpose we differentiate the equations (1), (2), (3), and (15) - (20) with respect to the policy variables, assuming here that learning is purely private ( $\epsilon = 0$ ). Signing the effects is, however, not possible without making further assumptions. We therefore define the following three conditions:

$$\Gamma_{y_1 y_1}^1 y_1 + \delta \Gamma_{y_2 L}^2 y_2 \geq 0 \quad (21)$$

$$\Gamma_{y_2 y_2}^2 y_2 + \Gamma_{y_2 L}^2 y_1 \geq 0 \quad (22)$$

$$\Gamma_{LL}^2 y_1 + \Gamma_{y_2 L}^2 y_2 \geq 0 \quad (23)$$

All these conditions imply that the effect of learning on the second-period marginal costs of turbine production is not too large.

**Proposition 2** *Assume that taxes and subsidies are on a level such that both types of firms, fossil fuel utilities, and some wind-turbine operators are able to operate in the*

market simultaneously and that learning among the wind-turbine producers is purely private. Then

1. Enhancing the subsidy rate in one period (other policy instruments being held constant) yields<sup>8</sup>

$$\frac{\partial x_t}{\partial \sigma_t} > 0, \frac{\partial x_t}{\partial \sigma_{-t}} > 0, \frac{\partial k_t}{\partial \sigma_t} < 0, \frac{\partial k_t}{\partial \sigma_{-t}} < 0, \frac{\partial q_t}{\partial \sigma_t} > 0, \frac{\partial q_t}{\partial \sigma_{-t}} = 0, \frac{\partial b_t}{\partial \sigma_t} > 0, \frac{\partial b_t}{\partial \sigma_{-t}} < 0, \\ \frac{\partial p_t}{\partial \sigma_t} = 0, \frac{\partial p_t}{\partial \sigma_{-t}} = 0, \frac{\partial Q_t}{\partial \sigma_t} = 0, \text{ and } \frac{\partial Q_t}{\partial \sigma_{-t}} = 0.$$

Further,  $\frac{\partial y_t}{\partial \sigma_t} > 0$  ( $< 0$ ) if and only if the LHS of (22) is strictly positive (negative).

Moreover, if (21) is satisfied, then  $\frac{\partial y_t}{\partial \sigma_{-t}} > 0$  and  $\frac{\partial n}{\partial \sigma_t} > 0$ .

2. Enhancing the tax rate in one period (other policy instruments being held constant) yields

$$\frac{\partial x_t}{\partial \tau_t} > 0, \frac{\partial x_t}{\partial \tau_{-t}} > 0, \frac{\partial k_t}{\partial \tau_t} < 0, \frac{\partial k_t}{\partial \tau_{-t}} < 0, \frac{\partial q_t}{\partial \tau_t} > 0, \frac{\partial q_t}{\partial \tau_{-t}} = 0, \frac{\partial b_t}{\partial \tau_t} > 0, \frac{\partial b_t}{\partial \tau_{-t}} < 0, \\ \frac{\partial p_t}{\partial \tau_t} = 1, \frac{\partial p_t}{\partial \tau_{-t}} = 0, \frac{\partial Q_t}{\partial \tau_t} < 0, \text{ and } \frac{\partial Q_t}{\partial \tau_{-t}} = 0.$$

Further,  $\frac{\partial y_t}{\partial \tau_t} > 0$  ( $< 0$ ) if and only if the LHS of (22) is strictly positive (negative).

Moreover, if (21) is satisfied, then  $\frac{\partial y_t}{\partial \tau_{-t}} > 0$  and  $\frac{\partial n}{\partial \tau_t} > 0$ .

The proof is rather lengthy since we have to differentiate a 7-by-7 equation system. But it follows standard techniques and can be obtained from the authors on request. For the comparative statics effects of a simultaneous increase in the subsidy rates (the uniform subsidy) see the Appendix.

As we would expect, if the subsidy (tax) rate in one period is raised, the output  $k$  of the fossil fuel utilities will decline in both periods, while both the output of wind-power production (i.e.  $\int_0^{x_t} q_t(\tilde{x})d\tilde{x}$ ) and the number of wind-turbine operators  $x$  (and hence the number of wind turbines sold) increase in both periods. An increase in the subsidy (tax) in one period also increases the output  $q$  of each wind-turbine operator in the same period, while the output of wind-turbine operators in the other period

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<sup>8</sup>We use  $-t$  to denote the respective other period, i.e.  $-t = 3 - t$  for  $t = 1, 2$ .



does not change. A change in the subsidy rates leaves electricity price  $p$  and total output of electricity  $Q$  unchanged in both periods. The reason is that due to perfect competition the electricity price is determined solely by the marginal costs  $\xi$  of the fossil fuel producers (unless electricity from fossil fuel producers is completely driven out of the market). By contrast, an increase of the tax rate in one period increases electricity price  $p_t$  by the same amount and reduces total output  $Q_t$  of electricity. Price and output in the respective other period are not affected.

Interestingly, however, an increase in the subsidy (tax) in one period drives up the price  $b$  for the wind turbines in the same period but reduces it in the other. The intuition is that a higher subsidy for clean electricity boosts the demand for wind turbines but due to increasing marginal costs this demand can only be satisfied at higher prices. The higher level of production in the first period induces more learning and thus lowers both costs and prices in the second period. Moreover, if the subsidy (tax) rate is raised, the effects on the number of wind-turbine producers and their respective output is ambiguous, although total output must increase.

From the results of Proposition 2 it follows directly that in both cases - efficient outcome with a positive tax and no subsidies and second-best optimal solution with a positive subsidy and no taxes - the electricity output of the conventional firms is lower, while both the electricity output of wind-turbine operators and the number of wind turbines is higher than in the unregulated market outcome. This finding may explain why lobbying activities by conventional utilities attempt to achieve less regulation while lobbying activities by the wind energy sector are in favour of more regulation. We also observe that introducing the tax to induce the first-best outcome increases the electricity price compared to the unregulated market outcome, while this price is the same for both the second-best outcome with subsidies and the unregulated market outcome. From a political point of view, it might be more difficult to introduce the first-best solution as the price increase of electricity will then be directly linked to regulation. The regulator's resulting positive budget and redistribution (e.g. by lowering other

taxes) might, however, go unnoticed by the consumers. Conversely, in the second-best regulation the electricity prices remain constant and consumers might appreciate the increased share of renewable energy without linking the regulator's budget burden (financing the subsidies) to the regulation.

## 5.2 Second-best Optimal Subsidies without Spillovers

We are now ready to determine the second-best optimal subsidy rate for clean electricity. In this section we do this first for the case of purely private learning. Let us assume that the Pigouvian level for the emission tax is not feasible for political reasons and is therefore given exogenously, with  $\tau_t = 0$  as a special case. In this case, the regulator maximizes welfare with respect to  $\sigma_1$  and  $\sigma_2$ . Taking into account the behavioral equations (15) through (20), some straightforward calculations yield the following result on the second-best optimal subsidy rates:

**Proposition 3**    1. *If the regulator can control only the subsidy rate on wind power, the second-best optimal subsidy rate on wind power follows the rule*

$$\sigma_t = D'_t(k_t) - \tau_t \tag{24}$$

2. *The subsidy rate of the first period should be higher than the subsidy rate of the second period, i.e.  $\sigma_1 \geq \sigma_2$  if and only if  $D'_1(k_1) - \tau_1 \geq D'_2(k_2) - \tau_2$ , i.e. if the difference between marginal damage and the suboptimal tax rate is larger in the first period.*

3. *In the special case of constant marginal damage we obtain  $\sigma_1 = \sigma_2$ .*<sup>9</sup>

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<sup>9</sup>For  $CO_2$  the empirical literature largely finds marginal damage to be constant (see Tol, 2005 and others).

4. *If the regulator can only set a uniform subsidy over time, the "third-best" optimal subsidy rate follows the rule*

$$\sigma = \frac{[D'_1(k_1) - \tau_1] \frac{\partial k_1}{\partial \sigma} + \delta [D'_2(k_2) - \tau_2] \frac{\partial k_2}{\partial \sigma}}{\frac{\partial k_1}{\partial \sigma} + \frac{\partial k_2}{\partial \sigma}} \quad (25)$$

For the proof see the Appendix. Result i) implies that subsidy rates are positive whenever the exogenous emission tax rate is lower than marginal damage. It also implies that for the special case  $\tau_t = 0$  the optimal subsidy on wind power is equal to the marginal damage generated by burning fossil fuels. For the accidental case  $\tau_t = D'_t(k_t)$  the subsidy is zero, as already shown in section 4. Even if the regulator can only set a uniform subsidy, that subsidy rate will be positive given the comparative statics results of Proposition 2.3), i.e.  $\frac{\partial k_t}{\partial \sigma} < 0$ , and given that the emission tax rates are lower than marginal damage in each period.<sup>10</sup> Moreover, the uniform "third-best optimal" uniform subsidy rate is a weighted average of the two second-best optimal subsidy rates per period since it accounts for the marginal damage in both periods. Part 3 shows that the (second-best) optimal subsidy rates do not have any increasing or decreasing time profile to account for any learning effects.

Finally, we investigate how the second-best optimal subsidy rates depend on an exogenously given tax.

**Proposition 4** *Assume marginal damage is constant. An increase of emission tax  $\tau_t$  requires lowering the second-best optimal subsidy rate  $\sigma_t$  by the same amount.*

The proof is simply given by differentiating (24):

$$\frac{\partial \sigma_t}{\partial \tau_t} = D''_t(k_t) \frac{\partial k_t}{\partial \tau_t} - 1 = -1 \quad \text{for} \quad D''_t(k_t) = 0. \quad (26)$$

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<sup>10</sup>Note that in 2005 we observed prices higher than 20 euros per ton of  $CO_2$  in Europe. This price was above the marginal damage of  $CO_2$  calculated in several studies. See in particular Tol (2005). Nordhaus and Boyer (2000), for example, calculate an optimal tax rate of 9 euros per ton  $CO_2$  in 2005.

Proposition 4 implies that the second-best optimal non-uniform subsidy rate is equal to marginal damage if the emission tax is zero. However, it is not a perfect substitute for an emission tax. Simple rearrangement of the first-order conditions shows that the electricity output generated from wind power is equal in both cases but the output of electricity from fossil fuels is higher. Thus we can state the following result:

**Proposition 5** *Assume marginal damage is constant. In a regime of second-best optimal subsidies on wind power, the output of electricity generated from fossil fuel exceeds the efficient level, implying that total environmental damage is higher than optimal, whereas the output of electricity generated from wind power is equal to the first-best level.*

Assessing the political implications of these results, it is interesting to compare existing subsidy rates to their optimal levels. Consider the optimal real-world level of those subsidies. In Germany the feed-in tariff amounts on average to about 0.08 euros per  $kWh$ . Modern combined cycle power plants emit about 0.4 kg  $CO_2$ /kWh (see Deutsche Emissionshandelsstelle, 2005). As discussed recently by Tol (2005), there is no consensus on the marginal damage of one ton of  $CO_2$ . So look at two different (relatively extreme) values of 5 and 100 euros /ton  $CO_2$ . For 5 euros /ton  $CO_2$  we end up with marginal damage in modern power plants of  $0.4 \frac{kg:CO_2}{kWh} * 5 \frac{euros}{ton:CO_2} = 0.2 \frac{ct}{kWh}$ , while for 100 euros /ton  $CO_2$  we obtain a marginal damage of  $4 \frac{ct}{kWh}$ . Thus even if we assume a high amount (100 euros /ton  $CO_2$ ) of marginal damage and further assume that there is no tax on fossil fuels (contrary to the European reality with an emission market), our theory suggests that the second-best optimal subsidy should be no higher than 0.04 euros per  $kWh$ . Adding the subsidy to the marginal cost of conventional electricity production (0.03 euros per  $kWh$ ), we end up at 0.07 euros per  $kWh$ . This, however, is still lower than 0.08 euros per  $kWh$ .

In addition we have to bear in mind that one  $kWh$  generated by wind power does not have the same value as one  $kWh$  generated by fossil fuels since the supply of wind (and sunlight) is stochastic and cannot be used by the utilities to crowd out one  $kWh$  generated by burning fossil fuels. We have neglected this feature in our model. If we take it into account, the optimal subsidy rate for electricity generated by wind power will be even lower.

### 5.3 Comparative Statics with Spillovers

If learning spillovers exist, the comparative static effects change compared to the case with private learning only. In particular, fewer effects can be signed unambiguously. Differentiating the equations (1), (2), (3), and (15) through (20) with respect to  $\sigma_t$  and assuming that learning spillovers exist, i.e.  $0 \leq \epsilon \leq 1$ , we obtain the results in Proposition 6. In order to be able to sign the comparative static effects, we introduce two additional conditions which again ensure that both the cost and the marginal cost reductions induced by learning are not too high:

$$\delta\epsilon\Gamma_L^2 + \Gamma_{y_1y_1}^1 y_1 \geq 0 \quad (27)$$

$$\Gamma_{y_2y_2}^2 y_2(n-1) + \Gamma_{y_2L}^2 y_1 n \geq 0 \quad (28)$$

**Proposition 6** *i) Given that producers of wind power and fossil fuel utilities are both active in the market and learning spillovers exist, we obtain*

$$\frac{\partial p_t}{\partial \sigma_t} = 0, \frac{\partial p_t}{\partial \sigma_{-t}} = 0, \frac{\partial Q_t}{\partial \sigma_t} = 0, \frac{\partial Q_t}{\partial \sigma_{-t}} = 0, \frac{\partial q_t}{\partial \sigma_t} > 0, \text{ and } \frac{\partial q_t}{\partial \sigma_{-t}} = 0.$$

*ii) If further conditions (22) and (27) are satisfied, then  $\frac{\partial x_1}{\partial \sigma_1} > 0$ ,  $\frac{\partial x_1}{\partial \sigma_2} > 0$ ,  $\frac{\partial b_1}{\partial \sigma_2} < 0$ ,  $\frac{\partial k_1}{\partial \sigma_1} < 0$ , and  $\frac{\partial k_1}{\partial \sigma_2} < 0$ .*

*iii) If condition (28) is satisfied, then  $\frac{\partial x_2}{\partial \sigma_1} > 0$ ,  $\frac{\partial b_2}{\partial \sigma_1} < 0$ , and  $\frac{\partial k_2}{\partial \sigma_1} < 0$ .*

*iv) The effects are ambiguous for the output of wind turbines  $y_t$ , the number of wind turbine producers  $n$ , and for the effects  $\frac{\partial b_t}{\partial \sigma_t}$ ,  $\frac{\partial x_2}{\partial \sigma_2}$ , and  $\frac{\partial k_2}{\partial \sigma_2}$ .*

The proof again follows standard methods of comparative statics and can be obtained from the authors on request.

Here too, price and output of total electricity are not affected by varying the subsidy rates because the marginal costs of the fossil fuel utilities remain unchanged. Total output of wind power increases if the subsidy rate is increased in the same period and remains unchanged if the subsidy is increased in the other period. All other effects are ambiguous without additional conditions. Under conditions (27) and (28) we get increasing output of wind turbines and decreasing electricity output from fossil fuel producers. An increase of the subsidy rate in one period leads to a fall in the prices of wind turbines in the other period.

## 5.4 Second-best Optimal Subsidies with Spillovers

Finally we look at the second-best optimal subsidy policy in the presence of learning spillovers. In this case, those subsidy rates for electricity generated by e.g. wind power should not only take into account the marginal damage of emissions generated from burning fossil fuels but also the market imperfections caused by the spillovers. Not surprisingly, the optimal subsidy rate consists of two parts, where the second part is due to the learning spillovers:

$$\sigma_t = D'_t(k_t) + \frac{\epsilon n \Gamma_L^2 [((n-1) \frac{\partial y_1}{\partial \sigma_t} + y_1 \frac{\partial n}{\partial \sigma_t}) \frac{\partial k_{-t}}{\partial \sigma_{-t}} - ((n-1) \frac{\partial y_1}{\partial \sigma_{-t}} + y_1 \frac{\partial n}{\partial \sigma_{-t}}) \frac{\partial k_{-t}}{\partial \sigma_t}]}{\frac{\partial k_t}{\partial \sigma_t} \frac{\partial k_{-t}}{\partial \sigma_{-t}} - \frac{\partial k_t}{\partial \sigma_{-t}} \frac{\partial k_{-t}}{\partial \sigma_t}} \quad (29)$$

Using the comparative statics effects of the preceding section we cannot sign the second term of this subsidy unambiguously. Intuitively, the spillovers should call for higher subsidies. If by increasing the subsidy the direct effects dominate the indirect effects (e.g.  $\frac{\partial x_1}{\partial \sigma_1} > \frac{\partial x_2}{\partial \sigma_1}$ ), one can show that the subsidy is positive. But the latter inequality may not hold in general. To the best of our knowledge there is however no empirical evidence specifically indicating that spillovers are a great deal stronger in the production sectors of renewable energy equipment than in any other sector.

## 6 Conclusion

In this paper we have scrutinized subsidy policies for clean energy, as applied in many countries all over the world. In particular, we have set up a model enabling us to investigate whether learning effects justify subsidizing electricity generated from emission-free, (so-called) renewable resources such as wind and solar power. We have characterized the first-best allocations for both private learning and learning spillovers and we have investigated the instruments suitable for decentralizing those allocations. We have established that for the case of purely private learning, the regulator should only internalize the external effects of emissions by introducing an emission tax. With learning spillovers, the regulator should additionally subsidize production of wind turbines and the entry of wind-turbine producers. We have also studied second-best optimal subsidy policies where subsidies on electricity generated by wind power are the only instrument available to the regulator. Finally, we have looked at the comparative static effects of these instruments. On the one hand, our results suggest that the regulator does not have to bother about learning effects if he can expect learning to be mainly private because the second-best optimal subsidy rate is determined only by the marginal damage of emissions. On the other hand, if there are learning spillovers the regulator should take those effects into account. However, little can be said in general about the sign of such second-best optimal subsidy rates that have to correct for both emissions from pollution and insufficient learning due to non-internalized spillovers.

Our results clearly indicate that current regulation in many European countries with high subsidy rates is not optimal and that the subsidy paid to wind-power operators is too high if learning is entirely private. If learning spillovers exist among turbine producers (or producers of other equipment generating emission free electricity), the second-best optimal subsidies might be slightly higher than those without spillovers. Accordingly, the challenge for future empirical research on renewable energies is to test whether learning spillovers or private learning plays the leading role in the learning

process.

Note finally that the results on second-best optimal subsidies under exogenously given emission taxes cannot be transferred in a one-to-one way to a system of tradable permits, as currently implemented in the European Union for regulating  $CO_2$  and in the US for regulating  $SO_2$  and  $NO_X$ . The reason is that the total amount of emissions is determined by the total emission cap set by the regulator. Thus one unit of electricity created by wind or solar power leads to a decreasing demand curve for tradable permits. Since the supply of permits remains constant, the price for permits (unlike the emission tax rate) will fall and other firms will buy those permits, thus keeping the total amount of pollution constant. Accordingly, a subsidy on clean electricity in the presence of permit trading would have no environmental benefit whatsoever. This also shows that a policy mix consisting of permit trading and a subsidy for creating electricity from clean resources, in particular feed-in tariffs, is inconsistent. If governments want to limit the price for emissions for reasons of international competitiveness and at the same time to provide positive incentives for employing clean energy, then an emission tax appears to be a better instrument than tradable permits.

## 7 Appendix

**Extension of Proposition 2** As an extension of the results in Proposition 2 we derive the comparative statics results for identical subsidy rates in both periods. We obtain the following results: Enhancing identical subsidy rates simultaneously (other policy instruments being held constant) yields  $\frac{\partial x_t}{\partial \sigma} > 0$ ,  $\frac{\partial k_t}{\partial \sigma} < 0$ ,  $\frac{\partial q_t}{\partial \sigma} > 0$ ,  $\frac{\partial y_t}{\partial \sigma} \leq 0$ ,  $\frac{\partial p_t}{\partial \sigma} = 0$ ,  $\frac{\partial Q_t}{\partial \sigma} = 0$ , and  $\frac{\partial b_1}{\partial \sigma} \frac{\partial b_2}{\partial \sigma} < 0$  with  $\frac{\partial b_1}{\partial \sigma} > 0$  if and only if  $\frac{y_2}{q_2(x_2)} C_{\tilde{x}}^2 > \frac{y_1}{q_1(x_1)} C_{\tilde{x}}^1$ .

If the conditions (22) and (23) hold, we have  $\frac{\partial n}{\partial \sigma} > 0$ . The proof can be obtained from the authors on request.

**Proof of Proposition 3** The first-order conditions of the welfare maximum with



respect to  $\sigma_1$  are given by

$$\begin{aligned}
W_{\sigma_1} = & (P_1(Q_1) - \xi - D'_1(k_1)) \frac{\partial k_1}{\partial \sigma_1} + \delta(P_2(Q_2) - \xi - D'_2(k_2)) \frac{\partial k_2}{\partial \sigma_1} \\
& + P_1(Q_1) \int_0^{x_1} \frac{\partial q_1(\tilde{x})}{\partial \sigma_1} d\tilde{x} - \int_0^{x_1} C_{q_1}^1(q_1, \tilde{x}) \frac{\partial q_1(\tilde{x})}{\partial \sigma_1} d\tilde{x} \\
& + \delta(P_2(Q_2) \int_0^{x_2} \frac{\partial q_2(\tilde{x})}{\partial \sigma_1} d\tilde{x} - \int_0^{x_2} C_{q_2}^2(q_2, \tilde{x}) \frac{\partial q_2(\tilde{x})}{\partial \sigma_1} d\tilde{x}) \\
& + (P_1(Q_1)q_1 - C^1(q_1, x_1) - \Gamma_{y_1}^1(y_1) - \delta\Gamma_{y_1}^2(y_2, y_1))n \frac{\partial y_1}{\partial \sigma_1} \\
& + \delta(P_2(Q_2)q_2 - C^2(q_2, x_2) - \Gamma_{y_2}^2(y_2, y_1))n \frac{\partial y_2}{\partial \sigma_1} \\
& + [(P_1(Q_1)q_1 - C^1(q_1, x_1))y_1 - \Gamma^1(y_1) - F \\
& + \delta((P_2(Q_2)q_2 - C^2(q_2, x_2))y_2 - \Gamma^2(y_2, y_1))] \frac{\partial n}{\partial \sigma_1} = 0
\end{aligned} \tag{30}$$

Using the behavioral conditions (15) - (20), the subsidy rates  $s_{out}$  and  $s_{ent}$  drop out in (17) and (20) and by using the envelope theorem we can simplify equation (30) to obtain

$$\begin{aligned}
& (\tau_1 - D'_1(k_1)) \frac{\partial k_1}{\partial \sigma_1} + \delta(\tau_2 - D'_2(k_2)) \frac{\partial k_2}{\partial \sigma_1} \\
& - \sigma_1 \int_0^{x_1} \frac{\partial q_1(\tilde{x})}{\partial \sigma_1} d\tilde{x} - \delta\sigma_2 \int_0^{x_2} \frac{\partial q_2(\tilde{x})}{\partial \sigma_1} d\tilde{x} \\
& \quad - \sigma_1 q_1 n \frac{\partial y_1}{\partial \sigma_1} - \delta\sigma_2 q_2 n \frac{\partial y_2}{\partial \sigma_1} \\
& \quad - \sigma_1 q_1 y_1 \frac{\partial n}{\partial \sigma_1} - \delta\sigma_2 q_2 y_2 \frac{\partial n}{\partial \sigma_1} = 0
\end{aligned} \tag{31}$$

Solving  $\sigma_1$  using the comparative statics results  $-\frac{\partial k_1}{\partial \sigma_1} = \int_0^{x_1} \frac{\partial q_1(\tilde{x})}{\partial \sigma_1} d\tilde{x} + q_1 \frac{\partial x_1}{\partial \sigma_1}$ ,  $-\frac{\partial k_2}{\partial \sigma_1} = \int_0^{x_2} \frac{\partial q_2(\tilde{x})}{\partial \sigma_1} d\tilde{x} + q_2 \frac{\partial x_2}{\partial \sigma_1}$ ,  $\frac{\partial x_1}{\partial \sigma_1} = y_1 \frac{\partial n}{\partial \sigma_1} + n \frac{\partial y_1}{\partial \sigma_1}$ , and  $\frac{\partial x_2}{\partial \sigma_1} = y_2 \frac{\partial n}{\partial \sigma_1} + n \frac{\partial y_2}{\partial \sigma_1}$ , we obtain:

$$\begin{aligned}
\sigma_1 = & -(D'_1(k_1) - \tau_1) \\
& - \frac{\delta(D'_2(k_2) - \tau_2) \frac{\partial k_2}{\partial \sigma_1} + \delta\sigma_2 (\int_0^{x_2} \frac{\partial q_2(\tilde{x})}{\partial \sigma_1} d\tilde{x} + q_2 n \frac{\partial y_2}{\partial \sigma_1} + q_2 y_2 \frac{\partial n}{\partial \sigma_1})}{\frac{\partial k_1}{\partial \sigma_1}}
\end{aligned} \tag{32}$$

Differentiating the welfare function with respect to  $\sigma_2$  we obtain the following symmetric result:

$$\sigma_2 = -(D'_2(k_2) - \tau_2)$$

$$- \frac{(D'_1(k_1) - \tau_1) \frac{\partial k_1}{\partial \sigma_2} + \delta \sigma_1 (\int_0^{x_1} \frac{\partial q_1(\tilde{x})}{\partial \sigma_2} d\tilde{x} + q_1 n \frac{\partial y_1}{\partial \sigma_2} + q_1 y_1 \frac{\partial n}{\partial \sigma_2})}{\frac{\partial k_2}{\partial \sigma_2}} \quad (33)$$

Solving these two equations for  $\sigma_1$  and  $\sigma_2$  we obtain the optimal subsidy rates as given by equation (24).

**Proof of part 3** The first-order conditions with respect to  $\sigma$  are identical to equation (30) if we replace  $\sigma_1$  by  $\sigma$ . Simplifying with the envelope theorem we get

$$\begin{aligned} & (\tau - D'_1(k_1)) \frac{\partial k_1}{\partial \sigma} + \delta (\tau - D'_2(k_2)) \frac{\partial k_2}{\partial \sigma} \\ & - \sigma \int_0^{x_1} \frac{\partial q_1(\tilde{x})}{\partial \sigma} d\tilde{x} - \delta \sigma \int_0^{x_2} \frac{\partial q_2(\tilde{x})}{\partial \sigma} d\tilde{x} \\ & \quad - \sigma q_1 n \frac{\partial y_1}{\partial \sigma} - \delta \sigma q_2 n \frac{\partial y_2}{\partial \sigma} \\ & \quad - \sigma q_1 y_1 \frac{\partial n}{\partial \sigma} - \delta \sigma q_2 y_2 \frac{\partial n}{\partial \sigma} = 0 \end{aligned} \quad (34)$$

Solving for  $\sigma$  yields equation (25).

**Proof of proposition 2:** Note that for private learning we have  $L = y_1$ . Differentiating the behavioral conditions and simplifying by using the envelope theorem yields:

$$\frac{\partial x_t}{\partial \sigma_t} = y_t \frac{\partial n}{\partial \sigma_t} + n \frac{\partial y_t}{\partial \sigma_t} \quad (35)$$

$$\frac{\partial x_{-t}}{\partial \sigma_t} = y_{-t} \frac{\partial n}{\partial \sigma_t} + n \frac{\partial y_{-t}}{\partial \sigma_t} \quad (36)$$

$$\frac{\partial Q_t}{\partial \sigma_t} = \int_0^{x_t} \frac{\partial q_t(\tilde{x})}{\partial \sigma_t} d\tilde{x} + q_t \frac{\partial x_t}{\partial \sigma_t} + \frac{\partial k_t}{\partial \sigma_t} \quad (37)$$

$$\frac{\partial Q_{-t}}{\partial \sigma_t} = \int_0^{x_{-t}} \frac{\partial q_{-t}(\tilde{x})}{\partial \sigma_t} d\tilde{x} + q_{-t} \frac{\partial x_{-t}}{\partial \sigma_t} + \frac{\partial k_{-t}}{\partial \sigma_t} \quad (38)$$

$$\frac{\partial p_t}{\partial \sigma_t} = P'_t(Q_t) \frac{\partial Q_t}{\partial \sigma_t} \quad (39)$$

$$\frac{\partial p_{-t}}{\partial \sigma_t} = P'_{-t}(Q_{-t}) \frac{\partial Q_{-t}}{\partial \sigma_t} \quad (40)$$

$$P'_t(Q_t) \frac{\partial Q_t}{\partial \sigma_t} = 0 \quad (41)$$

$$P'_{-t}(Q_{-t}) \frac{\partial Q_{-t}}{\partial \sigma_t} = 0 \quad (42)$$

$$\frac{\partial q_t}{\partial \sigma_t} = \frac{1}{C_{q_t q_t}^t(q_t, \tilde{x})} > 0 \quad (43)$$

$$\frac{\partial q_{-t}}{\partial \sigma_t} = 0 \quad (44)$$

$$\frac{\partial b_t}{\partial \sigma_t} = q_t - C_{x_t}^t(q_t, x_t) \frac{\partial x_t}{\partial \sigma_t} \quad (45)$$

$$\frac{\partial b_{-t}}{\partial \sigma_t} = -C_{x_{-t}}^{-t}(q_{-t}, x_{-t}) \frac{\partial x_{-t}}{\partial \sigma_t} \quad (46)$$

$$\frac{\partial b_t}{\partial \sigma_t} y_1 + \delta \frac{\partial b_{-t}}{\partial \sigma_t} y_2 = 0 \quad (47)$$

$$\frac{\partial b_t}{\partial \sigma_t} = \Gamma_{y_1 y_1}^1 \frac{\partial y_1}{\partial \sigma_t} + \delta [\Gamma_{LL}^2 \frac{\partial y_1}{\partial \sigma_t} + \Gamma_{Ly_2}^2 \frac{\partial y_2}{\partial \sigma_t}] \quad (48)$$

$$\frac{\partial b_{-t}}{\partial \sigma_t} = \Gamma_{y_2 y_2}^2 \frac{\partial y_2}{\partial \sigma_t} + \Gamma_{y_2 L}^2 \frac{\partial y_1}{\partial \sigma_t} \quad (49)$$

In the following we use some writing simplifications:

$$A = \Gamma_{y_2 y_2}^2 \Gamma_{LL}^2 - (\Gamma_{Ly_2}^2)^2 > 0 \quad (50)$$

$$B = \Gamma_{LL}^2 y_1^2 + 2\Gamma_{Ly_2}^2 y_1 y_2 + \Gamma_{y_2 y_2}^2 y_2^2 > 0 \quad (51)$$

$$D = C_{x_2}^2 y_2^2 \delta (\Gamma_{y_2 y_2}^2 \Gamma_{y_1 y_1}^1 + \delta A) + C_{x_1}^1 [y_1^2 \delta A + C_{x_2}^2 n \delta B + y_1^2 \Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 + n C_{x_2}^2)] > 0 \quad (52)$$

With our model assumptions  $A$ ,  $B$ , and  $D$  are all positive. Solving the 15 equations (35) - (43) yields:

$$\frac{\partial y_1}{\partial \sigma_1} = \frac{C_{x_2}^2 q_1 y_2 \delta \overbrace{(\Gamma_{y_2 L}^2 y_1 + \Gamma_{y_2 y_2}^2 y_2)}^{\text{Condition: (22)}}}{D} > 0 \quad (53)$$

$$\frac{\partial y_2}{\partial \sigma_1} = \frac{-C_{x_2}^2 q_1 y_2 \overbrace{[(\Gamma_{y_1 y_1}^1 y_1 + \delta \Gamma_{y_2 L}^2 y_2) + \Gamma_{LL}^2 y_1]}^{\text{Condition: (21)}}}{D} > 0 \quad (54)$$

$$\frac{\partial b_1}{\partial \sigma_1} = \frac{C_{x_2}^2 q_1 y_2^2 \delta (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta A)}{D} > 0 \quad (55)$$

$$\frac{\partial b_2}{\partial \sigma_1} = \frac{-C_{x_2}^2 q_1 y_1 y_2 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta A)}{D} < 0 \quad (56)$$

$$\frac{\partial n}{\partial \sigma_1} = \frac{q_1(\Gamma_{y_1 y_1}^1 y_1(\Gamma_{y_2 y_2}^2 + C_{x_2}^2 n) + \delta[y_1 A + C_{x_2}^2 n \overbrace{(\Gamma_{y_1 y_1}^2 y_1 + \Gamma_{y_2 y_1}^2 y_2)}^{\text{Condition: (23)}}])}{D} > 0 \quad (57)$$

$$\frac{\partial x_1}{\partial \sigma_1} = \frac{q_1[\Gamma_{y_1 y_1}^1(\Gamma_{y_2 y_2}^2 + C_{x_2}^2 n y_1^2) + \delta(y_1^2 A + C_{x_2}^2 n B)]}{D} > 0 \quad (58)$$

$$\frac{\partial x_2}{\partial \sigma_1} = \frac{q_1 y_1 y_2 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta A)}{D} > 0 \quad (59)$$

Since total output is not affected ( $\frac{\partial Q_t}{\partial \sigma_t} = 0$  and  $\frac{\partial Q_{-t}}{\partial \sigma_t} = 0$ ), we obtain:

$$\frac{\partial k_t}{\partial \sigma_1} < 0 \quad (60)$$

The effects for  $\sigma_2$  are symmetric. The comparative statics for  $\tau_t$  are very much the same except for:

$$\frac{\partial p_t}{\partial \tau_t} = 1 \quad (61)$$

$$\frac{\partial Q_t}{\partial \tau_t} = \frac{1}{P'_t(Q_t)} \quad (62)$$

For the comparative statics with respect to a uniform subsidy  $\sigma$  we obtain:

$$P'_t(Q_t) \frac{\partial Q_t}{\partial \sigma} = 0 \quad (63)$$

$$\frac{\partial Q_1}{\partial \sigma} = \int_0^{x_t} \frac{\partial q_t(\tilde{x})}{\partial \sigma} d\tilde{x} + q_t \frac{\partial x_t}{\partial \sigma} + \frac{\partial k_t}{\partial \sigma} = 0 \quad (64)$$

$$\frac{\partial p_t}{\partial \sigma} = P'_t(Q_t) \frac{\partial Q_t}{\partial \sigma} = 0 \quad (65)$$

$$\frac{\partial q_t}{\partial \sigma} = \frac{1}{C_{q_t q_t}^t(q_t, \tilde{x})} > 0 \quad (66)$$

$$\begin{aligned} \frac{\partial x_1}{\partial \sigma} &= \frac{1}{N} [-\Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 + C_{x_2}^2 n) q_1 y_1^1 - \delta^2 A q_2 y_1 y_2 \\ &\quad + \delta (-A q_1 y_1^2 - C_{x_2}^2 B n q_1 - \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 q_2 y_1)] > 0 \end{aligned} \quad (67)$$

$$\frac{\partial x_2}{\partial \sigma} = \frac{1}{N} [-(\delta A + \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2) y_2 (q_1 y_1 + \delta q_2 y_2)] \quad (68)$$

$$-C_{x_1}^1 n q_2 (\Gamma_{y_1 y_1}^1 + \delta B)] > 0 \quad (69)$$

$$\frac{\partial y_1}{\partial \sigma} = \frac{1}{N} [\delta \overbrace{(C_{x_1}^1 q_2 y_1 - C_{x_2}^2 q_1 y_2)}^{\geq 0} \overbrace{(\Gamma_{y_2 y_2}^2 y_2 + \Gamma_{y_2 L}^2 y_1)}^{\text{Condition: (22)}}] \geq 0 \quad (70)$$

$$\begin{aligned} \frac{\partial y_2}{\partial \sigma} &= \frac{1}{N} [-\delta \overbrace{(C_{x_1}^1 q_2 y_1 - C_{x_2}^2 q_1 y_2)}^{\geq 0} \overbrace{(\Gamma_{LL}^2 y_1 + \Gamma_{y_2 L}^2 y_2)}^{\text{Condition (23)}} \\ &\quad + \Gamma_{y_1 y_1}^1 y_1 \underbrace{(C_{x_2}^2 q_1 y_2 - C_{x_1}^1 q_2 y_1)}_{\geq 0}] \geq 0 \end{aligned} \quad (71)$$

$$\begin{aligned} \frac{\partial n}{\partial \sigma} &= \frac{1}{N} [-\delta (A + \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2) (q_1 y_1 + \delta q_2 y_2) - C_{x_2}^2 \Gamma_{y_1 y_1}^1 n q_1 y_1 \\ &\quad - \delta C_{x_1}^1 n q_2 \underbrace{(\Gamma_{y_2 y_2}^2 y_2 + \Gamma_{y_2 L}^2 y_1)}_{\text{Condition: (22)}} - \delta C_{x_2}^2 n q_1 \underbrace{(\Gamma_{LL}^2 y_1 + \Gamma_{y_2 L}^2 y_2)}_{\text{Condition: (23)}}] > 0 \end{aligned} \quad (72)$$

$$\frac{\partial b_1}{\partial \sigma} = \frac{1}{N} [\delta \overbrace{(C_{x_1}^1 q_2 y_1^2 - C_{x_2}^2 q_1 y_1 y_2)}^{\geq 0} (\delta A + \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2)] \geq 0 \quad (73)$$

$$\frac{\partial b_2}{\partial \sigma} = \frac{1}{N} [\overbrace{(-C_{x_1}^1 q_2 y_1^2 + C_{x_2}^2 q_1 y_1 y_2)}^{\geq 0} (\delta A + \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2)] \geq 0 \quad (74)$$

The denominator  $N$  is negative and is defined as follows:

$$N = -(C_{x_1}^1 y_1^2 + \delta C_{x_2}^2 y_2^2) (\delta A + \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2) - C_{x_1}^1 C_{x_2}^2 n (\Gamma_{y_1 y_1}^1 y_1^2 + B) < 0$$

**Proof of Proposition 6 (comparative statics if learning spillovers exist):**

The stability of the equilibrium with private learning follows from the model assumptions immediately. In the case of learning spillovers, however, we need to assume the stability explicitly.

Totally differentiating the first-order conditions and the zero-profit conditions (15) - (20) with respect to  $\sigma_1$  and  $\sigma_2$  yields the following system:

$$M * \begin{pmatrix} \partial y_1 / \partial s_1 \\ \partial y_2 / \partial s_1 \\ \partial n / \partial s_1 \\ \partial b_1 / \partial s_1 \\ \partial b_2 / \partial s_1 \\ \partial q_1 / \partial s_1 \\ \partial q_2 / \partial s_1 \\ \partial k_1 / \partial s_1 \\ \partial k_2 / \partial s_1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ q_2 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad (75)$$

$$M * \begin{pmatrix} \partial y_1 / \partial s_2 \\ \partial y_2 / \partial s_2 \\ \partial n / \partial s_2 \\ \partial b_1 / \partial s_2 \\ \partial b_2 / \partial s_2 \\ \partial q_1 / \partial s_2 \\ \partial q_2 / \partial s_2 \\ \partial k_1 / \partial s_2 \\ \partial k_2 / \partial s_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ q_1 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (76)$$

$M$  is a 9x9 - matrix.  $M$  must be negative definite to guarantee stability. For the nine principal minors the following conditions must hold:  $|M_1|, |M_3|, \dots, |M_9| < 0$  and  $|M_2|, |M_4|, \dots, |M_8| > 0$ . To sign the comparative statics effects we are particularly interested in the 5x5 submatrix  $M_{sub}$  comprising the first five rows and columns of  $M$ .  $M_{sub}$  is given as follows:

$$\begin{pmatrix} -\Gamma_{y_1 y_1}^1 - \delta(1 + \epsilon(n-1))\Gamma_{LL}^2 & -\delta\Gamma_{y_2 L}^2 & -\delta\epsilon\Gamma_{LL}^2 y_1 & 1 & 0 \\ -(1 + \epsilon(n-1))\Gamma_{y_2 L}^2 & -\Gamma_{y_2 y_2}^2 & \Gamma_{y_2 L}^2 \epsilon y_1 & 0 & 1 \\ -\delta\epsilon(n-1)\Gamma_L^2 & 0 & -\delta\epsilon\Gamma_L^2 y_1 & y_1 & \delta y_2 \\ C_{x_1}^1 n & 0 & C_{x_1}^1 y_1 & 1 & 0 \\ 0 & C_{x_2}^2 n & C_{x_2}^2 y_2 & 0 & 1 \end{pmatrix}$$

The determinant  $|M_{sub}| = |M_5| = N$  is the denominator of several comparative statics effects. From stability it follows that  $|M_5| < 0$  and therefore  $N < 0$ .  $N$  is given as follows:

$$\begin{aligned} N = & -[C_{x_1}^1 (\Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 + C_{x_2}^2 n) y_1^2 + \delta((1 - \epsilon) A y_1^2 + (1 - \epsilon) C_{x_2}^2 \Gamma_{LL}^2 n y_1^2 \\ & + C_{x_2}^2 \Gamma_{y_2 y_2}^2 n y_2^2 + (2 - \epsilon) C_{x_2}^2 \Gamma_{y_2 L}^2 n y_1 y_2 + \epsilon \Gamma_L^2 (\Gamma_{y_2 y_2}^2 + C_{x_2}^2 n) y_1)) \\ & + \delta(\epsilon \Gamma_L^2 y_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta A) + C_{x_2}^2 (\delta(1 + \epsilon(n-1)) A y_2^2 \\ & + \delta \epsilon \Gamma_L^2 (G_{y_2 L}^2 (n-1) y_2 + \Gamma_{LL}^2 n y_1)) + \Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 y_2^2 + \epsilon n y_1 (\Gamma_L^2 - \Gamma_{y_2 L}^2 y_2)))] \end{aligned} \quad (77)$$

Again, we use the writing simplifications  $A$  and  $B$  that are positive given our model assumptions:

$$A = \Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2 > 0 \quad (78)$$

$$B = \Gamma_{LL}^2 y_1^2 + 2\Gamma_{y_2 L}^2 y_1 y_2 + \Gamma_{y_2 y_2}^2 y_2^2 > 0 \quad (79)$$

We obtain the following comparative statics effects:

$$\frac{\partial q_t}{\partial \sigma_t} = \frac{1}{C_{q_t q_t}^t(q_t, \tilde{x})} > 0 \quad (80)$$

$$\frac{\partial q_{-t}}{\partial \sigma_t} = 0 \quad (81)$$

$$\begin{aligned} \frac{\partial x_1}{\partial \sigma_1} = & \frac{-1}{N} [q_1 (\overbrace{(\Gamma_{y_1 y_1}^1 y_1 + \delta \epsilon \Gamma_L^2)}^{\text{Condition:(27)}} (\Gamma_{y_2 y_2}^2 + C_{x_2}^2 n) y_1 + \delta (A(1 - \epsilon) \\ & + C_{x_2}^2 n (\Gamma_{y_2 y_2}^2 y_2^2 + (2 - \epsilon) \Gamma_{y_2 L}^2 y_1 y_2 + (1 - \epsilon) \Gamma_{LL}^2 y_1^2))] > 0 \\ & \underbrace{\hspace{10em}}_{\text{Condition:(22):if:}\epsilon=1} \end{aligned} \quad (82)$$

$$\begin{aligned} \frac{\partial x_2}{\partial \sigma_1} = & \frac{-1}{N} [q_1 (\delta (1 + \epsilon(n - 1)) A y_1 y_2 + \delta \epsilon \Gamma_L^2 (\overbrace{(\Gamma_{y_2 y_2}^2 y_2 (n - 1) - \Gamma_{y_2 L}^2 y_1 n)}^{\text{Condition:(28)}} \\ & + \Gamma_{y_1 y_1}^1 y_1 (\Gamma_{y_2 y_2}^2 y_2 - \epsilon n \Gamma_{y_2 L}^2 y_1))] > 0 \end{aligned} \quad (83)$$

$$\begin{aligned} \frac{\partial b_1}{\partial \sigma_1} = & \frac{1}{N} [q_1 \delta (\epsilon \Gamma_L^2 y_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta A) + C_{x_2}^2 (\delta (1 + \epsilon(n - 1)) y_2 A y_2 \\ & + \epsilon \Gamma_L^2 (\overbrace{(\Gamma_{y_2 L}^2 (n - 1) y_2 + \Gamma_{LL}^2 n y_1)}^{\text{Condition:(23)}} \\ & + \Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 y_2^2 + \epsilon n y_1 (\Gamma_L^2 - \Gamma_{y_2 L}^2 y_2))) \geq 0 \\ & \underbrace{\hspace{10em}}_{\text{Condition:(22):if:}\epsilon=1} \end{aligned} \quad (84)$$

$$\begin{aligned} \frac{\partial b_2}{\partial \sigma_1} = & \frac{1}{N} [C_{x_2}^2 q_1 (\delta (1 + \epsilon(n - 1)) A y_1 y_2 - \delta \epsilon \Gamma_L^2 (\overbrace{(\Gamma_{y_2 y_2}^2 y_2 (n - 1) + \Gamma_{y_2 L}^2 y_1 n)}^{\text{Condition:(28)}} \\ & + \Gamma_{y_1 y_1}^1 y_1 (\Gamma_{y_2 y_2}^2 y_2 - \epsilon n \Gamma_{y_2 L}^2 y_1))] < 0 \end{aligned} \quad (85)$$

$$\begin{aligned} \frac{\partial x_1}{\partial \sigma_2} = & \frac{1}{N} (q_2 y_1 \delta (\underbrace{\delta \epsilon \Gamma_L^2 \Gamma_{y_2 L}^2 - \Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 y_2}_{\text{If:condition:(27):and(22),then:<0}} - \delta (1 - \epsilon) A y_2) > 0 \end{aligned} \quad (86)$$

$$\begin{aligned} \frac{\partial x_2}{\partial \sigma_2} = & \frac{1}{N} [q_2 (C_{x_1}^1 n (\overbrace{(\Gamma_{y_1 y_1}^1 y_1 + \delta \epsilon \Gamma_L^2)}^{\text{Condition:(27)}} y_1 + \delta (y_2 (\overbrace{(\Gamma_{y_2 y_2}^2 y_2 + (2 - \epsilon) \Gamma_{y_2 L}^2 y_1)}^{\text{Condition:(22):if:}\epsilon=1}} \\ & + (1 - \epsilon) \Gamma_{LL}^2 y_1^2)) \end{aligned} \quad (87)$$

$$\begin{aligned} & + \delta (\delta (1 + (n - 1) \epsilon) y_2 A y_2 + \delta \epsilon \Gamma_L^2 (\underbrace{(\Gamma_{y_2 L}^2 (n - 1) y_2 + \Gamma_{LL}^2 y_1 n)}_{\text{Condition:(23)}} \\ & + \Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 y_2^2 + \epsilon n y_1 (\Gamma_L^2 - \Gamma_{y_2 L}^2 y_2))) \geq 0 \\ & \underbrace{\hspace{10em}}_{\text{Condition:(22):if:}\epsilon=1} \end{aligned} \quad (88)$$

$$\frac{\partial b_1}{\partial \sigma_2} = \frac{1}{N} (C_{x_1}^1 q_2 y_1 \delta ( \underbrace{\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 y_2 + \delta \epsilon \Gamma_L^2 \Gamma_{y_2 L}^2}_{\text{If:condition:(27):and(22),then:>0}} + \delta(1 - \epsilon) A y_2) < 0 \quad (90)$$

$$\frac{\partial b_2}{\partial \sigma_2} = \frac{-1}{N} [q_2 y_1 ( \underbrace{\delta \epsilon \Gamma_L^2 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta A)}_{<0} \quad (91)$$

$$+ C_{x_1}^1 ( \underbrace{\Gamma_{y_2 y_2}^2 ( \underbrace{\Gamma_{y_1 y_1}^1 y_1 + \delta \epsilon \Gamma_L^2}_{\text{Condition:(27)}} ) + \delta(1 - \epsilon) A y_1 ) ] \underset{>0}{\geq} 0 \quad (92)$$

If  $\frac{\partial x_1}{\partial \sigma_1} > 0$  and  $\frac{\partial q_1}{\partial \sigma_1} > 0$ , then - due to the constant total electricity output -  $\frac{\partial k_1}{\partial \sigma_1} < 0$ . Equally we get  $\frac{\partial k_2}{\partial \sigma_1} < 0$  and  $\frac{\partial k_1}{\partial \sigma_2} < 0$ .

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