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# Subsidies for Renewable Energies in the Presence of Learning Effects and Market Power

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Abstract: We study the impact of learning by doing, learning spill-overs, and imperfect competition in a model with two types of electricity producers, an oligopolistic sector of polluting fossil-fuel utilities and a competitive fringe of non-polluting generators of electricity from renewable energy sources (RES-E). Furthermore we consider an upstream industry of RES-E equipment producers engaged in learning by doing. We show that a first-best policy requires two instruments, a tax in the fossil-fuel sector and an output subsidy for RES-E equipment producers. We then study second-best-optimal feed-in tariffs that are paid to the generators of RES-E. By means of simulations we calculate the welfare loss of a second-best-optimal feed-in-tariff policy and analyze how market structure impacts on second-best-optimal feed-in tariffs.

Keywords: feed-in tariffs; environmental subsidies; learning by doing; spill-overs; market structure

JEL classification: Q42, L13, O38

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# 1 Introduction

Alongside issues such as the security of energy supply, the debate on global climate change and how to mitigate its adverse environmental effects has brought about political rethinking concerning the current and future use of fossil fuels. As a result, the promotion of renewable energy sources has become an energy-policy priority for many OECD economies. For instance, the member states of the European Union have agreed on binding targets to raise the share of renewable energies to 20% of gross final energy consumption by 2020. In terms of renewable electricity (RES-E) generation, the EU plans to source 21% of electricity consumption from renewable energy in 2010. Several other OECD countries such as Australia, New Zealand, Japan, Israel, and Korea, as well as a number of States in the US have also announced renewable-energy and renewable-electricity targets with varying degrees of ambition.

Among the different national policies in the European Union, feed-in-tariff schemes have been particularly effective in promoting the rapid expansion of RES-E capacity and production.[1] The United States also provides production subsidies for RES-E.[2] A popular argument in favor of subsidy policies such as feed-in tariffs is the existence of learning effects in the renewable energy industry. A number of empirical studies indicate that there is considerable potential for cost reductions through learning by doing in the wind turbine industry, the photovoltaic module industry, and other RES-E technologies (Grübler et al., 1999; Hansen et al., 2003; Junginger et al., 2005; Isoard and Soria, 2001; McDonald and Schrattenholzer, 2001; Neij, 1997, 1999; van der Zwaan and Rabl, 2004). If this is the case, the allocation of subsidies is justified in the early stages of renewable resource use, as such subsidies encourage learning by doing and enable renewable energy producers to realize cost savings by moving downward on their learning curves. Without subsidies, these technologies would not be able to compete with fossil-fuel utilities. It is further argued that once learning has occurred and firms have eventually achieved competitiveness, the subsidies should be cut back.

From an economic viewpoint, however, public policy intervention is justified only if learning by doing generates spill-over effects that benefit other market participants without compensation. The spill-overs thus represent positive externalities which, together with the negative externalities through pollution, lead to an undersupply of new pollution-reducing

[1]The highest feed-in-tariff rates are currently paid in Germany, where producers of onshore wind power installations are granted €0.092 per kwh during the first five years of operation (or more, depending on the efficiency of the installation) and the base rate of €0.052 per kwh subsequently. In the case of photovoltaic power the tariff for modules installed in 2009 lies between €0.32 and €0.43 per kwh.

[2]At the federal level, the Renewable Energy Production Incentive offers $0.015 per kwh of renewable energy generation, denoted in 1993 US-$ and indexed for inflation. Moreover, around 40 incentive programs are currently established in individual states, utilities, and through non-profit cooperations (DSIRE, 2008).

technologies by the market (Jaffe et al., 2005; Helm and Schöttner, 2008).

The model we develop in this paper is based on three main strands in the literature. The first of these strands can be traced back to the seminal work by Buchanan (1976) and concerns the allocative inefficiency of Pigouvian emission taxes for imperfectly competitive firms. In the context of an imperfect market structure, there is a trade-off between the social gain from emission abatement and the social loss from monopolistic or oligopolistic output restriction, which the regulator has to take into account when setting the tax rate (Lee, 1975; Barnett, 1980).

Second, there is a growing literature studying environmental policies in the presence of imperfectly competitive eco-industries (Requate, 2005; David and Sinclair-Desgagné, 2005; Canton et al., 2008; David et al., 2011; David and Sinclair-Desgagné, 2010). The term 'eco-industries' is used to refer to providers of abatement goods and services, such as the producers of RES-E equipment discussed in the present paper. Assuming the polluting sector to be perfectly competitive, David and Sinclair-Desgagné (2010) find that a first-best policy consists of a combination of pollution taxes and abatement subsidies.

The third strand analyzes the impacts of learning by doing and learning spill-overs on output, prices, and industrial structure. This large body of literature considers both monopolistic and oligopolistic markets (Spence, 1981; Fudenberg and Tirole, 1983) and perfectly competitive industries (Ghemawat and Spence, 1985; Petrakis et al., 1997). According to Spence (1981), the main determinants of costs and firm performance in the presence of learning by doing are the learning rate, the extent to which the firm's costs decline through learning, the degree of learning spill-overs, and demand elasticity. Fudenberg and Tirole (1983) focus on the strategic interaction of firms in the presence of learning by doing when firms correctly anticipate the effect of their learning on their rivals' actions. In the context of environmental-economic models, the effects of learning by doing on the timing and total quantity of pollution abatement and on optimal policy instruments such as emission taxes and/or abatement subsidies have been studied by Goulder and Mathai (2000) for a single abatement technology and by Bramoullé and Olson (2005) for heterogeneous abatement technologies. However, neither of these studies considers the possibility of learning spill-overs, which represent an additional market failure as they lead to a divergence of social and private returns on learning by doing. In a recent paper, Fischer and Newell (2008) assess different policies for reducing $CO_2$ emissions and promoting renewable energy in the presence of technological progress through learning, R&D, and knowledge spill-overs. They conclude that in a perfect-competition framework an optimal portfolio of policy options will include an emissions price and subsidies for technological R&D and learning.

In this paper we shall not consider technological progress through R&D, but instead focus on the effects of learning and learning spill-overs in an imperfect-competition framework.

In particular, we take account of the vertical structure of the renewable energy industry by assuming an upstream sector of RES-E equipment producers and a downstream sector of RES-E producers that buy the equipment and sell electricity to the consumers. Firms in the upstream sector can lower their costs through learning by doing, i.e. private learning and/or learning spill-overs. Furthermore, the producers of renewable electricity compete with conventional, fossil-fuel electricity producers. In the framework of a two-period model we assess two policy options: (a) an optimal policy consisting of an emissions tax combined with an output subsidy for RES-E equipment producers, and (b) a feed-in-tariff policy where a subsidy is paid to the producers of RES-E. We assume the fossil-fuel industry to form a Cournot oligopoly, with an exogenously given number of firms. This is a realistic representation of the European and other OECD countries' electricity markets, which are mostly dominated by a small number of large utilities. For the upstream RES-E equipment industry, we consider both the case of perfect and imperfect (quantity) competition in the upstream market.[3] The findings of Petrakis et al. (1997) indicate that, in the case of purely private learning, subsidies for RES-E producers should only take account of environmental damage, but are not necessary to spur learning. In our model, market power in the fossil-fuel and RES-E equipment industries creates additional distortions that the regulator has to take into account when deciding on subsidies for RES-E.

In the optimal policy, the tax in both periods corrects for the marginal damage caused by pollution and for oligopolistic competition. With perfect competition in the RES-E equipment industry, the optimal subsidy in the first period only takes account of the learning spill-overs neglected by the firms. In the case of an oligopoly of RES-E equipment firms, an optimal subsidy should also target the strategic effects induced by imperfect competition. Assuming that first-best levels of policy instruments are ruled out for political reasons, we then study a situation where subsidies are paid to the generators of renewable electricity, mimicking the common feed-in-tariff policy approach. We show that the second-best feed-in tariffs take account of environmental damage, distortions through market power and learning spill-overs. However, they perform much worse than first-best policies. A sensitivity analysis shows that both the ability of firms to learn via increase in their level of output and the size of the learning spill-overs have little impact on the performance of second-best optimal feed-in tariffs. The main factor with an impact on efficiency is the elasticity of

[3] The prevailing market structure in the RES-E equipment market is not so obvious. For example, the six market leaders in the wind turbine industry Vestas (Denmark), GE Wind (United States), Gamesa (Spain), Enercon (Germany), Suzlon (India), and Siemens (Denmark) accounted for 85% of the world market in 2008, but smaller expanding players such as Sinovel (China), Acciona (Spain), Goldwind (China), and Nordex (Germany) are stepping up competition in the market for wind turbines (BTM-C, 2009). However, many wind turbine manufacturers are still mainly active in their domestic market and a few neighboring markets in the same region (Lewis and Wiser, 2007). For instance, Enercon, Vestas, and Siemens supply over 50% of the German, Dutch, and UK markets, respectively, Suzlon almost 70% of the Indian market, and GE Wind over 40% of the US market (BTM-C, 2009).

electricity demand: the less elastic the demand, the higher the welfare loss of a second-best-optimal feed-in-tariff policy will be in comparison with the first-best alternative. We also show that liberalization of electricity markets makes for decreasing feed-in tariffs in the short run but will raise these tariffs in the long run (when demand is more elastic).

The remainder of the paper is organized as follows: In the next section we set up the model. Section 3 analyzes the maximization problem of the social planner. In section 4 we illustrate the optimal policy in a decentralized economy. In section 5 we analyze a feed-in-tariff policy and derive the second-best-optimal levels of the feed-in tariffs. We then use a numerical example to investigate the effects of market structure on the size of feed-in tariffs and analyze the welfare effects of different policy combinations. Section 6 summarizes the results and draws some policy conclusions.

## 2 The model

We study a stylized electricity market with an exogenously given number of $m$ identical oligopolistic fossil-fuel utilities engaging in quantity (Cournot) competition and a competitive fringe of RES-E producers with a continuum of firms. For simplicity we assume that the fossil-fuel utilities use a unique, mature technology generating emissions of a single homogeneous pollutant. Output by a typical conventional utility is denoted by $k_i$. Its cost function is given by $K(k_i)$ and it has positive and increasing marginal costs, i.e. $K'(k_i) > 0$and $K''(k_i) > 0$. Total output from fossil-fuel utilities is then given by $Q^f = \sum_{i=1}^{m} k_i$. Due to symmetry of the firms, total output of fossil-fuel utilities will be equal to $mk$ in a social optimum and in market equilibrium, and therefore $Q^f = mk$.

For simplicity we assume that emissions are proportional to the use of fossil-fuel inputs. Through appropriate choice of the social damage function we can write the damage as a function of the fossil-fuel utilities' output, i.e. $D(Q^f)$ with positive and constant or increasing marginal damage, i.e. $D'(Q^f) > 0$ and $D''(Q^f) \geq 0$.

The generation of RES-E is emission-free and RES-E firms are heterogeneous. Their cost function is represented by $C(q, \tilde{x})$, where $q$ denotes output and $\tilde{x}$ is a location parameter. This parameter reflects the assumption that the production cost of the RES-E generators depends on the location of their installations, e.g. wind turbines or solar panels. For instance, electricity produced by wind turbines is more effective and thus less costly at coastal sites, where the wind blows more steadily than at sites further into the countryside. For solar panels, it is more effective at sites with stronger solar radiation than at more cloudy sites. Besides being more realistic than simply assuming the downstream firms to be symmetric, this assumption also induces a nicely downward-sloping inverse demand function for RES-E equipment. The cost function of the RES-E producers satisfies $C_q > 0$,

$C_{\tilde{x}} > 0$, $C_{qq} > 0$, $C_{q\tilde{x}} > 0$ for $q < \bar{q}$, where $\bar{q}$ is the maximal capacity of, for instance, a wind turbine. Marginal costs are positive and increasing in both output and the location parameter. The increasing marginal cost can be explained by maintenance costs. The better the maintenance the higher the efficiency, and the lower the probability of default. We further assume that $\lim_{q \to \bar{q}} C_q(q, x) = \infty$. In other words, perfect maintenance becomes prohibitively expensive. Moreover, to guarantee that second-order conditions are satisfied, we assume overall convexity of the cost function, implying $C_{\tilde{x}\tilde{x}} > 0$ and $C_{qq}C_{\tilde{x}\tilde{x}} - [C_{q\tilde{x}}]^2 > 0$.

Besides the producers of electricity, we consider an upstream sector of RES-E equipment producers with an exogenously given number of $n$ symmetric firms, characterized by their cost functions. Since we assume that RES-E equipment producers engage in learning by doing, we have to consider at least two periods $t = 1, 2$. Hence, we use $\Gamma^1(y_{1i})$and $\Gamma^2(y_{2i}, L_i)$ to denote upstream firm $i$'s cost in period 1 and 2, respectively, where $y_{ti}$ is firm $i$'s output level in $t = 1, 2$. A firm's cost in $t = 1$ is solely determined by its own output, while in $t = 2$ costs also depend on a variable $L_i$ that represents the experience gathered by firm $i$. The experience in period 2 depends on firm $i$'s own level of production in the first period $y_{1i}$ (private learning) but also on the other firms' aggregate output in the past, multiplied by the degree of learning spill-overs ($\varepsilon$). Thus experience is given by $L_i = y_{1i} + \sum_{j=1, j \neq i} \varepsilon y_{1j}$. For $\varepsilon = 0$ learning is purely private, while for $\varepsilon = 1$ there are complete learning spill-overs, implying that for a single firm it does not matter whether it produces one additional unit itself or whether the other firms do so.[4] In a symmetric allocation the aggregate experience is the same for each firm, i.e.

$$L = [1 + (n-1)\varepsilon] y_1. \tag{1}$$

The cost function of the RES-E equipment producers satisfies the following properties: $\Gamma^t_{y_t} > 0$, $\Gamma^t_{y_t y_t} > 0$, i.e. positive and increasing marginal costs in output, and $\Gamma^2_L < 0$, $\Gamma^2_{Ly_2} < 0$, i.e. lower costs and marginal costs in the second period due to learning by doing. Further we assume that $\Gamma^2_{LL} > 0$, implying that the marginal effect of learning is decreasing. To guarantee satisfaction of second-order conditions we again assume overall convexity of $\Gamma^2$ through

**Condition 1** *:* $\Gamma^2_{LL}\Gamma^2_{y_2y_2} - \left[\Gamma^2_{Ly}\right]^2 > 0.$

Condition 1 implies that the "own-convexity" effect dominates the cross-effect and also guarantees satisfaction of the second-order conditions for both the social optimum and the firms profit maximum under decentralized decision making.

[4]There is little empirical evidence on the size of spill-over effects in the renewable energy industry. For the semiconductor industry Irwin and Klenow (1994) estimate a spill-over coefficient of about $\varepsilon = 0.33$.

We assume that each downstream firm buys only one RES-E equipment device, e.g. one wind turbine, per period. Since the downstream firms are asymmetric, we denote the output of firm $\tilde{x}$ by $q_t(\tilde{x})$. Furthermore, we use $X$ to represent the marginal location above which the downstream firms do not produce. Therefore, due to $C_{\tilde{x}} > 0$ and $C_{q\tilde{x}} > 0$, it is efficient that all firms with $\tilde{x} < X$ produce if the firm at location $X$ produces. This argument is also consistent with the behavior of the downstream firms in a decentralized economy. If it is profitable for the marginal firm at location $X$ to produce, the same must hold for any $\tilde{x} < X$. We can also interpret $X$ as the total number of RES-E equipment producers in the market in each period $t$, so in a symmetric allocation

$$X_t = ny_t \tag{2}$$

represents the total output of RES-E equipment and hence the total capacity installed in $t$. Total output by fossil-fuel electricity generators in period $t$ is then given by $Q_t^f = mk_t$, and total "clean" electricity by $Q_t^c = \int_0^{X_t} q_t(\tilde{x})d\tilde{x}$, such that overall total output is

$$Q_t = Q_t^f + Q_t^c = mk_t + \int_0^{X_t} q_t(\tilde{x})d\tilde{x}. \tag{3}$$

We denote demand for electricity by a downward-sloping inverse demand function

$$p_t = P_t(Q_t) \tag{4}$$

satisfying $P_t''(Q_t)Q_t + P_t'(Q_t) < 0$, requiring that the inverse demand function is not too convex. Anticipating a symmetric allocation, we are now ready to define welfare as

$$\begin{aligned} W = &\int_0^{Q_1} P_1(Q)dQ - mK_1(k_1) - \int_0^{X_1} C^1(q_1(\tilde{x}), \tilde{x})d\tilde{x} - n\Gamma^1(y_1) - D_1(mk_1) \\ &+ \delta\Big[\int_0^{Q_2} P_2(Q)dQ - mK_2(k_2) - \int_0^{X_2} C^2(q_2(\tilde{x}), \tilde{x})d\tilde{x} - n\Gamma^2(y_2, L) - D_2(mk_2)\Big], \end{aligned} \tag{5}$$

where $\delta$ denotes the discount factor.

## 3 The social optimum

Before we study the optimal policy instruments, it is useful to characterize socially optimal allocations. The social planner maximizes welfare with respect to $q_t(\tilde{x})$, $k_t$, and $y_t$. The first-order conditions are given by the following equations:

$$\begin{aligned}
W_{q_t} &= P_t(Q_t) - C_q^t(q_t(\tilde{x}), \tilde{x}) = 0, \qquad t = 1, 2,\ \tilde{x} \in [0, X_t], &(6)\\
W_{k_t} &= P_t(Q_t) - K_t'(k_t) - D_t'(mk_t) = 0, \qquad t = 1, 2, &(7)\\
W_{y_1} &= P_1(Q_1)q_1(X_1) - C^1(q_1(X_1), X_1) - \Gamma_{y_1}^1(y_1) - \delta\big[\Gamma_L^2(y_2, L)(1 + (n-1)\varepsilon)\big] = 0, &(8)\\
W_{y_2} &= P_2(Q_2)q_2(X_2) - C^2(q_2(X_2), X_2) - \Gamma_{y_2}^2(y_2, L) = 0. &(9)
\end{aligned}$$

The interpretation of the conditions for a welfare maximum is straightforward:[5] (6) requires that the optimal price of electricity, corresponding to the consumers' marginal willingness to pay, must be equal to marginal costs in the RES-E generation sector in each period, while (7) implies that in every period the marginal willingness to pay must equal the sum of marginal costs and marginal damage for the fossil-fuel firms. As (6) holds for all $\tilde{x} < X_t$, it also determines the optimal number of RES-E equipment devices. Note that $P_t(Q_t)q_t(X_t) - C^t(q_t(X_t), X_t)$ represents society's marginal willingness to pay for RES-E equipment in period $t$. Therefore, (8) and (9) imply that this marginal willingness to pay equals the marginal costs of RES-E equipment producers in $t = 1, 2$. Equations (8) and (9) thus define the optimal output levels for a single upstream producer. Note that since learning occurs in $t = 1$, the effects on marginal costs of both private learning and learning spill-overs are included only in equation (8). Since $-\Gamma_L^2 > 0$, (8) implies $\Gamma_{y_1}^1(y_1) > P_1(Q_1)q_1(X_1) - C^1(q_1(X_1), X_1)$. Thus it is optimal to set a production level of RES-E equipment with marginal cost of production exceeding the private benefit to consumers in period 1, because more output in period 1 decreases the costs of all other RES-E equipment producers in period 2.

# 4 Optimal policy

In this section we consider decentralized decision making and optimal regulation of markets. Since Cournot-oligopoly is the prevailing market structure on the electricity markets in most countries, we assume that the fossil-fuel producers act strategically when choosing their level of output, while the RES-E operators act as a competitive fringe. Both kinds of electricity producers, however, make their output decisions simultaneously. Concerning the RES-E equipment producers the existing market structure is not so obvious. As BTM-C (2009) reports for wind energy, in some countries such as France, Germany, Italy, and China there is quite a large number of wind turbine suppliers, while in other countries such as India, the Netherlands, and the UK the market is governed by only two or three firms. In the

[5] Since the welfare function is the sum of concave functions it is also concave, and therefore the second-order conditions are satisfied (Takayama, 1997).

following, we will first consider the simple case of perfect competition among the RES-E equipment producers. We will then work out the differences arising from the more complex case of quantity (Cournot) competition in the upstream market.

### 4.1 Perfect competition in the RES-E equipment market

We anticipate optimal decentralizing policies from the beginning by assuming the conventional firms to be subject to an emission (or output) tax $\tau_t$ in both periods and the RES-E equipment producers to receive an output subsidy $\sigma_1$ in the first period. Since emissions are proportional to output, an emission tax is equivalent to an output tax.

The profits of the clean electricity producers ($c$), the conventional electricity firms ($f$), and the RES-E equipment producers ($e$) are therefore given by:

$$\pi^c(q_t(\tilde{x}), \tilde{x}) = P_t(Q_t)q_t(\tilde{x}) - C^t(q_t(\tilde{x}), \tilde{x}) - b_t, \qquad t = 1, 2, \;\; \tilde{x} \in [0, X_t], \tag{10}$$

$$\pi^f(k_t) = P_t(Q_t)k_t - K_t(k_t) - \tau_t k_t, \qquad t = 1, 2, \tag{11}$$

$$\pi^e(y_1, y_2) = [b_1 + \sigma_1]y_1 - \Gamma^1(y_1) + \delta\big[b_2 y_2 - \Gamma^2(y_2, L)\big]. \tag{12}$$

Here $b_t$ represents the competitive price for RES-E equipment. The first-order condition for profit maximization of the clean electricity producers is then

$$P_t(Q_t) - C^t_q(q_t(\tilde{x}), \tilde{x}) = 0, \qquad t = 1, 2. \tag{13}$$

The marginal firm $X_t$ in the RES-E equipment sector is determined by the following free-entry zero-profit condition:

$$P_t(Q_t)q_t(X_t) - C^t(q_t(X_t), X_t) - b_t = 0, \qquad t = 1, 2, \tag{14}$$

while all intra-marginal firms make positive profits. In equilibrium, the fossil-fuel utilities take the output levels of their conventional competitors and the RES-E generators as given. For simplicity we assume that the conventional firms do not take into account possible strategic effects on the producers of RES-E equipment. In principle, they could bring down demand for RES-E equipment and thus the learning effects for the equipment producers by increasing their output in the first period. However, since the market share of electricity generated by renewable sources is still small in most countries, we neglect this strategic consideration. Therefore the behavioral condition of the conventional firms is given by

$$P_t(Q_t) + P_t'(Q_t)k_t - K_t'(k_t) - \tau_t = 0, \qquad t = 1, 2. \tag{15}$$

Note that (14) and (15) together determine the aggregate output level of electricity. The behavior of the RES-E equipment producers in the first and second periods is governed by the following two conditions:

$$b_1 + \sigma_1 - \Gamma^1_{y_1}(y_1) - \delta\Gamma^2_L(y_2, L) = 0, \tag{16}$$

$$b_2 - \Gamma^2_{y_2}(y_2, L) = 0. \tag{17}$$

We are now ready to define the optimal levels for the policy instruments in obtaining the first-best solution. Equating the first-order conditions for a welfare maximum with the first-order conditions for a profit maximum by the firms and solving for the policy instruments yields

$$\tau_t^* = P'(Q_t^*)k_t^* + D_t'(mk_t^*), \qquad t = 1, 2, \tag{18}$$

$$\sigma_1^* = -\delta(n-1)\varepsilon\Gamma^2_L(y_2^*, L^*). \tag{19}$$

The optimal tax in both periods corrects for the marginal damage caused by pollution and the low level of output due to oligopolistic competition in the fossil-fuel industry. Accordingly, it is possible for the optimal tax rate to become negative if $|P'(Q_t^*)k_t^*| > D_t'(mk_t^*)$. The optimal output subsidy for RES-E equipment producers in $t = 1$ accounts for the individually neglected learning spill-overs imposed on the other $n - 1$ firms. We can summarize our results as follows:

**Proposition 1** *Consider an electricity market with Cournot competition among polluting utilities, a competitive fringe of electricity suppliers using renewable energy, and a competitive upstream market of RES-E equipment producers. If emissions are proportional to output, the first-best allocation can be decentralized by charging a tax on emissions (or output) that corrects for both the externality of pollution and the output contraction due to oligopoly power, and by paying a subsidy on RES-E equipment that corrects for insufficient public learning. The emission tax and the subsidy follow the rules (18) and (19), respectively.*

If emissions are not proportional to output, but firms have a separate abatement technology, the emission tax will only correct for the pollution and a separate output subsidy would be necessary to correct for the output contraction.

#### 4.1.1 The impact of market concentration in the fossil-fuel industry

The comparative-statics effects of increasing the number of fossil-fuel utilities $m$ can be analyzed by differentiating the equations (2)–(4) and (13)–(19) with respect to $m$ and solving the resulting system of equations for the endogenous variables.[6] Clearly, due to a higher number of firms the market share of single fossil-fuel utilities decreases and the total production of fossil fuel based electricity increases. Thus, as there is less strategic output contraction and higher pollution, the optimal tax rate $\tau_t$ will increase in both periods:

$$\frac{\partial k_t}{\partial m} < 0, \qquad \frac{\partial Q_t^f}{\partial m} > 0, \qquad \frac{\partial \tau_t}{\partial m} > 0, \qquad t = 1, 2.$$

Moreover, the electricity generated by the marginal renewable electricity producer decreases, so that some green electricity is crowded out of the market:

$$\frac{\partial q_t(X_t)}{\partial m} < 0, \qquad \frac{\partial Q^c}{\partial m} < 0, \qquad t = 1, 2.$$

So in contrast to what is often claimed in the public debate, green electricity providers gain from market power and market concentration of the conventional utilities.

Overall electricity production from dirty and green firms increases, and the price for electricity decreases accordingly:

$$\frac{\partial Q_t}{\partial m} > 0, \qquad \frac{\partial p_t}{\partial m} < 0, \qquad t = 1, 2.$$

The crowding-out effect on green electricity production decreases the RES-E generators' willingness to pay for RES-E equipment devices, so both individual and aggregate RES-E equipment production decreases, together with the RES-E equipment price:

$$\frac{\partial y_t}{\partial m} < 0, \qquad \frac{\partial X_t}{\partial m} < 0, \qquad \frac{\partial b_t}{\partial m} < 0, \qquad t = 1, 2.$$

The sign of the subsidy rate's variation in response to market concentration is ambiguous, so the optimal subsidy policy response to an increasing number of fossil fuel firms is not straightforward. In order to illustrate this ambiguity, we construct a numerical example where the optimal subsidy rate either increases or decreases depending on how strongly the RES-E equipment producers costs are reduced through learning.[7] A possible interpretation could be as follows: Since the subsidy internalizes the learning spill-overs neglected by the RES-E equipment firms, decreasing output of RES-E equipment leads to a decrease in learning and learning spill-overs, resulting in a lower optimal subsidy rate. If, by contrast, learning by doing leads to a relatively large reduction of production costs in the RES-E equipment industry, it is socially optimal to increase the subsidy rate in order to prevent more crowding-out of RES-E equipment production.

[6] The proof is provided in appendix A.1.

[7] The numerical example is described in appendix A.2.

### 4.2 Market power in the RES-E equipment industry

If there is oligopolistic (Cournot) competition in the RES-E equipment sector, an inverse demand function for RES-E equipment has to be defined. This can be derived from the zero-profit condition for RES-E producers:

$$B_t(X_t) = P_t(Q_t)q_t(X_t) - C^t(q_t(X_t), X_t). \tag{20}$$

The marginal renewable electricity producers' willingness to pay for one RES-E equipment unit is exactly $B_t(X_t)$. If the RES-E equipment producers notice their market power, they will produce less than optimal. Thus an optimal subsidy on output not only corrects for the neglected learning spill-overs, but also for the output contraction. In order to achieve a first-best allocation a subsidy must be paid in both periods, and we can write the profit of the RES-E equipment producers as follows:

$$\pi^E(y_1, y_2) = [B_1(X_1) + \sigma_1]y_1 - \Gamma^1(y_1) + \delta\big[[B_2(X_2) + \sigma_2]y_2 - \Gamma^2(y_2, L)\big]. \tag{21}$$

As the number of RES-E equipment producers is exogenous and they engage in oligopolistic competition, their behavior in a symmetric equilibrium is governed by the following conditions for the first and the second period, respectively:

$$\begin{aligned} B_1(X_1) + B_1'(X_1)y_1 + \sigma_1 - \Gamma^1_{y_1}(y_1) & \\ +\delta\Big[B_2'(X_2)(n-1)\frac{\partial \tilde{y_2}}{\partial y_1} - \Gamma^2_L(y_2, L)\Big] &= 0, \\ B_2(X_2) + B_2'(X_2)y_2 + \sigma_2 - \Gamma^2_{y_2}(y_2; L) &= 0. \end{aligned} \tag{22}$$

In equation (22) $\partial\tilde{y_2}/\partial y_1$ represents the other firms' output contraction (expansion) in period 2 as a reaction on a particular firm's output expansion in the first period. This is the typical effect of shifting the reaction curves outwards in the second period through investment in the first one (Dixit, 1980). Thus the normal reaction is $\partial\tilde{y_2}/\partial y_1 < 0$ which in fact happens if $\varepsilon$ is not too large.[8] We are now ready to derive the optimal level of the subsidy rates in both periods:

$$\sigma_1^* = -B_1'(X_1^*)y_1^* - \delta\Big[B_2'(X_2^*)(n-1)\frac{\partial \tilde{y_2}^*}{\partial y_1} + (n-1)\varepsilon\Gamma^2_L(y_2^*, L^*)\Big], \tag{23}$$

$$\sigma_2^* = -B_2'(X_2^*)y_2^*. \tag{24}$$

[8]If $\epsilon$ is sufficiently large, the reaction is ambiguous. The reason is that the other firms gain in a similar way from experience of the firm that increases its output in the first period. For the derivation of $\partial\tilde{y_2}/\partial y_1$, please consult appendix A.3.

The optimal subsidy for RES-E equipment producers in the first period is now composed of three terms. The first one corrects for the output contraction due to oligopolistic competition. This effect is mitigated by the second term representing the strategic output expansion of the firms in the first period. The third term in (23) corrects for the learning spill-overs in the same way as in section 4.1. In the second period, the optimal subsidy only corrects for the output contraction due to oligopolistic competition. It is equal to zero when the RES-E equipment sector is competitive. To sum up:

**Proposition 2** *Consider an electricity market as described before, except that now there is Cournot competition on the market for RES-E equipment. Then the first-best allocation can be decentralized by charging a tax on emissions (or output) and by paying two different subsidy rates for RES-E equipment production. In period 1 the subsidy corrects for insufficient public learning and strategic behavior by RES-E equipment producers. In period 2 the subsidy only corrects for insufficient output of RES-E equipment. The optimal subsidy rates are given by (23) and (24), respectively.*

#### 4.2.1 The impact of market concentration in the RES-E equipment industry

In the following, we analyze the impact of market structure when there is oligopolistic competition in both the fossil-fuel industry and the RES-E equipment sector. For this purpose we conduct comparative-statics analyses with respect to the number of fossil-fuel firms $m$ and the number of RES-E equipment firms $n$, respectively.[9] In order to unambiguously sign the comparative statics effects, we assume both the learning spill-over coefficient $\varepsilon$ and the strategic cross-period effect $\partial \tilde{y}_2/\partial y_1$ to be equal to zero. These simplifications do not imply major drawbacks for the interpretation of our results, since by continuity the results must also hold for small values of $\varepsilon$ and $\partial \tilde{y}_2/\partial y_1$.

We first analyze the impact of changes in market structure in the conventional industry by differentiating equations (2) – (4), (13)–(15), (18), (20), and (22) - (24) with respect to the number of fossil fuel utilities $m$ and solving the resulting system of equations for the endogenous variables. Since the signs of the comparative-statics effects on output and prices in all industries and the emission tax rates are consistent with those summarized in section 4.1.1 we do not report them here. In addition, we can sign the variation of the subsidy paid to the RES-E equipment producers which is negative in both periods, implying that subsidies decrease in response to increasing competition in the fossil fuel industry:

$$\frac{\partial \sigma_t}{\partial m} < 0, \qquad t = 1, 2.$$

[9] Both proofs follow the techniques described in appendix A.1 and can be obtained from the authors upon request.

Since we neglected the learning spill-overs and the strategic cross-period effect $\partial \tilde{y_2}/\partial y_1$ in the RES-E equipment industry, the decrease in the subsidy rate can be attributed to the decreasing production of RES-E equipment, leading to smaller output contraction by the RES-E equipment firms.

We now turn to the comparative-statics effects of the number of firms in the RES-E equipment industry. Clearly, the higher degree of competition in the RES-E equipment sector decreases the individual output level of a typical RES-E equipment firm, but enhances the aggregate output of RES-E equipment and dampens the market price for RES-E equipment:

$$\frac{\partial y_t}{\partial n} < 0, \qquad \frac{\partial X_t}{\partial n} > 0, \qquad \frac{\partial b_t}{\partial n} < 0, \qquad t = 1, 2.$$

The overall output of electricity also increases in both periods and leads to decreasing electricity prices, whereas the individual output levels of both a typical fossil-fuel firm and the marginal renewable electricity producer decrease:

$$\frac{\partial Q_t}{\partial n} > 0, \qquad \frac{\partial p_t}{\partial n} < 0, \qquad \frac{\partial q_t(X_t)}{\partial n} < 0, \qquad \frac{\partial k_t}{\partial n} < 0, \qquad t = 1, 2.$$

The reason for this result is that declining RES-E equipment prices enable more renewable electricity producers to enter the market, thus crowding out fossil-fuel based electricity production. The crowding-out effect on conventional electricity in turn explains the decline in the emission tax rate:

$$\frac{\partial \tau_t}{\partial n} < 0, \qquad t = 1, 2.$$

We again cannot unambiguously sign the impact of the number of RES-E equipment firms on the subsidy rates without imposing further assumptions on the cost functions in the RES-E sector. We thus simplify by assuming the effects of learning by doing on the cost of RES-E equipment producers to be close to zero, i.e. $\Gamma^2_{LL} \approx 0$ and $\Gamma^2_{Ly_2} \approx 0$. The signs of the comparative-statics effects then depend on the rates of change of the marginal costs of both RES-E equipment producers and RES-E generators, i.e. the second derivative of the RES-E equipment producers' cost function with respect to output and the second derivative of the RES-E generators' cost function with respect to the location parameter. Therefore, if $C^t_{X_tX_t}$ and $\Gamma^t_{y_ty_t}$ in $t = 1, 2$ are sufficiently small, we can sign the impact of market structure in the RES-E equipment industry on the subsidy rates as follows:

$$\frac{\partial \sigma_t}{\partial n} < 0, \qquad t = 1, 2.$$

For the RES-E generators the assumption on the cost function implies that marginal costs are not allowed to increase too steeply when the location of their installations becomes less favorable. The economic intuition for the latter result is that stronger competition in the RES-E equipment industry leads to decreasing subsidy rates for RES-E equipment producers, because there is less market power and thus smaller incentives for strategic output contraction.

## 5 Feed-in tariffs

In the following, we consider a situation where first-best policy instruments are ruled out. Instead, we analyze feed-in tariffs as currently implemented in many European and other OECD countries. Under a feed-in tariff policy, generators of renewable electricity receive a fixed price $\zeta_t$ (which may vary across periods) per unit of electricity fed into the electricity grid. Although in some countries, such as Germany, the fossil-fuel utilities have to pay these tariffs to the RES-E generators according to their share of the market, we here reproduce the Dutch and Danish system where the tariffs are paid by the government. The reason for choosing this approach is that payment of such tariffs by the fossil-fuel utilities may induce further strategic behavior by these firms with respect to their market shares.[10] As long as the market share of RES-E firms is small, these effects are however likely to be small. Moreover, we assume that firms in the conventional sector pay an exogenously given emission (or output) tax $\tau_t$, which may deviate from the first-best tax level. Under this policy regime the firms' profits are given by the following expressions:

$$\pi^F(k_t) = [P_t(Q_t) - \tau_t]k_t - K_t(k_t), \qquad t = 1,2, \tag{25}$$

$$\pi^E(y_1, y_2) = b_1 y_1 - \Gamma^1(y_1) + \delta[b_2 y_2 - \Gamma^2(y_2, L)], \tag{26}$$

$$\pi^G(q_t(\tilde{x}), \tilde{x}, \zeta_t) = \zeta_t q_t(\tilde{x}) - C^t(q_t(\tilde{x}), \tilde{x}) - b_t, \qquad t = 1,2. \tag{27}$$

With perfect competition in the RES-E equipment sector the first-order conditions for profit maximization by the firms are given by

$$P_t'(Q_t)k_t + P_t(Q_t) - \tau_t - K_t'(k_t) = 0, \qquad t = 1,2, \tag{28}$$

$$b_1 - \Gamma^1_{y_1}(y_1) - \delta\Gamma^2_L(y_2, L)] = 0, \tag{29}$$

$$b_2 - \Gamma^2_{y_2}(y_2, L) = 0, \tag{30}$$

$$\zeta_t - C^t_{q_t}(q_t, \tilde{x}) = 0, \qquad t = 1,2, \tag{31}$$

and the free-entry condition for RES-E generators yields

$$\zeta_t q_t(X_t) - C^t(q_t, X_t) - b_t = 0, \qquad t = 1,2. \tag{32}$$

[10] See Gersbach and Requate (2004) on modeling strategic behavior when emission taxes are reimbursed according to market share.

With oligopolistic competition in both the fossil-fuel and the RES-E equipment sector the first-order conditions for the RES-E equipment producers yield

$$\begin{aligned} B^1(X_1,\zeta_1) + B^1_{X_1}(X_1,\zeta_1)y1 - \Gamma^1_{y_1}(y_1) & \\ +\delta[B^2_{X_2}(X_2,\zeta_2)(n-1)\frac{\partial \tilde{y_2}}{\partial y_1} - \Gamma^2_L(y_2,L)] &= 0 \\ B^2(X_2,\zeta_2) + B^2_{X_2}(X_2,\zeta_2)y_2 - \Gamma^2_{y_2}(y_2,L) &= 0, \end{aligned} \tag{33}$$

where the demand for RES-E equipment devices $B_t(X_t,\zeta_t)$ is again defined by the free-entry condition for RES-E generators.

## 5.1 Second-best-optimal feed-in tariffs

We will now study the structure of a second-best-optimal feed-in tariff given that emission taxes are fixed and possibly non-optimal. We therefore consider all the endogenous variables $y_t$, $q_t(\tilde{x})$, $k_t$ in $t = 1,2$ and welfare given by equation (5) as functions of the feed-in-tariff rates $\zeta_1$ and $\zeta_2$.

As is always the case under a second best analysis, the second best formulas for the policy instruments will contain the reactions of the firms' choice variables on increasing feed-in-tariff rates $\zeta_1$ and $\zeta_2$. It is therefore useful to briefly study the signs of these effects:[11]

**Lemma 1** *With oligopolistic competition in the fossil-fuel industry only increasing the feed-in tariff for RES-E generators in period $t = 1,2$ yields:* $\frac{\partial q_t(\tilde{x})}{\partial \zeta_t} > 0$, $\frac{\partial k_t}{\partial \zeta_t} < 0$, $\frac{\partial X_t}{\partial \zeta_t} > 0$, $\frac{\partial p_t}{\partial \zeta_t} < 0$, $\frac{\partial Q_t}{\partial \zeta_t} > 0$, $\frac{\partial y_t}{\partial \zeta_t} > 0$, $\frac{\partial b_t}{\partial \zeta_t} > 0$, $\frac{\partial q_{-t}(\tilde{x})}{\partial \zeta_t} = 0$, $\frac{\partial k_{-t}}{\partial \zeta_t} < 0$, $\frac{\partial X_{-t}}{\partial \zeta_t} > 0$, $\frac{\partial p_{-t}}{\partial \zeta_t} < 0$, $\frac{\partial Q_{-t}}{\partial \zeta_t} > 0$, $\frac{\partial y_{-t}}{\partial \zeta_t} > 0$, $\frac{\partial b_{-t}}{\partial \zeta_t} < 0$, *where* $" - t" := 3 - t$.

As expected, increasing the feed-in tariff in one period increases electricity production by the intra-marginal RES-E generators in that period. Since their output decision in a particular period only depends on the feed-in tariff paid in that period, increasing the feed-in tariff in one period does not affect the RES-E generators output in the respective other period. Moreover, due to higher feed-in rates, more RES-E producers become competitive, inducing demand for RES-E equipment and production in the RES-E equipment industry to increase. The RES-E equipment price responds to increasing demand by RES-E generators, rising in the period where the feed-in tariff is increased, but falling in the respective other period. In addition, higher feed-in tariffs induce a crowding-out effect on conventional electricity production in both periods. The overall impact on electricity production is positive, and the electricity price decreases accordingly.

[11] The proof can be obtained from the authors upon request.

We are now ready to derive the formulas for the second-best-optimal feed-in tariff rates $\zeta_1$ and $\zeta_2$. Differentiating welfare with respect to the feed-in tariffs and inserting the behavioral conditions gives us two symmetric expressions in $\zeta_1$ and $\zeta_2$.[12] Solving these for the feed-in-tariff rates yields

$$
\begin{aligned}
\zeta_1^{pc} =& P_1(Q_1) + [D_1'(mk_1) - \tau_1 + P_1'(Q_1)k_1]\frac{H_2 m\frac{\partial k_1}{\partial \zeta_1} - H_1 m\frac{\partial k_1}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2} \\
&- \delta \Gamma_L^2 (n-1)\epsilon \frac{H_1 n\frac{\partial y_1}{\partial \zeta_2} - H_2 n\frac{\partial y_1}{\partial \zeta_1}}{C_2 H_1 - C_1 H_2} \\
&+ \delta[D_2'(mk_2) - \tau_2 + P_2'(Q_2)k_2]\frac{H_2 m\frac{\partial k_2}{\partial \zeta_1} - H_1 m\frac{\partial k_2}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2},
\end{aligned}
\tag{34}
$$

$$
\begin{aligned}
\zeta_2^{pc} =& P_2(Q_2) + [D_2'(mk_2) - \tau_2 + P_2'(Q_2)k_2]\frac{C_2 m\frac{\partial k_2}{\partial \zeta_1} - C_1 m\frac{\partial k_2}{\partial \zeta_2}}{[C_1 H_2 - C_2 H_1]} \\
&- [\Gamma_L^2 (n-1)\epsilon] \frac{C_1 n\frac{\partial y_1}{\partial \zeta_2} - C_2 n\frac{\partial y_1}{\partial \zeta_1}}{[C_1 H_2 - C_2 H_1]} \\
&+ \frac{1}{\delta}[D_1'(mk_1) - \tau_1 + P_1'(Q_1)k_1]\frac{C_2 m\frac{\partial k_1}{\partial \zeta_1} - C_1 m\frac{\partial k_1}{\partial \zeta_2}}{[C_1 H_2 - C_2 H_1]},
\end{aligned}
\tag{35}
$$

where the superscript '*pc*' denotes perfect competition in the RES-E equipment sector, and $C_1$, $C_2$, $H_1$, and $H_2$ describe the reaction of clean electricity production when the feed-in-tariff rate changes in a particular period, i.e. $C_1 = q_1(X_1)\frac{\partial X_1}{\partial \zeta_1} + \frac{\partial Q_1^c}{\partial \zeta_1}$, $C_2 = q_1(X_1)\frac{\partial X_1}{\partial \zeta_2}$, $H_1 = q_2(X_2)\frac{\partial X_2}{\partial \zeta_1}$ and $H_2 = q_2(X_2)\frac{\partial X_2}{\partial \zeta_2} + \frac{\partial Q_2^c}{\partial \zeta_2}$.

The feed-in-tariff rates given by equations (34) and (35) consist of the electricity price in the respective period $t = 1, 2$ plus a mark-up that takes into account both the marginal pollution damage and the strategic effects in the oligopolistic fossil-fuel industry, as well as the learning spill-overs in the RES-E equipment industry.

Each of the three parts of the mark-up term is multiplied by a weighting factor containing the comparative-statics effects with respect to the feed-in tariffs. Unfortunately, since the indirect effects of increasing the feed-in tariff in one period on output in the respective other period do not vanish, the signs of the second-best feed-in tariffs cannot be unambiguously determined. However, our numerical calculations suggest that the indirect effects are likely to be small. Accordingly, we will assume in the following that the direct effects dominate the indirect effects, i.e. $\frac{\partial k_t}{\partial \zeta_t} > \frac{\partial k_t}{\partial \zeta_{-t}}$, $\frac{\partial y_t}{\partial \zeta_t} > \frac{\partial y_t}{\partial \zeta_{-t}}$, and $\frac{\partial X_t}{\partial \zeta_t} > \frac{\partial X_t}{\partial \zeta_{-t}}$. This assumption enables us to interpret the composition of the second-best optimal feed-in tariffs in a straightforward fashion. For brevity, we focus on the interpretation of $\zeta_1$, but the interpretation of $\zeta_2$ is similar.

[12]The derivation of the second-best-optimal feed-in tariffs is provided in appendix A.4.

Following our assumption concerning the magnitude of the comparative-statics effects, the weighting factor of the first mark-up term in equation (34) is positive. This implies that if the tax rate falls short of (exceeds) marginal damage – provided that the strategic output contraction of the fossil-fuel utilities is not too large – this will have a positive (negative) impact on the feed-in-tariff rate, i.e. the feed-in tariff paid to the renewable electricity generators will lie above (below) the market price for electricity. Similarly, if output contraction due to oligopolistic competition in the fossil-fuel industry is very large, the second-best optimal feed-in-tariff rate will be reduced. The weighting factor of the second mark-up term in equation (34) is also positive, implying that the existence of learning spill-overs in the RES-E equipment industry will have a positive effect on the feed-in tariff in the first period. If learning is purely private, the second term vanishes, and the feed-in tariff will only correct for environmental damage and distortions in the fossil-fuel industry. The sign of the third mark-up term in equation (34) relating to the second-period effects in the fossil-fuel industry is ambiguous, since the weighting factor can be either positive or negative. If the weighting factor is *positive* and the emission tax falls short of marginal damage in $t = 2$, or if the weighting factor is *negative* and the emission tax exceeds marginal damage in $t = 2$, then the third term will further raise the feed-in tariff in $t = 1$ (provided the strategic output contraction is not too large). The intuition for this effect is that the regulator anticipates that fossil-fuel utilities might shift their production to $t = 1$ when facing high emission taxes in $t = 2$. In order to mitigate this reaction, the regulator increases the feed-in tariff in $t = 1$. However, compared to the first two (direct) effects, the impact of the third mark-up term on the feed-in-tariff rate is likely to be small. To sum up:

**Proposition 3** *Consider an electricity market as described above and perfect competition among RES-E equipment producers. Assume an exogenous, possibly non-optimal tax is charged on emissions. In each period the second-best-optimal feed-in tariff is equal to the market price for electricity plus a term that corrects for the difference between marginal damage and the emission tax rate, the output contraction of fossil-fuel utilities and insufficient learning spill-overs, taking into account the firms' reactions on the feed-in tariffs. The second-best-optimal feed-in-tariff rates are given by (34) and (35), respectively.*

In the case of oligopolistic competition in both the fossil fuel and the RES-E equipment industry, the structure of the second-best optimal feed-in tariff becomes a bit more complex, as it also takes into account the strategic effects in the RES-E equipment sector. Using the same techniques as for the derivation of equations (34) and (35) we arrive at:

$$
\begin{aligned}
\zeta_1^{oc} =& P_1(Q_1) + [D_1'(mk_1) - \tau_1 + P_1'(Q_1)k_1]\frac{H_2 m\frac{\partial k_1}{\partial \zeta_1} - H_1 m\frac{\partial k_1}{\partial \zeta_2}}{C_2H_1 - C_1H_2} \\
& - [B^1_{X_1}(X_1,\zeta_1)y_1 + \delta B^2_{X_2}(X_2,\zeta_2)(n-1)\frac{\partial \tilde{y_2}}{\partial y_1} + \delta\Gamma^2_L(n-1)\epsilon]\frac{H_1 n\frac{\partial y_1}{\partial \zeta_2} - H_2 n\frac{\partial y_1}{\partial \zeta_1}}{C_2H_1 - C_1H_2} \\
& + \delta[D_2'(mk_2) - \tau_2 + P_2'(Q_2)k_2]\frac{H_2 m\frac{\partial k_2}{\partial \zeta_1} - H_1 m\frac{\partial k_2}{\partial \zeta_2}}{C_2H_1 - C_1H_2} \\
& - \delta B^2_{X_2}(X_2,\zeta_2)y_2\frac{H_1 n\frac{\partial y_2}{\partial \zeta_2} - H_2 n\frac{\partial y_2}{\partial \zeta_1}}{C_2H_1 - C_1H_2},
\end{aligned} \tag{36}
$$

$$
\begin{aligned}
\zeta_2^{oc} =& [D_2'(mk_2) - \tau_2 + P_2'(Q_2)k_2]\frac{C_2 m\frac{\partial k_2}{\partial \zeta_1} - C_1 m\frac{\partial k_2}{\partial \zeta_2}}{[C_1H_2 - C_2H_1]} \\
& - B^2_{X_2}(X_2,\zeta_2)y_2\frac{C_1 n\frac{\partial y_2}{\partial \zeta_2} - C_2 n\frac{\partial y_2}{\partial \zeta_1}}{[C_1H_2 - C_2H_1]} \\
& + P_2(Q_2) + [D_1'(mk_1) - \tau_1 + P_1'(Q_1)k_1]\frac{C_2 m\frac{\partial k_1}{\partial \zeta_1} - C_1 m\frac{\partial k_1}{\partial \zeta_2}}{\delta[C_1H_2 - C_2H_1]} \\
& - [B^1_{X_1}(X_1,\zeta_1)y_1 + \delta B^2_{X_2}(X_2,\zeta_2)(n-1)\frac{\partial \tilde{y_2}}{\partial y_1} + \delta\Gamma^2_L(n-1)\epsilon]\frac{C_1 n\frac{\partial y_1}{\partial \zeta_2} - C_2 n\frac{\partial y_1}{\partial \zeta_1}}{\delta[C_1H_2 - C_2H_1]},
\end{aligned} \tag{37}
$$

where the superscript '$oc$' denotes oligopolistic competition in the RES-E equipment sector, and $C_1$, $C_2$, $H_1$, and $H_2$ again denote the reaction of green electricity production when the feed-in tariff rate changes in a particular period. Note that the comparative statics effects of increasing the feed-in tariffs on the endogenous variables are in line with Lemma 1. Compared to equations (34) and (35), equations (36) and (37) include an augmented second mark-up term and an additional fourth mark-up term, representing the distortions caused by oligopolistic competition in the RES-E equipment industry.

Assuming again that the direct comparative-statics effects dominate the indirect effects, the weighting factor of the augmented second term in equation (36) is positive. This implies that the feed-in tariff in $t = 1$ will increase compared to the case of perfect competition in the RES-E equipment industry as it also accounts for the strategic output contraction by the RES-E equipment firms, i.e. $B^1_{X_1}(X_1,\zeta_1)y_1 < 0$. This effect is mitigated by the fact that RES-E equipment firms want to expand their output in the first period in order to shift their reaction curves outwards in the second, as represented by the term $B^2_{X_2}(X_2,\zeta_2)(n-1)\frac{\partial \tilde{y_2}}{\partial y_1} > 0$. Moreover, the fourth term in (36) indicates that the feed-in tariff in $t = 1$ also takes into account the strategic output contraction by RES-E equipment firms in the second period, which, due to $B^2_{X_2}(X_2,\zeta_2)y_2 < 0$, will raise the feed-in tariff if the weighting factor is positive and will decrease the feed-in tariff if the weighting factor is negative.

The composition of $\zeta_2^{oc}$ can again be interpreted analogously, with the predominant effects arising from the third and the fourth mark-up terms in equation (37). We therefore summarize the results in the following proposition:

**Proposition 4** *Consider an electricity market as described above and oligopolistic competition among RES-E equipment producers and assume an exogenous, possibly non-optimal tax is charged on emissions. In addition to the components described in proposition 3, the second-best-optimal feed-in tariff in each period also accounts for the output contraction of RES-E equipment producers. The second-best-optimal feed-in-tariff rates are given by (36) and (37), respectively.*

## 5.2 Welfare comparisons through simulations

In this section we calculate the implications of a second-best-optimal feed-in-tariff policy on welfare and compare these to the first-best solution. For this purpose, we simultaneously solve the system of equations (1)–(4) and (13)–(19) and calculate the social welfare when first-best policies are applied. We also work out the social welfare of a second-best feed-in-tariff policy by simultaneously solving the system of equations (1), (2), (4), (28) – (35). Following Fischer and Newell (2008) we assume iso-elastic electricity demand and quadratic cost and damage functions, yielding linear electricity supply and linear marginal damage functions (see table 1). Table 2 summarizes the parameter values employed in our study, most of which have been adopted from Fischer and Newell (2008).[13] The slope parameter of marginal pollution damage ($d$) is consistent with a constant marginal damage of US-$43 per ton of $CO_2$ (see Tol, 2005). The learning parameter ($b$) is calibrated to induce a learning rate of about 20%, which is at the upper limit of most empirical studies (see Junginger et al., 2005).

Table 1: Functional forms

| Functional form | Description |
|---|---|
| $C_t(q_t(\tilde{x}), \tilde{x}) = c_1 q_t + \frac{c_2}{2}(q_t + f\tilde{x})^2$ | Cost function of the RES-E generators in $t = 1, 2$ |
| $K_t(k_t) = h_1 k_t + \frac{h_2}{2} k_t^2$ | Cost function of the fossil-fuel firms in $t = 1, 2$ |
| $\Gamma^1(y_1) = \frac{\gamma}{2} y_1^2$ | Cost function of the RES-E equipment producers in $t = 1$ |
| $\Gamma^2(y_2, L) = \frac{\gamma}{4}(y_2 - bL)^2 + \frac{\gamma}{4} y_2^2$ | Cost function of the RES-E equipment producers in $t = 2$ |
| $L = y_1 + (n-1)\varepsilon\tilde{y}_1$ | Learning by doing in the RES-E equipment industry in $t = 1$ |
| $D_t(mk_t) = \frac{d}{2}(mk_t)^2$ | Pollution damage in $t = 1, 2$ |
| $P_t(Q_t) = Q_t^{\alpha}$ | Electricity demand function in $t = 1, 2$ |

[13] Fischer and Newell (2008) have calibrated their values to simulations that study the impact of different $CO_2$ reduction goals (taken from the Energy Information Administration's National Energy Modeling System, EIA, 2006) on the electricity market.

Table 2: Parameter values

| Parameter | Base value | Description |
|---|---|---|
| $\alpha$ | -4 | Elasticity of electricity demand |
| $h_1$ | 0.07 | Intercept of fossil-fuel utilities cost function |
| $h_2$ | $1.8 * 10^{-14}$ | Scaling parameter in fossil-fuel utilities cost function |
| $\gamma, b$ | 0.1, 0.2 | Scaling parameters in RES-E equipment producers cost function |
| $c_1$ | 0.1 | Intercept of RES-E producers cost function |
| $c_2, f$ | $1.2 * 10^{-13}$, 0.05 | Scaling parameters in RES-E producers cost function |
| $d$ | 0.027 | Scaling parameter in pollution damage function |
| $\varepsilon$ | 0.5 | Learning spill-over coefficient |
| $\delta$ | 0.95 | Discount rate |

For the second-best calculations, we consider three alternative scenarios for the exogenously given emission tax: $\tau_t = 0$ (no emission tax), $\tau_t = \frac{1}{2}\tau_t^*$ (emission tax rate equal to half its first-best value), and $\tau_t = \tau_t^*$ (first-best emission tax).

The results for perfect and imperfect competition are displayed in table 3 and table 4, respectively. The first row displays the percentage differences between optimal welfare and welfare resulting from second-best-optimal feed-in tariffs, given certain fixed levels of the emission tax. The results yield two main conclusions. When the exogenous emission tax is equal to the first-best level, the welfare loss from a second-best-optimal feed-in tariff policy is very small. When the exogenous tax rate falls short of its first-best level, however, the welfare loss is considerably higher. Thus a second-best-optimal feed-in tariff is much less efficient than the emission tax in internalizing both the environmental and competition effects in the fossil-fuel industry. In the case of imperfect competition among the RES-E equipment firms, the welfare losses through second-best-optimal feed-in tariffs are even bigger, since the feed-in tariff now also has to correct for strategic output contraction in the RES-E equipment sector.

Tables 3 and 4 also indicate how producer and consumer surplus are affected by the change from first-best to second-best-optimal policies. Consistent with the above-mentioned observations on social welfare, the impact of switching from a first-best tax/subsidy policy to a second-best feed-in-tariff policy is much more pronounced when the exogenous emission tax falls short of its first-best level. The renewable electricity and the renewable equipment sector benefit from the introduction of feed-in tariffs compared to a first-best policy, increasing their market shares and surpluses at the expense of fossil-fuel-based electricity producers. The implementation of second-best-optimal feed-in tariffs also leads to significant electricity price increases that negatively affect the consumer surplus. Moreover, since dirty electricity is crowded out of the market, second-best-optimal feed-in-tariff policies reduce pollution damage. Note also that in our calculations the second-best optimal feed-in tariffs lie below the electricity price when the exogenous emission tax falls short of its optimal value. This happens because the strategic effect in the fossil-fuel sector (driven by the inelastic electricity demand) overcompensates both marginal damage and learning spill-overs.

Table 3: Deviation of different second-best feed-in-tariff policy scenarios relative to a first-best emission-tax/learning-subsidy policy: oligopoly in the fossil-fuel industry only

| ΔVariable (in %) | FITs with exogenous emission tax $\tau_t = \tau_t^*$ | FITs with exogenous emission tax $\tau_t = \frac{1}{2}\tau_t^*$ | FITs with exogenous emission tax $\tau_t = 0$ |
|---|---|---|---|
| ΔWelfare | -0.00019 | -12.8395 | -28.3360 |
| ΔConsumer surplus | | | |
| t=1 | 0.00003 | -6.6435 | -13.3265 |
| t=2 | -0.06055 | -6.9582 | -12.6583 |
| ΔProducer surplus (green electricity) | | | |
| t=1 | -3.04845 | 33129.8 | 60761.2 |
| t=2 | -0.93635 | 27386.2 | 56470.4 |
| ΔProducer surplus (dirty electricity) | | | |
| t=1 | -0.00013 | -22.3643 | -32.3027 |
| t=2 | 0.24836 | -21.0085 | -35.0382 |
| ΔProducer surplus (RES-E equipment) | | | |
| t=1 | -6.4724 | 9696.1 | 15631.5 |
| t=2 | -0.4688 | 8812.1 | 15162.8 |
| ΔElectricity price | | | |
| t=1 | -0.00017 | 37.189 | 77.3519 |
| t=2 | 0.32540 | 38.927 | 73.2385 |
| ΔTotal output of green electricity | | | |
| t=1 | 0.00022 | 3214.13 | 4660.57 |
| t=2 | -0.41655 | 2869.29 | 4364.36 |
| ΔTotal output of dirty electricity | | | |
| t=1 | 0.00004 | -27.6829 | -42.480 |
| t=2 | -0.07889 | -27.6182 | -42.822 |
| ΔRES-E equipment price | | | |
| t=1 | 6.3946 | 988.383 | 1279.48 |
| t=2 | 0.2128 | 837.516 | 1132.71 |
| ΔTotal number of RES-E equipment | | | |
| t=1 | -2.99688 | 885.39 | 1152.45 |
| t=2 | -0.51587 | 848.39 | 1137.19 |
| ΔDamage | | | |
| t=1 | 0.00008 | -47.7023 | -66.9146 |
| t=2 | -0.15771 | -47.6088 | -67.3067 |

Table 4: Deviation of different second-best feed-in tariff policy scenarios relative to a first-best emission tax/learning subsidy policy: oligopoly in both the fossil-fuel and the RES-E equipment industry

| ΔVariable (in %) | FITs with exogenous emission tax $\tau_t = \tau_t^*$ | FITs with exogenous emission tax $\tau_t = \frac{1}{2}\tau_t^*$ | FITs with exogenous emission tax $\tau_t = 0$ |
|---|---:|---:|---:|
| ΔWelfare | -0.00049 | -12.8568 | -29.7965 |
| ΔConsumer surplus | | | |
| t=1 | -0.0844 | -6.3105 | -13.313 |
| t=2 | $6.1 * 10^{-8}$ | -5.6881 | -7.515 |
| ΔProducer surplus (clean electricity) | | | |
| t=1 | -8.4055 | 33582.7 | 60067.2 |
| t=2 | -0.8523 | 31630.1 | 82887.5 |
| ΔProducer surplus (dirty electricity) | | | |
| t=1 | 0.3394 | -23.8109 | -32.3581 |
| t=2 | -0.00006 | -26.4725 | -56.2294 |
| ΔProducer surplus (RES-E equipment) | | | |
| t=1 | -53.4453 | 4702.22 | 7333.17 |
| t=2 | -12.7662 | 8624.34 | 18971.9 |
| ΔElectricity price | | | |
| t=1 | 0.44742 | 0.75797 | 77.270 |
| t=2 | -0.00006 | 0.10866 | 42.287 |
| ΔTotal output of clean electricity | | | |
| t=1 | -0.5867 | -0.9682 | 4663.3 |
| t=2 | -0.00009 | -0.1394 | 5609.2 |
| ΔTotal output of dirty electricity | | | |
| t=1 | -0.1101 | -0.18374 | -42.487 |
| t=2 | $6.8 * 10^{-7}$ | -0.02638 | -46.924 |
| ΔRES-E equipment price | | | |
| t=1 | 11.9904 | 11.7026 | 1315.11 |
| t=2 | 1.7154 | 1.6489 | 1431.46 |
| ΔTotal number of RES-E equipment | | | |
| t=1 | -5.9587 | -6.19962 | 1138.29 |
| t=2 | -0.8296 | -0.93460 | 1317.91 |
| ΔDamage | | | |
| t=1 | -0.220 | -47.759 | -66.923 |
| t=2 | $1.4 * 10^{-6}$ | -47.862 | -71.829 |

### 5.3 The impact of market structure on the size of feed-in tariffs

To investigate the impact of changes in market structure in the conventional electricity sector on the second-best-optimal feed-in tariffs, we again consider the numerical example from the previous section and study the impact of market structure (represented by the number of oligopolistic firms) on the second-best-optimal feed-in tariffs and market performance.

Figures 1 – 3 illustrate the results for the case of oligopolistic competition in the fossil-fuel industry and perfect competition among RES-E equipment producers assuming an emission tax rate equal to zero. Similar to the comparative-statics results described in section 4.1.1, more competition among fossil-fuel utilities leads to an increasing output of fossil-fuel electricity and hence to a decrease in electricity prices. This effect crowds out production of renewable electricity and thus also depresses demand and prices in the RES-E equipment sector. This mechanism is always present. Interestingly, however, the impact on the second best-optimal level of the feed-in tariffs is less pronounced.

From figure 1 we see that, if the demand elasticity is low ($\epsilon = 1/\alpha = -1/4.0$ and below), the second-best-optimal feed-in-tariff rate decreases as electricity markets become more competitive. The reason is that total output is hardly affected by increasing competition, so there is no great increase in marginal damage either. The dominating effect on the second-best-optimal feed-in tariffs, given by (34) and (35), is therefore the fall in electricity prices (first terms in these formulas). So in the short run (when demand elasticity is low), liberalizing energy markets brings about lower feed-in tariffs, which benefits public budgets and consumers who have to pay less to subsidize renewable energy.

If, by contrast, demand elasticity is relatively high ($\epsilon = 1/\alpha = -1/2.0$ and higher), the second-best optimal feed-in-tariff rate increases as the electricity market becomes more competitive (see figure 2). The intuitive reason is that increased output induces higher emissions and hence higher marginal damage, whereas the strategic output corrective of the feed-in-tariff rate (term $P_1'(Q_1)k_1$ in (34) and $P_2'(Q_2)k_2$ in (35)) decreases. To counteract this effect, feed-in-tariff rates must be enhanced in both periods. So liberalizing the electricity markets has the opposite effect in the long run: (second-best-optimal) feed-in tariffs have to be raised, thus offsetting the positive effect of market liberalization for consumers and public budgets. For intermediate values of demand elasticities we obtain a U-shaped relationship between the number of firms and the size of the feed-in tariff (see figure 3).

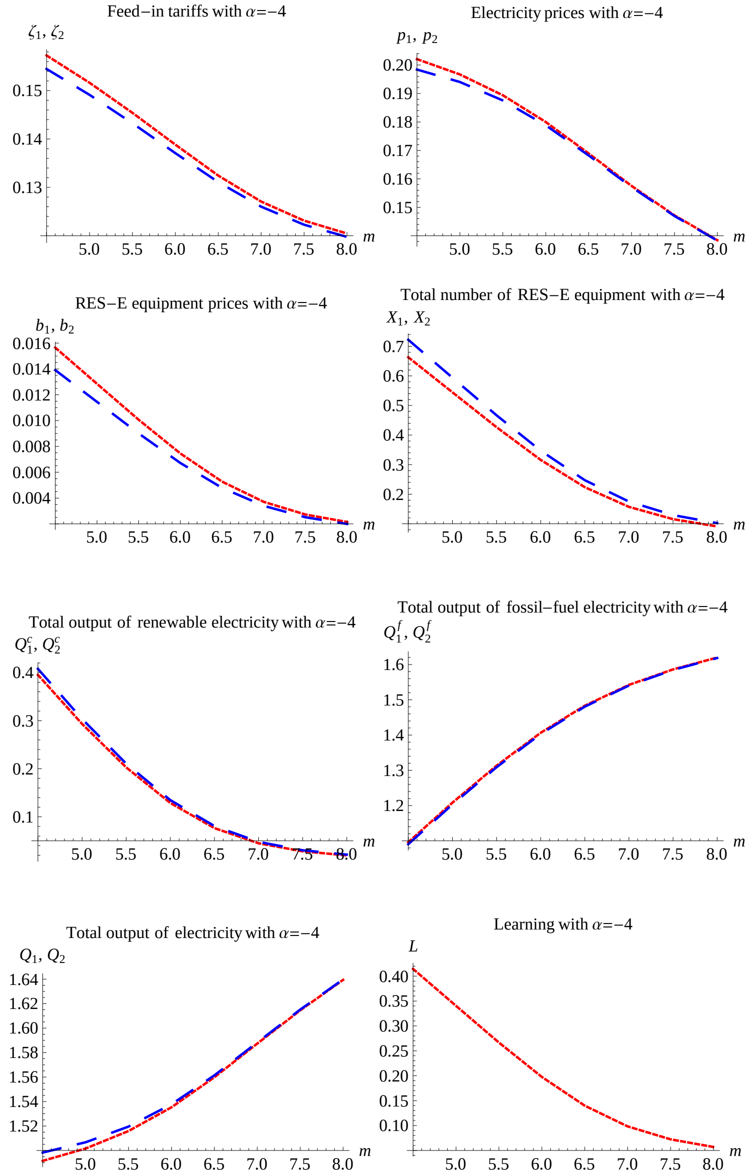


Figure 1: Impact of increasing the number of fossil-fuel firms with perfect competition in the RES-E equipment industry and low elasticity of demand (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

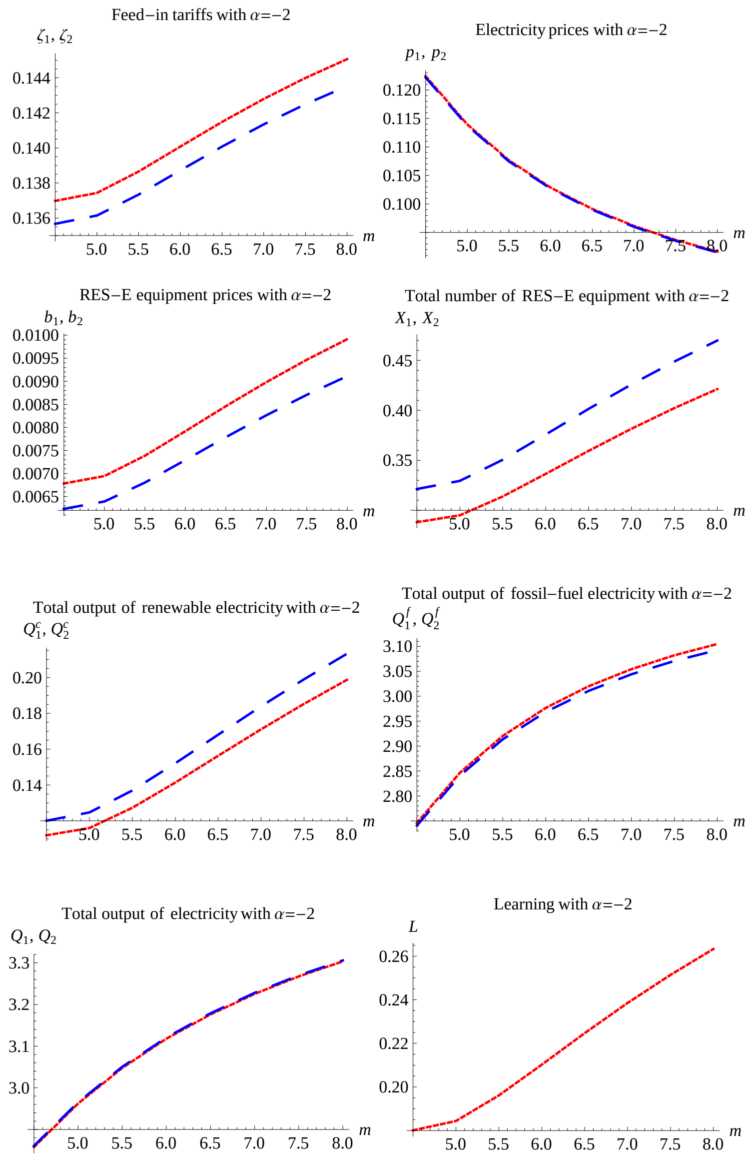


Figure 2: Impact of increasing the number of fossil-fuel firms with perfect competition in the RES-E equipment industry and high elasticity of demand (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

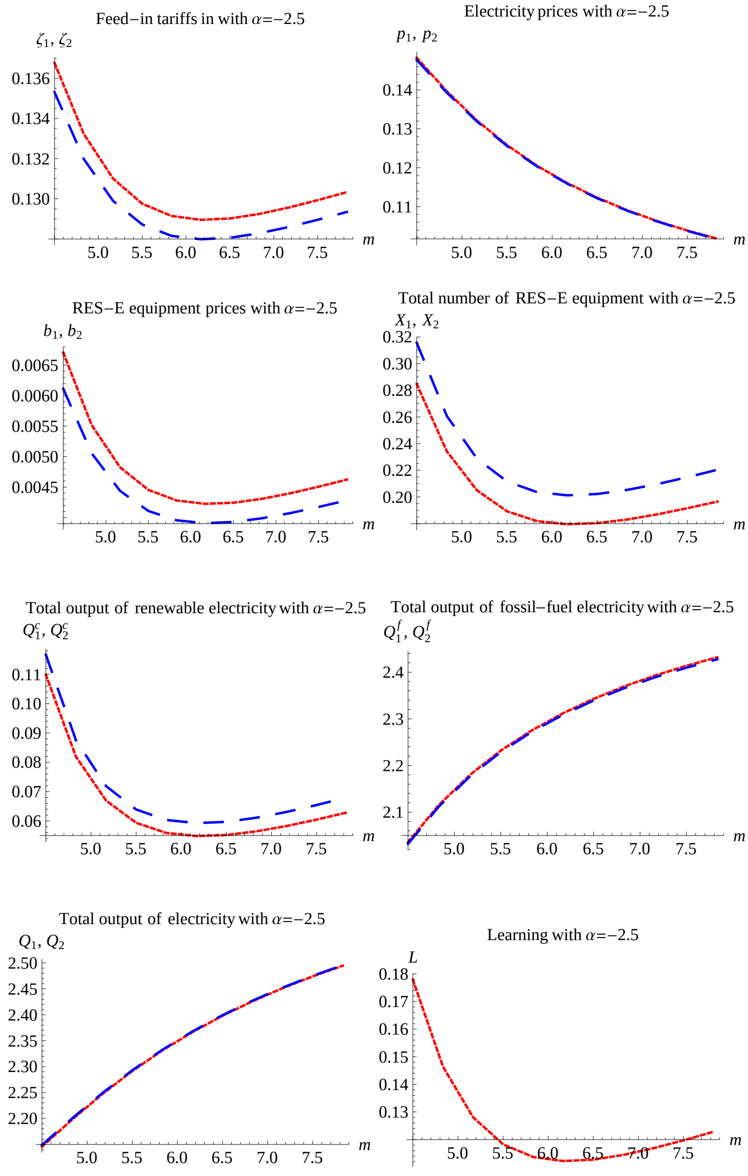


Figure 3: Impact of increasing the number of fossil-fuel firms with perfect competition in the RES-E equipment industry and intermediate elasticity of demand (short-[long-]dashed lines for $t = 1$ $[t = 2]$).

In the case of oligopoly power in the RES-E equipment industry the effects of increasing competition in the fossil-fuel sector are qualitatively similar, but differ quantitatively (see figures 4 and 5). In general, imperfect competition among RES-E equipment producers induces higher prices and lower production of RES-E equipment, which in turn leads to a lower output of clean electricity. In addition, the second-best-optimal feed-in tariffs are higher than in the case of perfect competition since they also internalize the strategic output contraction in the RES-E equipment sector by indirectly subsidizing that market. Another interesting observation concerns the relative size of the feed-in-tariff in the first compared to the second period. When the emission tax fully accounts for the externalities in the fossil-fuel industry we obtain a higher feed-in tariff in the first than in the second period (see figure 5). By contrast, when the emission tax is equal to zero, the feed-in tariff in the second period is higher than in the first period (see figure 4). Therefore, the statement that feed-in-tariffs should decrease over time to account for the learning effects in the RES-E industry does not hold in general.

Finally, figures 6 and 7 illustrate the impact of market structure in the RES-E equipment sector. With increasing competition on the market for RES-E equipment, falling RES-E equipment prices trigger more market entry by RES-E operators, and both green electricity and total electricity output increase while dirty electricity is crowded out to some extent. The impact on the second-best-optimal feed-in-tariff rates is ambiguous, depending on the chosen emission tax level. When the emission tax is equal to zero, the second-best-optimal feed-in tariff rates decrease in both periods (see figure 6). The intuitive reason for this result is that negative externalities are reduced in both the RES-E equipment industry (due to smaller oligopolistic output contraction) and in the fossil-fuel industry (due to crowding out of dirty electricity production and thus lower marginal damage). By contrast, when emission taxes are equal to their first-best levels, the second-best-optimal feed-in tariff rate increases in the first and decreases in the second period (see figure 7). As the emission tax now fully internalizes all external effects in the fossil-fuel sector, the increasing feed-in tariff in the first period can be explained by the positive externalities of learning spill-overs that are now predominant in the RES-E equipment industry. Since no learning occurs in the second period, the feed-in tariff then decreases due to the declining oligopolistic output contraction of RES-E equipment producers. In addition, similar to the results shown in figures 4 and 5, second-best-optimal feed-in-tariff rates may be higher in the second than in the first period, again depending on the emission tax level.

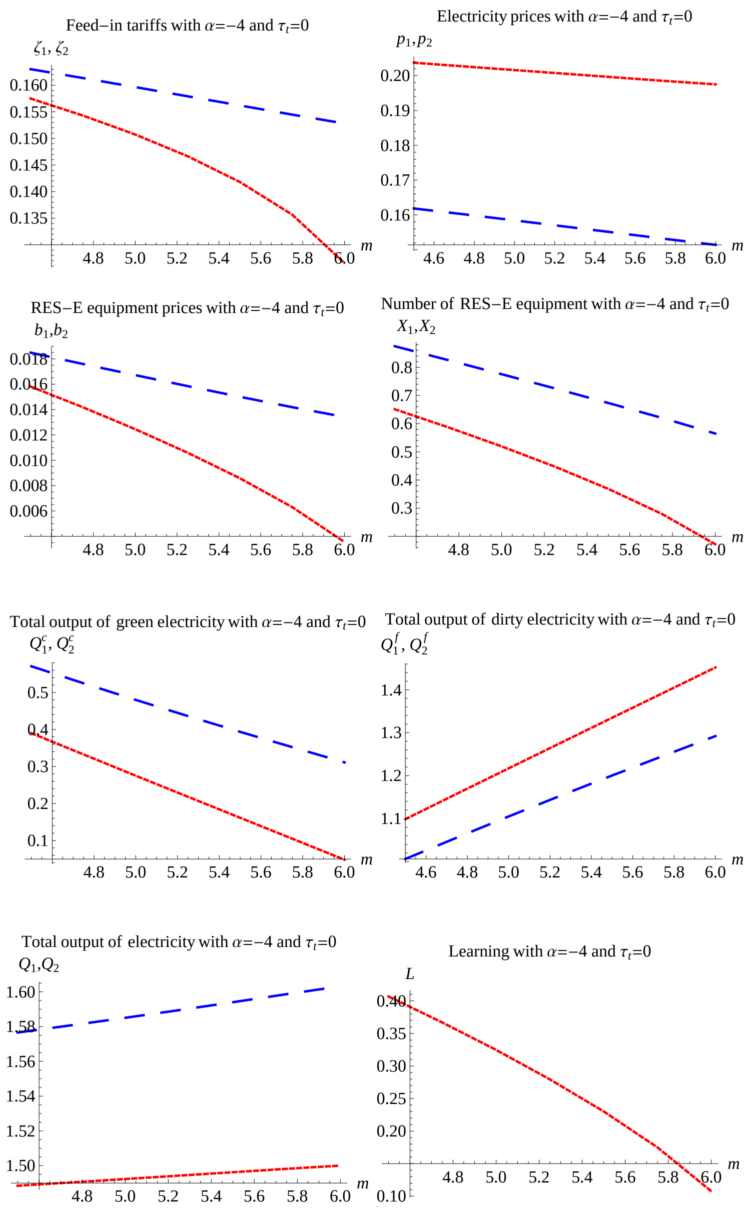


Figure 4: Impact of increasing the number of fossil-fuel firms with imperfect competition in the RES-E equipment industry and emission taxes equal to zero (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

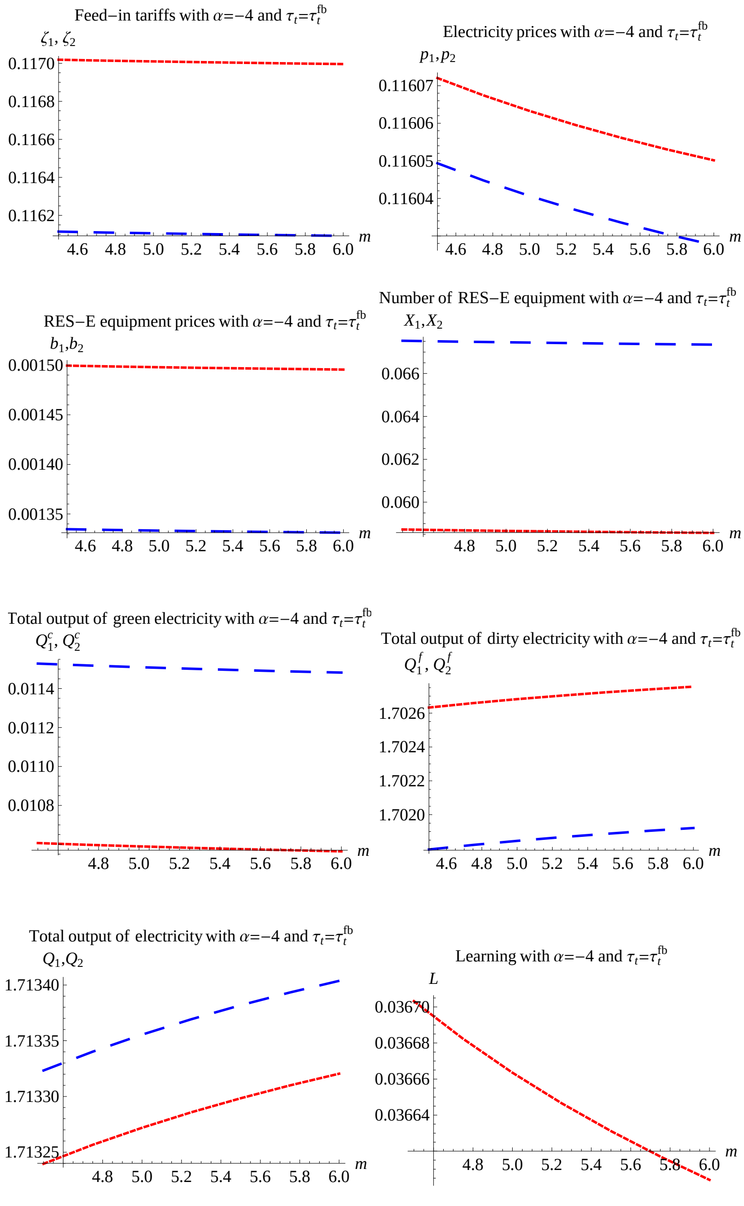


Figure 5: Impact of increasing the number of fossil-fuel firms with imperfect competition in the RES-E equipment industry and first-best emission taxes (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

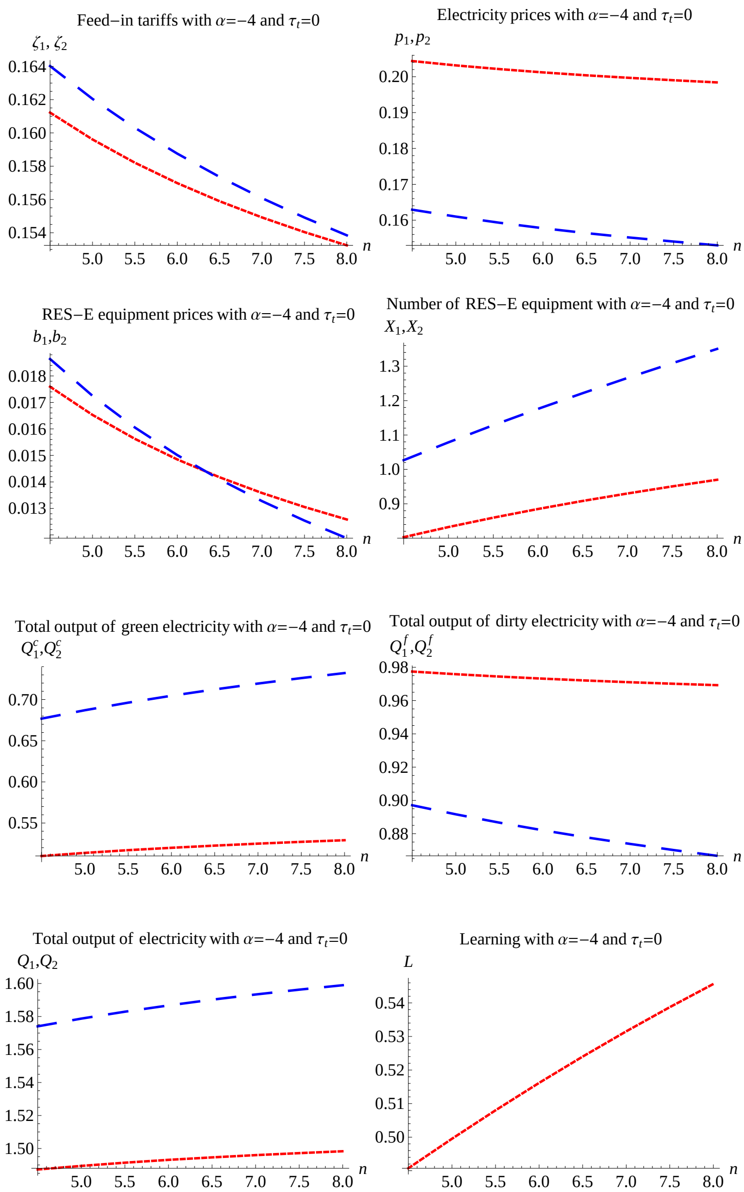


Figure 6: Impact of increasing the number of RES-E equipment firms with imperfect competition in the RES-E equipment industry and emission taxes equal to zero (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

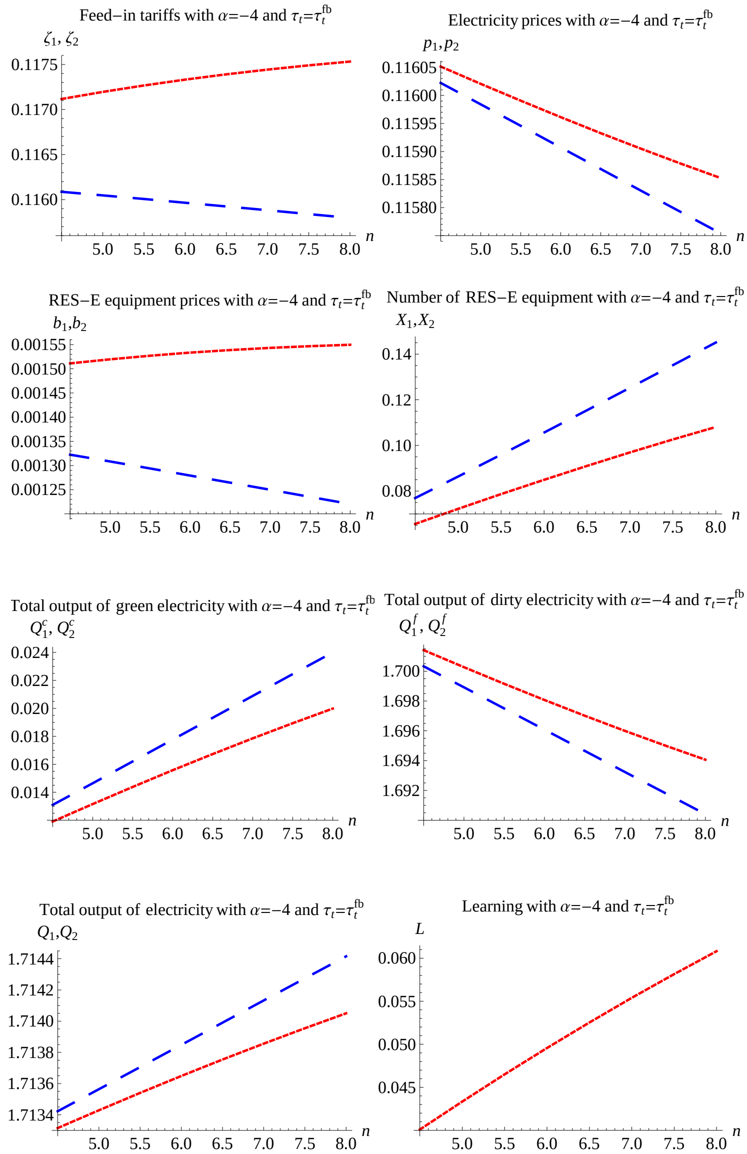


Figure 7: Impact of increasing the number of RES-E equipment firms with imperfect competition in the RES-E equipment industry and first-best emission taxes (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

### 5.4 Sensitivity analysis

To test the stability of our numerical results, we conduct a sensitivity analysis with respect to the parameters determining the degree of learning spill-overs, the magnitude of cost reductions through learning by doing in the RES-E equipment industry, and the elasticity of electricity demand. For brevity, we focus on the impact of these parameters on welfare differences between first-best and second-best policies. The results for the case of perfect competition in the RES-E equipment industry are displayed in table 5 and for the case of oligopolistic competition in the RES-E equipment industry in table 6. In both tables the first line carries forward the results of the baseline case in table 3 and table 4, respectively. In both cases we see that the impact made on the relative performance of second-best policies by varying either the ability of firms to learn or the degree of learning spill-overs is rather small. When the emission tax is not set at its first-best level, higher learning ability ($b = 0.3$) and complete learning spill-overs ($\varepsilon = 1$) both slightly improve the relative performance of second-best feed-in-tariff policies compared to the baseline scenario. By contrast, lower learning ($b = 0.01$) and no learning spill-overs ($\varepsilon = 0$) both slightly reduce the relative performance of those policies. On the other hand, varying the demand elasticity for electricity, by contrast, leads to fairly large impacts on the relative performance of second-best policies. When demand is more elastic ($\epsilon = 1/\alpha = -1/3.5$)[14] the welfare loss induced by second-best policies relative to optimal welfare is significantly lower compared to the baseline. Similarly, less elastic demand ($\epsilon = 1/\alpha = -1/4.5$) leads to a significantly higher welfare loss of second-best-optimal feed-in-tariff policies compared to the baseline. Therefore, the results from the sensitivity analysis indicate that in our framework of imperfect competition demand elasticity has a much larger impact on policy performance than the parameters relating to the learning effects and spill-overs in the RES-E equipment industry.

Table 5: Sensitivity analysis: oligopoly in the fossil-fuel industry only

| $\Delta$Welfare relative to first best policy (%) | FITs with exog. tax $\tau_t = \tau_t^*$ | FITs with exog. tax $\tau_t = 0.5\tau_t^*$ | FITs with exog. tax $\tau_t = 0$ |
|---|---|---|---|
| Baseline | -0.00019 | -12.8395 | -28.3360 |
| More elastic demand ($\alpha = -3.5$) | -0.00009 | -7.13675 | -17.0856 |
| Less elastic demand ($\alpha = -4.5$) | -0.19674 | -20.3974 | -44.0165 |
| High learning ($b = 0.3$) | -0.00068 | -12.6169 | -27.9531 |
| Low learning ($b = 0.01$) | $-2.9 * 10^{-7}$ | -13.5577 | -29.5668 |
| Complete learning spill-overs ($\varepsilon = 1$) | -0.00077 | -12.6361 | -27.9057 |
| Purely private learning ($\varepsilon = 0$) | $-3.0 * 10^{-6}$ | -13.2521 | -29.0426 |

[14]Recall that $\alpha$ is the elasticity of the *inverse* demand function.

Table 6: Sensitivity analysis: oligopoly in both the fossil-fuel and the RES-E equipment industry

| ΔWelfare relative to first best policy (%) | FITs with exog. tax $\tau_t = \tau_t^*$ | FITs with exog. tax $\tau_t = 0.5\tau_t^*$ | FITs with exog. tax $\tau_t = 0$ |
|---|---|---|---|
| Baseline | -0.00049 | -12.8568 | -29.7965 |
| More elastic demand ($\alpha = -3.5$) | -0.00887 | -7.16979 | -18.0884 |
| Less elastic demand ($\alpha = -4.5$) | -0.67618 | -20.3506 | -44.5619 |
| High learning ($b = 0.3$) | -0.000718 | -12.6247 | -29.3786 |
| Low learning ($b = 0.01$) | $-2.5 * 10^{-6}$ | -13.58 | -31.4121 |
| Complete learning spill-overs ($\varepsilon = 1$) | -0.21601 | -12.5984 | -29.324 |
| Purely private learning ($\varepsilon = 0$) | -0.14676 | -13.2663 | -30.5291 |

# 6 Conclusion

In this paper we have set up a model to investigate the performance of subsidy policies, notably feed-in tariffs, for employing renewable energy sources in electricity production such as wind or photovoltaic power. As the existence of learning by doing and learning spill-overs is one of the most prominent arguments advanced by policy makers in favor of such subsidies, we explicitly account for these effects by considering an RES-E equipment industry that benefits from cost reductions through private and public learning. We find that the regulator can obtain the first-best allocation by implementing a tax on emissions and an output subsidy for RES-E equipment producers. The optimal tax is characterized by two counteracting components. It internalizes the externalities of emissions but also corrects for the strategic output contraction by the oligopolistic fossil-fuel firms. The output subsidy for RES-E equipment producers accounts for the learning spill-overs and, in the case of an oligopolistic RES-E equipment industry, also for the strategic behavior of the firms.

Since many European governments pay subsidies on clean electricity via feed-in tariffs rather than subsidizing RES-E equipment directly, we study the performance of such policies compared to the first-best alternative. Second-best-optimal feed-in tariffs take account of the learning spill-overs in the RES-E equipment industry. If emission taxes do not (fully) internalize the externalities caused by using fossil-fuels, they also account for marginal pollution damage and the strategic output contraction caused by oligopolistic market structure in the fossil-fuel industry.

Although feed-in tariffs perform much worse than a first-best policy, our results suggest that in the presence of learning spill-overs in the RES-E equipment industry and oligopolistic competition in the fossil-fuel sector, feed-in tariffs for renewable electricity producers may be justified if first-best policies are ruled out and as long as emissions are not regulated by tradable emission allowances. Given the current situation, where most European and other OECD economies' electricity markets are still dominated by a few large conventional utilities, our numerical results potentially call for a short-term *decrease* in feed-in tariff levels and a long-term *increase* in those levels as electricity markets are progressively liberalized. However, since our model considers environmental regulation of the conventional electricity sector through emission taxes, our results cannot be directly transferred to the current situation in the European Union, which regulates the $CO_2$ emitted by industrial sources through a cap-and-trade scheme of emission allowances. Under such a scheme, feed-in tariffs are not very useful, as they have no further mitigating effects on emissions. In fact, they would induce a lower allowance price and thus provide disincentives among the conventional electricity producers to further abate emissions (del Río Gonzalez, 2007; Sijm, 2005; Sorrel and Sijm, 2003). This problem could be solved if the regulator set a more stringent emission cap accounting for the emission reductions achieved through feed-in tariffs. Taxation of $CO_2$ emissions, by contrast, would render this adjustment of the emission cap superfluous.

In our model we have made several simplifying assumptions to keep the analysis tractable. In particular, we have assumed only one type of homogeneous RES-E equipment, while in reality several different types of RES-E equipment exist, notably wind turbines, photovoltaic panels, and bio-gas power plants. Within each of these types further product differentiation exists. Some countries (e.g. Poland) pay a unique feed-in tariff for "clean" electricity independent of which type of RES-E equipment is used, whereas other countries, notably Germany, have a highly differentiated system of feed-in tariffs with a spread in feed-in rates of up to 500%. It must be left to further research to account for product differentiation of this kind and assess resulting policy accordingly. Since the level of second-best-optimal feed-in tariffs crucially depends on the degree of potential market power, it would be particularly interesting from an empirical viewpoint to test for market power in the RES-E equipment sector.

# A Appendix

## A.1 Proof of the comparative-statics effects of market concentration with imperfect competition in the fossil-fuel industry only

In order to analyze the impact of market structure in the fossil fuel industry on output, prices and the policy instruments we differentiate equations (2)–(4), and (13)–(19) with respect to the number of fossil fuel utilities. Simplifying via the envelope theorem then yields the following system of equations:

Aggregate electricity production:

$$\frac{\partial Q_1}{\partial m} = \int_0^{X_1} \frac{\partial q_1(\tilde{x})}{\partial m} d\tilde{x} + q_1(X_1)\frac{\partial X_1}{\partial m} + m\frac{\partial k_1}{\partial m} + k_1 \tag{38}$$

$$\frac{\partial Q_2}{\partial m} = \int_0^{X_2} \frac{\partial q_2(\tilde{x})}{\partial m} d\tilde{x} + q_2(X_2)\frac{\partial X_2}{\partial m} + m\frac{\partial k_2}{\partial m} + k_2 \tag{39}$$

Electricity production of the intra-marginal RES-E firms:

$$\frac{\partial q_1(\tilde{x})}{\partial m} = \frac{P_1'(Q_1)}{C_{qq}^1(q_1(\tilde{x}), \tilde{x})}\frac{\partial Q_1}{\partial m} \qquad \forall \tilde{x} \leq X_1 \tag{40}$$

$$\frac{\partial q_2(\tilde{x})}{\partial m} = \frac{P_2'(Q_2)}{C_{qq}^2(q_2(\tilde{x}), \tilde{x})}\frac{\partial Q_2}{\partial m} \qquad \forall \tilde{x} \leq X_2 \tag{41}$$

Electricity production of the fossil fuel utilities:

$$0 = [P_1'(Q_1) + P_1''(Q_1)k_1]\frac{\partial Q_1}{\partial m} + [P_1'(Q_1) - K_1''(k_1)]\frac{\partial k_1}{\partial m} - \frac{\partial \tau_1}{\partial m} \tag{42}$$

$$0 = [P_2'(Q_2) + P_2''(Q_2)k_2]\frac{\partial Q_2}{\partial m} + [P_2'(Q_2) - K_2''(k_2)]\frac{\partial k_2}{\partial m} - \frac{\partial \tau_2}{\partial m} \tag{43}$$

Production of the RES-E equipment firms:

$$0 = \frac{\partial b_1}{\partial m} - [\Gamma_{y_1 y_1}^1 + \delta\Gamma_{LL}^2(1 + (n-1)\varepsilon)]\frac{\partial y_1}{\partial m} + \frac{\partial \sigma_1}{\partial m} - \delta\Gamma_{y_2 L}^2\frac{\partial y_2}{\partial m} \tag{44}$$

$$0 = \frac{\partial b_2}{\partial m} - \Gamma^2 y_2 y_2\frac{\partial y_2}{\partial m} - \Gamma_{y_2 L}^2(1 + (n-1)\varepsilon)\frac{\partial y_1}{\partial m} \tag{45}$$

Emission tax:

$$\frac{\partial \tau_1}{\partial m} = P_1''(Q_1)k_1\frac{\partial Q_1}{\partial m} + [P_1'(Q_1) + mD_1''(mk_1)]\frac{\partial k_1}{\partial m} + D_1''(mk_1)k_1 \tag{46}$$

$$\frac{\partial \tau_2}{\partial m} = P_2''(Q_2)k_2\frac{\partial Q_2}{\partial m} + [P_2'(Q_2) + mD_2''(mk_2)]\frac{\partial k_2}{\partial m} + D_2''(mk_2)k_2 \tag{47}$$

Output subsidy for the RES-E equipment firms:

$$\frac{\partial \sigma_1}{\partial m} = -\delta(n-1)\varepsilon\Gamma_{LL}^2(1 + (n-1)\varepsilon)\frac{\partial y_1}{\partial m} - \delta(n-1)\varepsilon\Gamma_{y_2 L}^2\frac{\partial y_2}{\partial m} \tag{48}$$

Total number of RES-E equipment:

$$\frac{\partial X_1}{\partial m} = n\frac{\partial y_1}{\partial m} \tag{49}$$

$$\frac{\partial X_2}{\partial m} = n\frac{\partial y_2}{\partial m} \tag{50}$$

Electricity prices:

$$\frac{\partial p_1}{\partial m} = P_1'(Q_1)\frac{\partial Q_1}{\partial m} \tag{51}$$

$$\frac{\partial p_2}{\partial m} = P_2'(Q_2)\frac{\partial Q_2}{\partial m} \tag{52}$$

RES-E equipment prices:

$$\frac{\partial b_1}{\partial m} = P_1'(Q_1)q_1(X_1)\frac{\partial Q_1}{\partial m} - C^1_{X_1}\frac{\partial X_1}{\partial m} \tag{53}$$

$$\frac{\partial b_2}{\partial m} = P_2'(Q_2)q_2(X_2)\frac{\partial Q_2}{\partial m} - C^2_{X_2}\frac{\partial X_2}{\partial m} \tag{54}$$

Substituting $\frac{\partial q_1(\tilde{x})}{\partial m}$ and $\frac{\partial q_1(\tilde{x})}{\partial m}$ from equations (40) and (41) into (38) and (39) leads to the following expressions for the change in aggregate electricity production:

$$\frac{\partial Q_1}{\partial m} = \frac{1}{1 - P_1'(Q_1)CC_1}\left[m\frac{\partial k_1}{\partial m} + q_1(X_1)\frac{\partial X_1}{\partial m} + k_1\right] \tag{55}$$

$$\frac{\partial Q_2}{\partial m} = \frac{1}{1 - P_2'(Q_2)CC_2}\left[m\frac{\partial k_2}{\partial m} + q_2(X_2)\frac{\partial X_2}{\partial m} + k_2\right], \tag{56}$$

where $CC_1 = \int_0^{X_1} \frac{1}{C^1_{qq}(q_1(\tilde{x}),\tilde{x})}d\tilde{x}$ and $CC_2 = \int_0^{X_2} \frac{1}{C^2_{qq}(q_2(\tilde{x}),\tilde{x})}d\tilde{x}$. We can now write the system of equations in matrix form and solve for the comparative-statics effects. We assume that $\Gamma^2_{Ly_2}$ is sufficiently small, which together with condition 1 implies that the effect of learning on the marginal cost of RES-E equipment producers in the second period is not too large. We can then unambiguously sign the effects as follows, where $Det$ denotes the determinant of the matrix:

$$
\begin{aligned}
Det &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \Big\{ \Big[ (\Gamma_{y_1y_1}^1 + C_X^1 n)\big[(K_1'' + mD_1'')(P_1'CC_1 - 1) + mP_1'\big] \\
&\quad + n(K_1'' + mD_1'')P_1'q_1^2 \Big] \Big[ (\Gamma_{y_2y_2}^2 + C_X^2 n)\big[(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'\big] \\
&\quad + n(K_2'' + mD_2'')P_2'q_2^2 \Big] + \delta(1 + (n-1)\varepsilon)^2 \big[(K_1'' + mD_1'')(P_1'CC_1 - 1) + mP_1'\big] \\
&\quad \Big[ \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2y_2}^2 - (\Gamma_{y_2L}^2)^2)}^{Condition 1} \big[(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'\big] \\
&\quad + \Gamma_{LL}^2 C_X^2 n \big[(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'\big] + \Gamma_{LL}^2 n(K_2'' + mD_2'')P_2'q_2^2 \Big] \Big\} > 0 \\
\frac{\partial k_1}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \Big\{ \Big[ (\Gamma_{y_2y_2}^2 + C_X^2 n)((K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2') \\
&\quad + (K_2'' + mD_2'')nP_2'q_2^2 \Big] \Big[ D_1''k_1[(\Gamma_{y_1y_1}^1 + nC_X^1)(P_1'CC_1 - 1) + nP_1'q_1^2] \\
&\quad + P_1'k_1(\Gamma_{y_1y_1}^1 + C_X^1 n) \Big] + \delta(1 + (n-1)\varepsilon)^2 \overbrace{(\Gamma_{LL}^2(\Gamma_{y_2y_2}^2 + C_X^2 n) - (\Gamma_{y_2L}^2)^2)}^{Condition 1} \\
&\quad \big[(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'\big] \big[(P_1'CC_1 - 1) - P_1'k_1\big] \\
&\quad + \delta(1 + (n-1)\varepsilon)^2 \Gamma_{LL}^2 k_1 (K_2'' + D_2''m)nP_2'q_2^2 \big[D_1''(P_1'CC_1 - 1) + P_1'\big] \\
&\quad + \delta(1 + (n-1)\varepsilon)\Gamma_{y_2L}^2 k_2 K_2'' nP_1'P_2'q_1q_2 \Big\} < 0 \\
\frac{\partial k_2}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \Big\{ \big[(K_1'' + mD_1'')(P_1'CC_1 - 1) + mP_1'\big] \big[P_2' + D_2''(P_2'CC_2 - 1)\big] \\
&\quad \Big[ \Gamma_{y_1y_1}^1 k_2(\Gamma_{y_2y_2}^2 + C_X^2 n) + \delta(1 + (n-1)\varepsilon)^2 \overbrace{(\Gamma_{LL}^2(\Gamma_{y_2y_2}^2 + C_X^2 n) - (\Gamma_{y_2L}^2)^2)}^{Condition 1} \Big] \\
&\quad + (\Gamma_{y_2y_2}^2 + C_X^2 n)nk_2[P_2' + D_2''(P_2'CC_2 - 1)] \\
&\quad \Big[ C_X^1(K_1'' + D_1''m)((P_1'CC_1 - 1) + P_1'q_1^2) + C_X^1 mP_1' \Big] \\
&\quad + D_2''k_2nP_2'q_2^2 \Big[ \Gamma_{y_1y_1}^1[(K_1'' + D_1''m)(P_1'CC_1 - 1) + mP_1'] \\
&\quad + n[C_X^1(K_1'' + D_1''m)((P_1'CC_1 - 1) + P_1'q_1^2) + C_X^1 mP_1'] \\
&\quad + \delta(1 + (n-1)\varepsilon)^2 \Gamma_{LL}^2 \big[(K_1'' + mD_1'')(P_1'CC_1 - 1) + mP_1'\big] \Big] \\
&\quad + (1 + (n-1)\varepsilon)\Gamma_{y_2L}^2 k_1 K_1'' nP_1'P_2'q_1q_2 \Big\} < 0 \\
\frac{\partial q_1(\tilde{x})}{\partial m} &= -\frac{1}{Det} C_{qq}^2 P_1' \Big\{ \big[k_1 K_1''(\Gamma_{y_1y_1}^1 + C_X^1 n)\big] \\
&\quad \Big[ (\Gamma_{y_2y_2}^2 + C_X^2 n)[(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'] + (K_2'' + D_2''m)nP_2'q_2^2 \Big] \\
&\quad + \delta(1 + (n-1)\varepsilon) \Big[ (1 + (n-1)\varepsilon)k_1 K_1'' \overbrace{(\Gamma_{LL}^2(\Gamma_{y_2y_2}^2 + C_X^2 n) - (\Gamma_{y_2L}^2)^2)}^{Condition 1} \\
&\quad [(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'] + \Gamma_{LL}^2 k_1 K_1''(1 + (n-1)\varepsilon)(K_2'' + D_2''m)nP_2'q_2^2 \\
&\quad + \Gamma_{y_2L}^2 k_2 K_2''(K_1'' + D_1''m)nP_2'q_1q_2 \Big] \Big\} < 0
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial q_2(\tilde{x})}{\partial m} &= -\frac{1}{Det}C^1_{qq}P'_2\Big\{\big[(K''_1+mD''_1)(P'_1CC_1-1)+mP'_1\big]\\
&\Big[\Gamma^1_{y_1y_1}k_2K''_2(\Gamma^2_{y_2y_2}+C^2_Xn)+\delta(1+(n-1)\varepsilon)^2k_2K''_2\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}\Big]\\
&+k_2K''_2n(\Gamma^2_{y_2y_2}+C^2_Xn)\big[C^1_X[(K''_1+D''_1m)(CC_1-P'_1)+mP'_1]\big]\\
&+\Gamma^2_{y_2L}K''_1k_1(1+(n-1)\varepsilon)(K''_2+D''_2m)P'_1q_1q_2n\Big\}<0\\
\frac{\partial Q_1}{\partial m} &= -\frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{k_1K''_1(\Gamma^1_{y_1y_1}+C^1_Xn)\\
&\Big[(\Gamma^2_{y_2y_2}+C^2_Xn)\big[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2\big]+(K''_2+mD''_2)nP'_2q^2_2\Big]\\
&+\delta(1+(n-1)\varepsilon)\Big[k_1K''_1(1+(n-1)\varepsilon)\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}\\
&\big[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2\big]+(1+(n-1)\varepsilon)\Gamma^2_{LL}k_1K''_1(K''_2+D''_2m)nP'_2q^2_2\\
&+\Gamma^2_{y_2L}k_2K''_2(K''_1+D''_1m)nP'_2q_1q_2\Big]\Big\}>0\\
\frac{\partial Q_2}{\partial m} &= -\frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{k_2K''_2\big[(K''_1+mD''_1)(P'_1CC_1-1)+mP'_1\big]\\
&\Big[\Gamma^1_{y_1y_1}(\Gamma^2_{y_2y_2}+C^2_Xn)+\delta(1+(n-1)\varepsilon)^2\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}\Big]\\
&+k_2K''_2n(\Gamma^2_{y_2y_2}+C^2_Xn)\Big[(K''_1+D''_1m)[C^1_X(P'_1CC_1-1)+P'_1q^2_1+C^1_XP'_1m]\Big]\\
&+(1+(n-1)\varepsilon)\Gamma^2_{y_2L}k_1K''_1(K''_2+D''_2m)nP'_1q_1q_2\Big\}>0\\
\frac{\partial y_1}{\partial m} &= -C^1_{qq}C^2_{qq}\Big\{k_1K''_1P'_1q_1(\Gamma^2_{y_2y_2}+C^2_Xn)\big[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2\big]\\
&-\delta\Gamma^2_{y_2L}k_2K''_2(1+(n-1)\varepsilon)P'_2q_2\big[(K''_1+mD''_1)(P'_1CC_1-1)+mP'_1\big]\\
&+k_1K''_1(K''_2+D''_2m)nP'_1P'_2q_1q^2_2\Big\}<0\\
\frac{\partial y_2}{\partial m} &= \frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{\Gamma^2_{y_2L}k_1K''_1(1+(n-1)\varepsilon)P'_1q_1\big[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2\big]\\
&-k_2K''_2P'_2q_2\Big[\big[\Gamma^1_{y_1y_1}+\delta(1+(n-1)\varepsilon)^2\Gamma^2_{LL}+C^1_Xn\big]\\
&\big[(K''_1+mD''_1)(P'_1CC_1-1)+mP'_1\big]+(K''_1+D''_1m)nP'_1q^2_1\Big]\Big\}<0\\
\frac{\partial b_1}{\partial m} &= -\frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2]\\
&\Big[\Gamma^1_{y_1y_1}k_1K''_1P'_1q_1(\Gamma^2_{y_2y_2}+C^2_Xn)+\delta(1+(n-1)\varepsilon)^2k_1K''_1P'_1q_1\\
&\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}\Big]+(K''_2+D''_2m)nP'_1P'_2q_1q^2_2k_1K''_1\\
&[\Gamma^1_{y_1y_1}+(1+(n-1)\varepsilon)\Gamma^2_{LL}]+\delta(1+(n-1)\varepsilon)k_2K''_2nP'_2q_2\Gamma^2_{y_2L}\\
&\big[(K''_1+D''_1m)(C^1_X(P'_1CC_1-1)+P'_1q^2_1)+C^1_XP'_1m\big]\Big\}<0
\end{aligned}
$$

$$\frac{\partial b_2}{\partial m} = -\frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{\big[K''_1(P'_1CC_1-1)+m(P'_1+D''_1(P'_1CC_1-1))\big]P'_2q_2k_2K''_2$$

$$\big[\Gamma^1_{y_1y_1}\Gamma^2_{y_2y_2}+nC^1_X\Gamma^2_{y_2y_2}+\delta(1+(n-1)\varepsilon)^2\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}\big]$$

$$+P'_1P'_2q^2_1q_2n\Gamma^2_{y_2y_2}k_2K''_2(K''_1+D''_1m)+(1+(n-1)\varepsilon)\Gamma^2_{y_2L}k_1K''_1nP'_1q_1$$

$$\Big[(K''_2+D''_2m)q_2+C^2_X[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2]\Big]\Big\}<0$$

$$\frac{\partial \tau_1}{\partial m} = \frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{\Big[-((P'_1)^2+k_1K''_1P''_1)(\Gamma^1_{y_1y_1}+C^1_Xn)k_1+D''_1k_1(K''_1-P'_1)$$

$$\big[\Gamma^1_{y_1y_1}(P'_1CC_1-1)+n(C^1_X(P'_1CC_1-1)+P'_1q^2_1)\big]\Big]$$

$$\Big[(\Gamma^2_{y_2y_2}+C^2_Xn)\big[(K''_2+mD''_2)(P'_2CC_2-1)+mP'_2\big]+(K''_2+mD''_2)nP'_2q^2_2\Big]$$

$$+\delta(1+(n-1)\varepsilon)^2k_1\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}$$

$$[K''_2(P'_2CC_2-1)+m(P'_2+D''_2(P'_2CC_2-1))]$$

$$[-((P'_1)^2+k_1K''_1P''_1)+(K''_1-P'_1)(P'_1CC_1-1)]$$

$$+\Gamma^2_{y_2L}k_2K''_2nP'_2q_1q_2[-((P'_1)^2+k_1K''_1P''_1)+\delta(1+(n-1)\varepsilon)m(P'_1+P''_1k_1)]$$

$$+\Gamma^2_{LL}k_1(1+(n-1)\varepsilon)(K''_2+D''_2m)nP'_2q^2_2$$

$$[-((P'_1)^2+k_1K''_1P''_1)+\delta(1+(n-1)\varepsilon)(K''_1-P'_1)(P'_1CC_1-1)]\Big\}>0$$

$$\frac{\partial \tau_2}{\partial m} = \frac{1}{Det}C^1_{qq}C^2_{qq}\Big\{[(K''_1+mD''_1)(P'_1CC_1-1)+mP'_1]$$

$$\Big[-((P'_2)^2+k_2K''_2P''_2)[\Gamma^1_{y_1y_1}k_2(\Gamma^2_{y_2y_2}+C^2_Xn)+\delta(1+(n-1)\varepsilon)^2k_2$$

$$\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}]+D''_2k_2(K''_2-P'_2)$$

$$[[(\Gamma^2_{y_2y_2}+C^2_Xn)(P'_2CC_2-1)+nP'_2q^2_2](\Gamma^1_{y_1y_1}+C^1_Xn)$$

$$+\delta(1+(n-1)\varepsilon)^2[\overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_Xn)-(\Gamma^2_{y_2L})^2)}^{Condition1}(P'_2CC_2-1)+\Gamma^2_{LL}nP'_2q^2_2]]\Big]$$

$$+(K''_1+D''_1m)k_2n(\Gamma^2_{y_2y_2}+C^2_Xn)\Big[-((P'_2)^2+k_2K''_2P''_2)$$

$$[((P'_1CC_1-1)+mP'_1)C^1_X+P'_1q^2_1]+D''_2P'_1q^2_1(K''_2-P'_2)(P'_2CC_2-1)\Big]$$

$$+D''_2n^2P'_1P'_2q^1_1q^2_2k_2(K''_1+D''_1m)(K''_2-P'_2)+\Gamma^2_{y_2L}(1+(n-1)\varepsilon)k_1K''_1nP'_1q_1q_2$$

$$[-((P'_2)^2+k_2K''_2P''_2)+D''_2m(P'_2+P''_2k_2)]\Big\}>0$$

The sign of the comparative-statics effects on the subsidy in the RES-E equipment industry is ambiguous, and appendix A.2 further explores this ambiguity by providing a numerical example where both cases (positive and negative sign of the variation of the subsidy rate) can occur.

$$\frac{\partial \sigma_1}{\partial m} = \frac{1}{Det} C^1_{qq} C^2_{qq} \delta\varepsilon(n-1)\Big\{k_1 K_1''(1+(n-1)\varepsilon) \overbrace{(\Gamma^2_{LL}(\Gamma^2_{y_2y_2}+C^2_X n)-(\Gamma^2_{y_2L})^2)}^{Condition1} P_1' q_1 \big[(K_2''+mD_2'')(P_2'CC_2-1)+mP_2'\big] + \Gamma^2_{LL} k_1 K_1''(1+(n-1)\varepsilon)(K_2''+D_2''m) n P_1' P_2' q_1 q_2^2 + \Gamma^2_{y_2L} k_2 K_2'' P_2' \Big[(\Gamma^1_{y_1y_1}+C^1_X n)\big[(K_1''+mD_1'')(P_1'CC_1-1)+mP_1'\big] + (K_1''+D_1''m) n P_1' q_1^2\Big]\Big\} \lessgtr 0$$

## A.2 The ambiguity of the comparative-statics effect $\partial\sigma_1/\partial m$

In order to assess the ambiguous sign of $\partial\sigma_1/\partial m$, we numerically simulate the system of equations given by (2)–(4), and (13)–(19) over the number of firms in the fossil-fuel industry for different values of $b$. The parameter $b$ determines the extent to which a RES-E equipment firm can reduce its costs and marginal costs in the second period through learning in the first period. The results are illustrated in Figure 8. For a low value of $b = 0.1$, the optimal subsidy for RES-E equipment producers decreases with an increasing number of fossil-fuel firms, whereas it increases for a relatively high value of $b = 0.8$.

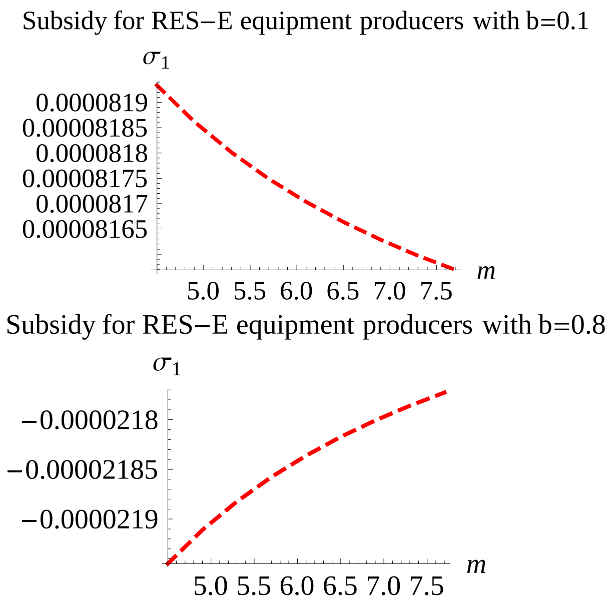


Figure 8: The ambiguous effect of market structure in the fossil-fuel industry on the optimal learning subsidy rate.

### A.3 Derivation of the strategic effect $\partial\tilde{y_2}/\partial y_1$

In order to analyze the effect of an output increase by one firm on any of the $n-1$ other firms (for example, two firms $A$ and $B$) we first set up the FOCs of both firms in the second period:

$$B_2(X_2) + B_2'(X_2)y_2 + \sigma_2 - \Gamma^2_{y_2}(y_2, L) \;\; = \;\; 0, \tag{57}$$

$$B_2(X_2) + B_2'(X_2)\tilde{y_2} + \sigma_2 - \Gamma^2_{\tilde{y_2}}(\tilde{y_2}, \tilde{L}) \;\; = \;\; 0, \tag{58}$$

where $y_2$ and $L = y_1 + (n-1)\varepsilon\tilde{y_2}$ denote output and learning of firm $A$, and $\tilde{y_2}$ and $\tilde{L} = \tilde{y_1} + (n-2)\varepsilon\tilde{y_1} + \varepsilon y_1$ output and learning of firm $B$, respectively. The total number of RES-E equipment devices in the second period is given by $X_2 = y_2 + (n-1)\tilde{y_2}$. Differentiating (57) and (58) with respect to $y_1$ yields the following system of equations:

$$[2B_2'(X_2) + B_2''(X_2)y_2 - \Gamma^2_{y_2y_2}(y_2, L)]\frac{\partial y_2}{\partial y_1} \tag{59}$$

$$+[B_2'(X_2) + B_2''(X_2)y_2](n-1)\frac{\partial\tilde{y_2}}{\partial y_1} - \Gamma^2_{y_2L}(y_2, L) = 0,$$

$$[B_2'(X_2) + B_2''(X_2)\tilde{y_2}]\frac{\partial y_2}{\partial y_1} \tag{60}$$

$$+[nB_2'(X_2) + (n-1)B_2''(X_2)\tilde{y_2} - \Gamma^2_{\tilde{y_2}\tilde{y_2}}(\tilde{y_2}, \tilde{L})]\frac{\partial\tilde{y_2}}{\partial y_1} - \varepsilon\Gamma^2_{\tilde{y_2}\tilde{L}}(\tilde{y_2}, \tilde{L}) = 0.$$

Solving (60) and (61) for $\partial\tilde{y_2}/\partial y_1$ and $\partial y_2/\partial y_1$ we obtain the comparative-statics effect of increasing output by firm $A$ in period 1 on output of firm $B$ in period 2:

$$\frac{\partial\tilde{y_2}}{\partial y_1} = \frac{\Gamma^2_{y_2L}(B_2' + B_2''\tilde{y_2}) + \varepsilon[\Gamma^2_{\tilde{y_2}\tilde{L}}\Gamma^2_{y_2y_2} - \Gamma^2_{\tilde{y_2}\tilde{L}}(2B_2' + B_2''y_2)]}{D}, \tag{61}$$

where

$$D \;\; = \;\; -\Gamma^2_{\tilde{y_2}\tilde{y_2}}\Gamma^2_{y_2y_2} - (n+1)(B_2')^2 + \Gamma^2_{\tilde{y_2}\tilde{y_2}}(2B_2' + B_2''y_2)$$

$$+\Gamma^2_{y_2y_2}(nB_2' + (n-1)B_2''\tilde{y_2}) - (y_2 + (n-1)\tilde{y_2})B_2'B_2''.$$

## A.4 Derivation of the second-best-optimal feed-in tariffs

The second-best feed-in tariffs are obtained by differentiating welfare given by equation (5) with respect to the feed-in tariff rates $\zeta_1$ and $\zeta_2$, yields the following expression:

$$\begin{aligned}\frac{\partial W}{\partial \zeta_1} = \; & [P_1(Q_1) - K_1'(k_1) - D_1'(mk_1)]m\frac{\partial k_1}{\partial \zeta_1} \\ & + [P_1(Q_1) - C_q^1(q_1(X_1), X_1) - \Gamma_{y_1}^1(y_1) - \delta(1+(n-1)\varepsilon)\Gamma_L^2(y_2, L)]\frac{\partial X_1}{\partial \zeta_1} \\ & + \int_0^{X_1} [P_1(Q_1) - C_q^1(q_1(\tilde{x}), \tilde{x})]\frac{\partial q_1(\tilde{x})}{\partial \zeta_1}d\tilde{x} \\ & + \delta[P_2(Q_2) - K_2'(k_2) - D_2'(mk_2)]m\frac{\partial k_2}{\partial \zeta_1} \\ & + \delta[P_2(Q_2) - C_q^2(q_2(X_2), X_2) - \Gamma_{y_2}^2(y_2, L)]\frac{\partial X_2}{\partial \zeta_1} \\ & + \delta\int_0^{X_2} [P_2(Q_2) - C_q^2(q_2(\tilde{x}), \tilde{x})]\frac{\partial q_2(\tilde{x})}{\partial \zeta_1}d\tilde{x} = 0.\end{aligned} \tag{62}$$

Expanding equation (62) with $\zeta_t q_t \frac{\partial X_t}{\partial \zeta_t} - \zeta_t q_t \frac{\partial X_t}{\partial \zeta_t} + nb_t \frac{\partial y_t}{\partial \zeta_t} - nb_t \frac{\partial y_t}{\partial \zeta_t}$ for $t = 1, 2$ and using the behavioral conditions of the firms allows us to simplify (62) as follows:

$$\begin{aligned}0 = \; & [-P_1'(Q_1) + \tau_1 - D_1'(mk_1)]m\frac{\partial k_1}{\partial \zeta_1} \\ & + [P_1(Q_1) - \zeta_1][q_1(X_1)\frac{\partial X_1}{\partial \zeta_1} + \int_0^{X_1} \frac{\partial q_1(\tilde{x})}{\partial \zeta_1}d\tilde{x}] \\ & - \delta\Gamma_L^2(y_2, L)(n-1)\varepsilon n\frac{\partial y_1}{\partial \zeta_1} + \delta[-P_2'(Q_2) + \tau_2 - D_2'(mk_2)]m\frac{\partial k_2}{\partial \zeta_1} \\ & + \delta[P_2(Q_2) - \zeta_2]q_2(X_2)\frac{\partial X_2}{\partial \zeta_1}.\end{aligned} \tag{63}$$

Analogously, differentiating welfare with respect to $\zeta_2$ and simplifying yields:

$$\begin{aligned}0 = \; & [-P_1'(Q_1) + \tau_1 - D_1'(mk_1)]m\frac{\partial k_1}{\partial \zeta_2} + [P_1(Q_1) - \zeta_1]q_1(X_1)\frac{\partial X_1}{\partial \zeta_2} \\ & - \delta\Gamma_L^2(y_2, L)(n-1)\varepsilon n\frac{\partial y_1}{\partial \zeta_2} \\ & + \delta[-P_2'(Q_2) + \tau_2 - D_2'(mk_2)]m\frac{\partial k_2}{\partial \zeta_2} \\ & + \delta[P_2(Q_2) - \zeta_2][q_2(X_2)\frac{\partial X_2}{\partial \zeta_2} + \int_0^{X_2} \frac{\partial q_2(\tilde{x})}{\partial \zeta_2}d\tilde{x}].\end{aligned} \tag{64}$$

Solving the latter two expressions for $\zeta_1$ and $\zeta_2$ yields the second-best-optimal feed-in tariffs given in section 5.1.

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