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Keywords: Second-best, Climate Policy, Energy Policy, Feed-in tariff, Power Sector, EU

JEL Classification: C61, O33, Q48, Q54, Q55

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October 26, 2015

Abstract

This paper studies policy instruments that correct insufficient learning-by-doing (LbD) and research and development (R&D) of renewable electricity technologies and insufficient investments in energy efficiency (EE) in the presence of carbon pricing. The theoretical model analysis shows how to re-adjust the first-best in second-best situations, in which one of the policy instruments is restricted. Calibrated to the European power sector, the first-best choice of all instruments reduces the climate policy cost by one third. Feed-in tariffs turn out to be good substitutes for LbD, but not for R&D or EE subsidies.

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Highlights

- Interacting policy instruments addressing climate change, unanticipated benefits from R&D and learning as well as insufficient energy efficiency investments.
- Policy advice for adjusting available instruments in a second-best world when specific instruments are unavailable.
- Theoretical model analysis of the power sector and model calibration to European data and policy scenarios.
- Feed-in tariffs as good substitutes for output subsidies but faint substitutes for R&D and energy efficiency subsidies.

1 Introduction

Economists tend to give advice under the implicit assumption of the full availability of first-best instruments and institutions. This is of limited use for policy makers since institutions are often imperfect, and specific policy instruments are often unavailable due to political constraints, incomplete information or prohibitive transaction and compliance costs (Rodrik, 2008). This is of particular importance in the domain of climate and energy policy, where multiple market failures need to be corrected with interacting instruments. Typical market failures are (i) the overuse of fossil fuels, (ii) knowledge spillovers of learning-by-doing of low-carbon technologies, (iii) knowledge spillovers of research and development (R&D), and (iv) imperfect perception of consumers' benefits of energy efficiency improvements. Such an environment justifies the implementation of four climate and energy policy instruments, one instrument for each market failure (Bennear and Stavins, 2007; Tinbergen, 1952).

Our work focuses on the interaction of these market failures and policy instruments in a partial equilibrium model of the power sector. It studies how the remaining policy instruments can be re-adjusted in order to improve welfare, when at least one of the first-best optimal instruments is unavailable or restricted. As we will see, it is ex ante not obvious whether, in which direction and how far the remaining policy instruments should be re-adjusted. Our analysis sheds light on these interactions and re-adjustments, which provides guidance for policy makers. So far the literature has not addressed this issue in this practical energy policy-related form.

In practice, feed-in tariffs, which promote electricity generating renewable energy sources, are a cornerstone of many climate and energy policy portfolios, especially in Europe. Therefore, our work also studies how far feed-in tariffs can replace policy instruments that address the above-mentioned market failures. Our results show that feed-in tariffs are good substitutes for output subsidies that address learning-by-doing, whereas they are blunt substitutes for subsidies that address R&D or energy efficiency.

As we know from general second-best theory, the attainment of Pareto optimal conditions is no longer necessarily welfare improving if there are political constraints that prevent the attainment of at least one of the conditions of Pareto optimality (Lipsey and Lancaster, 1956). Thus, if there are multiple market failures, or in general, economic distortions, that are not remedied by economic policy, then the remedy of one market failure does not necessarily result in a welfare improvement. It might reduce the welfare losses created by the other market failures, exacerbate them, or not affect them (Lipsey and Lancaster, 1956).

More specifically, the literature has shown that pre-existing distortions (caused by taxes on capital or labor) create a second-best world, in which Pigouvian taxes are no longer the first-best response to address market failures. Parry *et al.* (1999) and Goulder *et al.* (1999) demonstrate that pre-existing taxes raise the general equilibrium costs of market-based environmental policies. Cremer and Gahvari (2001) show how Pigouvian taxes can be re-adjusted in an economically beneficial way by taking into account the incentives and revenues created by pre-existing taxes.

The research focus of this paper is of particular importance for the European Union (EU), because the pathway to an energy-efficient, low-carbon economy builds on a portfolio of multiple climate and energy policy instruments that are implemented at different governmental levels. The central instrument for reducing carbon emissions by 20% until 2020 is the EU emissions trading system (ETS), which covers around 45% of the EU's greenhouse gas emissions. Around 70% of the emissions in the EU ETS stem from the stationary power sector. Therefore, our analysis focuses on the power sector. Additional targets are set for generating 20% of the energy consumed in the EU by 2020 with renewable energy sources and for improving the efficiency of energy demand by 20% within the same time frame. Currently, the proposed framework for 2030 expands these targets to a 40% reduction in emissions, a 27% renewable energy share, and a 30% improvement in energy efficiency.

As there is no common, transnational instrument to reach the 20% renewable energy target in the EU, member states make use of country-specific regulation and policy instruments. Most member states have implemented a kind of feed-in tariff, i.e., renewable energy-based electricity generators receive a feed-in support payment in addition to their revenues from selling electricity in the spot market (feed-in premiums) or receive a cost-based fixed price when supplying to the grid (feed-in tariff). Part of the attractiveness of feed-in tariffs may be their revenue neutrality rather than their effectiveness.

However, the support of renewable energies and the EU ETS are interdependent. On the one hand, the pricing of carbon emissions increases the competitiveness of renewable energy technologies, enhances their diffusion and fosters learning-by-doing and R&D, which reduces electricity generation costs. On the other hand, the crowding-out of fossil-fuel technologies by renewable energy technologies results in lower carbon emissions. In the language of Lipsey and Lancaster (1956), the two instruments are jointly ameliorating. However, the two instruments can differ regarding their costs and effectiveness, and they can overlap in a detrimental way. In this sense, they are jointly deteriorating.

Against this background, the literature has critically examined the European climate and energy policy portfolio. Focusing on the interaction of the EU ETS with renewable energy support Böhringer and Rosendahl (2010), Böhringer *et al.* (2008), Böhringer *et al.* (2009), Fankhauser *et al.* (2010), Boeters and Koornneef (2011) and Requate (2015) show that overlapping policy instruments can have significant adverse effects on the efficiency and effectiveness of such policy portfolios. Böhringer and Rosendahl (2010) demonstrate that the additional diffusion of renewable energy technologies due to renewable energy support lowers the price for emissions in the ETS and thus promotes fossil fuel-based technologies. Such distortions can cause significant costs: Boeters and Koornneef (2011) show that the renewable energy target of the European Union creates excess costs of up to 33% relative to the case with an ETS as the only instrument, depending on the availability of low cost technologies and the stringency of the renewable energy target. We extend on this literature by focusing on policy instruments that address technical progress and by deriving second-best policies.

From a distributional point of view, a combination of policy instruments can have advantages, since it can balance the cost burden of climate and energy policy among different groups of producers and consumers (Kalkuhl *et al.*, 2013; Hirth and Ueckerdt, 2013). When a knowledge spillover externality exists, a combination of policy instruments is justified as well. Taking into account knowledge spillovers, Kalkuhl *et al.* (2012) find that quotas for renewable energy technologies and feed-in tariffs are almost as cost-efficient as first-best R&D subsidies. Although renewable energy policies might be good substitutes for R&D subsidies, they are identified as poor substitutes for carbon pricing (Kalkuhl *et al.*, 2013). We extend this argument by distinguishing between technical progress via learning, R&D and investments in energy efficiency.

In order to study the first- and second-best choice of policy instruments in the power sector, we build on the model by Fischer and Newell (2008) (hereafter FN) extended by Fischer *et al.* (2013) (hereafter FNP). FN and FNP calibrate their model to the power sector of the United States of America (USA) and compare the welfare effects of policy instruments that are relevant for the USA. The following paper provides new insights and novel results by analyzing the second-best re-adjustments of policy instruments, by introducing feed-in tariffs and by calibrating the model to EU data.

The paper proceeds as follows. In Section 2 the model is set up and solved analytically. Based on this model, second-best policy portfolios are theoretically discussed in Section 3. Section 4 presents the numerical implementation of the model and its calibration to the EU power sector. It compares the qualitative insights of the previous section to quantitative results for the EU and discusses them critically. Section 5 concludes by formulating policy implications.

2 Model setup and solution

This section describes and solves a two-period partial equilibrium model of the electricity market that will be used for our policy analysis. The model closely follows FN and FNP. The model setup is, however, rewritten in a more general manner. For a more detailed and more specific description, the reader may refer to the original sources. The model focuses on those features that are necessary for the inspection of multiple interacting market failures and corresponding policy instruments in a first- and second-best world. Compared to FN, the model extension by FNP includes investments in energy efficiency by consumers, which we also feature in our new model version. First, a non-technical overview of the model features is given, followed by a mathematical description of the key equations of the model. Second, the model is solved by deriving optimality conditions.

2.1 Non-technical overview

Electricity can be generated with renewable and fossil fuel-based technologies. Both are subject to convex increasing production costs. Our analysis focuses on immature renewable energy technologies that are subject to cost reductions from R&D efforts and learning-by-doing. Today's R&D creates knowledge that helps to reduce future production costs. Today's accumulation of experience, represented by the total volume of electricity generation, reduces future production costs as well. The utilization of a technology is governed by a price-taking representative producer that maximizes profits, i.e., revenues from electricity generation minus production costs, R&D expenditures, and costs of regulation.

Electricity is demanded by a representative consumer who draws utility from its consumption. Besides spending her income on electricity, she can invest in three types of energy efficiency measures that take effect either in the short-term (within the first period), in the long-term (within the second period), or both (across both periods). Examples are the replacement of old refrigerators by modern ones or the improvement of house insulation in combination with modern electrical heating. The energy efficiency measures reduce the required electricity expenditures for a given level of utility drawn from consumption. The representative consumer maximizes utility, i.e., the value of consumed electricity services minus the costs of electricity required to generate these services minus expenditures on energy efficiency improvements. We discount the future in order to obtain the net present value of electricity services and costs.

Our model considers four market failures. Each can be corrected with a specific corresponding instrument. First, without regulation, carbon emissions are above their socially optimal level. However, climate change impacts are not modeled. We assume that an emissions trading system (ETS) with an emissions target, given by an exogenous policy decision, is imposed in order to reduce CO_2 emissions from electricity generation. As such, even if the resulting permit price is below the social cost of carbon, overlapping policies will not affect overall emissions. This makes welfare comparable across policy scenarios, while ignoring future climate change impacts. This implies that we carry out a cost-effectiveness analysis with respect to a given emissions target. As a consequence, we rule out the re-adjustment of support for renewable energies or energy efficiency improvements as a reaction to an emissions target that may be suboptimal from a social point of view.

Second, electricity producers using immature renewable energy technologies do not perceive and internalize the full benefit of productivity gains through learning-by-doing. Although we do not explicitly model technology spillovers across producers (following FN's model), we suppose that a knowledge externality exists that renewable energy producers ignore. Consequently, without policy intervention renewable energy production is lower than socially optimal. Thus, an output subsidy can be granted to correct for this market failure.

Third, in the same way, electricity producers using immature renewable energy technologies perceive and internalize only a fraction of the benefits from their R&D efforts due to knowledge spillovers. Since producers do not take the full social benefit of their R&D investments into account, R&D investments are below the socially optimal level. Thus, an R&D subsidy for renewable energy producers can be granted in order to raise R&D investments and their social benefits.

Fourth, the consumer perceives only a fraction of the benefits of her investments in energy efficiency. As a consequence, she underinvests in energy efficiency measures in the short- and long-term, and electricity demand is above its socially optimal level. To address this market failure, specific subsidies can be granted to encourage investments in three different types of energy efficiency measures (short-, long-term and both).

2.2 Mathematical representation

This subsection depicts and explains the key model equations.

2.2.1 Electricity generation

Each *representative electricity producer* using technology i maximizes profits according to the following expression:

$$\max_{\{q^{i1},q^{i2},h^{i1}\}} \Pi^i,$$
$$\Pi^i = n^1[(p^1+\phi^{i1})q^{i1} - C^{i1}(q^{i1}) - \tau^1\mu^i q^{i1} - (1-\sigma^{i1})R^{i1}(h^{i1})] \qquad (1)$$
$$+\delta n^2[(p^2+\phi^{i2})q^{i2} - C^{i2}(q^{i2} \mid \rho n^1 q^{i1}, \rho n^1 h^{i1}) - \tau^2\mu^i q^{i2}]$$

The indices 1 and 2 indicate the first and second model period $t = \{1;2\}$. n is the number of years subsumed in each period. Second-period values are discounted by the factor $0 < \delta < 1$. p^t signifies the equilibrium electricity price in period t. ϕ^{it} denotes a technology-specific net subsidy that the regulator may distribute per unit of production. Accordingly, a negative value of ϕ^{it} denotes a net tax. q^{it} is the quantity of electricity produced with technology i in period t. q^{i1} and q^{i2} are producers' two basic control variables.

Carbon emissions intensity μ^i is technology-specific, but time-invariant. Renewable energy technologies and nuclear power are assumed to have a carbon intensity of zero, whereas fossil fuel technologies have positive carbon intensities. Total emissions stemming from a fossil fuel technology i in period t are expressed as $n^t\mu^i q^{it}$. τ^t is the period-dependent price for one unit of carbon emissions. When restricting emissions by a binding cumulative emissions cap ξ, the carbon price will emerge endogenously so that $\xi \geq \sum^t \sum^i (n^t\mu^i q^{it} + \epsilon^t)$ holds. ϵ^t denotes non-electricity emissions that are not explicitly modeled but captured by climate policy.[1]

We pay special attention to the representation of production costs. C^{it} is the corresponding technology- and period-specific cost function with the properties $C^{it}_{q^{it}} > 0$ and $C^{it}_{q^{it}q^{it}} > 0$. Throughout the paper, a lower index denotes a derivative with respect to this variable. This implies that production costs are convex in output. We assume, however, that it is possible for immature renewable energy technologies to decrease their production costs through learning-by-doing and R&D investments. Let us therefore focus on immature renewable and carbon-free energy technologies $i \in r$. r denotes a subset of all technologies. The technologies subsumed in r are subject to cost-reducing technical progress, such as wind or solar power. Other carbon-free technologies, like nuclear power and hydro power as well as fossil fuel technologies, are treated as mature technologies without further cost reduction potential.

[1] We keep ϵ^t constant at $\epsilon^t = \bar{\epsilon}^t$ in the theoretical analysis, whereas we will model it explicitly in the numerical analysis.

The first mechanism to reduce production costs of immature renewable energy technologies r is the accumulation of knowledge via R&D. First-period technology-specific R&D adds new knowledge h^{i1} to the knowledge stock H^{i0} existing in period 1. Hence, h^{i1} is the third control variable for producers using immature renewable energy technologies. The resulting equation of motion reads $H^{i2} = H^{i0} + n^1 h^{i1}$. The fruits of R&D become effective in the second period. This means first-period knowledge h^{i1} eventually results in lower second-period production costs $C^{i2}\ \forall\ i \in r$, but has no impact on $C^{i2}\ \forall\ i \notin r$. R&D expenditures $R^{i1}(h^{i1})$ are convex in the creation of new knowledge:

$$R^{i1}(h^{i1}),\ R^{i1}_{h^{i1}} > 0,\ R^{i1}_{h^{i1}h^{i1}} > 0 \tag{2}$$

Notably, only the fraction ρ of knowledge h^{i1} generates private benefits from R&D for a specific producer in period 2. Hence, $\rho = 1$ characterizes the case of full private benefits from R&D, whereas $\rho = 0$ reflects the extreme case of no private benefits. A lower ρ results in lower private R&D investment and consequently in suboptimal knowledge creation from a social point of view. To address underinvestment in R&D, policy makers can introduce a technology-specific subsidy σ^{i1} for R&D expenditures.

The second mechanism that helps to drive down costs of immature renewable energy technologies r is the accumulation of experience via learning-by-doing. First-period technology-specific electricity output q^{i1} adds new experience to the stock of past experience Q^{i0}. The resulting equation of motion reads $Q^{i2} = Q^{i0} + n^1 q^{i1}$. We presume that Q^{i2} reduces $C^{i2}\ \forall\ i \in r$, whereas it does not have an effect on $C^{i2}\ \forall\ i \notin r$. As in the case of R&D, only the fraction ρ represents private benefits from learning. Again, if $\rho < 1$, producers are not able to fully benefit from their efforts and thus extend capacities below the social optimum. In order to correct this market failure, policy makers can incentivize the expansion of quantities with the net subsidy ϕ^{it} per unit of output.

We combine the two mechanisms in a two-factor learning curve. Since H^{i2} and h^{i1} differ only by the constant H^{i0} and the factor n^1, we can replace H^{i2} by h^{i1} with respect to qualitative marginal effects. The same argument applies to Q^{i2} and q^{i1}. Based on these considerations, we assume that the following relations hold for all immature renewable energy technologies $i \in r$ in period 2:

$$\begin{gathered} C^{i2}(q^{i2} \mid n^1 q^{i1}, \rho n^1 h^{i1}), \\ C^{i2}_{q^{i2}} > 0,\ C^{i2}_{q^{i2}q^{i2}} > 0, \\ C^{i2}_{q^{i1}} < 0,\ C^{i2}_{q^{i1}q^{i1}} > 0,\ C^{i2}_{h^{i1}} < 0,\ C^{i2}_{h^{i1}h^{i1}} > 0, \\ C^{i2}_{q^{i2}h^{i1}} = C^{i2}_{h^{i1}q^{i2}} < 0,\ C^{i2}_{q^{i1}q^{i2}} = C^{i2}_{q^{i2}q^{i1}} < 0,\ C^{i2}_{q^{i1}h^{i1}} = C^{i2}_{h^{i1}q^{i1}} > 0 \end{gathered} \tag{3}$$

Since we carry out a partial equilibrium analysis, other costs not captured by the power sector, such as opportunity costs and crowding out of other investments by energy-specific R&D investment, are implicitly subsumed in this cost function. The first line describes that second-period production costs are a function of second-period electricity output as well as first-period electricity output and new knowledge created via R&D. The second line posits that the production costs increase in second-period output in a convex fashion. The third line, on the contrary, posits that higher first-period output reduces second-period production costs, yet with a decreasing marginal effect. It assumes the same effect on production costs for knowledge created in the first period. The fourth line deals with cross-dependencies of variables. Accordingly, higher first-period output reduces the marginal cost of second-period production. Higher first-period knowledge reduces the marginal cost of second-period production as well. The last expression states that experience (learning-by-doing) and knowledge (R&D) act as substitutes: If learning has already reduced production costs, there will be less scope for further cost reductions via R&D. Likewise, when R&D has already driven down production costs, there will be less scope for learning.

2.2.2 Electricity demand

The definition of the consumer side, described by this subsection in compact form, is based on FNP, too. The consumer can invest in two short-term and one long-term type of energy efficiency measures: A higher e^{S1} reduces first-period electricity demand d^1, whereas e^{S2} reduces second-period electricity demand d^2. These are short-term energy efficiency measures indicated by the index S. e^{L1} represents long-term energy efficiency measures symbolized by the upper index $L1$: The investment takes place in the first period, while it increases energy efficiency in both periods. These energy efficiency measures are the three control variables of the consumer, and each measure is subject to convex investment costs:

$$\begin{aligned} &Z^{S1}(e^{S1}),\ Z^{S1}_{e^{S1}} > 0,\ Z^{S1}_{e^{S1}e^{S1}} > 0 \\ &Z^{S2}(e^{S2}),\ Z^{S2}_{e^{S2}} > 0,\ Z^{S2}_{e^{S2}e^{S2}} > 0 \\ &Z^{L1}(e^{L1}),\ Z^{L1}_{e^{L1}} > 0,\ Z^{L1}_{e^{L1}e^{L1}} > 0 \end{aligned} \tag{4}$$

A demand-side market failure is reflected in that, when the consumer makes her energy efficiency investments, she perceives only the fraction β^{S1}, β^{S2} and β^{L1}, respectively, of the full energy savings. $\beta = 1$ characterizes the case of full valuation, whereas $\beta = 0$ reflects the extreme case of no valuation. Since undervaluation of energy efficiency benefits causes a sub-optimal investment, a subsidy λ, which deducts a fraction of the investment costs, can be granted for each type of energy efficiency improvement.

Even though the consumer may undervalue the energy savings of investments, once investments are made, the full savings accrue to the consumer. Thus, the undervaluation parameters will reveal themselves in the first-order conditions for the consumer, but not in the welfare evaluation.

The *representative consumer* maximizes money-metric utility according to the following expression (in this partial equilibrium analysis abstracting from consumption of other goods):

$$\max_{\{v^1,v^2,e^{S1},e^{L1},e^{S2}\}} U,$$
$$U = n^1\left[v^1 - p^1 d^1(v^1,e^{S1},e^{L1}) - (1-\lambda^{S1})Z^{S1}(e^{S1} \mid \beta^{S1}) - (1-\lambda^{L1})Z^{L1}(e^{L1} \mid \beta^{L1})\right]$$
$$-\delta n^2\left[v^2 - p^2 d^2(v^2,e^{S2},e^{L1}) - (1-\lambda^{S2})Z^{S2}(e^{S2} \mid \beta^{S2})\right] \quad (5)$$

v^t denotes the value of electricity services for the consumer. On the one hand, higher consumption of electricity services results in higher electricity demand d^t, valued at the current electricity price p^t. On the other hand, the consumer can reduce electricity demand, required to achieve a certain level of electricity services, via one of the three energy efficiency measures introduced above, here for simplicity denoted by $e^{(S/L)t}$:

$$d^t_{v^t} > 0,\ d^t_{e^{(S/L)t}} < 0,\ d^t_{v^t e^{(S/L)t}} = d^t_{e^{(S/L)t} v^t} < 0 \quad (6)$$

Energy efficiency measures also mitigate the increase in energy demand at the margin as expressed by the cross derivatives. To close the model, it must hold that total electricity supply satisfies electricity demand d^t in each period:

$$\sum^{i} q^{it} \geq d^t \quad (7)$$

The full representation of the model with specific functional forms used for the numerical analysis is spelled out by FNP.

2.3 Solving the model

We solve the model by deriving the first-order conditions of the maximization problems described in Equations (1) and (5). We obtain the following first-order conditions derived from $\frac{\partial \Pi^i}{\partial q^{i1}} = \frac{\partial \Pi^i}{\partial q^{i2}} = \frac{\partial \Pi^i}{\partial h^{i1}} = \frac{\partial U}{\partial v^1} = \frac{\partial U}{\partial v^2} = \frac{\partial U}{\partial e^{S1}} = \frac{\partial U}{\partial e^{S2}} = \frac{\partial U}{\partial e^{L1}} = 0$ that characterize the equilibrium (see FN and FNP):

$$\begin{aligned}
-\rho\delta n^2 C^{i2}_{q^{i1}} + p^1 + \phi^{i1} &= C^{i1}_{q^{i1}} + \mu^i \tau^1 && (8)\\
p^2 + \phi^{i2} &= C^{i2}_{q^{i2}} + \mu^i \tau^2 && (9)\\
-\rho\delta n^2 C^{i2}_{h^{i1}} (1-\sigma)^{-1} &= R_{h^{i1}} && (10)\\
(d^1_{v^1})^{-1} &= p^1 && (11)\\
(d^2_{v^2})^{-1} &= p^2 && (12)\\
-\beta^{S1} n^1 p^1 d^1_{e^{S1}} (1-\lambda^{S1})^{-1} &= Z^{S1}_{e^{S1}} && (13)\\
-\beta^{S2} \delta n^2 p^2 d^2_{e^{S2}} (1-\lambda^{S2})^{-1} &= Z^{S2}_{e^{S2}} && (14)\\
\left(-\beta^{L1} n^1 p^1 d^1_{e^{L1}} - \beta^{L1} \delta n^2 p^2 d^2_{e^{L1}}\right)(1-\lambda^{L1})^{-1} &= Z^{L1}_{e^{L1}} && (15)
\end{aligned}$$

In the equations above, lower indices denote derivatives as usual. The left-hand side of each equation depicts marginal benefits, whereas the right-hand side depicts marginal costs. In equilibrium, marginal benefits and marginal costs are equalized. Note that several derivatives appearing on the left-hand side are negative so that the terms on the left-hand side of all equations are positive. On the demand side (Equations 11 and 12) marginal utility is expressed as the inverse of the derivative of electricity demand with respect to utility. Also note that $C^{i2}_{q^{i1}}$ is positive for immature renewable technologies $i \in r$, but zero for other technologies $i \notin r$. On the contrary, μ^i is zero for all $i \in r$, but non-negative for other technologies $i \notin r$. Equation (10) is only defined for immature renewables $i \in r$, because other technologies are not subject to R&D.

3 Theoretical policy analysis

This section derives the first-best set of policy instruments along the lines of FN and FNP. It then carries out a novel algebraic second-best policy analysis.

3.1 First-best policy portfolio

The first-best policy response to the respective externalities is the full internalization of these externalities. Hence, we assume that the full social benefits of R&D and of learning-by-doing including their spillovers are taken into account by private investors so that $\rho = 1$. Furthermore, we assume that the consumer perceives the full benefit of her investments in energy efficiency so that $\beta^{S1} = \beta^{S2} = \beta^{L1} = 1$. All remaining policy instruments are set to zero, i.e., $\phi^{i1} = \phi^{i2} = \lambda^{S1} = \lambda^{S2} = \lambda^{L1} = 0$. Carbon prices can be given by $\tau^1 = \bar{\tau}^1$ and $\tau^2 = \bar{\tau}^2$ in the benchmark situation. If a cumulative emissions target over both periods is given in policy scenarios, carbon prices will adjust endogenously such that

$\tau^1 = \delta\tau^2$ holds, taking discounting with the factor $0 < \delta < 1$ into account. Accordingly, the optimal carbon price rises over time.

Inserting these parameter choices into (8) to (15) yields the first-best optimal conditions (8)' to (15)'. We can now derive the choice of the policy instruments ϕ^{i1}, ϕ^{i2}, λ^{S1}, λ^{S2} and λ^{L1} such that (8) to (15) are equivalent to (8)' to (15)'. In this way, we obtain the set of first-best policy instrument choices (see FN and FNP):

$$\tau^1 = \bar{\tau}^1 = \delta\tau^2 \tag{16}$$

$$\phi^{i1} = -(1-\rho)\delta n^2 C^{i2}_{q^{i1}}, \ \phi^{i2} = 0 \ \forall \ i \in r \tag{17}$$

$$\sigma = 1-\rho \tag{18}$$

$$\lambda^{S1} = 1-\beta^{S1}, \ \lambda^{S2} = 1-\beta^{S2}, \ \lambda^{L1} = 1-\beta^{L1} \tag{19}$$

The policy instruments in the four equations correct the four market failures. The first equation describes how carbon pricing internalizes the social costs of carbon, or, rather, the costs of meeting the emissions target that is exogenously given by a policy decision. Carbon prices are allowed to float endogenously in the policy scenarios. The second equation describes how an output subsidy for immature renewable technologies internalizes the social benefit of learning-by-doing, which is not taken into account by decentralized renewable energy producers. The second-period output subsidy is zero, because second-period production has no impact on future costs beyond the model horizon. In the third equation, an R&D subsidy internalizes the social benefit of R&D. In the fourth equation, subsidies for energy efficiency investments internalize non-perceived benefits by the three types of energy efficiency improvements. In the absence of other market failures, there is no economic reason to impose further policy instruments, so that $\phi^{i1} = 0 \ \forall \ i \notin r$ and $\phi^{i2} = 0 \ \forall \ i$ is the first-best choice.

3.2 Second-best policy portfolios

If now, either due to political constraints or because transaction and enforcement costs are too high, one or more of the described market failures cannot be remedied with their first-best policy responses, the remaining policy instruments need to be adjusted in order to be welfare maximizing. This means that a change in one of the instruments described by Equations (16) to (19) calls for an adjustment of the remaining instruments. If, for example, the R&D subsidy is not available, the welfare maximizing choice of the renewable energy output subsidy and the energy efficiency subsidies will in general deviate from the first-best choice. Yet there is no general theory that tells us how the second-best solution looks compared to the first-best solution.

3.2.1 Welfare effects

First and foremost, it is helpful to write down the change in economic surplus for any policy intervention as derived in detail by FNP. Total economic surplus is the sum of producer and consumer surplus and hence obtained by combining Equations (1) and (5):

$$\begin{aligned} W = {} & n^1[v^1 - Z^{S1}(e^{S1}) - Z^{L1}(e^{L1}) - \sum_i C^{i1}(q^{i1}) - \sum_{i\in r} R^{i1}(h^{i1})] \\ & + \delta n^2[v^2 - Z^{S2}(e^{S2}) - \sum_i C^{i2}(q^{i2})] \end{aligned} \tag{20}$$

The consumer's electricity bill paid to electricity producers drops out as a pure transfer, since $p^t d^t = p^t \sum^i q^{it}$. By the same token, tax and subsidy payments are pure transfers between consumers and producers and drop out. We aim at an expression for the change in economic surplus due to the change in a policy intervention Ψ, given the choice of other policy interventions. We obtain this expression following FNP by totally differentiating the above expression for the economic surplus, inserting the previously derived first-order conditions and postulating that total electricity demand equals supply.

$$\begin{aligned} \frac{dW}{d\Psi} = {} & n^1 \sum_{i\in r} \left[-C^{i2}_{q^{i1}} \delta n^2 (1-\rho) - \phi^{i1}\right] \frac{dq^{i1}}{d\Psi} \\ & + n^1 \sum_{i\in r} (-C^{i2}_{h^{i1}}) \delta n^2 \frac{1-\rho-\sigma}{1-\sigma} \frac{dh^{i1}}{d\Psi} \\ & + n^1 p^1 d^1 \left(\frac{1-\beta^{S1}-\lambda^{S1}}{1-\lambda^{S1}} \frac{de^{S1}}{d\Psi} + \frac{1-\beta^{L1}-\lambda^{L1}}{1-\lambda^{L1}} \frac{de^{L1}}{d\Psi} \right) \\ & + \delta n^2 p^2 d^2 \left(\frac{1-\beta^{S2}-\lambda^{S2}}{1-\lambda^{S2}} \frac{de^{S2}}{d\Psi} + \frac{1-\beta^{L1}-\lambda^{L1}}{1-\lambda^{L1}} \frac{de^{L1}}{d\Psi} \right) \\ & + n^1 \sum_i \tau^1 \mu^i \frac{dq^{i1}}{d\Psi} + \delta n^2 \sum_i \tau^2 \mu^i \frac{dq^{i2}}{d\Psi} \\ & + n^1 \sum_{i\notin r} (-\phi^{i1}) \frac{dq^{i1}}{d\Psi} + \delta n^2 \sum_i (-\phi^{i2}) \frac{dq^{i2}}{d\Psi} \end{aligned} \tag{21}$$

This expression takes into account that total cumulative emissions are kept constant. Each line in the above equation expresses that an increase in the associated variable will create a positive welfare change as long as the marginal costs of the imposed policy instrument are smaller than the corresponding marginal social benefit—that is, as long as its market failure is under-internalized. (Note that $C^{i2}_{q^{i1}} < 0$ and $C^{i2}_{h^{i1}} < 0$.) The first line refers to the output subsidy for immature renewable technologies, the second line to the R&D subsidy, the third and fourth line to the subsidies for the three types of energy efficiency investments. Inserting the optimal choices of policy instruments according to Equations (17) to (19) results in a zero welfare change. This implies that we measure welfare changes relative to the first-best welfare maximum, which cannot be exceeded. The fifth line refers to carbon pricing. On the one hand, carbon pricing creates a positive welfare effect via tax revenues or revenues from auctioning off allowances. On the other hand, it reduces the output of the producers affected by carbon pricing ($\frac{dq^{it}}{d\Psi} < 0$). As a result, it creates a negative welfare effect. Optimal carbon pricing, however, does not create a welfare effect: According to (16), it is in this case $\tau^1 = \bar{\tau}^1 = \delta\tau^2$ and $n^1 \sum_i \mu^i dq^{i1} = n^2 \sum_i \mu^i dq^{i2}$ so that the fifth line drops out (see FNP). The last line refers to first-period net subsidies for technologies other than mature renewables and second-period net subsidies for any technology. A net tax ($-\phi^{it}$) creates a revenue but reduces output and creates a distortion so that the overall welfare effect is negative. A net subsidy ($+\phi^{it}$) augments output but requires a payment to producers. This means as long as all policy instruments discussed above are set to their optimal values, any additional policy intervention will be distortionary and result in a welfare loss. Hence, the first-best choice is $\phi^{i1} = 0 \ \forall\ i \notin r$ and $\phi^{i2} = 0 \ \forall\ i$.

3.2.2 Re-adjustment of policy instruments

In the following, our research goes beyond FN and FNP by addressing this research question: Suppose one of the first-best instruments is unavailable; how does this affect the welfare maximizing second-best adjustment of other policy instruments? The choice of the policy instruments and the direction of re-adjustment always refer to the way in which they are introduced in the model setup and appear in the optimality conditions in Equations (8) to (15). The emissions target is exogenously given and kept constant throughout the paper so that the scenario results are comparable given a specific state of the environment. Throughout this section, the remaining policy instruments that are not under scrutiny are kept constant at their first-best optimal levels so that we can focus on the second-best re-adjustment of one policy instrument in each step. (This assumption will be relaxed in the numerical analysis.) Detailed proofs, explanations and discussions of the propositions can be found in the Appendix.

(a) Output (learning) subsidies for immature renewable technologies

We have derived the first-best choice of the first- and second-period output subsidies for the case that all market failures are remedied as $\phi^{i1} = -(1-\rho)\delta n^2 C^{i2}_{q^{i1}}$, $\phi^{i2} = 0$, see Equation (17).

(aa) Now we suppose that the R&D subsidy σ is not (sufficiently) available as a policy instrument so that it is set below its first-best value, in the extreme case $\sigma = 0$.

Proposition 1. *A below-optimal R&D subsidy requires ceteris paribus a lower output (learning) subsidy for immature renewable energy technologies in the short-term and a higher output subsidy in the long-term in the second-best compared to the first-best in order to raise welfare.*

The proof with explanations and discussions can be found in the Appendix. It is important to note that we treat learning and R&D as substitutes and that we assume R&D improves existing technologies rather than creating new technologies. A change in these assumptions can result in the opposite relation between R&D and output (learning) subsidies. In the Appendix we also argue that the below-optimal R&D subsidy is expected to raise the second-period electricity and carbon prices.

(ab) Now we suppose that energy efficiency subsidies λ^t are not (sufficiently) available as policy instruments so that in the extreme case $\lambda^{S1} = \lambda^{S2} = \lambda^{L1} = 0$. Let us define the price elasticity of electricity demand as $\frac{\Delta d^t/d^t}{\Delta p^t/p^t}$. The emissions target is exogenously given. The remaining policy instruments are again kept constant.

Proposition 2. *Below-optimal energy efficiency subsidies require ceteris paribus a higher (lower) output subsidy for immature renewable energy technologies in the short- and long-term in the second-best compared to the first-best in order to raise welfare if the price elasticity of electricity demand is above (below) unity.*

For a more detailed argument see the Appendix. The lack of subsidies for energy efficiency investment is expected to raise the electricity and carbon prices in both periods due to the expansion of electricity demand.

(b) R&D subsidy for immature renewable energy technologies

We have derived the first-best choice of the R&D subsidy for the case that all market failures are remedied as $\sigma = 1 - \rho$, see Equation (18). Note that we have defined $(1 - \sigma^{i1}) \cdot R^{i1}(h^{i1})$ in multiplicative form in Equation (1). By expanding this term, we obtain $R^{i1}(h^{i1}) - \sigma^{i1} R^{i1}(h^{i1})$ in additive form. If σ^{i1} is kept constant, but $R^{i1}(h^{i1})$ changes, then the term $\sigma^{i1} R^{i1}(h^{i1})$ will nevertheless change as well. This means that higher (lower) R&D expenditures are accompanied by a higher (lower) R&D subsidy in absolute terms even though the factor σ^{i1} may be kept constant.

(ba) We suppose that the first-period subsidy ϕ^{i1} for immature renewable technologies is not (sufficiently) available, so that a suboptimal situation occurs, in which in the extreme case $\phi^{it} = 0$. The emissions target and the remaining policy instruments are constant as before.

Proposition 3. *A below-optimal output (learning) subsidy requires ceteris paribus a higher (lower) R&D subsidy in the second-best compared to the first-best in order to raise welfare if the output increase via R&D is larger (smaller) than the replacement of learning by R&D.*

Due to the limited support for (renewable) electricity generation, the electricity and the carbon price are expected to increase in both periods.

(bb) Let us assume once again that the three types of energy efficiency subsidies λ are not (sufficiently) available as policy instruments so that in the extreme case $\lambda^{S1} = \lambda^{S2} = \lambda^{L1} = 0$. The emissions target and the remaining policy instruments are kept constant.

Proposition 4. *Below-optimal energy efficiency subsidies require ceteris paribus a higher (lower) R&D subsidy in the second-best compared to the first-best in order to raise welfare if the price elasticity of electricity demand is above (below) unity.*

In this paragraph and in the following paragraphs, the interaction of climate and energy policy is analogous to the considerations above.

(c) Energy efficiency subsidies for consumers

In the first-best, the energy efficiency subsidies fully offset the three types of consumer undervaluation: $\lambda^{S1} = 1 - \beta^{S1}$, $\lambda^{S2} = 1 - \beta^{S2}$, $\lambda^{L1} = 1 - \beta^{L1}$, see (19). Note that the same considerations for subsidies defined in multiplicative or in additive form apply as for R&D subsidies in paragraph (b) above.

(ca) We assume that the R&D subsidy σ is not (sufficiently) available as a policy instrument so that in the extreme case $\sigma = 0$. As before we make the assumption that the emissions target and the remaining policy instruments are given.

Proposition 5. *A below-optimal R&D subsidy suggests ceteris paribus a higher subsidy for energy efficiency investment affecting the short-term*[2] *and lower energy efficiency subsidies affecting the long-term in the second-best compared to the first-best in order to raise welfare.*

(cb) We suppose that the first-period subsidy ϕ^{i1} for immature renewable energy technologies is not (sufficiently) available as a policy instrument so that in the extreme case $\phi^{it} = 0$. As before we make the assumption that the emissions target and the remaining policy instruments are given.

Proposition 6. *A below-optimal output (learning) subsidy for immature renewable energy technologies requires ceteris paribus lower energy efficiency subsidies affecting the short- and long-term in the second-best compared to the first-best in order to raise welfare.*

(d) Feed-in policies as feasible instruments

The discussed policy instruments, although adjusted in a second-best world, all aim at a specific externality. In reality, however, policy makers often make use of so-called feed-in policies, i.e., renewable electricity generators receive a feed-in support payment in addition to their revenues from selling electricity in the spot market ("feed-in premium") or receive

[2]Short-term refers to model period 1, whereas long-term refers to model period 2.

a cost-based fixed price when supplied to the grid ("feed-in tariff"). The main goal of such a feed-in support scheme is to foster the diffusion of renewable energy technologies and thus, through learning-by-doing, bring down generation costs. The resources to finance such a scheme can be raised either by taxing consumers, as is the case in Germany, or by taxing non-renewable energy producers, as is assumed in the model by Kalkuhl *et al.* (2013). In the following, we will examine how such feed-in systems can substitute optimal policy instruments.

We build this analysis on paragraph (a) about output subsidies. Nonetheless, the combination of the subsidy with the levy on producers of fossil shifts electricity generation from carbon-emitting to non-emitting technologies. This creates an additional lever to address the undervaluation of investments in R&D and energy efficiency. On the contrary, the tax has a distortionary effect with negative consequences for welfare. Let us first formulate a general proposition about feed-in tariffs. Therein, the emissions target is exogenously given, the subsidy for renewable energy output is accompanied by a tax on emitting technologies, and the remaining policy instruments are set to their first-best levels.

Proposition 7. *If the output subsidy for immature renewable energy technologies is accompanied by an output tax on the remaining (emitting) technologies, ceteris paribus the subsidy must be lower in the second-best compared to the first-best in order to raise welfare.*

The adjustment of the subsidy refers to its policy level as described by Equations (8) and (9). The economic intuition is straightforward: The tax on the remaining technologies shifts production from these technologies to immature renewable energy technologies so that their output increases. This means the tax takes over part of the impact of the subsidy. □

The second-best policy analysis replicates the previous second-best analysis, but makes use of renewable energy output subsidies.

(da) We assume that the R&D subsidy σ is not (sufficiently) available as a policy instrument so that in the extreme case $\sigma = 0$. The emissions target is exogenously given as before, the subsidy for renewable energy output is accompanied by a tax on emitting technologies, and the remaining policy instruments are kept constant at their first-best levels.

Proposition 8. *A below-optimal R&D subsidy requires ceteris paribus a lower feed-in tariff rate in the short-term and a higher feed-in tariff in the long-term in the second-best in order to raise welfare.*

In this case, the reasoning explained in the appendix follows *Proposition 1.*

(db) Let us finally suppose that energy efficiency subsidies λ^t are not (sufficiently) available as policy instruments so that in the extreme case $\lambda^{S1} = \lambda^{S2} = \lambda^{L1} = 0$. The subsidy for renewable energy output is accompanied by a tax on emitting technologies, while the assumptions on the emissions target and the remaining policy instruments are chosen as in the previous analyses.

Proposition 9. *Below-optimal energy efficiency subsidies require ceteris paribus a higher (lower) feed-in tariff in the short- and long-term in order to improve welfare in the second-best if the price elasticity of electricity demand is above (below) unity.*

In this case, the reasoning is more complex than for *Proposition 2*, because the tax and the subsidy work in opposite directions with respect to the quantity of generated electricity. The overall effect depends on whether the subsidy or the tax dominates the overall reaction of electricity generation and pricing. One can expect that the effect of the subsidy dominates, because the subsidy is granted for renewable energy technologies with learning potential, whereas the conventional technologies affected by the tax do not involve learning, nor other externalities, so that the effect of the tax is weaker. We end up with a result that mimics *Proposition 2*.

The feed-in tariff scenarios in general result in increased electricity prices, because the electricity tax comes on top of the electricity price. With respect to the interaction of climate and energy policy, the introduction of taxes on non-renewable energies additionally shifts electricity generation from fossil to carbon-free technologies. This shift reduces the CO_2 price. The non-availability of R&D subsidies, however, reduces renewable energy-based electricity generation, and the non-availability of energy efficiency subsidies increases electricity demand. Both effects oppose the reduction of the CO_2 price.

4 Applied policy scenario analysis

As shown by the theoretical considerations of second-best policy design in the previous section, the exact design of policy instruments often depends on the dominance of opposing effects. Thus, a numerical implementation of the model is needed in order to (i) quantify the opposing effects and (ii) check which effect dominates and in which direction the total effect finally points. Furthermore, as an example for an instrument that is often used in European countries, we analyze feed-in policies in more detail. We do so by calibrating the model to data for the EU. In the theoretical considerations in Section 3.2 we studied the impact of one below-optimal or non-available policy instrument on each other instrument separately (for reasons of mathematical tractability). In this section, we study for each scenario the impact of one non-available policy instrument on all remaining instruments. We describe the model calibration and then define the scenarios to

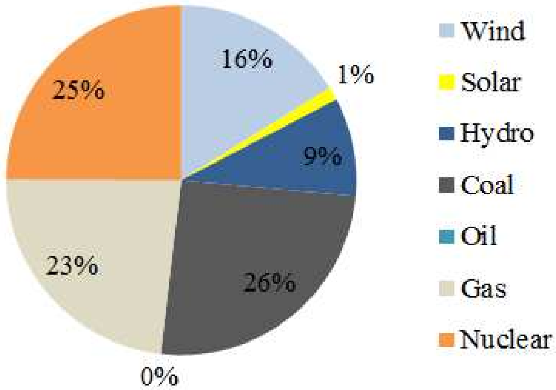

Figure 1: Electricity mix in scenario with CO_2 pricing for the EU in 2020 (the first model period) referring to the electricity output in the Baseline scenario by Capros *et al.* (2009).

be examined numerically. This will allow us to identify possible interactions between the adjustments of the second-best instruments.

4.1 Model calibration

The model characteristics, the specific functional forms and the parameter values are taken from FNP if not explicitly mentioned otherwise. Hence, the reader may refer to FNP for more details. The main difference is the calibration of the model to the European electricity market. This subsection gives a narrative overview of the choice of specific functional forms and their calibration to European data.

For the two stages, we assume that the short-term, period 1, runs from 2016 to 2020 and the long-term, period 2, runs from 2021 to 2040. Our calibrated model distinguishes among seven different power generation technologies: The carbon emitting technologies, coal (including lignite), gas, and oil. Solar (including further new renewable energies, such as tidal power, geothermal, etc.) and wind are assumed to be immature carbon-free technologies that are subject to cost reductions through learning-by-doing and R&D investments. For the remaining technologies, hydro and nuclear, we assume that their quantities are fixed or can be adjusted in the second period, respectively. Figure 1 illustrates the EU electricity mix in a scenario with CO_2 pricing for the year 2020.

The cost function for each power generation technology is assumed to increase in the generated quantity in a quadratic fashion. Consequently, the first-order derivative describing marginal costs is increasing linearly in quantity, meaning that the resulting supply schedule of each technology is linear over the explored policy space. The slopes of the supply curves are calibrated by comparing source-specific effective prices for electricity generation and their respective quantities from scenarios in the 2009 Energy Trends published by the European Commission's Directorate General for Energy (Capros *et al.*, 2009, p. 67). The Energy Trends describe two main scenarios. The Baseline scenario projects the development of the EU energy system under policies as of April 2009, which includes the ETS, while the Reference scenario includes the mandatory emission and energy targets for 2020 adopted subsequently. Both scenarios under comparison refer to an EU climate policy with a CO_2 emissions reduction of about 20% by 2030 compared to 2005. We draw upon the CO_2 and electricity prices as well as the shadow value of renewable energy in order to calculate the net producer price for each electricity technology. For example, the CO_2 price in the Baseline is 25 €'08/t for 2020 and 39 €'08/t in 2030; in Reference it is 16.5 €'08/t in 2020 and 18.7 €'08/t in 2030, and the average shadow value for renewable energy is 49.5 €'08/MWh in 2020 and 34.8 €'08/MWh in 2030. We adjust our benchmark calibration to these scenarios and fix the corresponding emissions across all scenarios. In the policy scenarios, however, CO_2 prices can freely adjust, given a cumulative emissions target derived from these scenarios.

To calculate the carbon cost burden for fossil sources, we compute the emissions intensity of each technology from the data as well. Together with the electricity prices, this information allows us to calibrate supply curves for each source.

For the renewable energy technologies, we take into account that the incentives for engaging in learning-by-doing must be incorporated into the calculation of the supply curves in the first stage to ensure that the first-order conditions hold. Cost reductions via learning and R&D are modeled as a two-factor learning curve in the form of a Cobb-Douglas function with negative exponents (that need not add up to one). The rate of private knowledge benefits is set to one half, i.e., $\rho = 0.5$ for both R&D and learning. Baseline R&D spending and other knowledge and investment cost parameters follow FNP.

The fraction of the benefit of energy efficiency improvements that the consumer perceives is set to 80%, i.e., $\beta = 0.8$. The reduction of electricity demand through investments in energy efficiency is modeled in the form of an exponential function with endogenous investments with a negative sign in the exponent. The representative consumer's utility rises in the consumption of electricity services.

We focus on the power sector, but since the existing EU ETS also includes additional sectors beyond the power sector, we take emissions abatement opportunities in these sectors into account as well to compute the CO_2 price effects of overlapping policies. To this end, the slope of the marginal costs of emissions reductions in the non-power sector is computed similarly by calculating the difference in the CO_2 prices between the two scenarios divided by the difference in emissions.

Table 1 shows the resulting parameter values for the supply curves and the CO_2

	Period 1 supply slope [€ /kWh^2]	Period 2 supply slope [€ /kWh^2]	CO_2 intensity [t/kWh]
Coal	2.4×10^{-13}	6.6×10^{-14}	0.91×10^{-03}
Natural gas	1.2×10^{-09}	6.2×10^{-10}	0.36×10^{-03}
Oil	1.9×10^{-13}	2.7×10^{-13}	0.88×10^{-03}
Nuclear	6.7×10^{-13}	2.3×10^{-13}	0
Hydro	9.0×10^{-13}	7.4×10^{-13}	0
Wind	2.3×10^{-13}	3.8×10^{-13}	0
Solar	3.0×10^{-12}	2.4×10^{-12}	0

Table 1: Technology parameters used for the model calibration to the EU.

intensities of fossil fuel technologies.

4.2 Definition of scenarios

We define the following scenarios.

No-Policy defines a scenario with no climate policies; i.e., we simulate the electricity sector outcomes with a zero CO_2 price and without subsidies for renewable energies or energy efficiency. Based on this scenario, we are able to calculate and compare the costs of policy scenarios as changes in outcomes attributed to these policies.

We examine nine different policy scenarios that are related to the propositions on second-best policies outlined in the previous section. All scenarios include carbon pricing, while the availability of additional policy instruments varies across scenarios. In each scenario, we require the policy mix to meet the same emissions target for the power sector (plus implicitly other ETS sectors). We keep this emissions target constant across all policy scenarios in order to keep the detrimental impacts (negative welfare effects) of climate change constant.

CO_2-Price assumes the only available instrument is carbon pricing (i.e., without subsidies for learning, R&D, or energy efficiency). It implements the current EU policy. The CO_2 price is adjusted for 2020 and 2030 so that the corresponding emissions reduction in the electricity and non-electricity sectors accords to the current EU climate policy with a 20% CO_2 reduction by 2030 compared to 2005. This means our numerical analysis deals with the European climate policy implemented today, not with possible more stringent future policies. This allows us to derive policy recommendations for the current state of the European economy and policy. We do not impose a 20% renewable share restriction nor a requirement of a 20% energy efficiency improvement, because we will study these policies endogenously under different scenario assumptions. In the following scenarios, CO_2 prices can float endogenous while keeping the cumulative emissions target over both periods constant.

1st-Best applies the first-best choice of the policy instruments, as derived in the algebraic analysis. Unlike the previous theoretical step-by-step analysis, all remaining policy instruments are re-adjusted simultaneously in the second-best.

No-R&D-Sub applies the second-best choice of the policy instruments without an R&D subsidy for immature renewable energy technologies.

No-Learn-Sub applies the second-best choice of the policy instruments without output (learning) subsidies for immature renewable energy technologies.

No-Effic-Sub applies the second-best choice of the policy instruments without any subsidies for energy efficiency improvements.

Feed-in considers the optimal policy combination, but with feed-in tariffs instead of simple output subsidies. Subsidies for R&D and energy efficiency are also available in this scenario. The feed-in tariffs are modeled as a combination of output subsidies for immature renewable energies and a tax on electricity. The tax and subsidy rates are chosen such that total subsidy payments exactly match total tax revenues. (The results reported by Tables 2 and 3 in columns 7 to 10 refer to this specification.) In this scenario the subsidies and taxes are restricted to the first period, because the implementation in the second period would be sub-optimal. In alternative robustness checks, we impose a tax on the overall electricity price, or impose a fixed (guaranteed) electricity price for comparison (not reported in the numerical results in Table 3). The latter two specifications come closer to the policy implementation in European countries. This comparison of different setups allows us to test whether the implementation of feed-in tariffs in economic models matters quantitatively.

Feed-in-No-R&D corresponds to scenario *No-R&D-Sub* with feed-in tariffs instead of output subsidies. No subsidies for investment in R&D are allowed in this scenario, and the available policy instruments are chosen such that a second-best situation is achieved.

Feed-in-No-Effic corresponds to scenario *No-Effic-Sub* with feed-in tariffs instead of output subsidies. No subsidies on investments in energy efficiency are allowed, and the available policy instruments are chosen such that a second-best situation is achieved.

Feed-in-Pure resembles scenario *Feed-in*, yet without the availability of subsidies for R&D or energy efficiency. Since the policy implementation in EU countries guarantees future subsidies for the sake of predictability of future revenues, we assume the same feed-in tariffs (tax and subsidy rates) in period 2 ad in period 1.

4.3 Application and summary of the theoretical results

This section applies the previous theoretical outcomes to the European policy scenarios. Table 2 depicts the results for each scenario, (1) to (10) (see column heads), and each variable in periods 1 and 2 (see first column), and summarizes the theoretical outcomes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	No-Policy	CO_2*-Price*	*1st-Best*	*No-R&D-Sub*	*No-Learn-Sub*	*No-Effic-Sub*	*Feed-in*	*Feed-in-No-R&D*	*Feed-in-No-Effic*	*Feed-in-Pure*
Propositions				(1)/(5)	(3)/(6)	(2)/(4)	(7)	(7)/(8)	(7)/(9)	
Policy cost wrt CO_2*-Price*	↓	ref	↓	↓	↓	↓	↓	↓	↓	?
Policy cost wrt *1st-Best*	↓	↑	ref	↑	↑	↑	↑	↑	↑	↑
Share renew 1 [%]	↓	?	ref	?	?	?	?	?	?	?
Share renew 2 [%]	↓	↓	ref	↓	↓	↓	↓	↓	↓	↓
Renew outp sub 1	n a	n a	ref	↓	n a	↑ if price elast of elec demand > 1; ↓ otherwise	↓	↓	?	?
							ref	↓	↑ if price elast of elec demand > 1; ↓ otherwise	?
Renew outp sub 2	n a	n a	ref=0	↑	n a	↑/↓ see above	ref=0	↑	↑/↓ see above	?
Renew R&D sub 1	n a	n a	ref	n a	↑ if outp incr via R&D > replacem of learning by R&D; ↓ otherwise	↑/↓ see above	ref	n a	↑/↓ see above	n a
Effic sub 1	n a	n a	ref	↑	↓	n a	↓	↑	n a	n a
Effic sub 2	n a	n a	ref	↓	↓	n a	↓	↓	n a	n a
Effic sub 1/2	n a	n a	ref	↓	↓	n a	↓	↓	n a	n a
Elec tax 1	n a	n a	ref=0	0	0	0	↑	↑	↑	↑
							ref	↓	↑/↓ see above	?
Elec tax 2	n a	n a	ref=0	0	0	0	ref=0	↑	↑/↓ see above	?
Renew R&D 1	↓	↓	ref	↓	↑/↓ see above	↑/↓ see above	ref	↓	↑/↓ see above	↓
Effic 1	↓	↓	ref	↑	↓	↓	ref	↑	↓	↓
Effic 2	↓	↓	ref	↓	↓	↓	ref	↓	↓	↓
Elec price 1	↓	↑	ref	ref	↑	↑	↑	↑	↑	↑
Elec price 2	↓	↑	ref	↑	↑	↑	↑	↑	↑	↑
CO_2 price 1	n a	↑	ref	ref	↑	↑	↓	↓	?	↑
CO_2 price 2	n a	↑	ref	↑	↑	↑	↓	?	?	↑

Table 2: Theoretical results for the EU climate and energy policy scenarios in periods 1 (short-term) and 2 (long-term). ↑ indicates that the corresponding policy instrument is to be adjusted upwards relative to ref(erence) in the same row in order to improve welfare, ↓ indicates the opposite adjustment to improve welfare. n a denotes not available. 0 indicates that a zero value is optimal. ? indicates that the direction of the optimal adjustment is ambiguous.

formulated in the previous propositions and explanations. The table highlights in which direction the various policy instruments need to be adjusted (upwards or downwards) compared to a reference value in order to elevate welfare, when one policy instrument is removed. Welfare effects are expressed as policy costs relative to *1st-Best* policy costs.

In the table, "Renew R&D sub 1" symbolizes an R&D subsidy for immature renewable energies that is only available in the first period. "Renew R&D" indicates the actual investment in research and development. If the subsidy for R&D is reduced, we expect a reduction in R&D as well. "Renew outp sub 1" or "Renew outp sub 2", respectively, symbolizes a subsidy for renewable energy output in period 1 (short-term) or period 2 (long-term). "Effic sub 1/2" symbolizes a subsidy for energy efficiency investments that affects both periods. Accordingly, the effect of this subsidy is attributed to both periods. Changes in electricity and CO_2 prices accord with the considerations of Section 3.2.

The scenarios that implement feed-in tariffs require further explanation. According to *Proposition 7*, the renewable energy output subsidy in the first period is lower in *Feed-in Opt* than in *1st-Best*, because it is accompanied by an electricity tax larger than zero. Following the argument of *Proposition 7*, the same is true for scenario *Feed-in-No-R&D* compared to *No-R&D-Sub* and for *Feed-in-No-Effic* compared to *No-Effic-Sub*. In scenario *Feed-in-No-Effic*, however, the first-period output subsidy can be re-adjusted upward or downward depending on the price elasticity of energy demand so that the overall adjustment of the output subsidy is ambiguous as indicated by the question mark. *Propositions 8 and 9* tell us how to adjust the first-period subsidy and electricity tax in *Feed-in-No-R&D* and *Feed-in-No-Effic* compared to *Feed-in*. The feed-in tariff scenarios result in higher electricity prices, because the electricity tax comes on top of the prices.

We expect second-period renewable energy shares in total electricity generation to be lower than in *1st-Best* in all other scenarios, because the *1st-Best* provides optimal support for renewable energies, and we do not examine above-optimal second-best policies. The situation is less clear in period one, because the effects of learning and R&D have not yet materialized. The numerical model analysis will shed light on such ambiguous aspects.

4.4 Numerical policy analysis

This section describes and interprets the simulation results. It pays special attention to the propositions derived in the algebraic policy analysis that have been translated into the qualitative policy results in Table 2. In the theoretical considerations in Section 3.2 we studied the impact of one below-optimal or non-available policy instrument on each other instrument separately. In the following numerical treatment we are able to study the impact of one non-available policy instrument on all remaining instruments simultaneously. This is supposed to reveal possible interactions between the adjustments of second-best instruments. Immature renewable energy technologies are represented by wind and solar power. The section concludes with a critical discussion of the methodology and the results.

4.4.1 Results

Table 3 depicts the results for each scenario, (1) to (10) (see column heads), and each variable in periods 1 and 2 (see first column). The table mirrors Table 2. (For further explanations of abbreviations used in the table see Section 4.3). One difference between the tables is that (immature) renewable energy technologies ("renew") are now split into wind and solar technologies. The electricity mix changes endogenously across scenarios but is not substantially different from the reference mix in scenario *CO_2-Price*. The CO_2 price is fixed in scenario *CO_2-Price*, whereas it declines endogenously in the other scenarios. Electricity prices, measured in Euros, endogenously determine the electricity market equilibrium. Wind and solar R&D as well as energy efficiency improvements emerge endogenously, too. They are measured in model-specific "physical" units. Investments in energy efficiency are normalized such that *CO_2-Price* investments are set to zero. Thus, investments smaller than in *CO_2-Price* show up as negative numbers. The investments in energy efficiency denoted by "Effic 1/2" are attributed to both periods. The relative magnitudes of policy instruments are expressed in percentage of *1st-Best* implementations. Since the *1st-Best* scenario assumes zero second-period output subsidies, second-period output subsidies are expressed relative to their first-period values. The values in brackets report the absolute magnitudes of policy instruments in EUR/MWh.

Scenario *CO_2-Price* with carbon pricing creates a loss, i.e., a policy cost, compared to *No-Policy* without any carbon or energy policy based on Equation (20). This cost reflects about 7.5 billion Euros. It serves as our reference and is set to 100%. The policy costs of the other scenarios are measured in percentage of the *CO_2-Price* cost. *1st-Best* entails policy costs that are about three quarters of the *CO_2-Price* cost. The remaining columns contain the second-best scenarios, which generate smaller cost savings than *1st-Best*. The cost reduction due to leaving out energy efficiency subsidies in column (6) is much more pronounced than the cost saving due to leaving out R&D or output subsidies for immature renewable energies in columns (4) and (5). This result underlines the important role of energy efficiency improvements and related policies in achieving emissions reductions effectively. Column (7) reports the results for scenario *Feed-in*, which adds an electricity tax to scenario *1st-Best*. Due to the economically inefficient tax, the cost saving (not visible in the table) is slightly smaller than in *1st-Best*. The *Feed-in-Pure* scenario in column (10) creates even higher policy costs than *CO_2-Price*. This means the distortion created by the tax instrument overcompensates the benefit of using the output subsidy, which is not present in scenario *CO_2-Price*. These results suggest that not making use of feed-in tariffs is welfare superior to making use of them. They also suggest that feed-in tariffs are inappropriate instruments for addressing the market failures in the domain of R&D and in the domain of energy efficiency.

The CO_2 price declines in scenario *1st-Best*, especially in the second period, because the policy instruments used in this scenario reduce electricity demand and foster wind and solar power. As a consequence, CO_2 emitting electricity generation is dampened. The second-best scenarios in the subsequent columns are in most cases less effective in reducing CO_2 prices. Scenario *Feed-in* introduces the tax instrument, which induces an additional shift of electricity generation from fossil to renewable energies. This is reflected by lower CO_2 prices. Note that total emissions generated by the power sector and by the other emissions trading scheme sectors are constant.

As predicted by Table 2, the second-period renewable energy share (electricity generation from wind and solar power divided by total electricity generation) never exceeds that of *1st-Best*. The first-period renewable energy share, on the contrary, exceeds it in scenarios without energy efficiency subsidies. In these scenarios, the higher electricity demand goes along with a higher renewable energy share. This implies that the additional energy production is biased towards renewable energies.

In the second-best scenarios the remaining policy instruments are re-adjusted so that welfare is maximized under the restriction of the non-availability of a specific policy instrument. In accordance with *Proposition 1*, the first-period output subsidies for immature renewable energy technologies are lower in column (4) *No-R&D-Sub* than in column (3) *1st-Best*. Also in accordance with *Proposition 1*, the second-period output subsidies for immature renewable energies are positive and hence higher than in *1st-Best*. In accordance with *Proposition 5*, both energy efficiency subsidies affecting the long-term, "Effic sub short 2" and "Effic sub long 1/2 " are slightly reduced in column (4) compared to column (3). Due to the interaction of policy instruments, the adjustment of the short-term subsidy for energy efficiency is more complicated. *Proposition 5* predicts a higher short-term subsidy. Yet *Proposition 6* predicts a lower short-term subsidy, because the renewable output subsidy is lower than in *1st-Best*. According to the numerical results, the latter effect dominates.

When comparing column (5), *No-Learn-Sub*, with column (3), *1st-Best*, the welfare maximizing second-best choice of the R&D subsidies for wind and solar turns out to be slightly higher than the first-best choice. This accords to *Proposition 3*, which proposes an ambiguous outcome. A clearer difference appears when calculating R&D subsidy payments per (first-period) physical output volume of the corresponding technology (not shown in the table). Then the R&D subsidy rate per output clearly rises in *No-Learn-Sub* compared

	(1) *No-Policy*	(2) *CO_2-Price*	(3) *1st-Best*	(4) *No-R&D-Sub*	(5) *No-Learn-Sub*	(6) *No-Effic-Sub*	(7) *Feed-in*	(8) *Feed-in-No-R&D*	(9) *Feed-in-No-Effic*	(10) *Feed-in-Pure*
Proposition				(1)/(5)	(3)/(6)	(2)/(4)	(7)	(8)	(9)	
Policy costs wrt *CO_2-Price* [%]	0	100	67.56	68.49	67.59	99.37	67.56	68.55	99.36	100.26
Share renew 1 [%]	25.42	26.45	26.23	26.23	26.15	26.45	26.25	26.24	26.45	26.60
Share renew 2 [%]	29.34	32.44	32.63	32.48	32.63	32.60	32.63	32.49	32.58	32.57
Wind output sub 1 [% (EUR/MWh)]	0	0	100 (0.66)	97 (0.63)	0	0	89 (0.59)	87 (0.56)	0	123 (0.82)
Solar output sub 1 [% (EUR/MWh)]	0	0	100 (5.11)	97 (4.93)	0	0	89 (4.55)	87 (4.43)	0	138 (7.07)
Wind output sub 2 [% (EUR/MWh)]	0	0	0	18* (0.12)	0	0	0	18* (0.12)	0	123* (0.82)
Solar output sub 2 [% (EUR/MWh)]	0	0	0	18* (0.91)	0	0	0	18* (0.92)	0	138* (7.07)
Wind R&D sub 1 [% (EUR/MWh)]	0	0	100 (0.41)	0	100 (0.41)	80 (0.37)	100 (0.41)	0	75 (0.30)	0
Solar R&D sub 1 [% (EUR/MWh)]	0	0	100 (0.81)	0	100 (0.82)	80 (0.77)	100 (0.81)	0	75 (0.61)	0
Effic sub short 1 [% (EUR/MWh)]	0	0	100 (0.12)	99.7 (0.12)	99.2 (0.12)	0	99.9 (0.12)	99.5 (0.12)	0	0
Effic sub short 2 [% (EUR/MWh)]	0	0	100 (0.45)	99.93 (0.46)	99.8 (0.45)	0	99.5 (0.45)	99.4 (0.46)	0	0
Effic sub long 1/2 [% (EUR/MWh)]	0	0	100 (0.64)	99.93 (0.64)	99.8 (0.64)	0	99.5 (0.64)	99.4 (0.64)	0	0
Elec tax 1 [EUR/MWh]	0	0	0	0	0	0	0.31	0.30	0	0.46
Elec tax 2 [EUR/MWh]	0	0	0	0	0	0	0	0.10	0	0.76
Wind R&D 1	0	0.01	0.06	0.01	0.06	0.07	0.06	0.01	0.06	0.02
Solar R&D 1	0	0.01	0.04	0	0.04	0.05	0.04	0	0.11	0.01
Effic 1	-1.68	0	3.46	3.48	3.47	-0.03	3.46	3.48	0	-0.02
Effic 2	-4.69	0	5.46	5.56	5.46	-0.11	5.46	5.55	-0.10	-0.02
Elec price 1 [EUR/MWh]	97.69	101.00	94.93	94.91	95.15	101.04	95.08	95.06	101.04	100.90
Elec price 2 [EUR/MWh]	85.28	98.00	86.97	87.24	86.99	97.67	86.97	87.22	97.83	97.95
CO_2 price 1 [EUR/t]	0	22.00	20.86	20.86	20.91	22.01	20.83	20.83	22.01	21.89
CO_2 price 2 [EUR/t]	0	39.00	29.46	29.70	29.48	38.72	29.46	29.66	38.75	38.30

Table 3: Simulation results for the ten EU climate and energy policy scenarios in periods 1 (short-term) and 2 (long-term). Policy costs are expressed in percentage of the policy costs of the *CO_2-Price* scenario with a carbon price only. The relative magnitudes of the policy instruments are expressed in percentage of *1st-Best*. (*Since *1st-Best* assumes zero second-period output subsidies, second-period output subsidies are expressed relative to their first-period values.)

to *1st-Best*. Based on *Proposition 3*, we conclude that in our model specification and calibration, the output increase resulting from higher R&D subsidies is larger than the replacement of learning by R&D. In accordance with *Proposition 6*, all types of energy efficiency subsidies slightly decrease in the second-best scenario *No-Learn-Sub* compared to *1st-Best*.

In column (6), *No-Effic-Sub*, the first-period output subsidies drop to zero,[3] and the R&D subsidies are reduced to 80% of the *1st-Best* values. Referring to *Proposition 2* and *Proposition 4*, this implies that the price elasticity of electricity demand is below unity in our model specification and calibration. As a consequence, the reduction of electricity from renewable energies translates into lower electricity demand. The reduction of electricity from renewable energies leads to a more than proportional increase in the electricity price, which in turn incentivizes higher investments in energy efficiency. Nonetheless, the non-availability of energy efficiency subsidies results in a strong reduction in energy efficiency investments as indicated by the negative numbers.

Column (7) reports scenario *Feed-in*, which adds an electricity tax to scenario *1st-Best*. As a result, the output subsidy rates are lower than in *1st-Best* in accordance with *Proposition 7*. Column (8) reports *Feed-in-No-R&D*, where no R&D subsidies for renewable energies are allowed. Similarly to *Proposition 1*, the resulting second-best optimal renewable energy output subsidies are lower in the first period and higher in the second period than in *Feed-in*. Furthermore, the subsidy rates are lower than in *No-R&D-Sub* as predicted by *Proposition 7*. The corresponding electricity taxes are adjusted in the same direction as the subsidies. The energy efficiency subsidies are adjusted downwards as expected.

Column (9) depicts scenario *Feed-in-No-Effic*, where no energy efficiency subsidies are allowed. Since the price elasticity of electricity demand is below unity as argued above, the renewable energy output subsidies for both periods as well as the R&D subsidies are adjusted downwards compared to *Feed-in*. As expected, the R&D subsidy rates in *Feed-in-No-Effic* are lower than in *No-Effic-Sub*, because the subsidies are accompanied by taxes.[4] Column (10), *Feed-in-Pure* deals with feed-in tariffs as practically implemented in Europe, in particular in Germany. This implementation excludes R&D and energy efficiency subsidies.[5] The output subsidy and tax rates exceed those of the *1st-Best* scenario.

[3] In this case the model generates a strong effect by finding a corner solution for the output subsidies. A possible reason is that the output subsidies' potential for reducing energy supply and demand is by far smaller than the potential of the energy efficiency subsidies that they replace.

[4] The model generates zero second-best output subsidy rates.

[5] We leave out R&D subsidies as well as energy efficiency subsidies in order to match the analysis with typical European feed-in tariff systems such as the German system.

Due to overlapping policy effects, the pattern of CO_2 and electricity prices is less clear than in the theoretical step-by-step analysis.

4.4.2 Discussion

This section critically discusses our results and positions them within the literature.

The policy effects generated by our numerical model application to the EU, summarized in Table 3, overall corroborate and illustrate our general theoretical findings, summarized in Table 2. This congruence shows that possible interdependencies between the re-adjustments of different second-best instruments are negligible. Otherwise, the numerical results, which take all interdependencies into account, would deviate from the step-wise theoretical results in Section 3.2.

The differences in the numerical results across scenarios are small in several cases. Thus, taking the results at face value, the error value of not re-adjusting *single* policy instruments in second-best situations is small, given the current situation of the European power sector and today's policies.

This result differs from that of Böhringer and Rosendahl (2010) and Boeters and Koornneef (2011) who find substantial welfare losses caused by overlapping policy instruments. The reason is that our analysis rules out the possibility of adverse distortive effects created by exogenously given overlapping policy constraints such as the 20% renewable energy target. Such constraints would undermine our study of second-best *optimal* policy scenarios.

Furthermore, we build our analysis on a baseline scenario, which includes moderate climate and policy targets that are in practice or decided *today*. Consequently, our results provide conservative advice for current policy implementations. Notably, we have carried out a *robustness check* with a more stringent CO_2 emissions reduction of 30% by 2030 compared to 1990 instead of 20% by 2030 compared to 2005. The results, however, hardly differ, especially when referring to welfare effects in relative terms. Possible more ambitious future emissions targets as proposed by the European Roadmap to 2050 (EU-COM, 2011) will likely increase the long-term magnitude of the estimated policy effects. Likewise, the benefits of supporting knowledge creation in the renewable energy sector via R&D and learning subsidies can become more pronounced over a longer time horizon. This is particularly true when taking the appearance of novel breakthrough technologies into account.

Higher values of the slope parameters that influence the adjustment of electricity generation from different technologies would also increase the magnitude of the policy effects. However, as in the analyses by FN and FNP, it is not the main purpose of our simulations to deliver precise quantifications, but to illustrate and validate our theoretical findings. Notwithstanding, we test the impact of different key parameter values in a *sensitivity analysis*. The parameter ρ governs the strength of knowledge spillovers. Its impact turns out to be relatively small. We also vary the magnitude of the feed-in tariff rates in both periods without finding a clear-cut qualitative change in the results. Overall, the order of magnitude of the effects that we find for the EU is similar to the order of magnitude that FN and FNP find for the USA.

In another robustness check, we find that the economic distortion that feed-in tariffs create is small and very similar across *different implementations* in the model. We implement them as a combination of fixed renewable energy subsidies and fossil fuel taxes (Kalkuhl *et al.*, 2013), or a combination of fixed renewable energy subsidies and a general tax on electricity, or a combination of a guaranteed electricity price payment and a general tax on electricity as in practice in Germany.

In accordance with FNP's finding for renewable performance standards and in contrast to Kalkuhl *et al.* (2012) and Kalkuhl *et al.* (2013), our results are critical with respect to feed-in tariffs as a substitute for first-best instruments. In particular, we find that energy efficiency improvements and related policies are crucial for efficiently achieving an emissions target. Energy efficiency improvements can hardly be replaced by other policy measures on the electricity supply side. But also within the domain of renewable energies, R&D-related policies cannot be efficiently replaced by output-related policies such as output subsidies or feed-in tariffs.

Although the numerical differences between the policy scenarios are in some cases small, the first-best policy reduces the European baseline cost burden imposed by the emissions target by about *one third* compared to carbon pricing as the sole instrument. In practice, the magnitudes estimated for the EU will differ across European countries, for example, depending on the country-specific potential of renewable energy sources.

5 Conclusion

We have studied the interaction of output (learning) and R&D subsidies for immature renewable energy-based power generation as well as subsidies for improving energy efficiency in the presence of carbon pricing. Our considerations and results should be helpful for policy makers who would like to know how they should re-adjust policy instruments in order to elevate welfare if a specific instrument is not (sufficiently) available for practical or political reasons.

According to our conservative numerical results, the policy cost of the European carbon emissions target, currently implemented in the EU ETS, has an order of magnitude of about 7.5 billion Euros. The EU ETS, however, creates an important environmental benefit that is not included in our analysis. Accordingly, the real "bird in the hand" is the EU ETS. The estimated welfare gains from the fine-tuning of single second-best instruments are in some cases small. Nonetheless, the joint re-adjustment of all policy instruments can reduce the current cost burden of the European climate and energy policy by up to one third or 2.5 billion Euros compared to a scenario with carbon pricing as the only instrument. Energy efficiency improvements contribute the largest cost reduction. For policy makers who strive for these "birds in the bush," our analysis provides the recipe to catch them.

To this end, we have theoretically derived detailed recommendations for the second-best re-adjustment of policy instruments. Additionally, we have studied to what extend feed-in tariffs can replace these instruments. We have modeled feed-in tariffs by combining the output subsidy for immature renewable energy technologies with a tax on electricity or the output of the remaining technologies. In this combined form, the output subsidy needs to be reduced compared to its use as a single instrument in order to improve welfare, because the tax does part of the job of the subsidy. Our results suggest that feed-in tariffs, as currently implemented in several European countries, are inappropriate instruments for addressing the market failures in the domain of R&D spillovers and in the domain of energy efficiency improvements. Nonetheless, the economic distortion that is created by a feed-in tariff is small. In this sense, feed-in tariffs are good substitutes for pure renewable energy output subsidies. The advantage of feed-in tariffs compared to pure subsidies is that cost neutrality is guaranteed such that the tax on electricity finances the subsidy for renewable energy technologies. The guaranteed future electricity prices also create certainty in income streams of investors. If investors are risk averse, this will lead to more R&D and learning. Yet subsidies that directly support R&D and investments in energy efficiency are more efficient than feed-in tariffs. Our results in particular suggest better investment incentives in the domain of energy efficiency.

Taking the discussed caveats into account, we hope that our analysis provides useful guidance for climate and energy policy design. Future research could model feed-in tariffs in specific European countries and assume more ambitious long-term climate policy targets. Today, however, more ambitious targets are still debated.

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7 Supplementary Appendix

(aa) *Proof of Proposition 1*:

Output subsidies cannot directly affect knowledge creation, but they can indirectly induce it by influencing the volume of electricity generation. We know from Equation (21) that in the presence of R&D spillovers any intervention Ψ that increases knowledge h^{i1} elevates welfare W. We know from (10) that the R&D investments are below the social optimum if σ is smaller than $(1-\rho)$. Furthermore, a below-optimal R&D subsidy results in below-optimal second-period output q^{i2}. We know from (3) that $C^{i2}_{h^{i1}q^{i2}} < 0$ so that the left-hand side of (10) becomes below-optimal. Hence, overall we need to augment the left hand side of (10) to come closer to the socially optimal subsidy rate. We know from (3) that $C^{i2}_{h^{i1}} < 0$, $C^{i2}_{h^{i1}q^{i1}} > 0$ and $C^{i2}_{h^{i1}q^{i2}} < 0$. This means policy makers need to *decrease* the subsidy for immature renewable energy output ϕ^{i1}, $\forall\ i \in r$ in the short-term, i.e., period 1, but *increase* the subsidy for immature renewable energy output ϕ^{i2}, $\forall\ i \in r$ in the long-term, i.e., period 2, in order to raise the magnitude of the cost reduction effect of knowledge, represented by $C^{i2}_{h^{i1}}$.[6] □

This finding requires further explanation and leaves room for discussion. The augmentation of the second-period subsidy appears straightforward and unambiguous: When more electricity is to be produced in the future, then any reduction of future costs will affect a larger generated quantity in the future and thus increase the benefits of today's R&D. The cutback of the short-term subsidy surprises: One might think that a higher output subsidy has to compensate for the shortfall of the R&D subsidy. However, the full benefit of learning-by-doing has already been exploited by the first-best output subsidy. A further increase of learning-by-doing would crowd out R&D investments. Yet, we aim at the enhancement of knowledge creation via R&D investment. One might argue, higher production enhances R&D in a complementary way. Though, the following consideration suggests the opposite: Suppose an initially immature technology has made tremendous progress in terms of cost reductions over time. The potential for further cost reductions through R&D for the *same* technology will be limited. Less technical progress through learning, on the contrary, leaves more room for cost reductions through R&D and hence creates an additional incentive for R&D investment. Following this argument, we assume R&D and learning act as substitutes. The interdependence of the R&D-related and the learning-related policy instruments will work in opposite directions, if one assumes that R&D and learning act as complements. (For a further discussion see FN.)

We refer to cost reductions within a given set of technologies in our analysis. We abstain from taking into account that research can create new (breakthrough) technologies. Thus, R&D with the aim to create new technologies is hardly affected by learning, and it is likely economically reasonable to support this kind of research even more when the potential of technical progress has been exploited for the existing technologies. This means the reduction of the short-term output subsidy in the second-best hinges upon the assumption that technical progress reduces the production costs of existing technologies. The result would likely be reversed if the creation of new technologies were taken into account.

Regarding the interaction of climate and energy policies, the question of how unavailable or inadequate R&D subsidies for immature renewable energies affect the

[6]Conversely, a higher output subsidy in the short-term would also expand output in the long-term via learning. This effect counteracts the incentive to reduce the first-period subsidy. Nevertheless, when the second-period output subsidy is available, one can induce higher second-period output via a higher second-period subsidy and reduce the first-period subsidy. If the second-period subsidy is not available, it is not evident whether the first-period subsidy should be de- or increased due to the two opposite effects.

electricity and the CO_2 price is of importance for policy makers. The long-term effect is straightforward: Less R&D in carbon-free technologies leads to higher production costs of these technologies, according to (3) and (10), and thus less carbon-free electricity generation q^{i2}, $i \in r$. Hence, the output of other technologies including fossil-based technologies must rise in order to satisfy electricity demand. As a result, the electricity and the carbon price for the second period will increase when emissions are curbed by a given emissions cap. The short-term impact within the first period is zero, because the effect of R&D is not realized before the second period and the burden on public finance does not affect the behavior of economic agents in the model.

(ab) *Proof of Proposition 2*:

We know from Equation (21) that in the presence of undervaluation of the representative consumer's true benefit of energy efficiency improvements, any increase in energy efficiency measures will raise welfare. We know from Equations (13), (14) and (15) that the left hand side of each equation will be too low from a social point of view if each λ is too low or zero. Hence, we need to augment the left hand side of each equation to come closer to the social optimum. The way to achieve this is to enlarge the marginal value of electricity demand reduction through investment in energy efficiency, signified by $p^t d^t_{e^t}$ and the three types of e^t. Basically, this requires an increase in the electricity volume times the electricity price. On the one hand, each output subsidy ϕ^{it} extends electricity output q^{it} in the same period. Additionally, ϕ^{i1} extends future output q^{i2} via learning. We know from (7) that electricity demand equals electricity supply in equilibrium. Furthermore, Equation (6) tells us that the magnitude of the marginal reduction of electricity demand through energy efficiency measures will become higher when the consumption of energy services is higher, i.e., $d^t_{e^t v^t} < 0$. We know implicitly that the consumption of energy services and energy demand are positively linked since $d^t_{v^t} > 0$ and hence $v^t_{d^t} > 0$. Therefore, higher output subsidies ϕ^{it} for immature renewable energy technologies (with an additional learning effect) in particular and for any electricity generation technologies (without an additional learning effect, but causing an output expansion in the same period) in both periods are the preferable choice with respect to welfare maximization. On the other hand, the subsidy and the increased electricity supply reduce the electricity price p^t. This consideration, on the contrary, suggests lower (or for the second period negative) electricity output subsidies. The overall effect on the marginal value of demand reduction depends on whether the price or the quantity sensitivity is stronger. A price elasticity of electricity demand above unity implies that electricity quantities react more sensitively than prices. □

Note that any subsidy or tax creates a transfer that is welfare neutral in the model. We assume that this transfer does not affect the consumer's calculus via a change in her budget. If this were taken into account, a higher subsidy would reduce the consumer's disposable income budget. This would in turn reduce her demand for electricity and hence the electricity price.

Regarding the interaction of climate and energy policy, the key question is how the lack of subsidies for energy efficiency investment affects the electricity and CO_2 price. It is apparent that less investment in energy efficiency increases electricity demand and hence electricity generation, as formally described by Equations (4), (7) and (13) to (15). This creates upward pressure on the electricity price in the corresponding period; since the electricity mix includes fossil energy, the use of fossil fuels will rise and drive up the CO_2 price for a given emissions cap.

(ba) *Proof of Proposition 3*:

This examination partly mirrors the examination of the output subsidy in the absence of the R&D subsidy in (aa). Yet there are two differences: First, producers' choice of output also depends on the electricity price p^t, whereas there is no explicit market price for knowledge. Second, unlike the output subsidy, the R&D subsidy is only available for the first period. (A second-period R&D subsidy is not reasonable, because it would affect a third model period, which is not taken into account.) We know from Equation (21) that in the presence of learning spillovers any intervention Ψ that increases output q^{i1} of immature renewable energy technologies will elevate welfare W. We know from (8) that the left hand side will be too low from a social point of view if ϕ is too low or zero. For the right hand side of (8), (3) says that low marginal production costs are associated with limited production q^{i1}. Hence, we need to augment the left hand side of (8) to come closer to the social optimum. Now there are two opposing effects. We know from (3) that $C^{i2}_{q^{i1}q^{i2}} < 0$, i.e., the magnitude of the marginal cost reduction through learning from the point of view of the first period will increase when there is more electricity production in the second period. This consideration suggests choosing a higher R&D subsidy in order to enhance the value of learning from first-period production. By contrast, the negative interdependence between learning and R&D as discussed in detail in (aa) and expressed by $C^{i2}_{h^{i1}q^{i1}} > 0$ in (3) implies that we require a lower R&D subsidy in order to leave more room for cost reductions via learning. Additionally, according to (8), first-period output implicitly increases in the first-period electricity price, because a higher p^1 on the left-hand side of (8) lowers the marginal effect $C^{i2}_{q^{i1}} < 0$, which ceteris paribus requires a larger q^{i1}. Furthermore, a higher second-period electricity price requires a lower first-period R&D subsidy so that the resulting cost reduction and second-period output expansion are smaller. □

Regarding the interaction of climate and energy policy, a relevant question is how the non-availability of the output (learning) subsidy for immature renewable energies affects the CO_2 price. The long-term effect is again straightforward. The difference with the non-availability of the R&D subsidy is that the output subsidy affects electricity generation of immature renewables in both periods, as can be seen in (8). Hence, in the short- and long-term, a lower subsidy for carbon-free technologies results in higher production costs of these technologies, according to (3) and (8), and hence less carbon-free output q^{i1}, q^{i2}, $i \in r$. The output of other electricity generation technologies including fossil-based technologies must rise in order to satisfy electricity demand. As a result, the electricity and the carbon price will increase in both periods when emissions are curbed by a given emissions cap.

(bb) *Proof of Proposition 4*:

This policy experiment mimics (ab), albeit with a notable difference: The first-period output subsidy augments the output of the first and second period, and a second-period subsidy the output of the second period. The R&D subsidy is granted in the first period, but affects output in the second period only. Neglecting income effects of transfers to producers, the R&D subsidy is unaffected by the unavailability of the short-term, i.e., first-period, energy efficiency subsidy λ^{S1}. The reason is that today's R&D decisions focus on the long-term situation when the fruits of R&D have become apparent. Therefore, the R&D subsidy is affected by the energy efficiency subsidies that affect the long-term, i.e., λ^{S2} and λ^{L1}. As in (ab), higher energy efficiency investments can be induced by increasing the marginal value of electricity demand reduction, expressed by $p^t d^t_{e^t}$ in (14) and (15). As a consequence, the overall effect on the marginal value of demand reduction depends on whether the price or the quantity sensitivity is stronger, as in (ab). A price elasticity of electricity demand above unity implies that electricity quantities react more sensitively than prices. Hence, given an elasticity above unity, one will aim at a larger electricity quantity in order to induce higher investments in energy efficiency. □

(ca) *Proof of Proposition 5*:

Energy efficiency investments cannot directly affect knowledge creation, but they can affect it indirectly by influencing the volume of electricity generation. We know from Equation (21) that in the presence of R&D spillovers any intervention Ψ that increases knowledge h^{i1} will elevate welfare W. Equations (13) to (15) state that the left hand side will be too low from a social point of view if λ is too low or zero. For the right hand side, we know from (4) that the resulting low marginal energy efficiency expenditures are associated with limited energy efficiency improvements e^{i1}. Hence, we need to augment the left hand side of (10) to come closer to the social optimum. The following argument is similar to the reasoning in (aa) and (ab). We know from (3) that $C^{i2}_{h^{i1}q^{i1}} > 0$ and $C^{i2}_{h^{i1}q^{i2}} < 0$. This means policy makers need to *decrease* immature renewable energy output in the short-term, i.e., period 1, and *increase* it in the long-term, i.e., period 2, in order to raise the magnitude of the cost reduction effect of knowledge, represented by $C^{i2}_{h^{i1}}$. More knowledge creation in the short-term will create higher output in the long-term since $C^{i2}_{h^{i1}} < 0$. According to (7), lower electricity supply translates into lower demand and vice versa in the market equilibrium. The means to decrease electricity demand and hence supply in period 1 is a higher energy efficiency subsidy for the first period. The means to increase demand and hence supply in period 2 is consequently a lower energy efficiency subsidy for the second period. □

(cb) *Proof of Proposition 6*:

The argument mimics that of (ca) above with a notable difference: Equation (21) states that in the presence of learning spillovers any intervention Ψ that increases output q^{i1} of immature renewable energy technologies will elevate welfare W. Now changes in energy efficiency imply changes in electricity demand via (4), which *directly* affects electricity supply via (7). As a consequence, policy makers can directly augment electricity output by reducing energy efficiency subsidies for the short- and long-term, which lowers the consumer's investments in energy efficiency and raises her electricity demand. □

(da) *Proof of Proposition 8*:

The feed-in tariff rate refers to the choice of the policy levels as described by Equations (8) and (9). The reasoning is equivalent to that of *Proposition 1*. Now we compare the situation with a feed-in tariff (including renewable energy output subsidies) and energy efficiency subsidies, but without R&D subsidies, to a situation with a feed-in tariff and energy efficiency subsidies and R&D subsidies as well. The proposition explains how to adjust the feed-in tariff when R&D subsidies are not available (for political reasons). *Proposition 7* holds as well. □

(db) *Proof of Proposition 9*:

The argument mimics that of *Proposition 2* at first glance. Now we compare the situation with a first-period feed-in tariff (including renewable energy output subsidies) and an R&D subsidy but without energy efficiency subsidies to a situation with a first-period feed-in tariff and an R&D subsidy and with energy efficiency subsidies. The proposition explains how to adjust the feed-in tariff when energy efficiency subsidies are not (sufficiently) available (for political reasons). At second glance, we need to take the effect of the tax on total electricity generation into account. The subsidy for immature renewable energies enhances electricity output, whereas the tax on the remaining technologies abates electricity output. Furthermore, the tax creates an additional distortion. On the contrary, the optimal output subsidy will, according to *Proposition 7*, be reduced, once a tax is added. This reduces the subsidy-induced distortion. In this sense, the tax opposes the subsidy. This also holds for the effect of the tax and the subsidy for the electricity price as outlined under *Proposition 2*. The overall effect depends on whether the subsidy or the tax dominates the overall reaction of electricity generation and pricing. Notwithstanding, one can expect that the effect of the subsidy dominates. The reason is that the subsidy is granted for renewable energy technologies with learning potential. Besides the direct output expansion, the subsidy therefore fosters learning (see Equation 8). On the contrary, the effect of the tax does not involve learning, nor other externalities, and is hence weaker. We end up with a result that mimics *Proposition 2*. □

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