More birds than stones – A framework for second-best energy and climate policy adjustments

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Abstract

Tinbergen's seminal work showed that we need as many policy instruments as there are market failures to address. In practice, however, regulatory power is often constrained, making it difficult or impossible to implement the first-best policy portfolio. We analyze analytically and numerically how available policy instruments should be adjusted vis-à-vis the first-best to account for under-internalized secondary market failures. As a concrete example, consider the power sector: alongside the external costs of emissions, evidence suggests that consumers undervalue energy efficiency investments, and knowledge spillovers hamper R&D and learning-by-doing in low-carbon technologies. By exploring the potential and limits of policy instrument substitution, we provide guidance for policymakers on how to adjust first-best policies in second-best situations. We calibrate the theoretical model to the European electricity sector and find that, compared with the first-best policy portfolio, relying on CO_2 pricing alone increases the policy cost of the EU CO_2 emissions target by about 30%. Uninternalized R&D spillovers contribute the most to this increase, and are the most difficult to address indirectly, even with learning subsidies. By contrast, almost 40% of the additional cost created by the absence of optimal energy efficiency subsidies can be recuperated by a second-best electricity tax.

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1 Introduction

Economists tend to give policy advice under the implicit assumption that all first-best instruments are available, institutions are perfect and enforcement is rigorous. Such advice is, however, of limited applicability for policy makers when some policy instruments are unavailable because of jurisdictional limitations, political constraints, incomplete information or prohibitive transaction and compliance costs (Rodrik, 2008).

This problem is particularly relevant for climate and energy policy governance, where several interacting policy instruments address multiple market failures. Often, several institutions—located in different agencies or at different government levels—are responsible for regulating segments of energy markets. At the same time, not every institution is willing or able to implement first-best policies, leaving other institutions with the task of addressing multiple policy goals with a limited set of policy instruments—in essence, trying to hit several birds with one stone. This violates the Tinbergen (1952) rule of one instrument per market failure (Bennear and Stavins, 2007). The legislative competence to regulate electricity markets in the European Union (EU) exemplifies this: governments at the EU, national and subnational levels have different regulatory responsibilities, making it difficult to implement a coordinated and coherent portfolio of policy instruments. Regulators in the U.S. face a similar problem: incomplete regulations implemented on the federal or state level interact with each other with ex-ante unclear consequences.

This article shows – to the best of our knowledge for the first time – how single energy policy instruments can be adjusted to achieve the second-best outcome if policy makers do not have access to a complete set of first-best energy and climate instruments to address all relevant market failures. We know from general second-best theory that the attainment of Pareto optimal conditions is not necessarily welfare improving if constraints exist that prevent the attainment of at least one of the conditions of Pareto optimality (Lipsey and Lancaster, 1956). Consequently, if there are multiple market failures that are not remedied by policy, then remedying one market failure does not necessarily improve welfare. Hence, it is ex ante not obvious whether, in which direction, and how far the remaining policy instruments should be adjusted to raise welfare. Our analysis sheds light on these adjustments in the energy sector. The article develops a novel theoretical framework for deriving second-best policy adjustments, simulates costs and benefits in a calibrated model of the European power sector, and provides guidance for energy policy makers with access to a limited set of instruments.

Those instruments are intended to address the following market failures: First, energy generation from fossil fuel combustion creates significant adverse environmental externalities. In particular, carbon dioxide (CO_2) emissions are the single most important contributor to global climate change (IPCC, 2013).

Two other market failures involve the knowledge externalities of learning-by-doing and research and development (R&D), which are pivotal if CO_2-free renewable energies technologies ("renewables") are to become cost-competitive with existing fossil fuel technologies. Cost reductions are partly driven by lessons learned from past experiences, represented by past output; this knowledge has public good characteristics and might be thus underprovided (Lindman and Söderholm, 2012). And since the benefits of R&D cannot be made fully private to R&D investors either, R&D efforts are insufficient from a social point of view as well, leaving CO_2 mitigation costs above their social optimum (Popp *et al.*, 2010; Acemoglu *et al.*, 2012).

A fourth market failure stems from externalities on the demand side. Insufficient investments in efficiency-improving measures lead to overly high energy consumption. This inefficiency is grounded in capital market imperfections that cause liquidity constraints, in split incentive structures (e.g., between landlords and tenants) or in misbehavior due to asymmetric or missing information (Gillingham *et al.*, 2009; Allcott and Greenstone, 2012).

In a first-best world, each of those four market failures is targeted by a specific, optimized instrument. Constraints on one of these policy instruments create a third-best situation, which can be improved via second-best adjustments of the remaining instruments. We present a framework to derive such second-best adjustments. Our theoretical analysis shows how a substitute instrument should be adjusted if another instrument is below its optimal level.

In particular, we consider the following policy instruments: CO_2 pricing, output (learning-by-doing) subsidies and research and development (R&D) subsidies for renewable energy, and energy efficiency subsidies as well. We assume that CO_2 pricing is available throughout the analysis, whereas the other instruments may or may not be available depending on local policy conditions. We also study a simple electricity tax as a second-best instrument.

We then assess the potential of such third- to second-best adjustment using a calibrated model of the EU electricity market. We compute the magnitude of the welfare loss caused by an unavailable policy instrument, the extent to which the remaining available instruments should be adjusted to compensate at least partly for the missing instrument, and how much of the foregone welfare can be recuperated. By addressing these questions, we add new insights to the design of second-best climate and energy policy instruments. We build on the model by Fischer and Newell (2008) (henceforth FN), extended by Fischer *et al.* (2017) (henceforth FPN), who used a calibration to the U.S. power sector to compare the welfare effects of hypothetical single policy instruments to CO_2 pricing and a first-best portfolio. In contrast, we focus on second-best adjustments in the European power sector.

Our results show that, for a given emissions target, the inability to address energy efficiency market failures creates the largest adverse welfare effect, followed by R&D spillovers and then learning-by-doing spillovers. This order raises concerns, since the vast majority of climate-related interventions in the EU power sector seem focused on the last externality, with subsidies supporting the production of renewable energy, often via feed-in tariffs. The electricity tax turns out to be a good second-best substitute for energy efficiency subsidies, recuperating more than third of the first-best cost reduction. In contrast, the electricity tax appears to be rather ineffective as a substitute for learning-by-doing subsidies.

The rest of this article proceeds as follows. Section 2 describes the policy background and reviews the related literature. Section 3 sets up and solves the model analytically. Based on this, section 4 derives second-best policy adjustments analytically. Section 5 explains the model calibration to the EU power sector and evaluates the policy portfolios numerically. Section 6 concludes with policy implications.

2 Policy background and literature review

This section first describes the European climate and energy policy context of our work. Second, against this background, it positions our work within the related literature.

2.1 Policy background

The climate and energy policy agenda of the European Union is based on three pillars. In each pillar, a specific target needs to be reached by 2030. First, the emission of greenhouse gases (GHG) should be reduced by 40% relative to 1990-levels. Second, the share of renewable energy sources should be at least 27%. Third, energy consumption should be reduced by 27% (European Council, 2014). Our analysis will replicate these policy targets.

In its previous round, to be concluded by the end of 2020, the EU climate and energy policy agenda aimed for the so-called 20-20-20 targets. These targets were defined in the EU Climate and Energy Package and adopted in 2009, consisting of a 20% reduction in EU GHG emissions relative to 1990 levels, a 20% share of renewables in EU energy consumption and a 20% reduction in energy consumption. These targets are to be reached by 2020.

The central instrument to reduce GHG emissions is the union-wide Emission Trading System (EU ETS), which caps emissions for large industrial polluters and covers about 45% of GHG remissions. Because about 70% of the emissions in the EU ETS come from the stationary power sector, our analysis will focus on this sector. Electricity is also a main player in compliance with the other two targets: renewable electricity accounted for 43% of gross final renewable energy consumption in the EU,[1] and electricity consumption is a primary target for energy efficiency policies.

Despite the EU-wide renewable energy targets, the choice and design of instruments to reach the targets are at the discretion of individual member states (RES Legal, 2018). Sweden, for example, promotes renewable electricity mainly through a quota system. Germany is currently moving from an FiT system (guaranteed electricity price above the

[1] https://www.eea.europa.eu/data-and-maps/indicators/renewable-gross-final-energy-consumption-4/assessment-4 accessed March 1, 2020.

market price for generators) to a system with market premia (a guaranteed fixed subsidy rate on top of the market price for electricity).[2] Other member states still rely mainly on FiTs. Not only is there considerable variation in the type of support schemes, but also in the methods of paying for them, whether by electricity surcharges or taxpayer finance. In other words, renewable generation is generally subsidized, and sometimes combined with an implicit or explicit tax on electricity.

The choice of instruments for meeting energy efficiency targets is similarly left largely to the discretion of the member states. At the EU level, only a fragmented set of single measures has been implemented, such as the controversial ban on conventional light bulbs. Member states, on the other hand, rely more on economic incentives. France, for example, has implemented a trading system of energy saving certificates, ensuring that energy suppliers meet government-mandated targets at least cost. Ireland builds on corporate tax incentives for energy efficiency investments (Landis *et al.*, 2013). Our analysis considers the general case of energy efficiency subsidies.

2.2 Literature review

European renewable energy support and emissions trading are interdependent and, in the absence of further market failures, can undermine each other's cost-effectiveness. On the one hand, CO_2 pricing increases the competitiveness of renewable energy technologies, enhances their diffusion, and fosters learning-by-doing and R&D, which reduces renewable generation costs and green certificate prices. On the other hand, the crowding-out of fossil-fuel technologies by renewable energy technologies results in lower CO_2 prices.

Against this background, an extensive literature has examined the European climate and energy policy portfolio. Focusing on the interaction of the EU ETS with renewable energy support policies Böhringer *et al.* (2008), Fischer and Preonas (2010), Flues *et al.* (2014) 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 CO_2 price in an ETS with a fixed cap and thus promotes fossil fuel-based technologies. Such distortions lead to significant costs: Boeters and Koornneef (2011) argue that the renewable energy target of the European Union creates excess costs of more than 30% 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. Notwithstanding, a combination of policy instruments 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).

[2] Whether Germanys FiT scheme qualifies as state aid has been the subject of litigation. If companies receive governmental support and gain advantages over their competitors, that will contradict EU law. In 2016, the EU's General Court decided that Germany's 2012 Renewable Energy Source Act involved state aid and demanded adjustments to the regulation.

Most of these studies focus on policy interactions with credit trading mechanisms. In contrast, rather than concentrating on automatic price adjustments, we focus on restrictions to price instruments that prevent externalities from being properly internalized. Importantly, we include additional market failures, particularly in knowledge creation and the perception of energy efficiency benefits.

Another substantial literature has focused on the influence of knowledge market failures in particular on optimal policy mixes, second-best CO_2 taxes, and alternative single policy instruments (e.g., FN, FPN, Kalkuhl *et al.* (2012)). Some have considered how restrictions on CO_2 pricing affect second-best innovation subsidies (e.g., Fischer (2008)). Most find that a variety of technology policies can address innovation spillovers but they are poor substitutes for CO_2 pricing.

The second-best theory literature has typically focused on the use of a single instrument in settings with pre-existing distortions, such as those caused by capital or labor taxes. Such distortions, unrelated to the environmental externality, create second-best situations in which Pigouvian taxes are no longer the first-best response to the environmental problem. Parry *et al.* (1999) as well as 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 adjusted by taking into account the incentives and revenues created by pre-existing taxes. Our paper follows this spirit by showing, how every policy instrument can be adjusted to minimize welfare losses in absence of the full first-best policy portfolio.

Other second-best theory studies have considered the role of additional policy levers when the government cannot address a market distortion directly. For example, in a setting of incomplete regulatory coverage, Bernard *et al.* (2007) consider the second-best response when emissions outside a regulatory boundary cannot be taxed directly. Although second-best questions of incomplete sectoral and regional coverage as well as pre-existing tax distortions have been covered well by the literature, more general questions of second-best responses in environments with multiple policies and multiple market failures, such as those encountered in electricity markets, including knowledge spillovers and undervaluation of potentials to improve efficiency, have received less attention. Hence, we will take up these issues in the following analysis.

3 Model setup and first-best solution

This section develops a two-period partial equilibrium model of an electricity market and its potential market failures. It then derives welfare effects and the first-best policy instruments.

3.1 Non-technical overview

We build on FN and FPN in the modelling of a stylized electricity market confronted with externalities on the supply and demand side that can be addressed with a set of first-best policies. Based on this model, we are going to derive a framework of optimal policy adjustments in the absence of the complete first-best policy set.

Electricity can be generated using immature renewable energy technologies ("renewables"), mature renewable technologies (hydro), nuclear power, or fossil-fuel-based CO_2-emitting technologies (coal, gas and oil). The utilization of each technology is governed by a price-taking and profit-maximizing representative producer. All technologies are subject to convex increasing production costs, but only immature renewables are subject to cost reductions via R&D investments and learning-by-doing. Following FN and FPN, we distinguish between two periods representing the present and the future. This distinction allows us to assume that R&D investments and learning-by-doing are triggered today, whereas the resulting cost reductions will materialize in the future, with time delay.

A representative utility-maximizing consumer demands electricity. Besides spending her income on electricity consumption, she can invest in efficiency improvements. The costly energy-efficiency measures reduce the electricity expenditures necessary for a given level of utility from energy services. Taking energy efficiency measures as well as subsidies and taxes into account, the representative consumer maximizes utility.

However, because of market failures, decentralized profit and utility maximization do not lead to the first-best allocation of resources. Our model considers four market failures, as discussed by FPN and Jaffe *et al.* (2005).

First, CO_2 emissions cause detrimental welfare effects by contributing to climate change. In the absence of regulation, the market generates excess electricity with fossil fuels compared with socially optimal levels. In order to reduce emissions to an (exogenously decided) target level, an ETS is imposed and kept constant across scenarios. Consequently, other policies do not affect overall emissions or the future welfare effects of climate change across scenarios.

Second, we assume that electricity producers using immature renewables do not perceive and internalize the full benefit of productivity gains from learning-by-doing (Lindman and Söderholm, 2012). Because of knowledge spillovers, without policy intervention, renewable energy production and the resulting knowledge creation are below the socially optimal level. Renewable production subsidies can correct this market failure.

Third, electricity producers using immature renewables perceive and internalize only a fraction of the benefits from their R&D efforts due to knowledge spillovers (Acemoglu *et al.*, 2012). Since producers do not take the full social benefit of their R&D investments into account, R&D investments and the resulting knowledge creation are below the socially optimal level. An R&D subsidy can correct this underprovision of public knowledge.

Fourth, the consumer perceives only a fraction of the benefits from her investments in energy efficiency (Allcott and Taubinsky, 2015; Gillingham *et al.*, 2009). As a consequence, she underinvests in energy efficiency measures, and electricity demand is above its socially optimal level. To address this market failure, subsidies can be granted to encourage investments in energy efficiency in the presence and the future.

3.2 Analytical model

The model has two time periods, indexed by $t \in \{1, 2\}$ as a subscript to all time-dependent variables.[3] Period t has a duration of n_t years, and second-period values are discounted by $0 < \delta < 1$.

3.2.1 Electricity supply

The set of all technologies i consists of fossil fuel-based technologies (superscript f) and immature renewable energy technologies (superscript r).

Power generation is costly, represented by C^{it}, a technology- and period-specific cost function that is convex and increasing in output. Fossil fuel-based technologies $f \in i$ emit technology-specific μ^f units of CO_2 per unit of generated electricity. Renewable energy technologies and nuclear power are assumed to have a CO_2 intensity of zero (i.e., $\mu^r = 0$), whereas fossil fuel technologies have positive CO_2 intensities.

Producers (generators) are price takers, and each generation owner optimally chooses the quantities q_1^i and q_2^i, given the effective producer price p_t^i that he receives. That price is a function of the equilibrium electricity price, denoted by p_t, and a set of policy instruments. Specifically, $p_t^i = p_t - \eta_t - \tau_t \mu^i + \omega_t^i$, where η_t is a tax on electricity generation, τ_t is a tax on CO_2 emissions, and ω_t^i is a technology-specific subsidy that will be applicable to renewable sources.

Fossil fuel technologies. The representative generator using fossil fuel f maximizes the present value of profits over the two periods:

$$\begin{gathered}\max_{\{q_1^f, q_2^f\}} \Pi^f, \\ \Pi^f = n_1[(p_1 - \eta_1 - \tau_1 \mu^f) q_1^f - C^{f1}(q_1^f) \\ +\delta n_2[(p_2 - \eta_2 - \tau_2 \mu^f) q_2^f - C^{f2}(q_2^f)\end{gathered}$$

Two first-order conditions result:

$$p_1 = C^{f1}_{q_1^f} + \eta_1 + \mu^f \tau_1 \quad (1)$$

$$p_2 = C^{f2}_{q_2^f} + \eta_2 + \mu^f \tau_2 \quad (2)$$

A lower index on a function denotes a partial derivative with respect to the indexed variable or time t as introduced before. The right-hand side of each equation represents marginal costs of generation, inclusive of policy costs. In the competitive profit maximum,

[3]Functions will retain the time index in a superscript to facilitate a concise representation of derivatives.

the marginal costs are equal to the electricity price.

Immature renewable technologies. Immature renewables (wind and solar) $r \in i$ differ in two important respects from fossil fuel technologies: First, they do not emit CO_2 when generating electricity. Second, over time, technical progress reduces generation costs via two mechanisms for knowledge creation.

The first mechanism depends on the accumulation of research via costly research efforts. The stock of cumulative R&D, H_1^r, is inherited in the first period for each technology r. Additional R&D, h^r created throughout period 1 is added to that stock, resulting in $H_2^r = H_1^r + n_1 h^r$, which contributes to lower second-period production costs. Technology-specific R&D expenditures $R^r(h^r)$ in period 1 are convex and increasing in the creation of new research.

The second mechanism reducing the generation costs of r is the accumulation of experience via learning-by-doing: First-period output q_1^r adds new experience to the technology-specific stock of learning $L_2^r = L_1^r + n_1 q_1^r$.

The second-period cost function is thus represented by $C^{r2}(q_2^r, L_2^r, H_2^r)$.[4] In addition to the standard assumptions of costs being increasing and convex with respect to output, we assume that the following relations hold for all immature renewables $r \in i$ in period 2:

$$C^{r2}_{L_2^r} < 0,\ C^{r2}_{H_2^r} < 0,$$
$$C^{r2}_{q_2^r H_2^r} = C^{r2}_{H_2^r q_2^r} < 0,\ C^{r2}_{L_2^r q_2^r} = C^{r2}_{q_2^r L_2^r} < 0,$$
$$C^{r2}_{L_2^r L_2^r} > 0,\ C^{r2}_{H_2^r H_2^r} > 0,\ C^{r2}_{L_2^r H_2^r} = C^{r2}_{H_2^r L_2^r} > 0$$

The first line states that total second-period production costs are decreasing in both kinds of knowledge. The second line affirms that marginal production costs are also decreasing with both cumulative experience and R&D. The third line recognizes that the returns to knowledge in terms of cost reductions are diminishing, whether that be from experience, research, or a combination of both.

An important question for the analysis is whether learning-by-doing and R&D are substitutes, in the sense that an increase in one, all else equal, will crowd out the other.[5] Note that studying the cross-partials in the cost function of R&D and learning-by-doing is not sufficient for the identification. Based on the decentralized behavior of renewable energy producers in the electricity market, which we will derive next, we will show in Appendix A.2 that whether learning and R&D are substitutes depends on the convexity of the cost function.

The representative renewable electricity producer maximizes profits over the two pe-

[4]In this partial equilibrium analysis, other costs not captured by the power sector, such as opportunity costs or crowding out of other investments by energy-specific R&D investment, are subsumed in the cost function.

[5]This definition differs slightly from that used in FN, who defined it relative to the knowledge production function, rather than the cost function.

riods by choosing electricity quantities, q_1^r, q_2^r, and R&D efforts, h^r.

$$\max_{\{q_1^r, q_2^r, h^r\}} \Pi^r,$$
$$\Pi^r = n_1[(p_1 + \omega_1^r - \eta_1)q_1^r - C^{r1}(q_1^r) - (1-\sigma)R^r(h^r)]$$
$$+\delta n_2[(p_2 + \omega_2^r - \eta_2)q_2^r - C^{r2}(q_2^r, L_2^r, H_2^r \mid \rho)]$$

Whereas the representative *industry* enjoys the full benefit of innovation (as seen in the profits equation), the representative *innovator* receives only the fraction ρ of the benefits of knowledge generation (which reveals itself in the first-order conditions). These spillovers lead to both learning and research market failures. If $\rho < 1$, private R&D investments and learning-by-doing are going to be sub-optimal from a social point of view. To address R&D underinvestment, policy makers can subsidize R&D expenditures with the subsidy rate σ. To correct the market failure of insufficient learning-by-doing, policy makers can incentivize learning with a technology-specific subsidy ω_t^r per unit of output. Output subsidies (such as in many feed-in tariff schemes) are often technology-specific, while most R&D support schemes such as tax incentives by EU member states or the EU's NER 300 program[6] are often technology-open.

The following first-order conditions describe the behavior of power generators taking into account insufficient property rights of knowledge creation.

$$C_{q_1^r}^{r1} = p_1 + \omega_1^r - \eta_1 - \rho\delta n_2 C_{L_2^r}^{r2} \quad (3)$$
$$C_{q_2^r}^{r2} = p_2 + \omega_2^r - \eta_2 \quad (4)$$
$$(1-\sigma)R_{h^r}^r = -\rho\delta n_2 C_{H_2^r}^{r2} \quad (5)$$

Again, lower indices on functions denote partial derivatives. The left-hand side of each equation depicts marginal costs, whereas the right-hand side depicts private marginal benefits. In equilibrium, marginal benefits and marginal costs are equalized. Note that $C_{L_2^r}^{r2}$ and $C_{H_2^r}^{r2}$ are negative so that both sides of all equations are positive.

Other technologies. Nuclear and hydro power are considered to provide baseload power with fixed capacity and are thus not affected by any of the market failures discussed in this paper. Without loss of generality, we ignore these two technologies in the algebraic treatment but will include them later in the numerical analysis.

3.2.2 Electricity demand

Let v_t describe the quantity of *electricity services consumed*, from which the consumer gets utility $u(v_t)$. The total quantity of *electricity consumed* in t is $\psi_t(e_t)v_t$, where $\psi_t(e_t)$ is the consumption rate per unit of electricity services. The costs of electricity services thus depend on both the price and the efficiency of its use. We interpret e_t as the

[6] A low-carbon R&D support scheme that is funded by revenues from auctioning EU ETS permits.

percentage reduction in energy intensity from costly efficiency improving measures in period t, by assuming that $\psi_t(e_t) = \psi_t^0 \exp(-e_t)$, where ψ_t^0 is the baseline energy intensity, so $\psi_t'(e_t) = -\psi_t(e_t)$. Energy efficiency measures are subject to convex investment costs $Z^t(e_t)$.

The representative consumer obtains money-metric utility from the consumption of electricity services net of the costs of energy and efficiency investments:

$$U = n_1 \left[u(v_1) - p_1\psi_1(e_1)v_1 - (1-\lambda_1)Z^1(e_1)\right]$$
$$-\delta n_2 \left[u(v_2) - p_2\psi_2(e_2)v_2 - (1-\lambda_2)Z^2(e_2)\right]$$

However, due to behavioral and other constraints, the consumer does not ultimately maximize this function. We assume that, when the consumer makes her efficiency investment decisions, she perceives only the fraction $\beta < 1$ of the full realized energy savings. Since the undervaluation of energy efficiency improvements causes a *demand-side market failure* and sub-optimal investments, a subsidy λ_t, which deducts a fraction of the investment costs, can be granted. Even though the consumer may undervalue the efficiency improvements ex-ante, once the investments are made, she benefits from the full savings. Thus, the undervaluation parameters will reveal themselves in the first-order conditions that govern the behavior of the consumer, but not in the welfare evaluation.

$$u_{v_1}(v_1) = p_1\psi_1(e_1) \tag{6}$$
$$u_{v_2}(v_2) = p_2\psi_2(e_2) \tag{7}$$
$$(1-\lambda_1)Z^1_{e_1} = \beta p_1 D_1 \tag{8}$$
$$(1-\lambda_2)Z^2_{e_2} = \beta p_2 D_2 \tag{9}$$

where $D_t = \psi_t(e_t)v_t$ is total equilibrium consumption in period t.

The first two equations show that marginal utility (expressed as the inverse of the first derivative of electricity demand with respect to utility) is equal to the electricity price and the consumption rate, respectively. The third and fourth lines show that the marginal costs of efficiency-improving measures need to be equal to the perceived marginal benefits elevated by the subsidy rate.

To close the model, total electricity supply must equal electricity demand D_t to clear the market in each period:

$$\sum_i q_t^i = \psi_t(e_t)v_t \equiv D_t \tag{10}$$

3.3 Equilibrium

The first order conditions (1) – (9) plus the market clearing condition (10) characterize the decentralized electricity market equilibrium. In addition, we add the emissions constraint, restricting total emissions over both periods to an intertemporal CO_2 emissions budget $\bar{M}$.

The market clearing CO_2 price path emerges endogenously such that $\bar{M} \geq \sum_t \sum_f n_t \mu^f q_t^f$ holds. Appendix A.1 shows how key variables respond to equilibrium changes.

3.4 Welfare

Equipped with this characterization of the electricity market, we can now compute the economic surplus at the equilibrium. This allows us then to pursue a novel contribution: to derive the welfare properties of specific energy policy instrument choices conditional to the availability of other instruments.

Since the environmental consequences are held constant by the CO_2 budget, our welfare measure, denoted by W, is simply total economic surplus: the sum of producer and consumer surplus and net revenues. The consumer's electricity bill paid to generators drops out as a pure transfer, since $p_t D_t = p_t \sum^i q_t^i$. By the same token, tax and subsidy payments are pure transfers between consumers or producers and taxpayers and they cancel out as well. The result is total discounted utility minus generation and investment costs. We can then denote the economic surplus as follows:

$$
\begin{aligned}
W = n_1 &\left(u(v_1) - Z^1(e_1) - \sum_f C^{f1}(q_1^f) - \sum_r C^{r1}(q_1^r) - \sum_r R^r(h^r) \right) \\
&+ \delta n_2 \left(u(v_2) - Z^2(e_2) - \sum_i C^{i2}(q_2^i) \right)
\end{aligned}
\tag{11}
$$

Because of the market failures, without policy intervention, the decentralized equilibrium is suboptimal. By totally differentiating the welfare function, we can derive the welfare implications of policy changes:

$$
\begin{aligned}
dW = n_1 &\left(u_{v_1} dv_1 - Z^1_{e_1} de_1 - \sum_f C^{f1}_{q_1^f} dq_1^f - \sum_r C^{r1}_{q_1^r} dq_1^r - \sum_r R^r_{h^r} dh^r) \right) \\
&+ \delta n_2 \left(u_{v_2} dv_2 - Z^2_{e_2} de_2 - \sum_i C^{i2}_{q_2^i} dq_2^i \right)
\end{aligned}
\tag{12}
$$

Next, we use the decentralized first-order conditions (1)–(9) to substitute for the expressions of marginal costs and marginal utility that must hold in equilibrium. Then, we use the fact that total changes in consumption equal total production changes: $\sum dq_t^i = dD_t$, and that total emissions are held fixed, so $n_1 \sum_f \mu^f dq_1^f = -n_2 \sum_f \mu^f dq_2^f$.

With these substitutions and much rearranging, we find the change in economic surplus can be expressed as

$$
\begin{aligned}
dW = {} & (\tau_1 - \delta\tau_2) n_1 \sum_f \mu^f dq_1^f \\
& + n_1 \sum_r \left((1-\rho)\delta n_2 (-C^{r2}_{L^r_2}) - \omega_1^r \right) dq_1^r \\
& - \omega_2^r \delta n_2 \sum_r dq_2^r \\
& + n_1 \delta n_2 \left(\frac{(1-\rho) - \sigma}{1-\sigma} \right) \sum_r (-C^{r2}_{H^r_2}) dh^r \\
& + n_1 p_1 D_1 \left(\frac{(1-\beta) - \lambda_1}{1-\lambda_1} \right) de_1 + \delta n_2 p_2 D_2 \left(\frac{(1-\beta) - \lambda_2}{1-\lambda_2} \right) de_2 \\
& + \eta_1 n_1 \sum_i dq_1^i + \eta_2 \delta n_2 \sum_i dq_2^i
\end{aligned}
\tag{13}
$$

The first line in (13) considers the welfare effects of CO_2. An increase in the first-period emissions (and a corresponding decrease in second-period emissions) is welfare improving if the discounted price of emissions is higher in the first period than in the second period.

The second line reveals that increases in first-period renewable generation improve welfare if the production subsidy is less than the spillovers from learning-by-doing. The third line recognizes that there are no spillover benefits from additional renewable generation in the second period, just additional subsidy costs.

The fourth line describes the welfare changes from induced changes in knowledge creation: Additional knowledge-generating R&D enhances welfare if σ is less than the spillover rate $(1-\rho)$.

Likewise, the fifth line reveals that in equilibrium, additional energy efficiency improvements are welfare enhancing as long as the subsidy is less than the degree of undervaluation $(1-\beta)$.

The sixth line shows the welfare effect of electricity taxes: ceteris paribus, a positive tax leads to an increasing welfare differential if electricity generation is increasing. Note that we later show that in the first-best $dW = 0$, so η_t must be zero in the first-best.

3.5 First-best policy portfolio

The first-best policy response to the respective externalities is their full internalization. The marginal social benefits of investments in energy efficiency and R&D as well as the social marginal benefits of learning-by-doing must equal their marginal costs. Simultaneously, the cumulative emissions target over both periods must be met. The policy instruments are chosen such that the decentralized market equilibrium system described by equations (1)–(10) yields the first-best optimum:

$$\tau_1^* = \delta\tau^2 \tag{14}$$
$$\omega_1^{r*} = (1-\rho)\delta n_2(-C_{L_2^r}^{r2}) \tag{15}$$
$$\omega_2^{r*} = 0 \tag{16}$$
$$\sigma^* = 1-\rho \tag{17}$$
$$\lambda_t^* = 1-\beta \tag{18}$$
$$\eta_t^* = 0 \tag{19}$$

The four policy instruments used in the first-best (indicated by asterisks) correct the four market failures. Equation (14) describes how CO_2 prices are set to meet the exogenously given emissions target. CO_2 prices float endogenously in the policy scenarios, and cost-effectiveness requires that the CO_2 price rises at the discount rate. Equation (15) describes how a first-best renewable production subsidy internalizes the learning-by-doing spillovers that are not taken into account by individual producers. The second-period output subsidy is zero since renewable technologies become established without having significant further cost-reduction potential.

In equation (17), an R&D subsidy rate σ^* equal to the unappropriated share of innovation benefits internalizes the social benefit of R&D for each technology. In equation (18), subsidies for energy efficiency investments at the rates λ_t^* internalize non-perceived benefits of energy efficiency improvements. In the absence of other market failures, there is no economic reason for using further policy instruments such as an electricity tax.

When we substitute the first-best policies into the relation of policy changes on the welfare change (13), we obtain $dW = 0$, so welfare cannot be improved with additional policy adjustments. As long as all policy instruments are set optimally, any additional policy intervention will be distortionary and result in a welfare loss.

4 Analytical derivation of second-best policies

If not all first-best instruments are available and not all market failures are addressed, we know from second-best theory that leaving the remaining instruments at their first-best levels cannot characterize a welfare optimum. If, for example, the utilization of the R&D subsidy is politically or technically restricted, the welfare maximizing second-best choice of the remaining instruments—the renewable output subsidy, the energy efficiency subsidies or an electricity tax—will deviate from the first-best choice. In the following, we will identify second-best instrument adjustments and see how they deviate from their first-best levels.

These adjustments need to balance the welfare gains of lessening one distortion—addressing an uninternalized market failure—against increasing another distortion—deviating from the first-best internalization of another market failure. Most second-best adjustments need to target their additional goal rather indirectly, such as through changes in equilibrium prices, sometimes across time periods. The conditions derived in Appendix A.1 will be instrumental for identifying these tradeoffs.

Let the superscript "$***|X$" denote the third-best case in which no further adjustments are made (from first-best policy instrument levels) following a restriction on instrument X, while "$**|X$" will denote the second-best outcome after the re-adjustment. Throughout this section, we focus on the second-best adjustment of a single policy instrument (which can be available in one or two model periods, depending on the instrument) at a time.[7] The remaining policy instruments that are not under scrutiny are kept constant at their first-best levels. This assumption will be relaxed in the second part of the numerical analysis with some simultaneous restrictions and then simultaneous adjustments of all remaining instruments available.

We can re-express (13) for our second-best situations using the optimal policy expressions (and noting that from (5), $\delta n_2(-C^{r2}_{H^r_2})/(1-\sigma) = R^r_h/\rho$):

$$\begin{aligned} dW = {} & n_1 \sum_r \left(\omega_1^{r*} - \omega_1^r\right) dq_1^r - \omega_2^r \delta n_2 \sum_r dq_2^r \\ & + n_1 \left(\frac{\sigma^* - \sigma}{\rho}\right) \sum_r R^r_{h^r} dh^r \\ & + n_1 p_1 D_1 \left(\frac{\lambda^* - \lambda_1}{1-\lambda_1}\right) de_1 + \delta n_2 p_2 D_2 \left(\frac{\lambda^* - \lambda_2}{1-\lambda_2}\right) de_2 \\ & + \eta_1 n_1 \sum_i dq_1^i + \eta_2 \delta n_2 \sum_i dq_2^i \end{aligned} \tag{20}$$

In all cases, the same emissions target will be met, and CO_2 pricing will follow the optimal path ($\tau_1 = \delta\tau_2$), such as through intertemporal emissions trading. The restriction of a policy lever always raises overall abatement costs. The CO_2 price reflects this by adjusting upward to compensate for lost abatement. Thus, the instruments deviate from their optimal levels not to make up for lost abatement; rather, they deviate to re-optimize incentives distorted by the unaddressed market failure. Hence, the first line in (13) drops out, and we are left with welfare change as a function of the deviations from optimal policies (recalling that $\omega_2^{r*} = \eta_{t*}$).

4.1 Insufficient energy efficiency subsidies

The potential for energy savings to deliver large emissions reductions is well known (Dietz *et al.*, 2009). The EU takes this into account by setting a target of 20% (27%) energy savings for the year 2020 (2030) compared with the projected energy use in this year. However, the EU-wide target has not been translated into binding targets for the member states. Only a fragmented set of single measures (such as the controversial ban on conven-

[7] Note that the adjustments response to a situation where a market failure is marginally undercorrected. The numerical simulations show that the theoretically predicted adjustments also hold for larger deviations from the first-best.

tional light bulbs) has been implemented but no common policy instrument addressing the insufficient uptake of efficiency-improving technologies. Against this background, we start our analysis with a scenario in which, despite insufficient efficiency-improving investments in the decentralized market equilibrium, efficiency subsidies are restricted, such that $0 \leq \lambda_t < \lambda_t^*$ with $t = \{1, 2\}$.

Relative to the first-best situation, lower energy efficiency subsidies mean that less abatement occurs through conservation. Hence, in equilibrium, electricity consumption, electricity prices, and CO_2 prices will all rise.

Let us define $\Delta_t^\lambda \equiv ((1-\beta)-\lambda_t))/(1-\lambda_t)$ as the under-internalization factor for energy-efficiency. Keeping all other policy instruments at their first-best level, equation (20) simplifies to $dW = n_1 p_1 D_1 \Delta_1^\lambda de_1 + \delta n_2 p_2 D_2 \Delta_2^\lambda de_2 \neq 0$. This describes a third-best situation.

When the undervaluation of energy efficiency is not fully internalized, a policy adjustment $d\Psi$ of the set of available instruments creates additional welfare if it induces additional energy efficiency investments ($de_t/d\Psi > 0$). At the same time, deviations of available instruments from first-best levels have detrimental effects on already corrected market failures and hence reduce welfare. Hence, positive welfare effects can be achieved as long as the former effect dominates the latter. This means that policy makers can shift the economy from a third- to a second-best equilibrium. Given the set of available policy levers, policy makers can adjust each lever such that welfare reaches an optimum, in which $dW/d\Psi = 0$ (and $d^2W/d\Psi^2 < 0$). This reasoning will guide us through all the following second-best adjustment analyses.

Second-best electricity taxes to correct for the undervaluation of energy efficiency improvements.

An electricity tax η_t is not part of the first-best policy portfolio. If efficiency investments cannot be induced directly, however, a straightforward vehicle to incentivize efficiency improvements is a higher electricity price. A tax on electricity generation reduces supply and raises prices. Positive electricity taxes ($\eta_t > 0$) thus encourage additional investments in efficiency.However, such taxes also come with welfare costs due to supply distortions.

Here, as in subsequent sections, we will solve for the optimal second-best levels of a given policy, assuming all others are held at their first-best levels, except for the exogenously restricted policy.

In the case of adjusting electricity taxes, we begin with the ceteris paribus assumption that $\tau_1 = \delta\tau^2$, $\omega_1^r = \omega_1^{r*}$, $\omega_2^r = \omega_2^{r*}$, and $\sigma = \sigma^*$, while $\lambda_t < \lambda_t^*$, so $\Delta_t^\lambda > 0$ for at least one of $t \in \{1, 2\}$. Note also that $\sum_i dq_1^i = dD_t$, from the demand-supply equilibrium. Simplifying the change in economic surplus (20), we obtain

$$dW = n_1 p_1 D_1 \Delta_1^\lambda de_1 + \delta n_2 p_2 D_2 \Delta_2^\lambda de_2 + n_1 \eta_1 dD_1 + \delta n_2 \eta_2 dD_2 \tag{21}$$

Next, we derive for each period t the second-best (indicated by two asterisks) electricity taxes $\eta_1^{**|\lambda}$ and $\eta_2^{**|\lambda}$ as a response to insufficient energy efficiency subsidies λ_1 and λ_2. The electricity tax policy includes two instruments, one in each time period.

Let us define the elasticities $\varepsilon_{\eta_t}^{e_s} \equiv \frac{de_s}{e_s}\frac{\eta_t}{d\eta_t}$ and $\varepsilon_{\eta_t}^{D_s} \equiv \frac{dD_s}{D_s}\frac{\eta_t}{d\eta_t}$; $\varepsilon_{\eta_t}^{e_s}$ represents the elasticity of efficiency-improving investments with respect to a change in the electricity tax in t, while $\varepsilon_{\eta_t}^{D_s}$ characterizes the total supply reaction to a change in η_t.

An electricity tax in a given period raises consumer prices and lowers total generation and consumption in that period, both directly and indirectly through efficiency improvements, so $\varepsilon_{\eta_t}^{e_t} > 0$ and $\varepsilon_{\eta_t}^{D_t} < 0$.[8] Electricity taxes will also have cross-period effects, due to the intertemporal linkages of knowledge investments and also emission price adjustments. The former tend to drive up equilibrium electricity prices in the other period, while the latter put downward pressure on prices.[9] The net effect may be unclear; however, we may assume that the (indirect) cross-period effect, whatever its sign, is smaller than the (direct) own-period effect: i.e., $|\varepsilon_{\eta_t}^{e_t}| > |\varepsilon_{\eta_t}^{e_s}|$ and $|\varepsilon_{\eta_t}^{D_t}| > |\varepsilon_{\eta_t}^{D_s}|$.

We can now express equation (21) with respect to marginal tax adjustments $d\eta_1$ as

$$dW = \left(n_1 p_1 D_1 \Delta_1^{\lambda} \varepsilon_{\eta_1}^{e_1} e_1 + \delta n_2 p_2 D_2 \Delta_2^{\lambda} \varepsilon_{\eta_1}^{e_2} e_2 + \eta_1 n_1 D_1 \varepsilon_{\eta_1}^{D_1} + \eta_2 \delta n_2 D_2 \varepsilon_{\eta_1}^{D_2}\right) \frac{d\eta_1}{\eta_1} \tag{22}$$

The whole expression is solved for $\frac{dW}{d\eta_1}$, multiplied by $\eta_1 \neq 0$ and set equal to zero. Then, η_1 can be adjusted until $\frac{dW}{d\eta_1} = 0$ holds and welfare cannot be further improved. Hence, solving for $\eta_1^{**|\lambda}$ yields, ceteris paribus, the second-best choice of $\eta_1^{**|\lambda}$, given η_2:

$$\eta_1^{**|\lambda} = \eta_1^* + \underbrace{\frac{n_1 p_1 D_1 \Delta_1^{\lambda} \varepsilon_{\eta_1}^{e_1} e_1 + \delta n_2 p_2 D_2 \Delta_2^{\lambda} \varepsilon_{\eta_1}^{e_2} e_2}{-n_1 \varepsilon_{\eta_1}^{D_1} D_1}}_{\eta_1^{adj|\lambda}} + \underbrace{\eta_2 \frac{\delta n_2 \varepsilon_{\eta_1}^{D_2} D_2}{-n_1 \varepsilon_{\eta_1}^{D_1} D_1}}_{\eta_1^{int}} \tag{23}$$

The first term is the first-best electricity tax, which as we know from (19) is $\eta_t^* = 0$. The second term $\eta_1^{adj|\lambda}$ is the primary adjustment—the first-order response of a second-best tax to below-optimal choices of λ_1 and λ_2. The numerator containing $\varepsilon_{\eta_1}^{e_t} > 0$ describes the positive efficiency investment response of the representative consumer to the tax-induced price increase. The denominator containing $\varepsilon_{\eta_1}^{D_1} < 0$ describes the negative supply and demand response to the tax. Thus $\eta_1^{adj|\lambda}$ is positive and increasing in Δ_t^{λ}; so choices of λ_t below $(1-\beta)$ result in larger values of $\eta_1^{**|\lambda}$. Furthermore, the larger the efficiency response relative to the supply response, the higher will be the second-best tax rate.

The interaction term η_1^{int} reflects the presence of a supply distortion when $\eta_2 \neq 0$ (and

[8]As we know from (8) and (9), $de_t/dp_t > 0$ with well-behaved demand. Meanwhile, from (1) – (4), $dp_t/d\eta_t > 0$. I.e., within each period, the incidence of an electricity tax falls partly on consumers, who respond by reducing energy consumption and improving efficiency.

[9]A tax in the second period reduces demand for renewable generation, which decreases the return of learning-by-doing, and thus also reduces generation in period 1, driving up the equilibrium electricity prices.Similarly, electricity taxes in period 1 reduce demand for renewable generation, which reduces learning and raises costs in the second period, driving up the equilibrium electricity prices.On the other hand, less consumption in one period means fewer emissions then, so to meet the same target the emissions price will fall, tending to lower prices.

$\varepsilon_{\eta_1}^{D_2} \neq 0$), which can be exacerbated when raising η_1. It follows the sign of $(\eta_2 \varepsilon_{\eta_1}^{D_2})$.

A similar expression holds for $\eta_2^{**|\lambda}$ as well. Following the same strategy, we obtain the analogous result for the second-period tax:

$$\eta_2^{**|\lambda} = \underbrace{\frac{n_1 p_1 D_1 \Delta_1^{\lambda} \varepsilon_{\eta_2}^{e_1} e_1 + \delta n_2 p_2 D_2 \Delta_2^{\lambda} \varepsilon_{\eta_2}^{e_2} e_2}{-\delta n_2 \varepsilon_{\eta_2}^{D_2} D_2}}_{\eta_2^{adj|\lambda}} + \underbrace{\eta_1 \frac{n_1 \varepsilon_{\eta_2}^{D_1} D_1}{-\delta n_2 \varepsilon_{\eta_2}^{D_2} D_2}}_{\eta_2^{int}} + \eta_2^* \tag{24}$$

where $\eta_2^* = 0$, $\eta_2^{adj|\lambda} > 0$, and η_2^{int} carries the same sign as $(\eta_1 \varepsilon_{\eta_2}^{D_1})$, given the corresponding properties as described above.

If only one of these instruments may be adjusted, we can clearly state that the electricity tax at hand should be adjusted upward.

Proposition 1. *In the second best, considering the adjustment of the electricity tax in a single period, below-optimal energy efficiency subsidies require ceteris paribus a higher (positive) electricity tax compared with the first-best.*

Proof. Setting $\eta_2 = 0$ as in the first-best (19) yields $\eta_2^{int} = 0$. Thus, if only η_1 can be adjusted, ceteris paribus, $\eta_1^{**|\lambda} - \eta_1^* = \eta_1^{adj|\lambda} > 0$. Similarly, if only η_2 can be adjusted, while $\eta_1 = 0 = \eta_1^{int}$, then $\eta_2^{**|\lambda} - \eta_2^* = \eta_2^{adj|\lambda} > 0$. □

In Appendix A.3 we discuss more generally how electricity taxes can be adjusted together in the second-best. From (23) and (24), we note that $\varepsilon_{\eta_t}^{D_s} = 0$ for $s \neq t$ also implies that $\eta_t^{int} = 0$ and $\eta_t^{**} = \eta_t^{adj}$. With non-zero cross-period demand effects, the second-best electricity taxes will deviate from this simple adjustment, with the net effect depending on the relative strength of the demand shifts. We leave the size of such compensatory adjustments to the numerical analysis in section 5. However, in Appendix A.3 we show that if cumulative demand (or its undervaluation) is much larger in one period than in the other, the second-best tax may be positive in that period and negative in the other, in order to compensate for an excess intertemporal price effect. However, for the second-best electricity tax to be adjusted downward in one period, it must be that the tax in the other period is adjusted upward. Thus, the second-best electricity tax must be higher in at least one period compared with the first-best.

In the following proposition, we consider the effect of undervaluation in a single period on the optimal simultaneous adjustment of electricity taxes in both periods. It reveals that the direct effect is strongest for the period in which the undervaluation occurs.

Proposition 2. *In the second-best, below-optimal energy efficiency subsidies in period t require ceteris paribus a higher (positive) electricity tax in that period, compared with the first-best. The adjustment to the electricity tax in the other period depends on the relative strength of demand and efficiency cross-price elasticities.*

Proof. Suppose the suboptimal policy is restricted to period t. Simplifying and solving

(23) and (24) simultaneously, we get:

$$\eta_1^{**}|_{\Delta_2^\lambda=0} = e_1 p_1 \Delta_1^\lambda \left(\frac{\varepsilon_{\eta_1}^{D_2}\varepsilon_{\eta_2}^{e_1} - \varepsilon_{\eta_2}^{D_2}\varepsilon_{\eta_1}^{e_1}}{\Xi} \right) > 0 \quad (25)$$

$$\eta_2^{**}|_{\Delta_2^\lambda=0} = e_1 p_1 \Delta_1^\lambda \frac{n_1 D_1}{\delta n_2 D_2} \left(\frac{\varepsilon_{\eta_2}^{D_1}\varepsilon_{\eta_1}^{e_1} - \varepsilon_{\eta_1}^{D_1}\varepsilon_{\eta_2}^{e_1}}{\Xi} \right) \quad (26)$$

$$\eta_1^{**}|_{\Delta_1^\lambda=0} = e_2 p_2 \Delta_2^\lambda \frac{\delta n_2 D_2}{n_1 D_1} \left(\frac{\varepsilon_{\eta_1}^{D_2}\varepsilon_{\eta_2}^{e_2} - \varepsilon_{\eta_2}^{D_2}\varepsilon_{\eta_1}^{e_2}}{\Xi} \right) \quad (27)$$

$$\eta_2^{**}|_{\Delta_1^\lambda=0} = e_2 p_2 \Delta_2^\lambda \left(\frac{\varepsilon_{\eta_2}^{D_1}\varepsilon_{\eta_1}^{e_2} - \varepsilon_{\eta_1}^{D_1}\varepsilon_{\eta_2}^{e_2}}{\Xi} \right) > 0 \quad (28)$$

where $\Xi \equiv \varepsilon_{\eta_2}^{D_2}\varepsilon_{\eta_1}^{D_1} - \varepsilon_{\eta_1}^{D_2}\varepsilon_{\eta_2}^{D_1} > 0$, Since own-period elasticities are larger than cross-period elasticities, all denominators are positive ($\Xi > 0$). For the same reason, the numerators in (25) and (28) are both positive (recalling that $\varepsilon_{\eta_t}^{e_t} > 0$ and $\varepsilon_{\eta_t}^{D_t} < 0$). The numerators in (26) and (27) depend on the relative cross-period price elasticities. Thus, the response to undervaluation in the first (second) period will necessarily be an increase in η_1^{**} (η_2^{**}), while the adjustment to η_2^{**} (η_1^{**}) is ambiguous. □

Second-best renewable production subsides to correct for undervaluation of energy efficiency improvements.

If power generation cannot be taxed, reducing renewable production subsidies might be the only adjustment option at hand. Output subsidies are often technology-specific: in Germany (under the Renewable Energy Sources Act), for example, subsidies differ across renewable technologies.

As a result, this policy adjustment has multiple effects—over time and across technologies—which may interact with each other. We begin by applying the same procedure as outlined previously: Using equation (20), we set the available instruments to their first-best levels with the exception of the output and energy efficiency subsides and solve the optimality condition $dW/d\omega_t^r = 0$ for $\omega_t^{r**|\lambda}$. The ceteris paribus assumption is that $\tau_1 = \delta\tau^2$, $\eta_1 = 0$, $\eta_2 = 0$, and $\sigma = \sigma^*$, while $\lambda_t < \lambda_t^*$, so $\Delta_t^\lambda > 0$ for at least one of $t \in \{1, 2\}$. Simplifying the change in economic surplus, we obtain

$$dW = n_1 p_1 D_1 \Delta_1^\lambda de_1 + \delta n_2 p_2 D_2 \Delta_2^\lambda de_2 + n_1 \sum_r \left(\omega_1^{r*} - \omega_1^r\right) dq_1^r - \delta n_2 \sum_r \omega_2^r dq_2^r \quad (29)$$

Following the same procedure as before, let us define the elasticities $\varepsilon_{\omega_t^r}^{e_s} \equiv \frac{de_s}{e_s}\frac{\omega_t^r}{d\omega_t^r}$ and $\varepsilon_{\omega_t^j}^{q_s^r} \equiv \frac{dq_s^r}{q_s^r}\frac{\omega_t^j}{d\omega_t^j}$. Substituting these elasticities into equation (29) and solving $dW/d\omega_t^r = 0$, we get

$$\omega_t^{r**|\lambda} = \omega_t^{r*} + \underbrace{\left(-n_1 p_1 D_1 \Delta_1^{\lambda}(-\varepsilon_{\omega_t^r}^{e_1})e_1 - \delta n_2 p_2 D_2 \Delta_2^{\lambda}(-\varepsilon_{\omega_t^r}^{e_2})e_2\right) / (\tilde{n}_t q_t^r \varepsilon_{\omega_t^r}^{q_t^r})}_{\omega_t^{r,adj|\lambda}} + \omega_t^{r,int} \tag{30}$$

where

$$\omega_t^{r,int} = \left((\omega_{s\neq t}^{r*} - \omega_{s\neq t}^{r})(\tilde{n}_s q_s^r \varepsilon_{\omega_t^r}^{q_s^r}) + \sum_{j\neq r} \sum_{s=\{1,2\}} (\omega_s^{j*} - \omega_s^j)(\tilde{n}_s q_s^j \varepsilon_{\omega_t^r}^{q_s^j}) \right) / (\tilde{n}_t q_t^r \varepsilon_{\omega_t^r}^{q_t^r}) \tag{31}$$

using $\tilde{n}_t = n_1$ for $t = 1$ and $\tilde{n}_t = \delta n_2$ for $t = 2$.

The first term is the main adjustment, $\omega_t^{r,adj|\lambda} < 0$. Since, as outlined in Appendix A.1, $de_t/dp_t > 0$ and $dp_s/d\omega_t^r < 0$, we know that $\varepsilon_{\omega_t^r}^{e_s} < 0$; i.e., by depressing electricity prices, renewable subsidies (in any period) diminish efficiency investments.[10] This must be balanced against the effect of an output subsidy adjustment on output and learning, captured in the denominator by $\varepsilon_{\omega_t^r}^{q_t^r}$. Underprovided efficiency investments are thus expanded at the margin by decreasing renewable energy subsidies.

The interaction term $\omega_1^{r,int}$ has multiple components, since renewable energy subsidy policy has up to $N^r \times 2$ instruments. First, the own-technology cross-period elasticity is positive, since the learning effect ensures that a higher subsidy in one period encourages more production in the other period: $\varepsilon_{\omega_1^r}^{q_2^r} > 0$. Thus, if the second-period subsidy ω_2^r is negative, this effect will attenuate the (otherwise downward) second-best adjustment in the first period. The remaining term reflects the crowding-out effect between competing renewable energy sources. Since subsidies for one technology tend to depress prices and output of the others, $\varepsilon_{\omega_1^r}^{q_t^j} < 0$ for $j \neq r$. Thus, this competition effect will tend to reinforce the downward adjustment effect if subsidies in competing sources are below the first-best, since the resulting price increase can help offset some underprovision of those technologies.[11]

Proposition 3. *In the second-best, below-optimal energy efficiency subsidies require ceteris paribus a decrease in the renewable production subsidy for a given immature renewable energy technology in a given period compared with the first-best.*

Proof. If $\omega_s^j = \omega_s^{j*}$ for $j \neq r$ and $\omega_{s\neq t}^r = \omega_{s\neq t}^{r*}$, then $\omega_t^{r,int} = 0$ and from (30) $\omega_t^{r**|\lambda} - \omega_t^{r*} = \omega_t^{r,adj|\lambda} < 0$. □

Intuitively, electricity prices need to rise to create a stimulus for the consumer's in-

[10] This holds both within and across periods: an increase in the subsidy in period 1 for either renewable energy source drives down costs and increases total supply in that period, lowering the equilibrium retail price. Furthermore, increased learning in period 1 carries over to lower costs and prices in period 2. Similarly, a higher subsidy in period 2 lowers costs and retail prices and increases renewable production in that period. That increased production increases the value to additional learning in the first period, driving down the electricity price in this period.

[11] With four or more instruments, the simultaneous solution is analytically intractable, but it will be done numerically later.

vestments in energy efficiency. Thus, downward adjustments of the renewable output subsidies (generally resulting in a renewable tax in the second period) are required to restrict power supply. Since the loss of some CO_2-free electricity will tend to increase abatement costs and hence CO_2 prices will rise, this will reinforce this supply effect on the price. In the second-best, these marginal costs balance the marginal benefit of higher electricity prices for energy efficiency. Compared with the electricity tax, however, output subsidies affect renewable energies only, hence the subsidy lever is less powerful.

Second-best R&D subsidy to correct for the undervaluation of energy efficiency improvements.

Suppose now that we want to adjust the R&D subsidy to correct for the undervaluation of energy efficiency improvements. Simplifying the change in economic surplus (20), yields

$$dW = n_1 p_1 D_1 \Delta_1^\lambda de_1 + \delta n_2 p_2 D_2 \Delta_2^\lambda de_2 + n_1 \sum_r R_h^r dh^r \left(\sigma^* - \sigma\right)/\rho \tag{32}$$

Let us define $\varepsilon_\sigma^{e_t} \equiv \frac{de_t}{e_t} / \frac{d\sigma}{\sigma}$. Substituting and solving for the second-best subsidy, we see that

$$\sigma^{**|\lambda} = \sigma^* + \rho \left(\frac{n_1 p_1 D_1 \Delta_1^\lambda e_1 \varepsilon_\sigma^{e_1} + \delta n_2 p_2 D_2 \Delta_2^\lambda e_2 \varepsilon_\sigma^{e_2}}{\sum_r n_1 h^r R_h^r \varepsilon_\sigma^{h^r}} \right) \tag{33}$$

Starting from the first-best R&D subsidy level, welfare will be increasing if the adjustment enhances energy efficiency provision. Since the research subsidy is not differentiated across time or technologies, the second-best subsidy has no interaction term, only an adjustment term. The denominator of this term reflects the costs of additional R&D and is positive. The numerator inside the brackets is the marginal benefit from the energy efficiency response, which has in theory an ambiguous sign. Clearly, $de_2/d\sigma < 0$: The R&D subsidy enhances knowledge creation h^r, which increases second-period electricity supply q_2^r via technical progress and decreases the electricity price resulting in lower energy efficiency investments e_2. Thus, when the marginal benefit of efficiency in the second period is larger, σ must be adjusted downward. However, $de_1/d\sigma$ has an ambiguous sign: when R&D and learning are substitutes, the additional knowledge and cost reductions created by σ lower the return to q_1^r. At the same time, cheaper renewable energy in the future lowers climate compliance costs and the CO_2 price path τ. The former effect tends to increase first-period prices and increase e_1, while the latter effect tends to lower prices in both periods and decrease e_1. If the crowding out of learning dominates, and the marginal benefit of efficiency is stronger in the first period, the second-best response may be to increase R&D to restrict renewable energy supply in that period.

Note that the degree of adjustment is stronger the the lower are knowledge spillovers. We summarize this result in the following proposition:

Proposition 4. *In the second-best, below-optimal energy efficiency subsidies in the second period require ceteris paribus a lower R&D subsidy for immature renewable energy tech-*

nologies compared with the first-best. Below-optimal energy efficiency subsidies in the first period can require ceteris paribus a higher R&D subsidy if sufficient learning is crowded out.

4.2 Insufficient R&D subsidies

Next, consider the case, in which the policy failure leads to insufficient subsidies to R&D, such that $0 \leq \sigma < \sigma^*$. For example, in the EU, support for R&D in renewable energy technologies is limited and fragmented (Zachmann *et al.*, 2014). In this situation R&D spillovers are under-internalized, and policies that incentivize R&D investments create added value at the margin.

Let us define $\Delta^\sigma \equiv ((1-\rho)-\sigma)/\rho$ as the under-internalization factor for R&D. Keeping all other policy instruments at their first-best level, equation (13) using (5) simplifies to $dW = n_1 \Delta^\sigma \sum_r R_h^r dh^r \neq 0$, a third-best situation.

Relative to the first-best, lower R&D subsidies mean less renewable generation in the second period. Hence, in equilibrium, electricity and CO_2 prices will rise, driving up energy efficiency investment and driving down electricity consumption.

Second-best renewable production subsides to correct for insufficient R&D efforts.

Although the economic intuition is basically the same as in section 4.1, the interdependence of R&D and learning creates additional complexity.[12]

Consider the effect of a subsidy to technology r. Let us define $\varepsilon^{h^r}_{\omega^j_t} \equiv \frac{dh^r}{h^r}\frac{\omega^j_t}{d\omega^j_t}$. The effects of second-period changes are straightforward: $\varepsilon^{h^r}_{\omega^r_2} > 0$, but $\varepsilon^{h^r}_{\omega^j_2} < 0$ for $j \neq r$. In other words, the subsidy to production of one technology in the second period crowds in its own R&D but crowds out that of other technologies, as more output drives down prices in period 2.

We consider that R&D and learning-by-doing act as *substitutes*, so $\varepsilon^{h^r}_{\omega^r_1} < 0$: in the case where *lower* output subsidies ω^r_1 are granted in the first period, *first-period* output q^r_1 and learning are reduced, thus extending the scope for technical progress via knowledge creation h^r. The rationale is that R&D and learning-by-doing both contribute to knowledge production, which exhibits decreasing marginal benefits. Less first-period renewable production also has a reinforcing effect of driving up CO_2 prices, making second-period renewable production more valuable (and offsetting secondary losses in competitiveness due to less learning). The essence of our knowledge substitutability assumption is that this primary effect from decreasing marginal benefits dominates.

The substitution effect also means that an increase in the subsidy to one technology in period 1 tends to crowd out production by other technologies in that period and thereby

[12] Throughout this subsection, we assume again that technologies r can be addressed independently by economic policy so that we can derive second-best conditions for each r, taking into account the r-specific marginal power generation cost and the potential to reduce it via technical progress.

crowd in underprovided R&D in other technologies. I.e., $\varepsilon^{h^j}_{\omega^r_1} > 0$, for $j \neq r$. Secondary effects may limit the scope of this response, as the additional learning supported by the subsidy tends to expand second-period production using r, crowding out production by other technologies in period 2 and lowering prices. These effects would feed back to lower the return to R&D in technology j; however, we assume that the primary direct effect dominates.

Using our elasticity definitions and the same procedure as before, we solve for the technology-specific second-best output subsidy for a given period:

$$\omega^{r**|\lambda}_t = \omega^{r*}_t + \underbrace{\Delta^{\sigma} \frac{n_1 \left(R^r_h h^r \varepsilon^{h^r}_{\omega^r_t} + \sum_{j \neq r} R^j_h h^j \varepsilon^{h^j}_{\omega^r_t} \right)}{\tilde{n}_t q^r_t \varepsilon^{q^r_t}_{\omega^r_t}}}_{\omega^{r,adj|\sigma}_t} + \omega^{r,int}_t \tag{34}$$

Recall that $\omega^{r,int}_t$ reflects the tradeoffs in the subsidy costs as output shifts across time and technologies, as previously discussed the case of second-best renewable production subsides that correct for the undervaluation of energy efficiency improvements. As before, $\omega^{r,int}_t$ may attenuate or accentuate the adjustment, but if all other subsidies remain at their first-best levels, $\omega^{r,int}_t = 0$. The primary adjustment factor is $\omega^{r,adj|\sigma}_t$, which is proportional to the underinternalization rate, Δ^{σ}.

Proposition 5. *In the second-best, a below-optimal R&D subsidy requires ceteris paribus a higher second-period output subsidy for a given immature renewable energy technology compared with the first-best, unless the production shifting crowds out too much R&D from other technologies.*

Proof. Ceteris paribus, $\omega^{r,int}_2 = 0$, so $\omega^{r**|\lambda}_2 - \omega^{r*}_2 = \omega^{r,adj|\sigma}_2 > 0$ if $R^r_h h^r \varepsilon^{h^r}_{\omega^r_2} > \sum_{j \neq r} R^j_h h^j (-\varepsilon^{h^j}_{\omega^r_2})$. ☐

We have established that $\varepsilon^{h^r}_{\omega^r_2} > 0$, because by enhancing second-period output, the second-period output subsidy raises the value of R&D. However, by crowding out second-period output from other technologies and thus the return to their R&D it is possible that $\varepsilon^{h^j}_{\omega^r_2} < 0$ for $j \neq r$. This latter effect can dominate if, for example, technology r is already mature and requires little R&D, while R&D in the other technologies is more important. More generally, one can expect bigger adjustments in subsidies to technologies for which R&D is more responsive and more important. In the numerical results, we will see this case comparing solar to wind energy.

Proposition 6. *In the second-best, a below-optimal R&D subsidy requires ceteris paribus a lower first-period output subsidy for a given renewable technology compared with the first-best, unless the production shifting crowds out too much R&D from other technologies.*

Proof. Ceteris paribus, $\omega^{r,int}_1 = 0$, so $\omega^{r**|\lambda}_1 - \omega^{r*}_1 = \omega^{r,adj|\sigma}_1 < 0$ if $R^r_h h^r (-\varepsilon^{h^r}_{\omega^r_1}) - \sum_{j \neq r} R^j_h h^j (\varepsilon^{h^j}_{\omega^r_1}) > 0$. ☐

Given that R&D and learning-by-doing are substitutes, $\varepsilon^{h^r}_{\omega^r_1} < 0$ and $\varepsilon^{h^j}_{\omega^r_1} > 0$. The ambiguity in the sign of the elasticities occurs because we have a single R&D policy, not a technology-specific one. If only one technology had its spillovers uninternalized, the direction of adjustment of a single policy would be unambiguous. However, when R&D spillovers are underinternalized for all technologies, one must balance the equilibrium effects on R&D in all technologies.

Second-best electricity taxes to correct for insufficient R&D efforts.

Electricity taxes are not technology-specific; they affect all generators in the same way, regardless of their CO_2 intensities or cost reduction potential. This difference will change some expected outcomes.

Following the earlier procedures, we solve for the second-best choice of $\eta^{**|\sigma}_t$:

$$\eta^{**|\lambda}_t = \eta^*_t + \underbrace{\Delta^\sigma \frac{n_1 \sum_r R^r_h h^r \varepsilon^{h^r}_{\eta_t}}{\tilde{n}_t(-\varepsilon^{D_t}_{\eta_t}) D_t}}_{\eta^{adj|\sigma}_t} - \eta^{int}_t \qquad (35)$$

An electricity tax in period 2 dampens total demand and thus tends to lower the return to R&D, so $\varepsilon^{h^r}_{\eta_2} < 0$, implying $\eta^{adj|\sigma}_2 < 0$. The question is, what effect does an electricity tax in period 1 have on R&D?

Unlike a targeted tax on renewable energy, an electricity tax in period 1 has countervailing effects on the value of R&D, because it dampens demand for all electricity sources. First, by discouraging learning in renewable energies, the tax can encourage substitution to R&D. Second, by depressing the supply of fossil energy as well—and encouraging energy efficiency investments—a higher first-period electricity tax also decreases CO_2 emissions. This lowers the CO_2 price path, meaning that less renewable generation may be needed in the second period, thus reducing incentives for investing in knowledge. If the substitution effect dominates, then $\varepsilon^{h^r}_{\eta_1} > 0$; if the emissions reduction effect dominates, then $\varepsilon^{h^r}_{\eta_1} < 0$. However, we may in any case assume that the demand-driven effect is stronger than the supply-substitution effect: $|\varepsilon^{h^r}_{\eta_2}| > |\varepsilon^{h^r}_{\eta_1}|$. As a result, we can state clearly that

Proposition 7. *In the second-best, a below-optimal R&D subsidy requires ceteris paribus a lower (negative) second-period electricity tax and, if learning and R&D are strong enough substitutes, a higher (positive) first-period electricity tax compared with the first-best.*

Proof. Solving (35) for both periods simultaneously, we get:

$$\eta^{**}_1 = \frac{\Delta^\sigma}{\Xi} \sum_r R^r_h h^r \left(\varepsilon^{D_2}_{\eta_1} \varepsilon^{h^r}_{\eta_2} - \varepsilon^{D_2}_{\eta_2} \varepsilon^{h^r}_{\eta_1}\right) \qquad (36)$$

$$\eta^{**}_2 = \frac{\Delta^\sigma}{\Xi} \frac{n_1 D_1}{\delta n_2 D_2} \sum_r R^r_h h^r \left(\varepsilon^{D_1}_{\eta_2} \varepsilon^{h^r}_{\eta_1} - \varepsilon^{D_1}_{\eta_1} \varepsilon^{h^r}_{\eta_2}\right) \qquad (37)$$

Since own-price effects dominate cross-period demand effects, $-\varepsilon^{D_1}_{\eta_1} > -\varepsilon^{D_1}_{\eta_2}$, and $\varepsilon^{h^r}_{\eta_2} < 0$, then $|\varepsilon^{h^r}_{\eta_2}| > |\varepsilon^{h^r}_{\eta_1}|$ is sufficient to ensure that $\eta^{**}_2 < 0$. Meanwhile, $\eta^{**}_1 > 0$ if $\varepsilon^{h^r}_{\eta_1} >$

$-\varepsilon^{h^r}_{\eta_2}\varepsilon^{D_2}_{\eta_1}/(-\varepsilon^{D_2}_{\eta_2})$, which requires enough of a first-period substitution effect with learning. □

The sign and magnitude of $\varepsilon^{h^r}_{\eta_1}$ is crucial for the direction of adjustment for the electricity tax in period 1. Ultimately, this ambiguity can only be resolved numerically. Simulations will also reveal the limitations of the electricity tax o make up for any inadequacy in R&D support. Since the electricity tax cannot distinguish between renewable and nonrenewable suppliers, its influence on R&D in specific renewable technologies is very indirect.

Second-best energy efficiency subsidies to correct for insufficient R&D efforts.

Energy efficiency subsidies influence R&D in the same way as electricity taxes—by affecting the total demand for electricity, as well as the CO_2 price path—so we forego formal proofs. Underprovided R&D is supported by more demand for electricity and thereby renewables in the second period, which is achieved by reducing energy-efficiency subsidies. In the first period, if more electricity demand boosts the return to R&D by driving up CO_2 prices, second-best energy efficiency subsidies may be lower then. If, on the other hand, more electricity demand expands learning enough to crowd out R&D, the second-best energy-efficiency subsidy may be positive in the first period.

4.3 Insufficient output (learning-by-doing) subsidies

Finally, let us suppose that the first-period output subsidy for renewables is constrained, such that $0 \leq \omega_1^r < \omega_1^{r*}$. For example, state aid rules might impose legal barriers to certain subsidies. In this situation, equation (13) using (3) simplifies to $dW = n_1 \sum_r (\omega_1^* - \omega_1^r) dq_1^r \neq 0$. In this third-best situation, welfare-improving policy adjustments need to incentivize more learning-by-doing via more renewable power generation in the first period. That means either spurring first-period generation directly or inducing learning-by-doing by raising the value of power generation in the second period indirectly.

Second-best R&D subsides for renewables to correct for insufficient learning-by-doing.

The R&D subsidy aims at balancing the marginal benefits from technical progress achieved through both R&D and learning-by-doing. Output subsidies depend on r-specific marginal generation costs, whereas the R&D subsidy depends only on the fraction ρ of the spillover benefits of knowledge generation, which is the same for all r. Therefore, a change of the R&D subsidy is not able to target specifically the technology that suffers from an underprovision of learning subsidies.

Holding the other policies at their first-best levels, the welfare change is similar to the case when second-best renewable production subsidies are adjusted to correct for insufficient R&D efforts. Now let us substitute instead $\varepsilon^{q_t^r}_{\sigma} \equiv \frac{dq_t^r}{q_t^r}\frac{\sigma}{d\sigma}$. Following the same procedures as before, we solve for the optimal second-best R&D subsidy:

$$\sigma^{**|\omega_1^r} = \sigma^* + \underbrace{\rho \left(\frac{\sum_r (\omega_1^{r*} - \omega_1^r) q_1^r \varepsilon_\sigma^{q_1^r}}{\sum_j h^j R_h^j \varepsilon_\sigma^{h^j}} \right)}_{\sigma^{adj|\omega_1^r}} \tag{38}$$

Proposition 8. *In the second-best, if learning and R&D are substitutes, a below-optimal first-period renewable production subsidy of one technology requires ceteris paribus a downward adjustment of the R&D subsidy compared with the first-best.*

Proof. If learning and R&D are substitutes[13], an increase in R&D crowds out learning, so the combination of $\varepsilon_\sigma^{q_1^r} < 0$ and $\omega_1^{r*} \geq \omega_1^r$ and $\omega_1^s = \omega_1^{s*}\ \forall s \neq s$ implies $\sigma^{adj|\omega_1^r} < 0$. □

However, as previously noted, there are some opposing effects that direct the sign of $\varepsilon_\sigma^{q_1^r}$. (i) If the substitution effect between technical progress via R&D and learning-by-doing is dominant, then a benevolent policy maker will reduce the R&D subsidy in order to create higher marginal benefits for learning. Less R&D and future renewable production also put upward pressure on the CO_2 price, reinforcing the expansion of first-period output. (ii) Conversely, by expanding second-period renewables production, a higher R&D subsidy can also raise the scope for learning-by-doing. If this market expansion effect prevails, a social planner will raise the R&D subsidy to increase today's R&D investment incentive. (iii) Different immature renewable technologies may respond differently, and the equilibrium effect of a change in σ may not be the same for all of them. For example, if more R&D disproportionately lowers the costs of solar energy and crowds out future wind generation, the change in competitiveness could encourage learning in solar while discouraging learning in wind. In this case, the sign of the second-best adjustment depends on which technology's learning is underinternalized and what the cross-technology effects of the R&D subsidy are.

Renewable energy technologies differ in their scope for cost-reductions and the effects of knowledge accumulation. The R&D subsidy is not, however, technology-specific. In the optimum, this uniform application does not matter, since we assume the underinternalization rate ρ is identical. However, if learning for only some technologies is underinternalized (or is internalized at different rates), the research subsidy becomes a much cruder policy to crowd-in learning, especially since cross-technology effects begin to spill over. Overall, due to these trade-offs and limitations, one can expect the second-best adjustment to be rather minor. The numerical simulations in section 5 will underscore this point.

Second-best electricity taxes to correct for insufficient learning-by-doing.

The economic intuition for this instrument substitution is straightforward. The restricted output subsidy is replaced by a negative tax on power generation. The larger the gap

[13] Following from sufficiently convex renewable cost functions, see Appendix A.2.

between the first-best and the actual subsidy, the larger will be the negative substitute tax rate. There is, however, a crucial difference: compared with the output subsidy, the electricity tax is neither restricted to immature renewables r nor technology-specific. This constrains adjustment possibilities and creates an additional distortion.

Following the same procedures, we solve for the second-best choice of $\eta_t^{**|\omega}$:

$$\eta_t^{**|\omega} = \eta_t^* + \underbrace{\frac{n_1 \sum_r (\omega_1^{r*} - \omega_1^r) q_1^r \varepsilon_{\eta t}^{q_1^r}}{\tilde{n}_t(-\varepsilon_{\eta t}^{D_t}) D_t}}_{\eta_t^{adj|\omega}} - \eta_t^{int} \tag{39}$$

An electricity tax in period 2 dampens demand for all electricity and thus tends to lower the return to knowledge investments, including learning; this effect is further reinforced by the fall in emissions prices, which reduces the competitiveness of renewable energy. Therefore, $\varepsilon_{\eta 2}^{q_1^r} < 0$, although the effect on total demand in period one ($\varepsilon_{\eta 2}^{D_1}$) remains ambiguous. Unlike for R&D, an electricity tax in period 1 has a direct effect on learning, by reducing electricity demand, lowering producer prices, and depressing CO_2 prices, so $\varepsilon_{\eta 1}^{q_1^r} < 0$.

Proposition 9. *In the second-best, a below-optimal first-period output subsidy for immature renewable energy technologies requires ceteris paribus lower (negative) electricity taxes in the first period, and lower (negative) taxes in the second period if adjustments are restricted to that period.*

Proof. The proof follows those of Propositions 1 and 2. Since $\varepsilon_{\eta t}^{q_1^r} < 0$, $\eta_t^{adj|\omega} < 0$ for $t \in \{1, 2\}$. These are the respective adjustments if the tax is only adjusted in one period or the other. If they are adjusted simultaneously, solving (39) for both periods, we get:

$$\eta_1^{**} = \frac{1}{\Xi D_1} \sum_r (\omega_1^{r*} - \omega_1^r) q_1^r \left(\varepsilon_{\eta 1}^{D_2} \varepsilon_{\eta 2}^{q_1^r} - \varepsilon_{\eta 2}^{D_2} \varepsilon_{\eta 1}^{q_1^r} \right) \tag{40}$$

$$\eta_2^{**} = \frac{n_1}{\Xi \delta n_2 D_2} \sum_r (\omega_1^{r*} - \omega_1^r) q_1^r \left(\varepsilon_{\eta 2}^{D_1} \varepsilon_{\eta 1}^{q_1^r} - \varepsilon_{\eta 1}^{D_1} \varepsilon_{\eta 2}^{q_1^r} \right) \tag{41}$$

Since own-period effects dominate cross-period effects, $\eta_1^{**|\omega} < 0$, so the response is to subsidize all electricity in the first period. If $\varepsilon_{\eta 2}^{D_1} > 0$ (when the emissions-price response dominates the learning-supression effect), then $\eta_2^{**|\omega} < 0$ as well. Otherwise, the direction of adjustment depends on the relative sizes of the elasticities. □

The numerical results in section 5 will show that $\eta_2^{**|\omega}$ is positive but numerically small and dominated by $\eta_1^{**|\omega} < 0$.

Second-best energy efficiency subsidies to correct for insufficient learning-by-doing.

As previously discussed, energy efficiency subsidies influence renewable output through the same mechanisms as electricity taxes. Both tend to lower the total demand for electricity, and the energy savings correspond to emissions savings that lower the CO_2 price path.

The second-best results thus correspond to those for the electricity tax, comprising negative adjustment and positive cross-period interaction terms. To encourage learning in a given renewable energy technology, one needs either more electricity demand in the first period, to boost learning directly, or in the second period, to induce learning indirectly. Consequently, in the second-best, a below-optimal first-period output subsidy for immature renewable energy technologies requires ceteris paribus *lower* energy efficiency subsidies in either the first or second period (or both), as compared with the first-best.

In the numerical simulations, we observe similar results to those with the electricity tax. First-period energy-efficiency subsidies are adjusted downward, while second-period subsidies are slightly higher than in the first-best.

4.4 Summary of second-best adjustments

Table 1 summarizes the theoretical directions of second-best adjustments for single policies. In each row one type of instrument is restricted while in each column another instrument is adjusted. Theoretically possible but empirically less likely alternative adjustments are given in parentheses.

Table 1: Second-best adjustments of single policy instruments

	Second-best adjustment						
Undercorrected	Electricity tax		Output subsidy		R&D subsidy	Efficiency subsidy	
market failure	η_1^{**}	η_2^{**}	ω_1^{**}	ω_2^{**}	σ^{**}	λ_1^{**}	λ_2^{**}
Efficiency: $\lambda_t < \lambda_t^*$	↑	↑	↓	↓	↓ (↑)	–	–
R&D: $\sigma < \sigma^*$	↑ (↓)	↓	↓ (↑)	↑	–	↑ (↓)	↓
Learning: $\omega_t < \omega_t^*$	↓	↓	–	–	↓ (↑)	↓	↓

↑ indicates upward, ↓ downward adjustments relative to the first-best.

5 Quantitative assessment of second-best policy adjustments

Based on the theoretical considerations in the previous section, the optimal adjustment of several policy instruments depends on interacting or opposing equilibrium effects. Thus, a quantitative assessment is necessary to (i) gauge the magnitude of the theoretically derived single policy adjustments and their effects, (ii) rank the adjustments according to their effectiveness, and (iii) determine which interacting or dominant effects occur when the instruments are adjusted simultaneously.

For this purpose, we calibrate the model to replicate EU energy policy projections. We then define scenarios characterized by the availability of instruments and compute the potential of second-best instruments adjustments to reduce policy costs of the exogenously given EU CO_2 emission reduction target in the presence of other market failures. We close with a critical discussion and comparison with the previous literature.

5.1 Calibration procedure

The calibration follows the recent official projections by the European Commission (2016) regarding the EU power sector. These projections are the basis of recent EU climate policy decisions. This section summarizes the procedure; further details can be found in Appendix A.4.

In the numerical model, we assume that period 1 runs from 2016 to 2020 and period 2 runs from 2021 to 2040. Time is discounted such that $n^t = (1 - (1 + r)^{-T^t})(1 + r)/r$ describes discounted effective years, where T^t is the number of years in period t and $r = 0.025$ is the discount rate. The discount factor between periods is $\delta = (1 + r)^{-T^1} = 0.88$.

The calibrated model covers seven power generation technologies: three fossil-fuel-based CO_2-emitting technologies, coal, gas and oil; two immature renewable energy technologies, wind and solar power, which are subject to cost reductions through learning-by-doing and R&D investments; and two baseload technologies, hydro and nuclear power, whose output is assumed to be exogenously given, because they are subject to significant fixed costs and political constraints. Each of the five fossil- and renewable energy-based power generation technologies responds to price changes and is modeled with a quadratic cost function (as detailed in Appendix A.4.1) such that generation costs rise with higher output.

Consequently, the first-order derivative that describes marginal costs is linearly increasing in quantity, which means that the resulting supply schedule of each technology is linear over the explored policy space. The slopes of the supply curves are calibrated by computing the difference between technology-specific prices (taking into account CO_2 prices and renewable energy subsides) and their generated quantities across two scenarios with the same underlying technology parameters. We use the Baseline Scenario and the Reference Scenario of Capros *et al.* (2009), published by the European Commission, to calibrate the technology-specific parameters (slopes of supply functions) while taking the quantities and policy variables from the Reference Scenario of the European Commission (2016). Both sets of scenarios are consistent in terms of the evaluated model and the underlying policies.

Since the two scenarios differ only in their policy assumptions, the supply schedule around the calibrated reference generation can be computed. The Baseline Scenario projects the development of the EU energy system with the EU ETS but without renewable energy and energy efficiency policies, whereas the Reference Scenario includes the mandatory CO_2 emissions and renewable energy policies for 2020, adopted subsequently. Appendix table A.1 presents the calibrated supply schedule slopes for the different technologies.

The model replicates the generation quantities of the most recent EU Reference Scenario 2016 defined by the European Commission (2016) in both model periods. Appendix figure A.1 illustrates the corresponding EU power generation mix in the years 2015 and 2040. The combined share of wind and solar power grows from 17% in 2015 to more than 36% in 2040. At the same time, the share of coal in the EU generation mix declines from 26% in 2015 to 9% in 2040 according to the projections of this scenario. Appendix table A.2 shows further parameter values of the calibrated model. Our benchmark scenario also replicates electricity and CO_2 prices of the Reference Scenario 2016. In period 1, the electricity (CO_2) price is $p_1 = 8.5$€c/kWh, i.e., Euro cents per kilo watt hour ($\tau_1 = 7.5$€/tCO_2, i.e., Euro per ton). In period 2, $p_2 = 9.1$€c/kWh ($\tau_2 = 45$€/tCO_2), respectively.

When calibrating renewable energy technologies, we consider future cost reductions via learning-by-doing and R&D as a combined two-factor learning curve in the form of a Cobb-Douglas function as explained in Appendix A.4.1. The choice of the parameter values for (the exponents of) this function follows FN, including the parameter values for solar power. The parameter values for wind power are updated to match estimates by Söderholm and Klaassen (2007) for Europe. We obtain learning rates of about 3% for wind and 17% for solar as well as R&D rates of about 5% for wind and 3% for solar. *Learning-by-doing and R&D act as substitutes* with elasticities of substitution around 1.7 (2.8) for wind (solar). The rate of private knowledge benefits is set to one half, i.e., $\rho = 0.5$ for both R&D and learning-by-doing, which is consistent with a social return to knowledge (i.e., including spillovers) that is about twice the private return (Jones and Williams, 1998; Hall *et al.*, 2010, the former henceforth JW).

Table 2: Parameters capturing market failures

	Parameter	Value	Source
Share of private knowledge	ρ	0.5	JW
Perceived energy efficiency benefit rate	β	0.9	FPN

JW refers to Jones and Williams (1998), FPN refers to Fischer *et al.* (2017).

On the demand side, the definition of functional forms and their calibration follow FPN. Electricity demand, derived from the consumers' maximization problem, has a constant elasticity of $\epsilon = 0.1$ (cf. FPN and Appendix A.4.2) that characterizes a short-run elasticity and captures the rebound effect.[14] The reduction in electricity demand through investments in energy efficiency is modeled via an exponential function detailed in Appendix A.4.2. We obtain an electricity price elasticity of energy efficiency investments of 0.19 (0.68) in period 1 (period 2).

The fraction of the benefit of energy efficiency improvements that the consumer perceives is set to 90%, i.e., $\beta = 0.9$. Given the wide range of results in the empirical literature on energy efficiency valuation and the multiplicity of potential rationales for

[14]For example, a 1% improvement in energy efficiency reduces demand by 0.9%.

undervaluation (Allcott and Greenstone, 2012; Allcott and Taubinsky, 2015), we use a fairly conservative value of 10% undervaluation. However, later, both parameters ρ and β are varied in order to check the robustness of our analysis; see Appendix A.5.

5.2 Definition of scenarios

Based on the parameterized model, we first simulate a scenario with no climate policies as a benchmark for calculating total compliance costs in subsequent policy scenarios. In this *No-Policy* scenario, we simulate the development of the electricity system in absence of a CO_2 price and without subsidies addressing learning-by-doing, R&D, or energy efficiency valuation market failures.

In all subsequent policy scenarios, we require the policy mix to meet the same cumulative emissions target for the EU power sector in order to keep the detrimental welfare effects of climate change constant. Using the emissions reduction pathway calculated by the European Commission (2016), we derive a CO_2 budget for both periods which is consistent with the EU's 40% reduction target in 2030. In all scenarios, the CO_2 price floats endogenously to ensure compliance with this budget. The availability of additional policy instruments, however, varies across scenarios.

First, we define the *C-Price-Only* scenario, which assumes the only available instrument is CO_2 pricing, that is, there are no subsidies for learning, R&D, or energy efficiency. It assumes a cumulative CO_2 cap in the power sector across both periods consistent with the EU's target of a 40% emissions reduction in the whole economy. This third-best scenario without adjustments generates the maximum compliance cost.[15]

Next, we define the *1st-Best* scenario, which applies the first-best choice of the policy instruments, as derived in the theoretical analysis. This scenario calculates the lowest compliance costs for meeting the emissions target.

Equipped with these benchmark scenarios, we examine three sets of policy scenarios P with restrictions related to the propositions outlined previously.

1. *No-Effic-Sub* denotes a (third-best) scenario without any subsidies for energy efficiency improvements.

2. *No-R&D-Sub* defines a (third-best) scenario, in which the R&D subsidy for immature renewable energy technologies is unavailable.

3. *No-Out-Sub* characterizes a (third-best) scenario, in which (learning) subsidies for immature renewable energy technologies are unavailable.

The complete unavailability of a policy instrument represents the extreme case of what has been analyzed in the analytical section 4 as marginally below-optimal instru-

[15]Sub-optimal policy adjustments can substantially increase compliance costs compared with an emissions cap alone (see FPN).

ments. Less extreme cases will have smaller policy effects. The corresponding *second-best* scenario, in which instruments are adjusted is again indicated by **.

5.3 Simulation results

We solve the model as a system of nonlinear equations by using Newton's method.

First, we solve the model for the first-best policy portfolio and compare it to scenario *C-Price-Only*. Then we determine third-best costs of scenarios with a restricted instrument. Next, we evaluate the second-best adjustments of single policies, applying the previous theoretical outcomes to the European policy scenarios. Finally, we allow the numerical model to solve for simultaneous adjustment of all the other policy instruments when one is removed. Our key metric to assess a policy P^{**} is relative policy costs (RPC) with respect to $RPC^{\text{1st-Best}} = 100\%$:

$$RPC^{P^{**}} = (W^{\textit{No-Policy}} - W^{P^{**}})/(W^{\textit{No-Policy}} - W^{\textit{1st-Best}}) \cdot 100\%,$$

where W^P denotes welfare from the power sector as defined in equation (11) in scenario P. To assess the potential of second-best adjustments to compensate for unavailable first-best instruments, we define the share of recuperated costs (SRC):

$$SRC^{P^{**}} = (RPC^P - RPC^{P^{**}})/RPC^P \cdot 100\%$$

5.3.1 Second-best evaluation: single policy instrument adjustments

Having set the two benchmarks for the second-best analysis, the costs of constraining one of the first-best instruments in a policy scenario P are calculated. The following tables present the second-best adjustments for each policy. Any restriction of a policy instrument creates a cost increase ($RPC^P > 100\%$) in the first place. Part of this cost increase can then be recuperated ($RPC^{P^**} < RPC^P$) by appropriate policy adjustments following the propositions discussed in the previous section. The recuperated costs (SRC) are reported in the last column of each table.

The numerical analysis enables us to identify the direction and magnitude of policy adjustments in the presence of countervaling effects and multi-period and multi-technology instruments.

Unavailable energy efficiency subsidies. Table 3 summarizes policy costs and instrument adjustments of scenario *No-Effic-Sub*. We observe approximately 15% higher costs of complying with the EU emissions target than in *1st-Best* if the other policy levers remain unadjusted.

Consistent with Propositions 1 and 2, a second-best electricity tax of 0.3 (0.6)€c/kWh in period 1 (2) can partially substitute for the missing subsidy, since the higher electricity price incentivizes additional energy efficiency investments. This tax represents 3 (7)% of the electricity price in period 1 (2) and can recuperate 37% of the welfare loss due to the

Table 3: Single instrument adjustments when no energy efficiency subsidies are available

Scenario	2nd-best adjustment		Prop.	*t*=1	*t*=2	*RPC*	*SRC*
No-Effic-Sub	None (3rd-best)	–	–	–	–	115.41%	–
	Electricity tax	$\eta_t^{**\|\lambda}$	1/2	+0.3€c	+0.6€c	107.20%	37.4%
*No-Effic-Sub***	Wind out. sub.	$\omega_t^{r**\|\lambda}$	3	–0.3€c	–0.5€c	108.32%	27.8%
	Solar out. sub.			–0.3€c	–0.5€c		
	R&D subsidy	$\sigma^{**\|\lambda}$	4	–0.5pp	–	110.62%	7.8%

Prop. indicates the corresponding proposition, ** indicates the second-best instrument choice, the second index describes the restricted instrument(s), pp means percentage points, €c means Euro cents per kilo watt hour, *RPC* relative policy costs and *SRC* the share of recuperated costs.

unavailability of energy efficiency subsidies. Several countries levy taxes on electricity. Germany, for example, taxes most electricity consumption by 2.05€c/kWh, which translates to a tax rate of about 14%. According to this estimate, this tax rate is too high if its aim is to incentivize first-best energy-efficiency improvements. Nonetheless, as we will see, the electricity tax is the most effective second-best instrument, able to compensate for about a third of the welfare losses caused by the missing first-best energy efficiency subsidies.

As posited by Proposition 3, the second-best output (learning) subsidies for wind and solar are adjusted downward, in this case by nearly as much as the electricity tax would be increased, with the intention of raising electricity prices. This allows policy makers to recapture 28% of the costs from the missing first-best instrument. Similarly, as outlined in Proposition 4, the second-best R&D subsidy needs to be adjusted downward, according to the simulation by 0.5pp. This adjustment, however, is less effective in inducing energy efficiency investments, since it affects only the second-period electricity price directly. Thus, it recuperates merely 8% of the welfare loss.

Unavailable R&D subsidies. Next, as reported in table 4, scenario *No-R&D-Sub* causes a cost increase of about 26% relative to *1st-Best*. The second-best response adjusts output subsidies for wind and solar power as expressed by Propositions 5 and 6. A positive second-period subsidy of around 0.5€c/kWh increases the value of renewable power in this period, and thus the present marginal profits of R&D. At the same time, the first-period output subsidy for wind (solar) is reduced by 0.02 (0.15)€c/kWh to extend the leeway and marginal value of R&D. These adjustments recoup 8% of the cost increase.

The second-best electricity tax as a response to the missing R&D support is negative in accordance with Proposition7, resulting in a small subsidy for electricity consumption of 0.12 (0.36)€c/kWh in period 1 (2) in order to create more demand for renewable energy, which increases the marginal benefits from R&D. However, the adjustment can recover only 4.5% of the additional costs. Energy efficiency subsidies are adjusted downward by 0.5 (1.9) percentage points in period 1 (2) to stimulate demand for

Table 4: Single instrument adjustments when no R&D subsidy is available

Scenario	2nd-best adjustment		Prop.	t=1	t=2	*RPC*	*SRC*
No-R&D-Sub	None (3rd-best)	–	–	–	–	125.9%	–
*No-R&D-Sub***	Wind out. sub.	$\omega_t^{r**\|\sigma}$	5/6	–0.02€c	+0.54€c	123.8%	8.0%
	Solar out. sub.			–0.15€c	+0.46€c		
	Electricity tax	$\eta_t^{**\|\sigma}$	7/8	–0.12€c	–0.36€c	124.7%	4.5%
	Efficiency sub.	$\lambda_t^{**\|\sigma}$	(7/8)	–0.50pp	–1.90pp	125.5%	1.6%

Prop. indicates the corresponding proposition, ** the second-best choice, the second index shows the restricted instrument(s), pp means percentage points, €c means Euro cents per kilo watt hour, *RPC* relative policy costs and *SRC* the share of recuperated costs.

renewable power generation in the second period. Though, the electricity demand measures recuperate only 1.6% of the initial costs.

Unavailable output subsidies for immature renewables. According to table 5, scenario *No-Out-Sub* raises the climate policy costs by a meager 0.38%—a very small amount compared with the costs of not addressing R&D spillovers.

Table 5: Single instrument adjustments when no renewables output subsidies are available

Scenario	2nd-best adjustment		Prop.	t=1	t=2	*RPC*	*SRC*
No-Out-Sub	None (3rd-best)	–	–	–	–	100.378%	–
*No-Out-Sub***	R&D subsidy	$\sigma^{**\|\omega_1^r}$	9	–0.00pp	–	100.378%	0.0%
	Electricity tax	$\eta_t^{**\|\omega_1^r}$	10	–0.08€c	+0.02€c	100.353%	6.6%
	Efficiency sub.	$\lambda_t^{**\|\omega_1^r}$	(10)	–0.50pp	–0.11pp	100.371%	1.7%

Prop. indicates the corresponding proposition, ** the second-best choice, the second lower index shows the restricted instrument(s), pp means percentage points, €c means Euro cents per kilo watt hour, *RPC* relative policy costs and *SRC* the share of recuperated costs.

Furthermore, in this scenario, it is more difficult to recuperate cost increases. In accordance with Proposition 8, the second-best-adjustment of the R&D subsidy proves to be ineffective because it is not able to address the technology-specific learning-externalities individually.

The most effective second-best adjustment is to subsidize all types of power generation with a negative electricity tax in period 1 in order to subsidize renewable generation, as formulated in Proposition 9. According to our theoretical considerations, the tax increase in period 2 can be explained by a dominant cross-period interaction term, meaning the positive second-period tax compensates for part of the negative first-period tax. A small subsidy (tax) of 0.08€c/kWh in period 1 (2) recuperates only 6.6% of the additional policy costs of missing output subsidies. As suggested by the theory, energy efficiency subsidies are adjusted downward, particularly by 0.50 (0.11)pp in period 1 (2), to enhance energy demand and supply and thus to increase the value of learning. Yet the effects are very modest: only 1.7% of the cost increase can be recuperated.

5.3.2 Second-best evaluation: multiple policy instrument adjustments

In this section, we allow all remaining instruments to adjust simultaneously to maximize welfare given an unavailable first-best instrument. In each scenario, we find that the policy that proofs to be the most-effective in the single policy adjustment also dominates the second-best, and the ability to adjust simultaneously provides little additional benefits. Small adjustments of additional instruments only help to reduce distortive effects of the primal adjustment. Table 6 reports for each scenario the second-best policy portfolio in both periods 1 and 2 including CO_2 prices, policy costs *RPC* relative to *1st-Best*, and the share of recuperated costs *SRC* via second-best adjustments.

Table 6: Summary of multiple instrument adjustments with one unavailable instrument

		*No-Effic-Sub***		*No-R&D-Sub***		*No-Out-Sub***	
Policy instrument	Unit	*t*=1	*t*=2	*t*=1	*t*=2	*t*=1	*t*=2
Wind out. sub.	€c/kWh	0.15	–	0.13	0.54	–	–
Solar out. sub.	€c/kWh	1.05	–	0.89	0.46	–	–
R&D subsidy	%	50.00	–	–	–	49.75	–
Efficiency sub.	%	–	–	10.00	10.00	9.98	9.98
Electricity tax	€c/kWh	0.31	0.59	0.00	0.00	–0.08	–0.02
CO_2 price	€/tCO_2	18.70	25.20	20.00	27.00	19.10	25.70
RPC	%	107.24		123.83		100.35	
SRC	%	37.31		7.98		6.69	

RPC represents relative policy costs, *SRC* are the share of recuperated costs.

In the absence of first-best energy efficiency subsidies (*No-Effic-Sub*), the electricity tax is the dominant policy substitute in the second-best, while all other instrument remain at their first-best levels. Without access to R&D subsidies (*No-R&D-Sub*)—similar to the adjustments of single instruments—second-best welfare gains come primarily from reducing the renewable energy output subsidy in period 1 and introducing a renewable energy output subsidy in period 2. When output (learning) subsidies are unavailable (*No-Out-Sub*), a negative electricity tax, i.e., a subsidy for overall power generation, will again be the next most effective instrument, now in combination with a minor reduction in the R&D subsidy and energy efficiency subsidies. Again, the costs of missing output subsidies are very small in the first place. The simultaneous adjustment of all instruments generates a slight reduction in policy costs compared with an electricity subsidy (a negative electricity tax) alone.

5.4 Discussion

The numerical analysis has shown that the potential of second-best adjustments is limited and can by no means fully substitute for the first-best portfolio. Nonetheless, in case of a market failure rooted in the undervaluation of the benefits of energy efficiency investments, a second-best electricity tax below 1€c/kWh can recuperate 37% of the additional policy costs vis-à-vis the first-best portfolio, given the EU emissions target. Notably, the implementation of second-best instruments requires information on both demand- and supply-side elasticities. Estimating these elasticities precisely is challenging. Since the energy efficiency market failure can be grounded in different sources, individual aspects and the actual circumstances should be considered when seeking for accurate parameter values.

In addition, the relationship between R&D and output subsidies partly depends on the substitutability of R&D and learning in knowledge creation. We show in Appendix A.2 that this depends on the relative steepness of the cost and knowledge functions. Our model calibration shows that the substitutability assumption holds for a reasonable parameterization. This might be different, however, for the development of novel breakthrough technologies—a case that we do not consider in this analysis. Given our model specification and calibration, however, the potential of R&D subsidies to subsitute for learning subsidies is very limited, and the ability of learning subsidies to substitute for R&D subsidies is moderate.

To evaluate the sensitivity of the numerical results, we test the effect of varying key parameter values on the share of recuperated costs (SRC). Details are presented in Appendix A.5. We conduct the following analyses: (1) We vary β, representing the share of anticipated benefits from energy efficiency investments (previously set to 0.9) between 0.55 and 0.95. (2) We vary ρ, representing the perceived share of private benefits from R&D and learning-by-doing (previously set to 0.5) between 0.35 and 0.75. (3) We vary the emissions reduction target for 2030 (previously set to 40%) vis-à-vis 1990, between 30% and 60% resulting in a corresponding change in the intertemporal emissions budget imposed on the model.

It turns out that under *No-Effic-Sub*, the SRC for (1) varies relatively linearly between 31% and 38%, for (2) between 39% and 34% as well as for (3) between 32% and 46%. Likewise, under *No-R&D-Sub*, the SRC for (1) varies between 1% and 9%, for (2) between 9% and 8% as well as for (3) between 3% and 12%. Finally, under *No-Out-Sub*, the SRC for (1) varies between 8% and 6%, for (2) between 5% and 8% as well as for (3) between 8% and 5%. Accordingly, the effectiveness of second-best policy adjustments is relatively robust to changes in these parameter values.

In further experiments, we finance the output subsidies for renewable energy by an electricity tax to mimic feed-in policies. We find that the economic distortion that feed-in policies create compared with the output subsidies alone is minor and similar across different implementations of feed-in policies in the model.[16]

[16] We implement them as a combination of a fixed subsidy for renewable energy and a corresponding tax on fossil energy (Kalkuhl *et al.*, 2013), or a combination of a fixed subsidy for renewable energy and a tax on electricity, or a combination of a guaranteed electricity price payment and a tax on electricity as in practice in Germany, without finding significant differences across these implementations.

6 Conclusion

In most real policy situations, it is almost impossible to implement first-best policy instruments because of conflicts with existing regulation, political economy constraints or the structure of political and administrative institutions. To provide guidance for policy makers faced with the resulting dilemma of several unaddressed market failures, we have presented a theoretical framework that reveals how to optimally adjust the available instruments in the second-best.

Applying a calibrated model of the European power sector, we have compared and ranked policy instrument adjustments. According to our conservative numerical results, the present value of addressing only the European CO_2 emissions target (and not addressing other market failures) has an order of magnitude of €36.9 billion. If European policy makers were able to implement the first-best policy portfolio, this would reduce policy costs to about €27.9 billion. Accordingly, the EU ETS is the "bird in the hand" generating the major environmental benefit, which is not valued in our welfare analysis. Considering that hitting a first- or second-best portfolio is difficult and creates governance costs, relying primarily on the EU emissions target might be more cost-effective than the maladroit attempts to fine-tune other single policy instruments.

Nonetheless, the simultaneous adjustment of policy instruments to address R&D and energy efficiency market failures can reduce the compliance cost of the European emissions reduction target by €575 million for R&D or €1.2 billion for energy efficiency, respectively. For policy makers seeking these "birds in the bush," our theoretical model analysis has derived a recipe how to "throw the available stones" by adjusting the available instruments in the right direction. Our calibrated model analysis provides the following quantitative ranking of the related policy costs and benefits (see table 6).

A missing R&D subsidy creates the largest cost increase (23%) compared with the first-best. However, only a limited fraction of these costs (8%) can be recuperated in the second best, primarily by adjusting downward the output subsidies to renewables. Because energy efficiency subsidies are demand-side instruments, they are rather ineffective in addressing supply-side market failures. Thus, the availability of R&D subsidies is very important. In contrast to this finding, EU public support for R&D in renewables is currently low compared with support for deployment (output). In 2010, the five largest EU countries spent about €48 billion on deployment but only €315 million on public support for R&D in wind and solar power technologies (Zachmann *et al.*, 2014).

Missing energy efficiency subsidies entail the second-largest cost increase (8%) over the first-best outcome. In this case, second-best electricity taxes are relatively good substitutes; they can recuperate a significant fraction (37%) of the costs, allowing the other available instruments to remain at their first-best levels. Although electricity taxation is relatively common in the EU, it can be politically difficult to adjust existing taxes that have been set for different policy goals. Other instruments, however, are less able to address underprovision of energy efficiency. As supply-side instruments, renewable production subsidies or R&D subsidies are poorly suited for addressing demand-side market failures.

According to our model results, missing output (learning-by-doing) subsidies for renewable energy create only a minor cost increase (1%). This result is in stark contrast to the European policy priority of giving substantial support to renewable energies via deployment (output) subsidies (feed-in-tariffs). The simultaneous adjustment of the remaining instruments (a slightly lower R&D subsidy, small negative electricity taxes and slightly lower efficiency subsidies) can recuperate a limited fraction of the costs (7%). However, because the initial cost increase is small and the second-best fine-tuning is complex and requires detailed market information, imprecise adjustments to policy instruments are likely and will increase policy costs.

In summary, our results indicate that supply side instruments cannot effectively be replaced by demand side instruments and vice versa, whereas an electricity tax is a relatively effective and flexible instrument for correcting either demand or supply side market failures. An electricity tax, however, creates an additional distortion by affecting all generators indiscriminately, whether they use fossil fuels or renewable energies. Therefore, electricity tax adjustments need to be calibrated carefully, particularly when the second-best magnitude of the adjustment is unknown. In Germany, for example, the electricity tax rate might already be too high compared with our estimates for the second-best.

In practice, optimal policies differ across European countries, depending, for example, on the country-specific potential of renewable energy sources. Furthermore, the course of renewable energy deployments and generation costs is uncertain. Hence, future research could analyze country-specific policies under different technology-related conditions and ambitious long-term climate policy targets. Future research could also deal with the political economy behind the (non-)availability of policy instruments. We have developed a tractable framework for deriving second-best policy adjustment in the energy sector. This framework can, however, easily be transferred to other sectors and policy domains where multiple market failures interact. Taking the discussed caveats into account, we hope that our analysis provides useful guidance for climate and energy policy design.

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A Appendix

A.1 Derivation of equilibrium changes

We can understand how key variables respond to changes by taking the total derivatives of the relevant first-order conditions and solving for the equilibrium changes, given the changes in the other variables at hand.

A.1.1 Demand and efficiency responses

From (8) or (9), we can totally differentiate and see how e_t responds to changes in the other variables:

$$(1-\lambda_t)Z^t_{e_t e_t} de_t - d\lambda_t Z^t_{e_t} = \beta \left(dp_t \psi_t(e_t) v_t - p_t \psi_t(e_t) v_t de_t + p_t \psi_t(e_t) dv_t \right)$$

Solving for de_t, we get

$$de_t = \frac{d\lambda_t Z^t_{e_t} + \beta \psi_t (dp_t v_t + dv_t p_t)}{Z^t_{e_t e_t}(1-\lambda) + \beta p_t \psi_t v_t}$$

Before any rebound ($dv_t = 0$), we see that $de_t/dp_t > 0$ and $de_t/d\lambda_t > 0$: higher prices and lower costs induce more energy efficiency investment.

If we totally differentiate (6) or (7)

$$u_{v_t v_t} dv_t = dp_t \psi_t(e_t) - p_t \psi_t(e_t) de_t$$

and solve these two equations simultaneously, we get:

$$\begin{aligned} de_t &= \left(d\lambda_t (-u_{v_t v_t}) Z^t_{e_t} + dp_t ((-u_{v_t v_t}) v_t - p\psi_t) \beta \psi_t \right) \Lambda^{-1} \\ dv_t &= \left(d\lambda_t p_t Z^t_{e_t} - dp_t (1-\lambda) Z^t_{e_t e_t} \psi_t \right) \Lambda^{-1} \end{aligned}$$

where $\Lambda = -u_{v_t v_t} Z^t_{e_t e_t}(1-\lambda) + p_t \beta \psi_t ((-u_{v_t v_t}) v_t - p_t \psi)$. The condition underlying our assumption that the rebound effect is less than 1 is that $(-u_{v_t v_t}) v_t - p_t \psi > 0$; this ensures that $\Lambda > 0$ and $de_t/dp_t > 0$, $de_t/d\lambda_t > 0$, $dv_t/dp_t < 0$ and $dv_t/d\lambda_t > 0$, while $dD_t/de_t < 0$ and, of course, $dD_t/dp_t < 0$.

A.1.2 Supply responses

1. $dq^i_t/dp^i_t > 0$, where $dp^i_t = dp_t - d\eta_t + d\omega^i_t$;[17]

2. $dq^r_1/dp^r_2 > 0$: higher returns to renewable energy in period 2 increase learning;

[17] For renewable energy technologies, this sensible result implies not only that costs are convex but that $C^{r2}_{q^r_2 q^r_2} > (C^{r2}_{H^r_2 q^r_2})^2/(C^{r2}_{H^r_2 H^r_2} + (1-\sigma)R^r_{h^r h^r}/\rho\delta n_2)$ and $C^{r1}_{q^r_1 q^r_1} > \rho\delta n_2((C^{r2}_{L^r_2 q^r_2})^2/C^{r2}_{q^r_2 q^r_2} - C^{r2}_{L^r_2 L^r_2})$.

3. $dq_2^r/dp_1^r > 0$: additional learning in period 1 lowers costs and increases output in period 2;

4. $dh^r/dp_2^r > 0$, so $dh^r/d\omega_2^r > 0$, but $dh^r/d\omega_2^j < 0$ for $j \neq r$: a subsidy to production of r's own technology in period 2 crowds in its own R&D, but subsidies to competing technologies crowd out r's R&D, as more output drives down prices in period two.

5. $dq_2^r/dh^r > 0$: additional R&D lowers costs and increases output in period 2;

6. dq_1^r/dh^r (conversely dh^r/dq_1^r) is in theory of ambiguous sign: R&D and learning in period 1 are substitutes ($dq_1^r/dh^r < 0$) if the cost function is sufficiently convex.[18] In the numerical analysis, our functional form assumptions imply that research and learning are *substitutes*.

7. If research and learning are substitutes, then $dh^r/dq_1^j > 0$: more production by a competing renewable technology in period 1 crowds out learning by r, shifting knowledge investment toward R&D; however, to the extent technology j's costs also fall in period 2, it crowds out some other generation then, which may attenuate the R&D incentives for r.

A.2 Derivation of conditions of knowledge substitutability between R&D and learning-by-doing

Totally differentiating the FOCs for renewable generation and R&D in a given year within a period:

$$C^{r1}_{q_1^r q_1^r} dq_1^r = d\hat{p}_1 - \rho\delta n_2 \left(C^{r2}_{L_2^r L_2^r} dq_1^r + C^{r2}_{L_2^r H_2^r} dh^r + C^{r2}_{q_2^r L_2^r} dq_2^r \right) \quad (42)$$

$$C^{r2}_{q_2^r q_2^r} dq_2^r = d\hat{p}_2 - C^{r2}_{q_2^r H_2^r} dh^r - C^{r2}_{q_2^r L_2^r} dq_1^r \quad (43)$$

$$(1-\sigma) R^r_{h^r h^r} dh^r = -\rho\delta n_2 \left(C^{r2}_{H_2^r H_2^r} dh^r + C^{r2}_{H_2^r L_2^r} dq_1^r + C^{r2}_{H_2^r q_2^r} dq_2^r \right) \quad (44)$$

Solving the system for a given dq_1^r:

$$\frac{dh^r}{dq_1^r} = \frac{\rho\delta n_2 \left(C^{r2}_{q_2^r H_2^r} \left(C^{r2}_{q_2^r L_2^r} - \frac{dp_2}{dq_1^r} \right) - C^{r2}_{H_2^r L_2^r} C^{r2}_{q_2^r q_2^r} \right)}{(1-\sigma) R^r_{h^r h^r} C^{r2}_{q_2^r q_2^r} + \rho\delta n_2 \left(C^{r2}_{H_2^r H_2^r} C^{r2}_{q_2^r q_2^r} - \left(C^{r2}_{q_2^r H_2^r} \right)^2 \right)}$$

$$= \frac{\left(C^{r2}_{q_2^r H_2^r} \left(C^{r2}_{q_2^r L_2^r} - \frac{dp_2}{dq_1^r} \right) - C^{r2}_{H_2^r L_2^r} C^{r2}_{q_2^r q_2^r} \right)}{\left((1-\sigma) R^r_{h^r h^r} / \rho\delta n_2 + C^{r2}_{H_2^r H_2^r} \right) C^{r2}_{q_2^r q_2^r} - \left(C^{r2}_{q_2^r H_2^r} \right)^2}$$

Solving the system for a given dh^r:

[18] That is, if $C^{r2}_{L_2^r H_2^r} C^{r2}_{q_2^r q_2^r} > C^{r2}_{H_2^r q_2^r} C^{r2}_{L_2^r q_2^r}$.

$$dq_1^r = \frac{\rho\delta n_2 \left(C^{r2}_{q_2^r L_2^r} C^{r2}_{q_2^r H_2^r} - C^{r2}_{H_2^r L_2^r} C^{r2}_{q_2^r q_2^r} \right) dh^r - \rho\delta n_2 C^{r2}_{q_2^r L_2^r} dp_2 + C^{r2}_{q_2^r q_2^r} dp_1}{C^{r1}_{q_1^r q_1^r} C^{r2}_{q_2^r q_2^r} + \rho\delta n_2 \left(C^{r2}_{L_2^r L_2^r} C^{r2}_{q_2^r q_2^r} - \left(C^{r2}_{q_2^r H_2^r} \right)^2 \right)}$$

The denominators need to be positive to have sensible results with respect to prices. The numerators are negative if marginal costs are steep enough: i.e $C^{r2}_{H_2^r L_2^r} C^{r2}_{q_2^r q_2^r} > C^{r2}_{q_2^r L_2^r} C^{r2}_{q_2^r H_2^r}$.

A.3 Derivation of conditions of electricity tax response to underinternalization of energy efficiency

Here we show more generally how electricity taxes can be adjusted simultaneously in the second-best. Note that in both cases (and also in subsequent cases that we explore) the adjustment terms η_t^{adj} are specific to the policy failure response, while the interaction terms η_t^{int} are not: the latter terms reflect the same distortions to electricity demand and are identical for any given tax adjustment. Solving (23) and (24) simultaneously, we see that the second-best taxes are a weighted combination of the adjustment terms for each period:

$$\eta_1^{**} = \zeta\, \eta_1^{adj} - \frac{\delta n_2 D_2 \varepsilon_{\eta_1}^{D_2}}{n_1 D_1 \varepsilon_{\eta_1}^{D_1}} \zeta\, \eta_2^{adj} \tag{45}$$

$$\eta_2^{**} = \zeta\, \eta_2^{adj} - \frac{n_1 D_1 \varepsilon_{\eta_2}^{D_1}}{\delta n_2 D_2 \varepsilon_{\eta_2}^{D_2}} \zeta\, \eta_1^{adj} \tag{46}$$

where $\zeta = \left(\frac{\varepsilon_{\eta_1}^{D_1} \varepsilon_{\eta_2}^{D_2}}{\varepsilon_{\eta_1}^{D_1} \varepsilon_{\eta_2}^{D_2} - \varepsilon_{\eta_2}^{D_1} \varepsilon_{\eta_1}^{D_2}} \right) > 1$.

In effect, the cross-period demand effects $\varepsilon_{\eta_t}^{D_s}$ influence the weights on the efficiency-driven adjustments. The terms η_t^{adj} are primarily driven by the value of the responses in the underprovided factors, in this case energy efficiency. In contrast, ζ and the relative weight on the other period's adjustment term depend on the overall demand-supply response. (Note that if $\varepsilon_{\eta_t}^{D_s} = 0$ for $s \neq t$, then $\zeta = 1$ and the second term in the above equations will become zero, in which case $\eta_t^{**} = \eta_t^{adj}$.)

With non-zero cross-period demand effects, the second-best electricity taxes will deviate from this simple adjustment, with the net effect depending on the relative strength of the demand shifts. In fact, the above equations show that if cumulative demand (or its undervaluation) is much larger in one period than in the other, the second-best tax may be positive in that period and negative in the other, in order to compensate for an excess intertemporal price effect. However, for the second-best electricity tax to be adjusted downward in one period, it must be that the tax in the other period is adjusted upward. Thus, the second-best electricity tax in either the first or second period must be higher compared with the first-best.

A.4 Parameterization and calibration of the numerical model

The numerical model is closely related to the model used by FN and FPN. Whereas FN and FPN calibrate it to match US electricity scenarios, we calibrate it to match official electricity market projections of the European Commission, which have been used to assess EU climate and energy policies, e.g., the economic costs of the EU's GHG reduction target of 40% versus 1990 in 2030. In the following, the functional forms, parameterization and calibration of the model are outlined. For a deeper discussion see FN and FPN.

A.4.1 Electricity supply

We distinguish between three types of electricity generation technologies. Fossil fuel-based technologies emit CO_2 when generating electricity and are already technologically mature. Immature renewable energy technologies are still subject to technological improvements via R&D and learning that reduce their marginal costs of production. Other technologies such as nuclear and hydro are neither emitting CO_2 nor are they subject to incremental technical progress and its respective externalities. We assume that period 1 (2) starts in 2016 (2021) and ends in 2020 (2040).

Fossil fuel technologies. In the numerical model, we distinguish between three fossil fuel technologies: coal, natural gas and oil. The convex cost functions of the analytical model are parameterized by quadratic cost functions. As a consequence, the resulting supply curves are linear in the neighborhood of the price changes considered.

$$C^{ft} = c_0^{ft} + c_1^{ft}(q_t^f - \bar{q}^{ft}) + \frac{1}{2}c_2^{ft}(q_t^f - \bar{q}^{ft})^2 \tag{47}$$

where $\bar{q}^{ft}$ is the baseline quantity of technology f in period t. Figure A.1 illustrates the baseline quantities at the beginning and end of the model horizon taken from the EU Reference Scenario 2016 (European Commission, 2016).

Since we assume perfect competition and zero profits, total baseline cost are $c_0^{ft} = \bar{p}^t\bar{q}^{ft}$ which are, however, irrelevant for the generators' decisions. It follows from the first-order condition of the baseline that $c_1^{ft} = \bar{p}^t$. The only remaining parameter is c_2^{ft} characterizing the slope of the supply schedule.

The slopes of the supply curves are calibrated by computing the difference between technology-specific effective prices (taking into account CO_2 prices and renewable subsides) and their generated quantities across two scenarios with the same underlying technology parameters. We use the Baseline and the Reference Scenario of Capros *et al.* (2009), published by the European Commission that outlines the policy and technology assumptions behind their projections. Since these two scenarios differ only in their policy assumptions, the supply schedules around the calibrated reference generation can be computed. The Baseline Scenario projects the development of the EU energy system including the EU ETS but without the renewable energy and energy efficiency targets, while

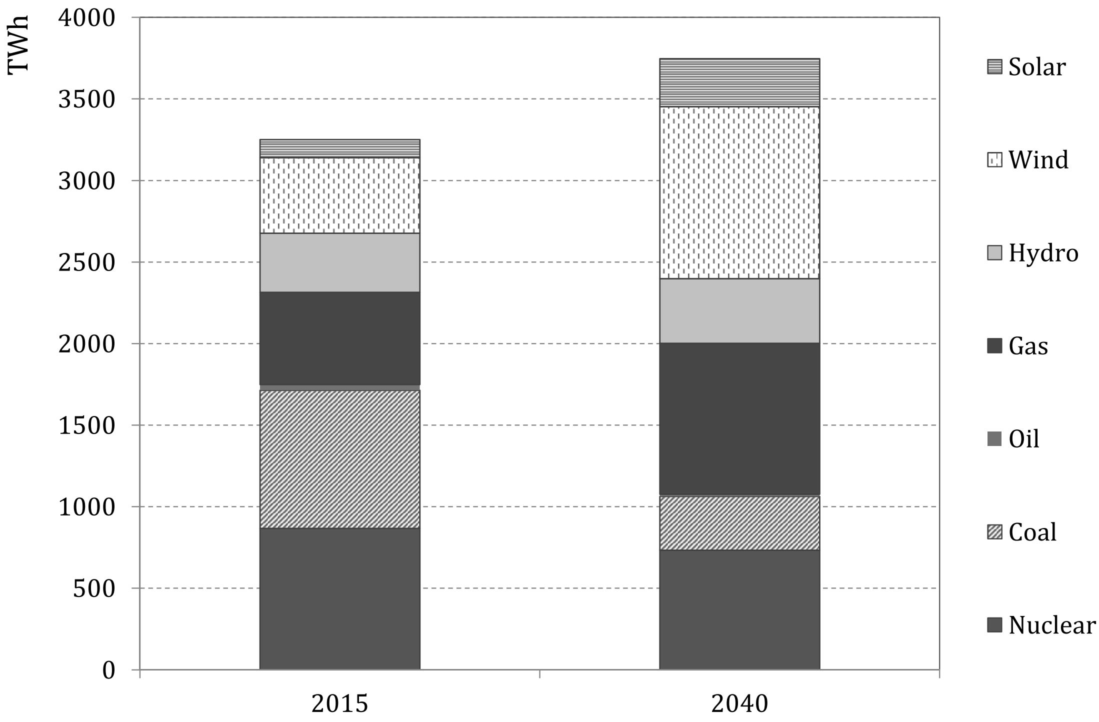

Figure A.1: Calibrated electricity mix (European Commission, 2016) at the beginning and end of our assessment's time horizon

the Reference Scenario includes the mandatory emission and renewable energy targets for 2020 adopted subsequently. Table A.1 presents the calibrated supply schedule slopes c_2^{ft} for the respective technologies r.

Table A.1: Calibrated supply slopes and CO_2 intensities of power generation technologies

Technology r	Period 1 slope €$(\text{kWh})^{-2}$	Period 2 slope €$(\text{kWh})^{-2}$	CO_2 intensity t/kWh
Coal	2.11×10^{-13}	6.63×10^{-14}	9.15×10^{-4}
Gas	1.85×10^{-13}	2.71×10^{-13}	3.65×10^{-4}
Oil	1.05×10^{-9}	6.17×10^{-10}	8.76×10^{-4}
Wind	2.22×10^{-13}	3.09×10^{-13}	0
Solar	2.73×10^{-12}	1.64×10^{-12}	0
Nuclear	0	0	0
Hydro	0	0	0

Nuclear and hydro power are assumed to be fixed.

Immature renewable energy technologies. In contrast to the fossil fuel technologies, the set of immature renewable technologies is characterized by (i) CO_2 emission-free electricity generation which is (ii) subject to cost reductions due to technical progress. Technical progress stems from learning-by-doing effects as well as R&D investments. We distinguish between two specific immature renewable technologies r, wind and solar, which are represented by the following cost functions:

$$C^{rt} = \left[c_0^{rt} + c_1^{rt}(q^{rt} - \bar{q}^{rt}) + \frac{1}{2} c_2^{rt}(q^{rt} - \bar{q}^{rt})^2 \right] \frac{\bar{K}^{rt}}{K^{rt}} \tag{48}$$

The slopes of the supply functions c_2^{rt} are calibrated following the procedure described for fossil fuel technologies. c_1^{rt} is solved via the first-order conditions under the baseline scenario. Then c_0^{rt} is calibrated such that the zero-profit condition holds under the baseline scenario. $\bar{K}^{rt}$ is the calibrated knowledge stock in the baseline, and K^{rt} is the endogenous knowledge stock in the respective scenario. An increase in the knowledge stock reduces both the intercept and the slope of the supply curve.

The knowledge stock is in turn a composite of cumulative experience from learning-by-doing and ideas from R&D of the previous period:

$$K^{rt} = \left(\frac{Q^{rt}}{\bar{Q}_1^r} \right)^{k_1^r} \left(\frac{H^{rt}}{\bar{H}^{r1}} \right)^{k_2^r} \tag{49}$$

In the first period, the knowledge stock is given and normalized to $K^{r1} = 1$ because investment decisions affect the available knowledge in the second period only. $\bar{q}_1^r$ describes the stock of experience at the beginning of period 1. It is calibrated so that the annual wind and solar generation in the baseline of period 1 contribute about 2 percent and 8 percent, respectively, to the already existing cumulative experience measured in units of generation. These values are consistent with the current contribution of wind and solar to cumulative EU generation of each technology (European Commission, 2016). $\bar{H}^{r1} = 1$ is normalized while the corresponding R&D cost function is calibrated. Following FPN and FN, the R&D cost function is assumed to read $R^r = \gamma_0^r (h^r)^{\gamma^r}$ with $\gamma^r = 1.2$. Accordingly, expanding the knowledge stock through R&D results in increasing marginal costs. The baseline R&D expenditures referring to the year 2010 come from IEA (2012). We solve for γ_0^r in the baseline to calibrate the function.

The choice of the parameter values for the exponents of the two-factor learning curve above builds on FN and is updated to match estimates by Söderholm and Klaassen (2007) for wind power in Europe. The resulting parameter values are $k_1^w = 0.083$ and $k_2^w = 0.315$ for wind as well as $k_1^s = 0.33$ and $k_2^w = 0.66$ for solar. These values lead to learning rates of about 3% for wind and 17% for solar as well as R&D rates of about 5% for wind and 3% for solar. As a result, learning and R&D act as substitutes with elasticities of substitution around 1.7 (2.8) for wind (solar).

Other technologies. In order to represent all important generation technologies and to match the quantities with those in the EU scenarios, we include hydro and nuclear power generation. For nuclear and hydro power generation, we assume that they do not respond to policy-induced price changes because of their long planning horizons, high fix costs as well as capacity and political constraints. Thus, their output remains fixed at the calibrated baseline value.

A.4.2 Electricity demand

The demand for electricity, derived from the consumers' maximization problem, has a constant elasticity: $D_t = (\psi_t)^{1-\epsilon}(p^t)^{-\epsilon}$, where ψ_t describes the consumption rate per unit of electricity services. Costs of electricity services thus depend on both the price p^t and the efficiency of its use. Similar to FPN, the elasticity $\epsilon = 0.1$ refers to a very short period of time. Notably, it captures the rebound effect.

The consumption rate ψ_t is a function of endogenous decisions into efficiency improving investments:

$$\psi_t = \bar{\psi}_t \exp\left(-e_t\right) \tag{50}$$

where $\bar{\psi}_t$ describes the baseline consumption rate. e_t denotes the percentage reduction in energy intensity via efficiency improving investments. These reductions are costly. Thus, similar to the representation of power generation, we assume linear marginal costs of efficiency improvements around the baseline. Accordingly, total costs follow a quadratic function:

$$Z^t = z_1^t e_t + \frac{1}{2} z_2^t \left(e_t\right)^2 \tag{51}$$

In the baseline it is $e_t = 0$ so that the first-order condition yields $z_1^t = \beta \bar{p}^t \bar{D}^t$. In other words, the intercepts of the marginal cost functions are partly determined by the perceived valuation factor β of efficiency improvements. Different to FPN who differentiate between short and long-run efficiency improvements across periods, we only allow for efficiency improvements within each period.

To calibrate the slopes of the marginal energy efficiency improvement costs, we closely follow FPN by deriving the implicit short, medium and long-run elasticities of electricity demand. To do so, we solve for energy efficiency investments from the first-order conditions, evaluated with no additional policy measures. Table A.2 shows the relevant calibrated parameters.

Table A.2: Calibrated demand side parameters, prices and emissions

Parameter	Symbol	Unit	t=1	t=2
Intercept energy effic. costs	z_1^t	€	2.49×10^{11}	2.88×10^{11}
Slope energy efficiency costs	z_2^t	€(%)$^{-1}$	3.98×10^{12}	1.15×10^{12}
Electricity demand	$\bar{D}^t$	kWh	3.25×10^{12}	3.53×10^{12}
Electricity price	$\bar{p}^t$	€c/kWh	8.5	9.0
CO_2 price	$\bar{\tau}^t$	€/tCO_2	7.5	35
Total CO_2 emissions	$\bar{M}$	t	1.781×10^9	

A.5 Sensitivity analysis

Three key parameter values of the numerical model are subject to uncertainty. We therefore conduct a sensitivity analysis of these parameter values to assess the robustness of the simulation results. We examine robustness in terms of the share of recuperated costs, denoted by SRC, which is a central metric of our policy assessment. SRC measures the potential of second-best adjustments to compensate for unavailable first-best instruments.

A.5.1 Energy efficiency undervaluation

One key parameter is β, which determines the share of perceived energy efficiency benefits. In our main analysis, we assume $\beta = 0.9$, i.e., a rather conservative value of 10% undervaluation. In order to check the robustness of the main results, we run simulations for $0.55 \leq \beta \leq 0.95$ for the three second-best policy scenarios with multiple adjustments of the remaining instruments in the absence of (i) energy efficiency subsidies (*No-Effic-Sub*), (ii) R&D subsidies (*No-R&D-Sub*) and (iii) renewable output subsidies (*No-Out-Sub*). Figure A.2 shows the results.

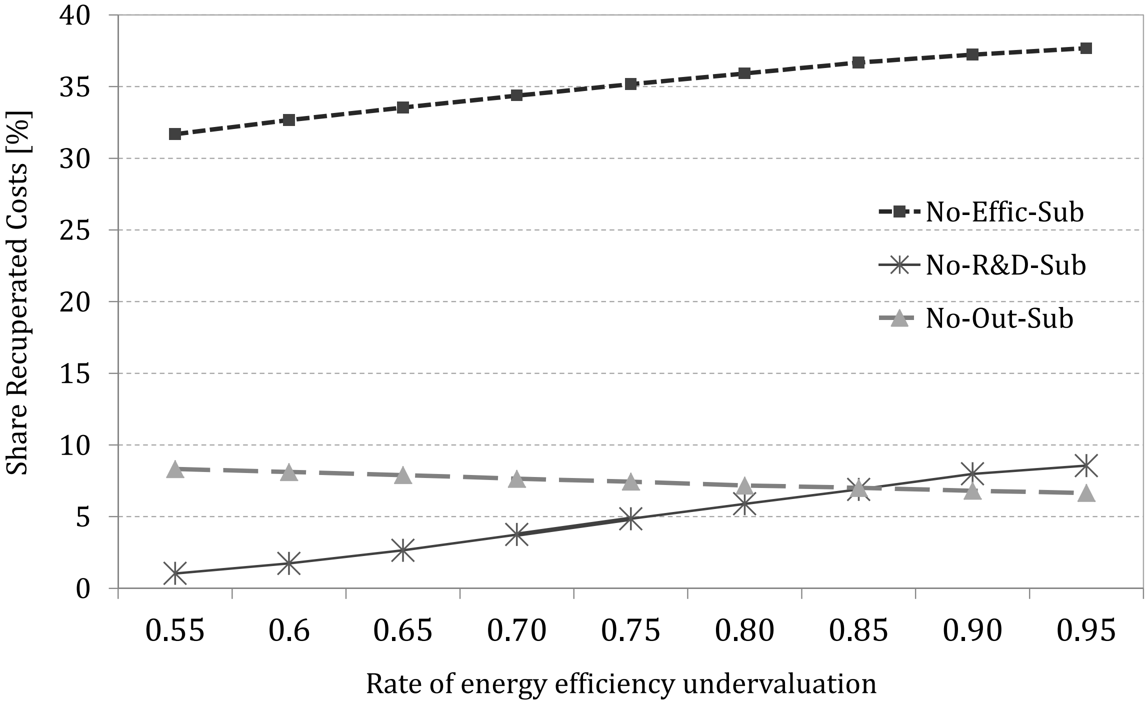

Figure A.2: Sensitivity of the share of recuperated costs (SRC) to rate of energy efficiency undervaluation (β) with multiple policy instrument adjustments

The second-best adjustment under *No-Effic-Sub* or *No-R&D-Sub* becomes less effective for higher degrees of undervaluation (lower β). The opposite behavior is observed under *No-Out-Sub*; however, as in the previous simulations, policy effects and costs are rather small in this scenario.

A.5.2 Knowledge undervaluation

Another key parameter is ρ, representing the share of perceived private knowledge benefits. In our main analysis, ρ is set to 0.5 for both R&D and learning-by-doing. This is consistent with a social return to knowledge that is about twice the private return Jones and Williams (1998). To check the robustness of our results, we run simulations for $0.35 \leq \rho \leq 0.75$ for the three second-best policy scenarios with multiple adjustments as described in the previous subsection and illustrated by figure A.3.

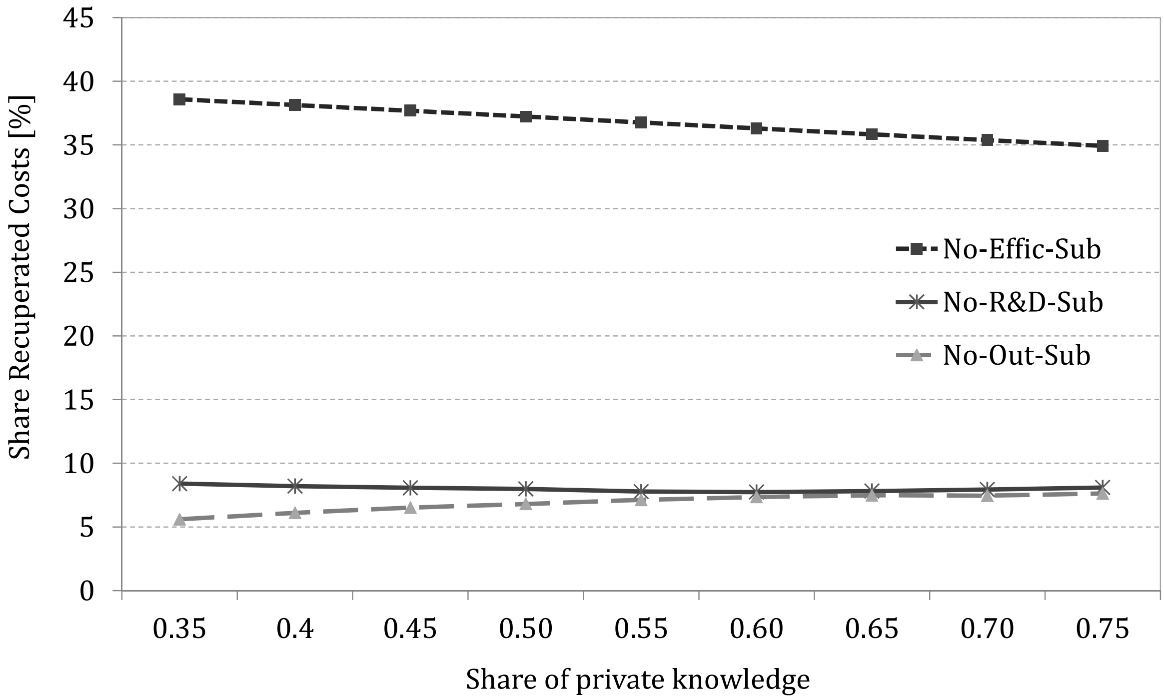

Figure A.3: Sensitivity of the share of recuperated costs (SRC) to private knowledge benefits share (ρ) with multiple policy instrument adjustments

We find relatively small effects from varying ρ for the effectiveness of second-best policy instrument adjustments, expressed as SRC. Higher shares of private knowledge ρ, representing a smaller market failure, slightly reduce the effectiveness of second-best adjustments under *No-Effic-Sub* and to a minor extent *No-R&D-Sub*. The opposite effect is observed under *No-Out-Sub*.

A.5.3 Stringency of the emissions target

The last key parameter studied in the sensitivity analysis is the extent of the CO_2 emissions reduction. Although politically already fixed—the EU decided to reduce CO_2 emissions in 2030 by 40% relative to 1990—it is nevertheless insightful for evaluations of new policies to analyze how sensitively the effectiveness of second-best adjustments reacts to changes in the stringency of the emissions target. To check the robustness of our previous results, we run simulations for emissions reductions $\bar{M}^{r2030}$ in 2030 relative to 1990 ranging from 30% to 60% for the three second-best policy scenarios. Figure A.4 sketches the results.

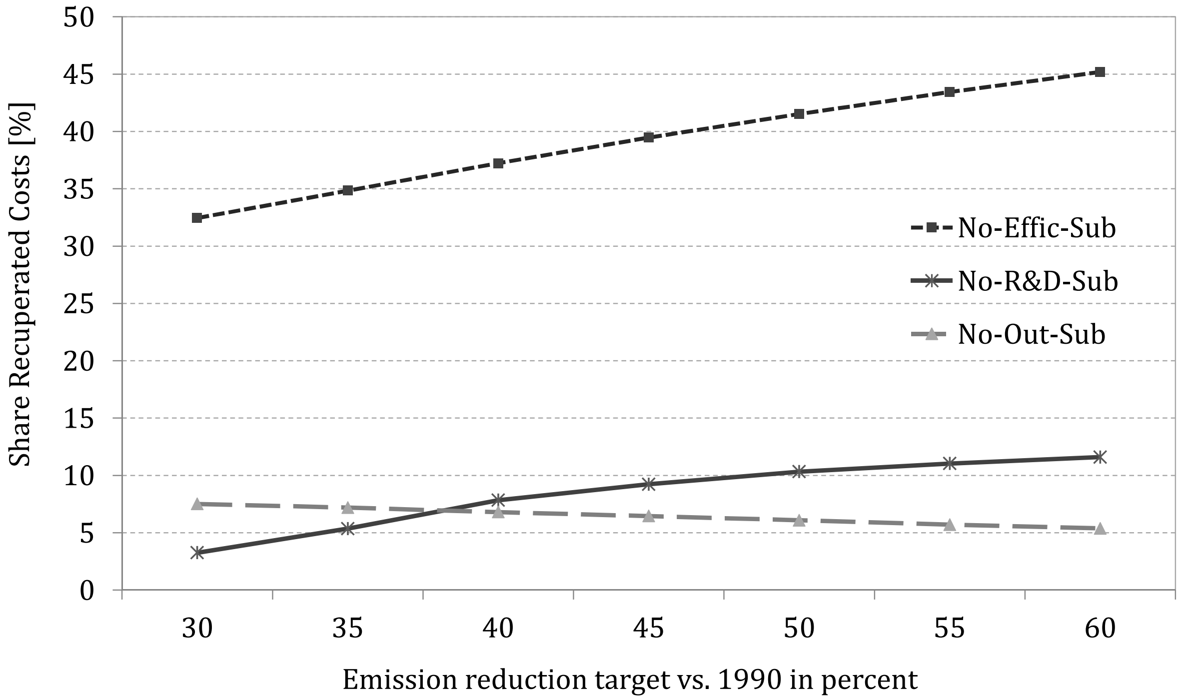

Figure A.4: Sensitivity of the share of recuperated costs (SRC) to emissions reduction targets for 2030 ($\bar{M}^{r2030}$) with multiple policy instrument adjustments

The sensitivity of SRC to changes in the emissions target is larger than in the previous cases. The more stringent the emissions target, the higher will be the potential SCR under *No-Effic-Sub* or *No-R&D-Sub*. Again, the opposite behavior with small deviations is observed under *No-Out-Sub*.