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Working Paper 18/286
March 2018

Economics Working Paper Series



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The Economics of Renewable Energy Support

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MARCH 2018

This paper uses theoretical and numerical economic equilibrium models to examine optimal renewable energy (RE) support policies for wind and solar resources in the presence of a carbon externality associated with the use of fossil fuels. We emphasize three main issues for policy design: the heterogeneity of intermittent natural resources, budget-neutral financing rules, and incentives for carbon mitigation. We find that differentiated subsidies for wind and solar, while being optimal, only yield negligible efficiency gains. Policies with smart financing of RE subsidies which either relax budget neutrality or use “polluter-pays-the-price” financing in the context of budget-neutral schemes can, however, approximate socially optimal outcomes. Our analysis suggests that optimally designed RE support policies do not necessarily have to be viewed as a costly second-best option when carbon pricing is unavailable. (JEL Q28, Q42, Q52, Q58, C61).

Decarbonization of energy systems to cope with the major challenges related to fossil fuels—limiting carbon dioxide (CO₂) emissions to mitigate global climate change, lowering local air pollution to yield health benefits, and enhancing the security of energy supply—will require drastic changes in the future mix of energy technologies in favor of using low-carbon, renewable energy (RE). Economists seem to agree that carbon pricing is the most efficient regulatory strategy (Goulder and Parry, 2008; Metcalf, 2009; Tietenberg, 2013), along with policies to address positive externalities related to technological innovation through R&D investments and learning (Jaffe, Newell and Stavins, 2005; Acemoglu et al., 2012). Policies aimed at subsidizing the deployment of RE technologies are often considered a costly second-best option failing to adequately reflect the heterogeneous marginal social costs of multiple fossil-based and RE technologies. Moreover, by lowering the price of energy services, RE subsidies undermine incentives for energy conservation (Holland, Hughes and Knittel, 2009). Yet, policies promoting clean energy from RE sources such as wind and solar are the most widely adopted

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form of actual low-carbon policy (Meckling, Sterner and Wagner, 2017).¹

This paper investigates how public policies aimed at supporting RE from wind and solar should be best designed in the presence of a carbon externality related to the use of non-renewable fossil fuels in energy supply and demand. An RE support scheme comprises two essential elements: (1) subsidies paid to firms producing electricity from RE and (2) a rule how these subsidies are financed. Examples of widely adopted forms for RE support include feed-in tariffs (FITs), guaranteeing a fixed output price per MWh of electricity sold, and market premiums which essentially are output subsidies added to the wholesale electricity price. The expenses for a FIT or output subsidy paid to RE firms are typically financed through levying a tax on energy demand of consumers. RE quotas, renewable or clean portfolio standards are widely adopted examples of technology or intensity standards which are blending constraints combining output subsidies for RE with input production taxes to finance the RE support. A generic way of thinking about the design of RE support schemes is therefore to ask how RE subsidies should be structured *and* financed.

Our analysis emphasizes three major issues for RE policy design which are of relevance for the decarbonization of real-world energy systems. First, wind and solar resources exhibit a large heterogeneity in terms of their temporal and spatial availability. Adding one MWh of solar electricity may thus yield very different CO₂ emissions reductions compared to adding one MWh of wind; the exact answer depends on the complex interactions between heterogeneous resource availability, time-varying energy demand, and the carbon-intensity and technology costs of installed production capacities. We investigate how RE subsidies should be structured to take into account these heterogeneous marginal external benefits. Second, most of the currently adopted forms of RE support are revenue-neutral, i.e. RE subsidies are financed through energy consumption taxes—either explicitly, as under a FIT or market premium approach, or implicitly, as for the case of technology or intensity standards. We analyze the implications of revenue-neutral RE support schemes in the context of optimal policy design. Third, in the absence of stringent carbon pricing and given that RE support schemes are currently the most widely adopted form of actual low-carbon policies, a future world with “Janus-faced” energy systems—comprising either clean energy from RE sources or highly carbon-intensive “dirty” fossil fuels (i.e., coal)—is not unlikely at all. While RE support policies induce investments in RE capacity and foster low-carbon energy growth, it is ultimately *cumulative* emissions that count for addressing climate change.² We thus investigate how the financing of RE subsidies can be

¹As of 2016, about 110 jurisdictions worldwide—at the national or sub-national level—had enacted policies subsidizing wind and solar power (REN, 2017). The *Renewable Energy Directive* by the European Commission (2010) established a policy framework for the promotion of RE in the EU with the aim to meet by 2030 27% of total EU-wide energy consumption with renewables. In the United States, the federal government provides sizable production and investment tax credits for RE and more than half of the states have adopted renewable portfolio standards mandating minimum levels of RE generation (U.S. Department of Energy, 2016).

²Edenhofer et al. (2018) estimate that approximately 340 Gt CO₂ emissions out of a global carbon

designed to provide incentives for carbon mitigation.

To conceptualize and examine the fundamental economic principles for designing RE support schemes for wind and solar power, we formulate theoretical and numerical equilibrium models of optimal policy design where society (i.e., the regulator) is concerned with the management of an environmental externality related to the use of fossil fuels. Decisions about energy supply and demand stem from profit- and utility-maximizing firms and consumers in the setting of a decentralized market economy. We first theoretically characterize the optimal structure and financing of RE subsidies as well as the conditions under which such policies can implement socially optimal outcomes. To assess different RE support schemes in an empirically plausible setting and to derive additional quantitative insights, we develop a numerical framework which extends the theoretical model and accommodates a number of features relevant for analyzing real-world electricity markets.³ While the model is calibrated with data for the German electricity market, our numerical simulations yield qualitative insights germane to the decarbonization of the electricity sector in many countries.

Our main findings can be summarized as follows. First, the optimal subsidy for an RE technology reflects both the environmental and market value of the underlying intermittent natural resource. The environmental value reflects the environmental damage avoided by replacing fossil-based with renewable energy supply. The market value reflects the economic rents for firms and consumers created by using intermittent resource. Accordingly, we find that the optimal RE subsidies for wind and solar differ. The quantitative analysis, however, suggests that the efficiency gains from differentiating RE subsidies across technologies are negligible. Second, under an optimal RE support scheme, the revenues raised from an energy demand tax exceed the expenses for RE subsidies. The important implication for policy design is that revenue-neutral support schemes, such as the widely adopted FIT or RE quota policies, cannot implement a social optimum. We estimate that revenue-neutral RE support schemes entail large efficiency losses compared to a first-best carbon pricing policy as they fail to appropriately incentivize the energy conservation channel. Third, we show that a RE support policy can implement the first-best outcome only if achieving the social optimum does not require a change in the fossil-based technology mix (relative to the unregulated market outcome). Fourth, the efficiency of RE support schemes importantly depends on the way in which RE subsidies are financed. We find that combining RE subsidies with an optimal tax on energy demand or using intensity or technology standards which link the financing of RE subsidies to the carbon intensity of fossil-based energy suppliers are particularly effective ways for improving policy

budget of around 700 Gt CO₂ (± 275 Gt CO₂)—consistent with having a “good chance” (i.e., 66%) of keeping global temperature below 2°C as envisaged by the Paris agreement—would be consumed by currently existing, under construction, and planned coal power plants.

³These include, among others, hourly wholesale markets, multiple energy technologies, time-varying and price-responsive demand, temporally and spatially heterogeneous quality of wind and solar resources, and output-dependent marginal cost and CO₂ emissions to reflect flexibility and efficiency constraints at the level of individual power plants.

design.

Importantly, our analysis shows that—when carbon pricing is unavailable due to political (and other) constraints—RE support policies do not necessarily have to be viewed as a “costly” second-best option. Their ability to closely approximate socially optimal outcomes crucially depends on (1) policy design, in particular how RE subsidies are financed, (2) market conditions (including the price responsiveness of energy demand and the composition of fossil-based energy supply), and (3) the social valuation of environmental damages associated with carbon-based energy supply.

To the best of our knowledge, this paper is the first to investigate the optimal design of public policies to support intermittent RE resources in the presence of a carbon externality. In light of the widespread use of RE policies to help decarbonize today’s energy systems, we thus believe that our analysis fills an important gap in the existing literature. At a broader level, the paper contributes to the literature in public and environmental economics focused on understanding the impacts and design choices of governmental regulation to address market failures and externalities related to pollution and technological progress through learning and R&D investments (see, for example, [Fullerton and Heutel, 2005](#); [Goulder and Parry, 2008](#); [Fischer and Newell, 2008](#); [Acemoglu et al., 2012](#)). While most studies have scrutinized various market-based and “command-and-control” approaches to carbon mitigation, the issue of how to best design public policies to promote energy from *intermittent* RE resources has received surprisingly little attention.

Recent empirical evidence ([Kaffine, McBee and Lieskovsky, 2013](#); [Cullen, 2013](#); [Novan, 2015](#)) has documented the temporal and spatial heterogeneity of intermittent wind and solar resources in terms of their environmental value, i.e. avoided CO₂ emissions per MWh of RE electricity. Based on an econometric ex-post assessment for Germany and Spain, [Abrell, Kosch and Rausch \(2017\)](#) find that the impacts of RE support policies on wholesale electricity prices vary substantially depending on whether wind or solar energy is subsidized. While these papers generally point out that the heterogeneous environmental and market values of different intermittent RE resources are not reflected in the prevailing policy incentives that guide investments in RE resources ([Callaway, Fowlie and McCormick, 2017](#)), the implications for policy design have not been analyzed. By typically adopting a simplified and aggregated representation of RE technologies, natural resource variability, and time-varying energy demand, most of the work analyzing RE support policies ([Fischer and Newell, 2008](#); [Rausch and Mowers, 2014](#); [Kalkuhl, Edenhofer and Lessmann, 2015](#); [Goulder, Hafstead and Williams, 2016](#)) has abstracted from the fact that wind and solar resources are heterogeneous—thereby ignoring the idiosyncratic ways in which distinct intermittent RE resources interact with energy supply and demand. Our framework investigates the optimal design of RE support schemes in the context of multiple intermittent RE resources.

A small and recent literature has started to examine the effects of intermittent

energy sources for the provision of electricity employing the peak-load pricing model (Crew and Kleindorfer, 1976; Crew, Chitru and Kleindorfer, 1995). Ambec and Crampes (2012) and Helm and Mier (2016) analyze the optimal and market-based mix of intermittent RE and conventional dispatchable energy technologies. They do not, however, investigate the question of government support for RE resources. Ambec and Crampes (2017) theoretically examine optimal RE policies in a setting with one intermittent RE resource, i.e. either wind *or* solar—thus not permitting to investigate the implications of multiple heterogeneous RE resources for optimal policy design. Fell and Linn (2013) and Wibulpolprasert (2016) take into account the temporal and spatial resource heterogeneity, but focus on comparing RE policies in terms of their cost-effectiveness to achieve a given and exogenously determined emissions target. In contrast, our analysis explicitly considers a carbon externality and analyzes optimal RE policy design when the choice of environmental quality is endogenous.

The remainder of this paper is organized as follows. Section I presents our theoretical model and results. Section II describes the empirical quantitative framework to investigate RE policies, including data sources and computational strategy. Section III presents and discusses our main simulation results.⁴ Section IV reports on a number of robustness checks and model extensions. Section V concludes.

I. Theoretical Model and Results

A. Model setup

We have in mind a situation where society is concerned with the management of an unpriced environmental externality that is related to the use of fossil fuels in energy production. Although the reasoning below fits alternative applications, we let climate change and CO₂ emissions abatement guide the modeling.⁵ We focus on the question how public policies supporting RE technologies should be best designed to address the carbon externality.

ENERGY TECHNOLOGIES AND PRODUCTION.—We consider a perfectly competitive electricity market in which in each period $t, t' \in \{1, 2\}$ electricity can be produced by conventional technologies (e.g., coal, gas, nuclear) and intermittent renewable energy technologies (e.g., wind and solar). Output from different technologies is a homogeneous good. Conventional technologies $i \in \{c, d\}$ are assumed to be fully dispatchable, i.e. production can be varied freely at any point in time up to the

⁴An online appendix which documents the computer codes to replicate the quantitative analyses presented in the paper. All model files, including the data, can be downloaded at: https://www.ethz.ch/content/dam/ethz/special-interest/mtec/cer-eth/economics-energy-economics-dam/documents/people/srausch/Online_Appendix_TheEconomics_of_RenewableEnergySupport.zip.

⁵Our framework could be extended to also consider other externalities related to fossil fuel use such as local air pollution and energy security considerations. We also abstract from explicitly representing externalities related to the deployment of RE technologies such as fostering innovation, learning, and local employment effects.

installed capacity limit.⁶ Conventional technology i produces electricity output at time t , q_{it} , incurring production cost $C_i(q_{it})$ where C is a continuous and weakly convex function ($C'_{it} := \partial C_i / \partial q_{it} \geq 0$ and $C''_{it} := \partial^2 C_i / \partial q_{it}^2 > 0$).⁷ CO₂ emissions associated with using technology i at time t depend on the level of output and are given by $E_i(q_{it})$. For all i , we assume that the marginal emissions rate is strictly positive ($E'_{it} := \partial E_i / \partial q_{it} > 0$) and increases weakly in the level of output ($E''_{it} := \partial^2 E_i / \partial q_{it}^2 \geq 0$). Relative to the clean technology c , the dirty technology d is characterized by a higher CO₂ emissions rate ($E'_{dt} > E'_{ct}$). In addition, we assume that:

ASSUMPTION 1: *In the absence of environmental policy, $C'_{ct}(q_{ct}) > C'_{dt}(q_{dt})$, implying that the clean fossil-based technology c is not in the market.*

While it would be straightforward to relax Assumption 1, it helps to focus on assessing the impacts of a supply-side driven fuel switch between high- and low-carbon technologies in response to an RE policy. Our numerical analysis will scrutinize this assumption by modeling a number of (discrete) conventional energy technologies which exhibit heterogeneous emissions intensities and are present in the initial situation without RE support. Also, note that $C'_{ct}(q_{ct}) > C'_{dt}(q_{dt})$ together with the convexity of cost functions implies that marginal cost functions for the clean and dirty conventional technology do not intersect.

We consider two RE technologies (e.g., wind and solar) which differ with respect to resource availability and investment cost for building production capacity. Output produced with either RE technology does not cause any CO₂ emissions. To reflect differences in resource availability, we index RE technologies by t and assume that:

ASSUMPTION 2: *RE technology t is available in period t but not in period t' .*

While in reality wind and solar resources are often available at the same time, Assumption 2 enables us to examine how RE support policies should be designed in light of heterogeneous RE resources. Our numerical analysis relaxes this assumption by incorporating data to characterize the empirical joint distribution of wind and solar resources.

Without loss of generality, marginal generation cost for each RE technology is normalized to zero. To produce output with RE technology t , it is required to install capacity k_t , creating investment cost equal to $G_t(k_t)$. Investment cost functions are strictly convex expressing the fact that investments first take place at most productive sites ($G'_t := \partial G_t / \partial k_t > 0$ and $G''_t := \partial^2 G_t / \partial k_t^2 > 0$). As RE technologies can produce output at zero marginal cost, output at time t is equal

⁶Note that conventional energy technologies can differ in terms of dispatchability, for example, due to ramping constraints and maintenance. We abstract from such considerations here.

⁷The convex cost functions for conventional energy technologies should be viewed as an implicit representation of multiple discrete suppliers with exogenously given production capacities ordered by marginal cost.

to the installed capacity k_t . Energy production from RE sources does not cause any emissions.

DEMAND AND ENERGY BALANCE.—Consumers derive gross utility, $S_t(d_t)$, from the consumption of d_t units of electricity at time t . With $p(d_t)$ denoting the inverse demand function, gross surplus at time t is $S_t(d_t) := \int_0^{d_t} p(\tilde{x})d\tilde{x}$. S_t is a continuous derivable function which we assume to be concave ($S'_t := \partial S_t / \partial d_t > 0$ and $S''_t := \partial^2 S_t / \partial d_t^2 \leq 0$).

We assume that energy demand only responds to price in the same period which is equivalent to assuming that:

ASSUMPTION 3: *The cross-price elasticity of energy demand at time t with respect to price at time t' is zero, i.e. $\partial d_t / \partial p_{t'} = 0, \forall t$.*

Assumption 3 considerably eases analytical complexity as it implies that $S_t(d_t)$ is separable across time periods. Importantly, this assumption does not rule out the possibility that consumers increase or decrease demand in response to current-period changes in the electricity price.

Energy balance requires that at any point in time total energy production equals energy demand:

$$(1) \quad k_t + \sum_i q_{it} = d_t.$$

ENVIRONMENTAL EXTERNALITY AND SOCIAL SURPLUS.—The environmental externality derives from CO₂ emissions due to burning fossil fuels associated with supplying energy from conventional technologies. CO₂ as a uniformly-mixed pollutant is assumed to cause time-independent marginal damage equal to δ per unit of $E_i(q_{it})$. δ may thus be viewed as the social cost of carbon (SCC) per ton of emitted CO₂.

The regulator is concerned with maximizing social surplus which is defined as gross utility net of private production cost associated with conventional and RE supply and the environmental damage to society caused by aggregate emissions:⁸

$$(2) \quad \mathcal{W} := \underbrace{\sum_t \left[S_t(d_t) - G_t(k_t) - \sum_i C_i(q_{it}) \right]}_{\text{=Economic surplus}} - \underbrace{\delta \sum_t \sum_i E_i(q_{it})}_{\text{=Environmental damage}}.$$

B. Social planner optimum

In the social optimum, the regulator chooses levels of output of conventional and RE technologies (\hat{q}_{it} and \hat{k}_t) which maximize social surplus \mathcal{W} subject to the

⁸We assume that environmental damage is additively separable from private consumption. Previous literature (see, for example, Carbone and Smith, 2008) has highlighted the importance of taking into account the non-separability between externalities and private utility for evaluating the effects of economic regulation. We leave this important extension for future research.

energy balance constraint (1) according to:

$$(3a) \quad C'_{it} + \delta E'_{it} \geq S'_t \quad \forall t, i \quad (\hat{q}_{it})$$

$$(3b) \quad G'_t = S'_t \quad \forall t \quad (\hat{k}_t).$$

The interpretation of the conditions for the social optimum is straightforward: energy produced by conventional technology i at time t (\hat{q}_{it}) is chosen such that the marginal social cost—comprising marginal private cost of production C'_{it} and the marginal environmental damage $\delta E'_{it}$ —are equal to marginal private surplus S'_t ; energy produced with (or production capacity of) the RE technology t (\hat{k}_t) is chosen such that marginal private investment cost G'_t and the marginal private surplus are equalized. The socially optimal pollution level is then given by $\hat{E} = \sum_{i,t} E_i(\hat{q}_{it})$.

Depending on how strong the environmental motive (δ) is, energy production from conventional technologies in the social optimum can take on two outcomes. If δ is “small”, then $(C'_{ct} + \delta E'_{ct}) / (C'_{dt} + \delta E'_{dt}) > 1$ implying that energy production with the clean technology is more costly and hence only the dirty technology is used. In contrast, for sufficiently high δ , only the clean conventional technology is used. To create a meaningful problem to examine RE support policies, we assume that the social optimum involves a positive amount of energy supplied from RE technologies at every t , i.e. $\hat{k}_t > 0$.⁹

C. The regulator’s problem in the decentralized economy

The fundamental problem of environmental regulation analyzed in this paper is to examine how RE support policies should be best designed to address the carbon externality associated with fossil-based energy supply in a decentralized market economy where equilibrium decisions about energy supply and demand stem from profit- and utility-maximizing firms and consumers (and can hence not be directly controlled as in the social planner problem analyzed in Section I.B).

Hence, the regulator’s problem is to maximize social welfare \mathcal{W} taking into account a set of constraints that describe the equilibrium responses of economic agents with respect to market information (prices) and policy choice variables:

$$(4) \quad \max_{\mathbf{b}=\{s_t, \tau_t, \kappa_{it}\}} \mathcal{W}(d_t, k_t, q_{it}; \delta)$$

⁹ If RE technologies are always more costly than conventional technologies (including the social cost of carbon), i.e. $G'_t(k_t) > \min\{C'_{ct}(\hat{q}_{ct}) + \delta E'_{ct}(\hat{q}_{ct}), C'_{dt}(\hat{q}_{dt}) + \delta E'_{dt}(\hat{q}_{dt})\}$, $\forall t$, there is no role for RE technologies in the social optimum and the fundamental problem of optimal RE policy support, which motivates our entire analysis, becomes trivial. By assuming that condition (3b) always holds as a strict equality, we rule out the case that energy supply in the social optimum is satisfied only with conventional energy production and that $\hat{k}_t = 0$.

s.t. (p_t, d_t, k_t, q_{it}) solve the market equilibrium conditions:

$$\begin{aligned}
(4a) \quad & S'_t = p_t + \tau_t \quad \forall t \quad (d_t) \\
(4b) \quad & C'_{it} + \kappa_{it} \geq p_t \quad \forall t, i \quad (q_{it}) \\
(4c) \quad & G'_t = \psi_t \quad \forall t \quad (k_t) \\
& \psi_t = \begin{cases} p_t + s_t & \text{if output subsidy or intensity standard} \\ s_t & \text{if feed-in tariff} \end{cases} \\
(4d) \quad & k_t + \sum_i q_{it} = d_t \quad \forall t \quad (p_t)
\end{aligned}$$

where p_t denotes the price of energy at time t .

For given policy choice variables \mathbf{b} , the equilibrium of the decentralized economy is defined by prices and quantities $\{p_t^*, d_t^*, k_t^*, q_{it}^*\}$ such that: (i) the marginal private utility from energy consumption equals the private marginal cost (4a), (ii) firms supplying energy with conventional technology i minimize cost of production (4b), (iii) firms supplying energy with RE technology t minimize cost (4c), and (iv) the wholesale energy markets clear (4d).¹⁰

POLICY INSTRUMENTS.— Table 1 categorizes the different policy controls for promoting RE supply contained in \mathbf{b} along two key dimensions: the structure of RE subsidies and the way RE subsidies are refinanced. RE producers can either receive a guaranteed fixed price per MWh sold ($\psi_t = s_t$), as is the case under a FIT, or they can receive the subsidy on top of the market price, as is the case under a market premium approach ($\psi_t = p_t + s_t$). Moreover, RE subsidies can be differentiated in terms of the support for each RE technology ($s_1 \neq s_2$) or they can be uniform ($s_1 = s_2$).

Several ways of financing RE subsidy payments are conceivable. Under FIT and premium systems the RE subsidies are often financed by levying a (time-constant) tax on energy demand (τ). In such a case, τ is endogenously determined by the following revenue-neutrality constraint which has to be added to the upper-level problem in (4):

$$(5) \quad \sum_t \tau d_t = \sum_t s_t k_t \quad (\tau).$$

Alternatively, it is possible to view the (time-varying) energy demand tax (τ_t) as a distinct policy instrument chosen to optimally incentivize energy conservation via the demand channel. In this case, the optimal policy involves choosing both (s_t, τ_t) .

Yet another way of refinancing RE subsidies applies if intensity or technology standards are used. Such standards are essentially blending constraints which

¹⁰ Assuming perfect competition with free entry and exit and price-taking consumers, it is straightforward to derive conditions (4a)–(4c) from the individual expenditure- and cost-minimization problems of optimizing consumers and firms, respectively.

TABLE 1. Taxonomy of policy designs which explicitly or implicitly promote RE supply.

		Refinancing of RE subsidies	
		Tax on energy demand (τ_t)	Input taxes on energy production (κ_{it})
Structure of technology-neutral or -differentiated RE subsidies (s_t)	No direct RE support		<i>Carbon tax</i> <i>Emissions trading</i>
	Guaranteed output price	<i>Feed-in tariff (FIT)</i>	<i>Technology or intensity standards:</i> <i>·RE quota or renewable portfolio standard (RPS)</i> <i>·Green offsets</i>
	Output subsidy	<i>Market premium</i>	

translate into implicit output subsidies for RE technologies (s_t) and implicit input taxes (κ_{it}) in energy production to finance RE subsidies (Holland, Hughes and Knittel, 2009). Consider the case of an RE quota which mandates that a certain share γ of total energy supplied has to come from RE sources—adding the following constraint to the lower-level equilibrium problem in (4):

$$(6a) \quad \underbrace{\sum_t k_t}_{=\text{Supply of RE credits}} \geq \gamma \underbrace{\sum_t \left(k_t + \sum_i q_{it} \right)}_{=\text{Demand for RE credits}} (p^{\text{Credits}}).$$

The RE quota can be conceived as a system of tradable credits where p^{Credits} corresponds to the post-trading equilibrium price of a credit determined by credit supply and demand.¹¹

A tradable RE standard is by definition revenue-neutral: expenses for RE subsidies are fully financed through implicit input taxes κ_{it} on energy producers. Output subsidies are paid to RE firms which receive one credit valued at price p^{Credits} for each MWh of electricity produced. From (6a) it then follows that the implicit per-MWh tax under an RE quota is:

$$(6b) \quad \kappa_{it}^{\text{RE quota}} = \gamma p^{\text{Credits}}.$$

The interpretation is that *all* energy firms have to hold γ credits for each MWh of energy produced. Because RE firms also receive one credit per MWh, their effective net support per MWh of electricity produced is

$$(6c) \quad s^{\text{RE quota}} := p^{\text{Credits}} - \gamma p^{\text{Credits}} = (1 - \gamma)p^{\text{Credits}}.$$

¹¹We focus here on the case most relevant for real-world RE policy in which the standard does not differentiate between heterogeneous types of RE sources.

We propose and analyze a new design for a tradable and revenue-neutral intensity standard which links the amount of RE energy output to overall emissions derived from using fossil fuels in energy production. We refer to such a scheme as “green offsets”. The main idea is that CO₂ emissions have to be compensated or offset by a certain amount of energy supplied from “green” (i.e., wind and solar) RE sources according to:

$$(7a) \quad \underbrace{\sum_t k_t}_{=\text{Supply of green offsets}} \geq \gamma \underbrace{\sum_t \sum_i E_{it}(q_{it})}_{=\text{Demand for green offsets}} (p^{\text{Credits}}).$$

γ here represents the “offset intensity”, i.e. the minimum amount of green energy required to offset overall CO₂ emissions from “dirty” energy production, which is chosen by the regulator. Here, p^{Credits} indicates the value of a tradable “green offset” certificate. In an energy system where RE is relatively abundant, p^{Credits} is small; it is zero if all energy comes from green sources. If fossil fuels are still the dominant sources of energy supply, p^{Credits} is large and provides an incentive for RE producers to increase their supply.

Analogously to the case of an RE quota, the implicit input tax per MWh of electricity produced under a revenue-neutral “green offset” standard is:

$$(7b) \quad \kappa_{it}^{\text{Green offsets}} = \gamma E'_{it} p^{\text{Credits}}.$$

A green offset policy is thus an RE support scheme with “polluter-pays-the-price” refinancing: the expenses for RE subsidies are *entirely* refinanced by levying production input taxes on fossil-based electricity firms which are proportional to the carbon intensity. This implies that RE firms with zero emissions receive a net support equal to the credit price:

$$(7c) \quad s^{\text{Green offsets}} := p^{\text{Credits}}.$$

Under both forms of intensity standards, and compared to policies such as a FIT and market premium which directly choose the level of RE support, the only policy choice variable of the regulator is the level of the intensity target γ which then implicitly determines the RE subsidy rate s and refinancing taxes κ_{it} through (6a) and (6b) in the case of an RE quota and (7a) and (7b) in the case of green offsets, respectively.

Finally, a carbon pricing policy—implemented through a CO₂ tax or a system of tradable emissions permits—can be represented as a specific input tax κ_i based on the carbon content of energy production without direct support for RE (i.e., $s_t = 0$). RE supply is, however, incentivized indirectly through lowering the production cost of RE technologies relative to fossil-based generation.

We now turn to characterizing optimal policies for RE support when the regulator can use different policy designs which draw on the instruments displayed in

Table 1. The second part of our theoretical analysis examines whether or not the various policy designs for RE support are optimal from a social perspective and characterizes the conditions under which RE policies can attain a social optimum.

D. Optimal policies for RE support

CARBON PRICING.—We begin by analyzing a carbon pricing instrument which can be implemented equivalently either through a carbon tax or a system of tradable emissions permits. While carbon pricing does not explicitly subsidize RE technologies, it establishes indirect support for RE by altering relative production cost in favor of RE technologies. The case of a carbon tax constitutes a useful benchmark against which to compare RE support policies. It is straightforward to show that:

PROPOSITION 1: *The social optimum can be implemented by using for each energy firm i an input tax equal to its marginal environmental damage at time t (i.e., $\kappa_{it} = \delta E'_{it}, \forall i, t$).*

Proposition 1 simply recaps the standard result that the environmental externality can be fully internalized with a Pigouvian pricing rule which implements the social optimum by introducing a tax equal to the marginal environmental damage (Baumol, 1972; Metcalf, 2009). A carbon pricing instrument is efficient for two reasons. First, it corrects the relative prices of energy technologies/fuels between fossil-based and RE technologies as well as between clean and dirty conventional technologies. At the same time, it does not distort choices for investments in RE technologies (i.e., wind vs. solar). Second, it corrects the price for energy services thereby incentivizing the optimal amount of energy conservation (i.e., the optimal level of energy demand).

DIRECT RE SUPPORT SCHEMES.—We now assume that carbon pricing or input taxes are not available, i.e. $\kappa_{it} = 0, \forall i$. How should the parameters of a direct RE support scheme—comprising subsidies s_t for RE firms and refinancing taxes τ_t levied on energy consumption—be chosen optimally? The following proposition characterizes the optimal policy:

PROPOSITION 2: *The optimal RE support scheme consisting of RE subsidies ψ_t^* —structured either as a feed-in tariff or a market premium—and an energy demand tax τ_t^* , is given by:*

$$\begin{aligned}\psi_t^* &= p_t + \delta E'_{dt} \\ \tau_t^* &= \delta E'_{dt}.\end{aligned}$$

PROOF: See Appendix A.A2. \square

The optimal RE policy support thus requires that, at the margin, consumers—in addition to paying for the non-environmental cost of using resources to supply energy (p_t)—bear the environmental damage associated with using fossil-based

energy ($\tau_t^* = \delta E'_{dt}$).¹² At the same time, RE supply is incentivized up to the point where the marginal private costs are equal to the marginal benefits which reflect the non-environmental and environmental value of the targeted RE resource.

An immediate implication of Proposition 2 is that:

COROLLARY 1: *The optimal feed-in tariff and optimal market premium policy lead to the same equilibrium allocation.*

PROOF: Using the definition of ψ in (4c), Proposition 2 implies that the optimal level of the FIT and market premium is given by, respectively:

$$(8a) \quad s_t^{*FIT} = p_t + \delta E'_{dt} \quad \forall t$$

$$(8b) \quad s_t^{*Premium} = \delta E'_{dt} \quad \forall t,$$

and thus yields identical zero-profit conditions for RE production (4c) for the case of a FIT and market premium. \square

The welfare-maximizing RE subsidy rate per unit of energy produced from a certain RE resource therefore depends on two factors each affecting one of the two main components in social welfare \mathcal{W} in equation (2). First, it depends on how much the usage of the RE resource towards supplying energy contributes to the economic (non-environmental) surplus—this is reflected by its “market value” expressed as unit revenues or the market price (p_t). Second, it depends on the environmental damage avoided by replacing conventional fossil-based energy supply with RE supply—this is reflected by its “environmental value” given by per-unit emissions rate of the (dirty) conventional technology valued at the social cost of carbon ($\delta E'_{dt}$).

If RE subsidies are structured such that firms directly receive the market income from supplying energy from the RE resource, as is the case under a market premium, the optimal RE subsidy does not need to explicitly reflect the market value of the RE resource. Hence, p_t does not appear in (8b) but instead shows up in zero-profit condition for RE production (4c). If RE firms are guaranteed a fixed price, as is the case under a FIT, the optimal subsidy rate reflects both the market and environmental value of the RE resource.

The optimal energy demand tax is equal for the FIT and market premium case and reflects the marginal environmental cost caused in each period. By imposing a tax equal to δ , the regulator pushes demand towards the first-best level of demand. The tax is higher in periods with high emissions thus causing a larger decrease in demand in high damage periods.

An important implication of (8b) is that the socially optimal FIT is higher for RE resources which are available in periods with high energy prices when demand is relatively large. In real-world systems, for example, electricity demand tends

¹²As we show below in Proposition 3, the clean conventional technology does not enter under (optimal) RE support policies, hence the marginal environmental damage is given by the marginal emissions rate of the dirty conventional technology, E'_{dt} .

to peak around midday when solar resources are available. Following this line of reasoning, the upshot of Proposition 2 is thus that the welfare-maximizing FITs should be higher for solar than for wind power. At the same time, however, the optimal RE subsidy in the case of a FIT or a market premium also depends on the environmental value of the RE resource that is promoted. Proposition 2 also suggests that the RE subsidies should be higher for RE resources which are available in periods in which the marginal (price-setting) conventional technology has a high CO₂ emissions intensity.

Proposition 2 thus implies that optimal RE subsidies should be differentiated to reflect the market and environmental heterogeneity of the underlying resource (e.g., wind and solar). The heterogeneity of wind and solar energy resources is due to differences in resource quality (how much is available?) and temporal availability (when is it available?) which, in turn, both interact with the characteristics of energy demand (temporal variation) as well as conventional energy supply (installed production capacity and carbon intensity of conventional producers).

NON-UNIFORMITY OF RE SUBSIDIES.—The following corollary substantiates the point that optimal RE subsidies should be differentiated by type of RE resource to reflect differences in the market and environmental value:

COROLLARY 2: *If either the social surplus function S_t is constant over time or the emissions rate of the marginal energy producer does not vary with output (i.e., $E'_{dt}(q_{dt}) = \text{const.}$), then*

- (i) *the optimal market premium ($s_t^{*Premium}$) is uniform across RE technologies;*
- (ii) *the optimal energy demand tax (τ_t^*) is uniform over time; and*
- (iii) *if, in addition, marginal cost of the dirty technology does not vary with output (i.e., $C''_{dt}(q_{dt}) = 0$), the optimal FIT (s_t^{*FIT}) is uniform across RE technologies.*

PROOF: See Appendix A.A3. \square

A constant social surplus function over time implies that energy demand does not vary over time. Hence, the wholesale price and the marginal emissions rate are the same in every time period t . Under these circumstances, the optimal RE subsidies and energy demand taxes are uniform. The same result is obtained by assuming that the emissions rate of the marginal energy producer (i.e., the dirty conventional technology) does not vary with output and, in addition for the case of a FIT, that marginal costs of the marginal energy producer are constant in output. Given real-world characteristics of energy supply and demand, these conditions are quite unlikely to hold in practice. First, conventional technologies exhibit substantial heterogeneity in terms of marginal costs, heat efficiencies, emissions rates etc. Second, energy demand varies substantially over time reflecting daily and seasonal fluctuations.

If RE resources were completely identical, then the optimal RE subsidies would be uniform. In reality, however, the temporal availability of wind and solar resources differs. Heterogeneous RE resources interact with time-varying energy

demand and heterogeneous energy supply from conventional sources. Proposition 2 simply expresses the fact that under these conditions p_t and $\delta E'_{dt}$ in equations (8a) and (8b) are not independent of t . Thus, the optimal FIT or market premium cannot be uniform across RE resource types. Similarly, the optimal tax on energy demand is non-uniform across time in a way that reflects the heterogeneous environmental damage in each time period thus pushing the quantity demanded towards the social optimum.

LINKING OF RE SUBSIDIES AND REFINANCING TAXES ON ENERGY DEMAND.—In practice, RE support schemes typically link RE subsidies and taxes on energy demand; for example, the level of the demand tax is often set in order to cover the expenses paid for RE subsidies. While Proposition 2 has characterized the optimal policy rules for RE subsidies and energy demand taxes, it does not shed light on how both instruments should be linked to one another. In particular, is it optimal to choose the energy demand tax such that it exactly yields the income needed to cover the expenses for the optimal RE subsidies? The following corollary shows that an RE support scheme designed in this way cannot be optimal:

COROLLARY 3: *Under an optimal RE support scheme $\{\psi_t^*, \tau_t^*\}$, and if RE firms do not supply the entire market (i.e., $k_t < d_t$), the revenues raised from an energy demand tax strictly exceed the expenses paid for RE subsidies.*

PROOF: See Appendix A.A4. \square

Corollary 3 offers yet another perspective on the rules for optimal RE support policies underlying Proposition 2. The optimal subsidy rate should, besides reflecting the market value of the targeted RE resource (p_t), subsidize RE supply according to the marginal environmental value of the resource ($\delta E'_{dt}$). Regardless of whether the RE subsidy is structured as a FIT or a market premium, the optimal energy demand tax to finance the RE subsidy is equal to this marginal environmental value, i.e. $\tau_t^* = \delta E'_{dt}$. The intuition is that the market-value component of the optimal RE support does not have to be “re-financed”: in the case of a market premium, RE producers directly receive the market value associated with RE production when selling into the market; in the case of a FIT, the market value for social welfare is indirectly accounted for as the regulator sells the energy bought from RE firms back into the market at the equilibrium wholesale price.

As long as RE production does not make up the whole market, the base for the energy demand tax is larger than the one for RE subsidies, in turn implying that the net income (tax revenues - subsidy payments) for the regulator is positive.¹³ The important policy implication from Corollary 3 is therefore that energy demand taxes, which are typically used to refinance RE subsidies, should not be determined by considerations about revenue neutrality: requiring that the tax income equals the payments for RE subsidies, implements a demand tax which is too low. Energy demand and fossil-based energy generation then exceed their

¹³Also, note that the optimal tax and subsidy rates are quantity-based, i.e. per unit of physical energy (MWh) consumed or supplied.

respective optimal level leading to too little energy conservation and too high environmental damage.

E. Can RE support policies implement the social optimum?

Do optimal RE support schemes $\{\psi_t^*, \tau_t^*\}$, comprising RE subsidies—either in the form of a FIT or a market premium—and an energy demand tax, achieve the social optimum which, in the setting of a decentralized market economy, can be implemented through carbon pricing (see Proposition 1)? And if so, what are the conditions under which an optimal RE support policy *can* implement a social optimum?

To answer this question, we begin by building intuition on how well (optimal) RE policies can address the environmental externality through appropriately exploiting the “fuel switch” channel for reducing pollution. Is a FIT, market premium, or an energy demand tax capable of changing the relative size of dirty to clean conventional energy producers, i.e. induce a fuel switch?

PROPOSITION 3: *With RE support through subsidies (ψ_t) or energy demand taxes (τ_t), the clean fossil-based energy technology does not enter the market despite social concerns for the environmental externality.*

PROOF: See Appendix A.A5. \square

The basic intuition behind Proposition 3 is that all instruments reduce the quantity of energy supplied from conventional generation either by partially crowding out conventional generation with increased supply from RE technologies (in the case of FIT and market premium) or by reducing energy demand (in the case of a demand tax). As (dirty) conventional energy generation is the marginal price-setting technology, the (wholesale) producer price of electricity declines. The lower producer price implies that the profitability of sub-marginal energy producers using the clean conventional technology is reduced, too. As the clean conventional energy producers are not in the market initially (i.e., before introducing either one of the policy instruments), they have no incentive to enter the market with these forms of policy support. This holds for both RE subsidies which are uniform or differentiated across RE technologies as well as for a uniform or time-specific energy demand tax.

Importantly, if one assumes that the clean conventional technology is initially in the market, the necessity of a fuel switch depends on which of the fossil-based technology is the marginal generator. As long as the dirty conventional producers remain “price-setting”, no switch from dirty to clean fossil fuels is needed. If a fuel switch is needed, the RE policies would need to achieve a re-ordering of the marginal cost of conventional technologies. This, however, is impossible as with these instruments the regulator cannot directly affect the LHS of the zero-profit conditions for conventional producers (4b).¹⁴ The important implication from

¹⁴Without policies affecting directly the marginal cost of production, there exists the possibility that

Proposition 3 is thus that RE support schemes comprising *a combination* of RE subsidies, with either a FIT or market premium structure, and refinancing taxes on energy demand, fail to efficiently exploit the “fuel switch” channel.

Given Proposition 3, it is straightforward to characterize the condition under which an optimal RE support scheme *can* attain the first-best allocation in the social optimum:

PROPOSITION 4: *The optimal RE support scheme consisting of RE subsidies ψ_t^* —structured either as a feed-in tariff or a market premium—and an energy demand tax τ_t^* implements the social optimum if and only if the clean fossil-based energy technology is not required to enter the market.*

PROOF: See Appendix A.A6. \square

Intuitively, if the social optimum requires an energy supply mix which involves a positive quantity of energy supplied from the clean fossil-based technology, an optimal RE support scheme will fail to implement the first-best allocation.¹⁵ Table 2 shows the four margins on which a socially optimal regulation of the environmental externality has to operate to efficiently exploit both the “fuel switch” and “energy conservation” channel. An optimal RE support scheme can only affect three of these four margins in a direct manner. By subsidizing RE firms, an RE subsidy (FIT or market premium) can correct the relative prices of energy supplied from conventional vs. RE sources. By differentiating RE subsidies to reflect heterogeneity in the environmental value, it can correct the relative prices of different types of RE resources (wind vs. solar). An energy demand tax can directly stimulate the energy conservation channel. However, an RE subsidy, an energy demand tax, or a combination of both, fails to correct the relative prices of clean vs. dirty conventional energy production.

Proposition 4 also suggests that if the clean conventional technology plays no or only a minor role in the social optimum, an optimally designed RE support scheme—taking into account the heterogeneous market and environmental value of the targeted RE resources as well as incentivizing the correct amount of energy conservation (possibly through time-specific demand taxes)—can achieve or come close to the first-best allocation.

How close the optimal RE support policy comes to attaining the social optimum thus depends on the extent to which a fuel switch from dirty to clean conventional energy supply is required. This, in turn, depends on the characteristics of the

the policy-induced reduction in energy demand can affect the relative marginal cost of conventional producers. For this to occur, the marginal cost functions of conventional producers, $C'_{it}(q_{it})$, need to intersect *and* the demand reduction has to move production levels from the right to the left of the intersection point. Given empirically plausibly marginal cost functions for conventional, fossil-based energy technologies, such a case can be safely discarded as a mere theoretical possibility which seems to be irrelevant for studying electricity supply under real-world conditions.

¹⁵If the clean fossil-based technology already supplied a positive quantity of energy in the unregulated market equilibrium without concerns for environmental quality, the “no fuel-switch” condition underlying Proposition 4 can be re-stated. An optimal RE support then implements the social optimum if and only if the clean fossil-based energy technology is not required to *expand its production relative to the unregulated market equilibrium*.

TABLE 2. Ability of different RE support policies to incentivize optimal abatement.

	Can the policy correct...			
	the relative prices of energy technologies/fuels?			the price of energy services ($\Delta p \lesseqgtr 0$)?
	renewables vs. fossil-based	within renewables: wind vs. solar	within fossil-based: low vs. high carbon	
<i>Single policy instruments</i>				
Carbon pricing	Y	Y	Y	Y (p $\uparrow\uparrow$)
FIT or market premium				
tech.-neutral	Y	N	N	N (p \downarrow)
tech.-differentiated	Y	Y	N	N (p \downarrow)
Energy demand tax	N	N	N	Y (p $\uparrow\uparrow$)
<i>RE support schemes combining single instruments</i>				
FIT or market premium with energy demand tax				
revenue neutral	Y	Y/N	N	N (p \uparrow)
optimal	Y	Y/N	N	Y (p $\uparrow\uparrow$)
Intensity or technology standards				
RE quota or RPS	Y	N	N	N (p \uparrow)
Green offsets	Y	Y	Y	N (p \uparrow)

energy system at hand. For example, consider a system in which conventional energy supply capacities are given by natural gas and coal-fired plants only. If the gas price is “high”, only coal-fired plants are used in an unregulated equilibrium. An optimal environmental policy may then entail a fuel switch inducing coal-fired plants to be more costly than gas-fired ones. In contrast, in a situation with “low” prices for natural gas, gas-fired plants may already be the cheaper technology even in the absence of environmental regulation. Adding social concerns about the environmental externality will thus not induce a switch to more costly *and* carbon-intensive coal-fired plants. Under such conditions, both an optimal RE support scheme and a direct carbon pricing policy can achieve the social optimum.

TECHNOLOGY OR INTENSITY STANDARDS.—RE support policies which are not efficient cannot implement a social optimum—even if achieving the socially optimal allocation does not require a fuel switch between dirty and clean fossil-based generation. As intensity standards such as a green quota or green offset are by construction revenue-neutral and, thus, not efficient (see Corollary 3), they fail to implement the social optimum.

PROPOSITION 5: *An RE quota or a system of green offsets cannot achieve the social optimum.*

PROOF: For the case of an RE quota, comparing conditions (3a) and (3b), which characterize the first-best solution, with the zero-profit equilibrium conditions for RE producers (4b) and conventional producers (4c), and using the definitions for implicit input taxes from (6b) and the implicit subsidy rate from (6c), yields,

respectively:

$$(9) \quad C'_{it} + \delta E'_{it} = C'_{it} + \gamma p^{Credits} = S'_t = p_t \quad \forall i, t$$

$$(10) \quad G'_t = p_t + (1 - \gamma) p^{Credits} = S'_t = p_t \quad \forall t .$$

From (10) it follows that $p^{Credits} = 0$ which, however, contradicts (9) which requires that $p^{Credits} > 0$ in order to efficiently internalize a positive marginal environmental damage $\delta > 0$. The proof for the case of an intensity standard with green offsets proceeds analogously using instead (7b) and (7c) for the definitions of implicit input taxes and subsidies. \square

Proposition 5 bears out the important insight that technology or intensity standards cannot reach a socially optimal allocation because the (implicit) subsidy to RE firms and the (implicit) input taxes on conventional energy producers are inherently linked over the market for certificates—which in turn reflects the feature that such policy schemes are revenue-neutral. If the quota price correctly reflects the marginal damage of emissions, the implied electricity price would correctly reflect the social cost. At the same time, however, an efficient stimulation of RE production requires that RE firms receive their market value plus an extra rent reflecting the marginal damage avoided (see Proposition 2). Thus, if the marginal damage is already reflected in the market price, the RE support should be zero. This, however, is impossible as the quota price links the tax and the support rate (i.e., the RE quota and system of green offsets are revenue-neutral). In fact, a quota price inducing an efficient tax level would imply that RE firms receive, on top of the subsidy rate, a too high market price resulting in over-investment in RE capacity. Pushing too much RE with zero marginal cost into the market would in turn cause an inefficiently low electricity price undermining the incentive for energy conservation. Thus, linking RE subsidies and refinancing taxes in a revenue-neutral manner and granting a subsidy on top of the wholesale electricity price to RE firms makes it impossible to establish policy signals which induce efficient levels of both RE investments and RE generation.

Lastly, note that the failure of technology or intensity standards to implement the social optimum does not depend on whether the RE support is differentiated across RE technologies to reflect the heterogeneity in the environmental value; rather, the inefficiency stems from the revenue-neutrality of such policy schemes.

II. Quantitative Empirical Framework

A. Overview

To assess alternative policy designs for RE support in an empirically plausible setting and to derive additional quantitative insights, we formulate a numerical model which extends our theoretical framework from Section I in a number of important ways. First, we include multiple discrete conventional energy technologies which differ in terms of heat efficiency, carbon intensity, and installed production

capacities (thus relaxing Assumption 1). Importantly, this enables us to represent the market conditions for the German electricity market in the year 2014 and to assess policy-induced changes in the technology mix and supply side of the market with finer granularity. Second, we increase the temporal resolution at which energy supply and demand decisions are modelled, thus adding realism in terms of firms’ short-term production (generation dispatch) and long-term investment decisions as well as diurnal and seasonal variations in consumers’ energy use. Importantly, this enables us to characterize with fine granularity the empirical joint distribution of wind and solar resources (thus relaxing Assumption 2).

The overall structure of the problem of optimal regulation remains identical: the regulator seeks to maximize social welfare \mathcal{W} , including the valuation of environmental damage at social marginal cost δ , by choosing an RE support scheme \mathbf{b} subject to market equilibrium conditions for energy supply and demand:

$$(11) \quad \begin{aligned} & \max_{\mathbf{b}} \mathcal{W}(\mathbf{p}(\mathbf{b}), \mathbf{x}(\mathbf{b}); \delta) \\ \text{s.t.} \quad & \mathbf{p}(\mathbf{b}), \mathbf{x}(\mathbf{b}) \in \mathcal{A}. \end{aligned}$$

\mathcal{A} is the set of feasible allocations defined by equilibrium prices $\mathbf{p}(\mathbf{b})$ and quantities $\mathbf{x}(\mathbf{b})$ associated with energy generation and investments embodying firms’ and consumers’ behavioral responses to policy choices \mathbf{b} .

The remainder of this section describes our quantitative empirical framework including the derivation of the market equilibrium conditions which define \mathcal{A} . We also provide detail on data sources, model calibration, and the computational strategy employed to solve the problem of optimal RE support policies.

B. Feasible equilibrium allocations \mathcal{A}

Our characterization of the partial equilibrium model of electricity supply and demand uses a complementarity-based formulation, i.e. a system of nonlinear inequalities with two classes of equilibrium conditions: zero-profit and market-clearing. Zero-profit and market-clearing conditions exhibit complementarity with respect to quantities \mathbf{x} and prices \mathbf{p} , respectively.¹⁶ We now describe in detail the structure and decision problems of economic agents to derive the conditions that define \mathcal{A} .¹⁷

PRODUCTION AND INVESTMENT.—Electricity can be supplied from conventional and renewable energy technologies. Different technologies are indexed by $i \in \mathcal{I}$ where $\mathcal{G} \subset \mathcal{I}$ contains RE technologies and $\mathcal{B} \subset \mathcal{I}$ contains conventional (non-

¹⁶A characteristic of economic equilibrium models is that they can be cast as a complementarity problem (Mathiesen, 1985; Rutherford, 1995), i.e. given a function $F: \mathbb{R}^n \rightarrow \mathbb{R}^n$, find $z \in \mathbb{R}^n$ such that $F(z) \geq 0$, $z \geq 0$, and $z^T F(z) = 0$, or, in short-hand notation and using the “ \perp ” operator to indicate complementarity between equilibrium conditions and variables, $F(z) \geq 0 \perp z \geq 0$.

¹⁷While the structure of the quantitative model is largely identical to the one of the theoretical model, we introduce a self-contained notation for the numerical model. In particular, note that to reduce notational complexity, we redefine the technology index i in the quantitative model to include both conventional and RE technologies.

renewable) technologies. Time (i.e., hours) is denoted by $t \in \mathcal{T} = \{1, \dots, T\}$. Firms using technology $i \in \mathcal{I}$ choose quantities of investment I_i and energy output X_{it} in order to maximize total profits from selling electricity in wholesale markets t . Total profits Π_i for energy producers using technology i are defined as:

$$(12) \quad \Pi_i(X_{i1}, \dots, X_{it}, \dots, X_{iT}, I_i) = \sum_t [(\pi_{it} - \kappa_{it})X_{it} - c_i^g(X_{it})] - c_i^i(I_i).$$

π_{it} denotes the wholesale price of electricity inclusive of any direct RE support. Conventional generators receive no RE support and sell their output at wholesale market price P_t at time t ; RE firms receive a subsidy per MWh electricity sold (S) which can either take on the form of a FIT or a market premium which is constant over the year:

$$\pi_{it} = \begin{cases} P_t, & \text{if } i \in \mathcal{B} \\ P_t + \omega_i S, & \text{if } i \in \mathcal{G} \text{ and RE support with a market premium} \\ \omega_i S, & \text{if } i \in \mathcal{G} \text{ and RE support with a feed-in tariff.} \end{cases}$$

ω_i and κ_{it} are policy choice variables which can be controlled by the regulator but are viewed as given by firms. ω_i implements a technology-specific differentiation of the RE support scheme; $\omega_i = 1, \forall i$, represents the case of uniform RE support across wind and solar technologies. κ_{it} is an input tax per MWh of electricity which can either represent an emissions tax or implicit taxes under an intensity standard. $c_i^g(X_{it})$ denote total generation cost associated with output, reflecting technology-specific heat efficiencies and fuel costs. For each technology category i , CO₂ emissions $E_i(X_{it})$ are a function of the output level. While we model electricity generation at the technology level, we specify $c_i^g(X_{it})$ and $E_i(X_{it})$ as quadratic functions to account for within-technology heterogeneity among individual electricity plants. Thus, the marginal cost and marginal emissions rate per MWh of electricity produced increase with output reflecting efficiency changes at the plant level. $c_i^i(I_i)$ denote investment costs for installing capacity I_i .

Profit-maximizing output and investment choices have to satisfy the following constraint expressing that output at any time t cannot exceed available capacity:

$$(13) \quad \alpha_{it} (\bar{K}_i + I_i) \geq X_{it} \quad \forall i, t$$

where α_{it} measures the availability of capacity which reflects the fact that conventional generators can be temporarily offline (due to, for example, maintenance and outages) and that the production of renewable generators depends on weather conditions. \bar{K}_i denotes existing production capacities for each technology.

Maximizing (12) subject to (16) yields the following FOCs for optimal firm

behavior, which can be written in complementarity notation as follows:

$$(14) \quad \frac{\partial c_i^i(I_i)}{\partial I_i} \geq \sum_t \alpha_{it} P_{it}^I \quad \perp \quad I_i \geq 0 \quad \forall i$$

$$(15) \quad \frac{\partial c_{it}^g(X_{it})}{\partial X_{it}} + \kappa_i + P_{it}^I \geq \pi_{it} \quad \perp \quad X_{it} \geq 0 \quad \forall i, t$$

$$(16) \quad \alpha_{it} (\bar{K}_i + I_i) \geq X_{it} \quad \perp \quad P_{it}^I \geq 0 \quad \forall i, t.$$

P_{it}^I is the shadow price of production capacity and is determined in equilibrium by (16). In equilibrium, $I_i = 0$ if the marginal cost of investment ($\partial c_i^i(I_i)/\partial I_i$) exceeds marginal revenues for investment—condition (14) then holds with a strict inequality. A positive equilibrium level of investment results if marginal investment cost equals marginal revenue which are given by the availability-weighted income created by renting out production capacity at price P_{it}^I . Similarly, a positive quantity of energy is supplied at time t by using technology i if marginal cost of generation equals marginal revenue including RE subsidies—condition (15) then holds with equality.

DEMAND AND WHOLESALE ELECTRICITY PRICES.—Electricity demand at time t , $D_t(P_t, \tau_t)$, is a function of the wholesale electricity price at time t (we therefore maintain Assumption 3) and an energy demand tax $\tau_t \geq 0$. The market-clearing condition for balancing energy supply and demand at time t determines the wholesale electricity price at time t :

$$(17) \quad \sum_i X_{it} = D_t(P_t, \tau_t) \quad \perp \quad P_t \text{ “free”} \quad \forall t.$$

Note that we allow for the possibility of negative prices in situations where, for example, due to a high availability of RE sources, consumers have to be compensated for demanding a positive quantity of energy.

DEFINITION OF EQUILIBRIUM AND WELFARE.—Given an RE support policy $\mathbf{b} = \{\omega_i, S, \tau_t, \kappa_i\}$, the set of feasible equilibrium allocations \mathcal{A} is characterized by (i) prices $\mathbf{p}(\mathbf{b}) = \{P_{it}^I, P_t\}$ for production capacity and wholesale energy output determined by market-clearing conditions (16) and (17) and (ii) quantities $\mathbf{x}(\mathbf{b}) = \{X_{it}, I_i\}$ of energy outputs and investments into production capacity determined by zero-profit conditions (14) and (15).

Analogously to the definition of social welfare in the theoretical model, welfare comprises the economic surplus net of environmental damage:

$$(18) \quad \mathcal{W} = \underbrace{\sum_t \left[\int_0^{D_t} \tilde{P}_t(\tilde{x}) d\tilde{x} - \sum_i (c_i^i(I_i) + c_{it}^g(X_{it})) \right]}_{=\text{Economic surplus}} - \delta \underbrace{\sum_{i,t} \int_0^{X_{it}} E_i(\tilde{x}) d\tilde{x}}_{=\text{Environmental damage}},$$

where $\tilde{P}_t = D^{-1}(P_t, \tau_t)$ is the inverse demand function. Note that the definition of the economic surplus also includes potential rents to the public sector due to excess revenues earned from the regulation of the externality (for example, from carbon pricing or an RE support scheme where revenues of the refinancing tax exceed the expenses for RE subsidies).

CONSTRAINED-OPTIMAL RE SUPPORT SCHEMES.—To represent real-world policies for RE support, we include additional constraints in the lower-level partial equilibrium problem which restrict the regulator’s choice of policy parameters \mathbf{b} .

Under a FIT and market premium support scheme the expenses for RE subsidies are fully covered by revenues generated with a time-independent energy demand tax τ which adjusts endogenously to ensure the following constraint is met:

$$(19) \quad \sum_t \tau D_t \geq \sum_{i \in \mathcal{G}} \sum_t (\pi_{it} - P_t) X_{it} \quad \perp \quad \tau \geq 0.$$

Under a revenue-neutral FIT or market premium support scheme the regulator chooses $\mathbf{b} = \{\omega_i, S\}$ subject to the system of equilibrium constraints (14)–(17) and refinancing rules (19). Setting $\omega_i = 1$ would impose the additional constraint that RE subsidies cannot be differentiated among RE technologies.¹⁸

Analogously to the conditions (6a) and (7a) for representing intensity standards in the theoretical model, an intensity standard for RE relates the amount of “green” energy supplied in the economy ($\sum_{i \in \mathcal{G}, t} X_{it}$) in a specific way to total energy supply $\Psi = \sum_{i, t} X_{it}$:

$$(20) \quad \sum_{i \in \mathcal{G}, t} X_{it} \geq \gamma \mathbb{F}(\Psi) \quad \perp \quad S \geq 0,$$

where for the case of an RE quota and a system of green offsets \mathbb{F} is given by, respectively:

$$\mathbb{F}(\Psi) = \begin{cases} \sum_{i, t} X_{it}, & \text{if RE quota} \\ \sum_{i, t} \int_0^{X_{it}} E_i(\tilde{x}) d\tilde{x}, & \text{if Green offsets.} \end{cases}$$

Under RE support through an intensity standard (RE quota or green offsets), the regulator chooses $\mathbf{b} = \{\gamma\}$ subject to the system of equilibrium constraints (14)–(17) and the intensity constraint (20) with the respective implicit input taxes given by: $\kappa_{it}^{\text{RE quota}} = \gamma S$ and $\kappa_{it}^{\text{Green offsets}} = \gamma E'(X_{it}) S$.

C. Computational strategy

The regulator’s problem of designing optimal RE support policies stated in (11) represents a *Mathematical Program under Equilibrium Constraints* (MPEC), i.e. a bi-level optimization problem which maximizes an objective function subject to

¹⁸Note that $\omega_i S$ corresponds to the policy choice variable s_t in the theoretical model in Section I.

a lower-level constraint set that contains an equilibrium problem (Luo, Pang and Ralph, 1996). We cast the equilibrium problem in the lower-level part as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995) solving for primal and dual variables (i.e., quantities and prices). The advantage of this approach is that it naturally accommodates equilibria with corner solutions, for example, zero technology-specific investments at a given point in time or non-binding capacity constraints in electricity production.

Owing to the lack of robust solvers (Luo, Pang and Ralph, 1996) for solving MPECs, we reformulate the MPEC problem as a gridded MCP for which standard solvers exist. Specifically, we use the MCP to perform a grid search over policy choice variables \mathbf{b} using the PATH solver (Dirkse and Ferris, 1995) for complementarity problems and the General Algebraic Modeling System (GAMS).

D. Empirical specification

This section describes how we specify our quantitative model to be consistent with year-2014 conditions of the German electricity market. The main idea is to construct an empirically plausible “no policy” reference case of the partial equilibrium model of German electricity supply and demand as described by the zero-profit and market-clearing equilibrium conditions (14)–(17). To cleanly investigate the economic and environmental impacts of alternative policy designs for RE support, the “no policy” reference case assumes that market decisions about energy supply and demand ignore the presence of the environmental externality, i.e. the equilibrium in the “no policy” benchmark represents an unregulated market outcome.¹⁹

To bring our model to the data, we need to specify the following parameters and functions: resource availability of RE (wind and solar) resources over time (α_{it}); cost and emissions functions for generation with technology i (c_i^g and E_i); cost functions for investments in production capacity for technology i (c_i^i); installed production capacities for conventional energy technologies in the benchmark (\bar{K}_i); and demand functions for energy at time t (D_t). We now describe in turn how these functions and parameters are specified based on data.

TEMPORAL RESOLUTION AND AVAILABILITY OF RE RESOURCES.—We model one year with hourly resolution to capture the temporal heterogeneity of RE supply and interactions with hourly energy demand and supply (dispatch) decisions of conventional energy producers. To reduce computational complexity, we select $T = 672$ representative hours. Based on data for all hours of the year, we construct for every season an average week. Each hour contained in an average week is obtained by averaging over the respective hour over all days belonging to that season.²⁰

¹⁹For $\delta = 0$, the regulator effectively maximizes market surplus (ignoring environmental damage) in which case the solution of the regulator’s problem in (4) coincides with the market outcome of the partial equilibrium model.

²⁰In light of the concern that this procedure for selecting representative hours of the year may un-

To characterize the daily and seasonal variation of wind and solar resources, we use hourly generation of wind and solar energy from the German transmission system operators (Amprion, 2018; Tennet, 2018; TransnetBW, 2018; 50Hertz, 2018). Hourly generation of hydro power is taken from the EnergyCharts (2015) provided by the Fraunhofer Institute for Solar Energy Systems. To derive hourly availability profiles for wind and solar resources (α_{it}), we assume that wind mills and solar panels would produce an energy output equal to their respective installed production capacity. This enables us to calculate α_{it} by relating observed hourly generation data for solar and wind to the maximally feasible energy output given installed capacities. α_{it} thus indicates the fraction of installed RE capacity available for production given the weather conditions that prevailed in 2014.

NON-RENEWABLE ENERGY TECHNOLOGIES.—The technological options for supplying electricity from different non-renewable fuel sources ($i \in \mathcal{B}$) are resolved at the technology level comprising lignite, hard coal, natural gas, nuclear, hydro, and others (i.e., mainly biomass and some electricity generated from oil and waste). To take into account the heterogeneity of fossil-based and CO₂-emitting plants in terms of heat efficiencies and emissions intensity, we assume that generation cost functions $c_i^g(X_{it})$ and emissions functions $E_i(X_{it})$ for lignite, hard coal, and natural gas are quadratic in output. The corresponding functions for all other non-renewable energy technologies are assumed to be linear.

To calibrate the functions $c_i^g(X_{it})$ and $E_i(X_{it})$, we first obtain plant-level heat efficiencies for German power plants from Open Power System Data (2017). Second, we assemble data on fuel prices and emissions coefficients by fuel. For the former, we take yearly averages of daily spot market prices for the year 2014 as provided by Bloomberg. The latter are based on IPCC standard emissions coefficients (Eggleston et al., 2006) for each fuel. Table 3 shows the data for carbon coefficients and fuel prices. Third, we construct plant-level fuel costs and CO₂ emission rates by multiplying the heat efficiency for each plant with the respective fuel price and emissions coefficient. Lastly, ordering all plants from low to high marginal cost, we then use ordinary least squares (OLS) to estimate the intercept and slope coefficients of the *marginal* generation costs and emissions functions. Table 4 reports the estimated coefficients.

Installed generation capacities for conventional energy technologies \bar{K}_i in 2014 are taken from Open Power System Data (2017). We assume that conventional energy firms do not invest in new capacity (i.e., $I_i = 0$ for $i \in \mathcal{B}$); production is thus restricted to what is feasible given pre-installed capacities.

INVESTMENT COSTS AND HETEROGENEOUS RESOURCE QUALITY.—While the costs for fossil fuels and emissions associated with energy supply from wind and solar are zero, i.e. $c_i^g(X_{it}) = E_i(X_{it}) = 0$ for $i \in \mathcal{G}$, the major cost incurred is the capital cost for installing production capacity. At the same time, there is considerable spatial variation regarding the resource availability of wind and solar. Investors

intentionally smooth out hours with extremely low or high resource availability, Section IV reports on robustness checks with respect to the number of hours.

TABLE 3. Carbon coefficients and fuel prices.

	Hard coal	Natural gas	Lignite
Carbon coefficients ^a (tCO ₂ /MWh)	0.202	0.354	0.364
Fuel price ^b (€/MWh)	8.58	21.16	4.39

Notes:^aBased on IPCC (Eggleston et al., 2006). ^bYearly average of daily spot market prices for 2014 based on price data provided by Bloomberg. For coal and natural gas prices, we use the “ICE CIF ARA Near Month future” and “NBP Hub 1st day futures”, respectively. All prices are converted to 2014 Euros using daily exchange rates provided by the European Central Bank.

TABLE 4. Benchmark production capacities \bar{K}_i and OLS-fitted quadratic functions for generation cost c_i^g , emissions E_i , and investment cost c_i^i .

	Energy supply technologies						
	Gas	Coal	Lignite	Hydro	Nuclear	Wind	Solar
<i>Installed production capacities in “no policy” reference case (\bar{K}_i)</i>							
MW	26'900	34'378	23'319	10'320	12'696	0	0
<i>Marginal generation cost functions ($dc_i^g(X_{it})/dX_{it}$)</i>							
Intercept ($\frac{\text{€}}{\text{MWh}}$)	28.41	17.24	9.38	4	9.09	0	0
Slope ($\frac{\text{€}}{\text{MWh}^2}$)	1.4×10^{-3}	3.04×10^{-4}	2×10^{-4}	0	0	0	0
<i>Marginal emissions functions ($dE_i(X_{it})/dX_{it}$)</i>							
Intercept ($\frac{\text{tCO}_2}{\text{MWh}}$)	0.27	0.71	0.78	0	0	0	0
Slope ($\frac{\text{tCO}_2}{\text{MWh}^2}$)	1.33×10^{-5}	1.25×10^{-5}	1.66×10^{-5}	0	0	0	0
<i>Marginal investment cost functions ($dc_i^i(I_i)/dI_i$)</i>							
Intercept ($\bar{\nu}_i, \frac{\text{€}}{\text{MW}}$)	–	–	–	–	–	60'618	41'752
Slope ($\frac{\text{€}}{\text{MWh}^2}$)	–	–	–	–	–	0.24	0.06

choose locations with the highest resource qualities first and then successively use sites with lower quality. We capture resource heterogeneity by assuming that investment cost per MWh electricity produced with wind mills or solar panels, $c_i^i(I_i)$, increases with the level of installed RE capacity. Table 4 reports the results from estimating empirical functions for $c_i^i(I_i)$.²¹

We assume that pre-installed production capacities for wind and solar in the initial no-policy reference case are zero, i.e. $\bar{K}_i = 0$ for $i \in \mathcal{G}$, but that new

²¹ We adopt the following approach. We use the concept of *full load hours* which translates the yearly electricity production of a site into the number of hours needed to generate this amount of electricity at full use of the capacity. This number will decline with deteriorating wind or solar resource quality due to geographical variation of the sites. We capture this geographical variation by assembling full-load hours (averaged over a period of four years to account for varying weather conditions) for each German state from [Agentur für Erneuerbare Energien \(2017\)](#). This information together with an estimation of total resource potential for each state (from the same source) allows us to construct a full-load hour curve by ordering the potentials of the states from highest to lowest. Assuming that the most favorable sites are developed first, we then obtain a resource curve describing a negative relation between full-load hours and the level of investment, I_i . In a second step, we adjust annualized investment cost for resource potential by dividing reported investment cost per installed MW for wind and solar from [Kost et al. \(2013\)](#) with full-load hours. Since the full-load hour curve, describing resource potential, declines with investment, the marginal investment cost curve we obtain increases in I_i . Finally, we fit quadratic investment cost functions for wind and solar using OLS.

capacity can be added if the return on these investments is positive according to the profit condition (14).

HOURLY ENERGY DEMAND.—To specify $D_t(P_t, \tau_t)$, we assume that electricity demand at time t reacts linearly to the tax-inclusive wholesale price at time t —thereby maintaining Assumption 3. We use historical data on hourly electricity demand (\bar{D}_t) from the European Network of Transmission System Operators (ENTSO-E, 2016) and hourly day-ahead electricity prices (\bar{P}_t) from European Power Exchange (EPEX, 2015) to calibrate for each time period t the following linear demand function:

$$D_t(P_t, \tau_t) = \bar{D}_t \left[1 - |\epsilon| \left(\frac{P_t + \tau_t}{\bar{P}_t} - 1 \right) \right].$$

where $\epsilon < 0$ denotes the price elasticity of energy demand. We assume $\epsilon = -0.15$ for the central case.²²

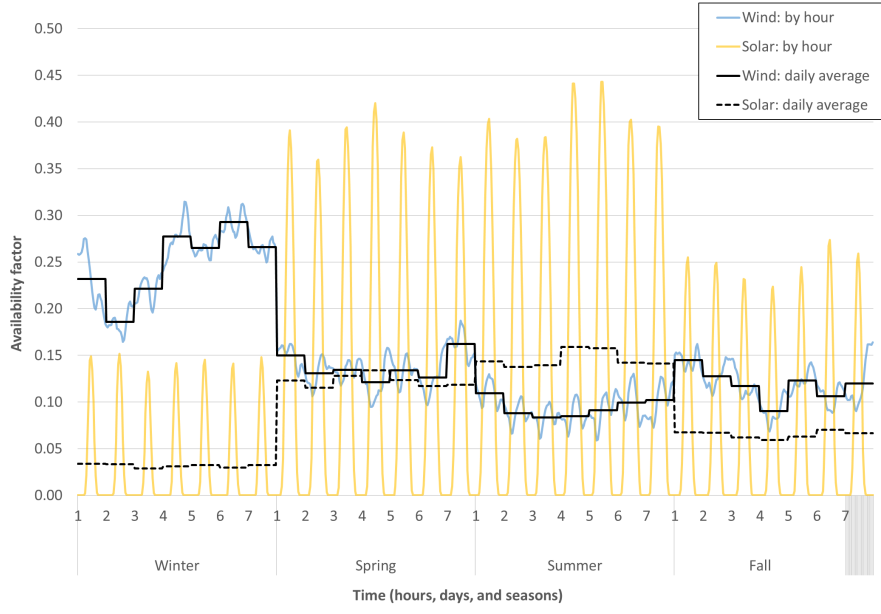
SOCIAL COST OF CARBON.—We choose δ to be consistent with a plausible range of estimates obtained from integrated assessment modelling exercises (US Government Interagency Working Group on Social Cost of Greenhouse Gases, 2016). Specifically, we use €50 and €100 per ton of CO₂ for our central and a high-damage case, respectively.²³

E. A first look at the data

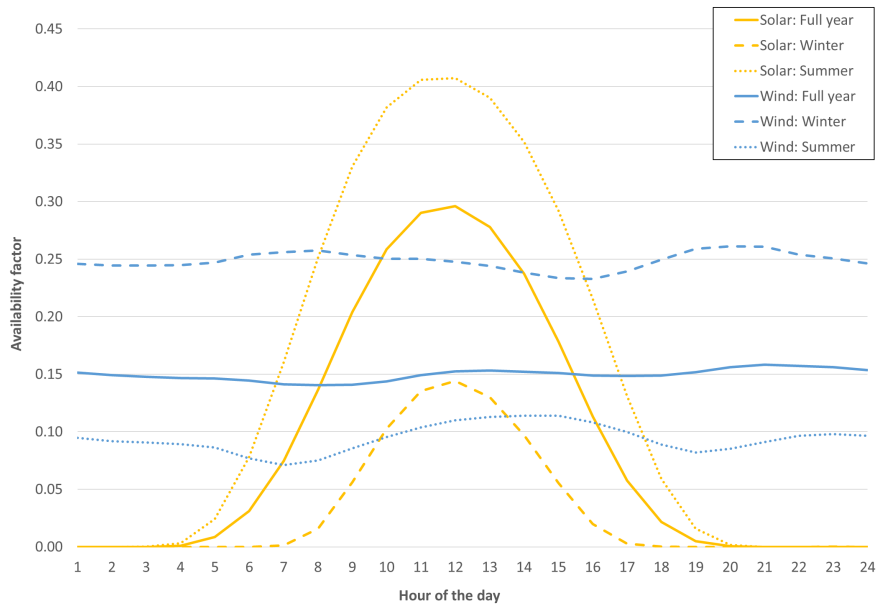
Figure 1 plots the time-series data for α_{it} showing in Panel (a) the hourly and daily average availability by season over the course of a full year and in Panel (b) the availability by hour over a typical day of the full year, winter, and summer period. It is evident that there exists substantial heterogeneity in terms of the temporal availability profiles of wind and solar resources. First, over a typical day of a year and a given season, solar resources are much more volatile compared to wind resources: while the availability profile for wind is relatively flat, solar is not available during evening and night hours and exhibits availabilities of up to 40% during the midday. Second, the seasonal availability patterns for the two resources differ. The availabilities of solar largely exceeds those for wind during the summer period (apart from night hours) which is reflected in the daily averages as well as the hourly profile over a typical day. Wind, however, has a higher availability during the winter period for all hours during the day, thus exceeding the availability of solar during peak hours around midday. The hourly profiles for the spring and fall season represent intermediate cases (not shown) which are qualitatively similar to the hourly profile of an average day for the full

²²Given the lack of clear-cut empirical evidence on the variation of the price-responsiveness of energy demand over hours of a day or seasons, we assume that ϵ is uniform across t .

²³We use the year-2015 estimates from US Government Interagency Working Group on Social Cost of Greenhouse Gases (2016) which are closest to our modelled base year. Our central-case value for δ is close to the reported mean of \$56 per ton of CO₂ in the study); our high value for δ is based on a high-impact, low-probability scenario with “catastrophic” climate events.



(a) By hour and season



(b) Over a typical day

FIGURE 1. Temporal availability of wind and solar resources (α_{it})

TABLE 5. Descriptive statistics for hourly distributions of key variables in unregulated market.

	Demand D_t (MWh)	Price P_t (€/MWh)	CO ₂ emissions E_i (thousand tons)			Marginal emissions E'_i (ton/MWh)	Availability factor α_i		
			Total	Gas	Coal		Lignite	Wind	Solar
Mean for given percentile range ^a									
>95%	77.4	46.5	41.7	4.6	18.4	18.7	0.31	0.22	0.09
75%-95%	73.9	41.4	40.2	3.1	18.4	18.7	0.39	0.15	0.16
50%-75%	67.6	32.3	38.0	0.9	18.4	18.7	0.42	0.15	0.13
<50%	53.4	20.6	27.2	0	8.6	18.6	0.87	0.14	0.04
Summary statistics ^b									
Mean	62.2	30.3	33.2	1.0	13.8	18.6	0.64	0.15	0.09
St. dev	10.3	9.7	7.2	1.5	6.1	.39	0.30	0.06	0.13
Median	63.6	23.6	36.3	0	17.6	18.7	0.75	0.13	0.01

Notes: ^aThe definition of percentiles is based on the amount of electricity demanded per hour. ^bBased on all hours.

year as shown in Panel (b).

Given variations in the hourly electricity price and the carbon intensity of electricity generation, in which ways does the heterogeneity of wind and solar resources potentially translate to different market and environmental values for RE technologies? Table 5 provides descriptive statistics for the hourly distributions of key price and quantity variables in a market where the environmental externality is unregulated. Two main insights emerge which, together with the documented heterogeneity in the availability of RE resources, suggest that the market and environmental values for wind and solar technologies differ. First, there is a substantial variation in the hourly electricity price, e.g. the mean for the two bottom quartiles (20.6 €/MWh) is less than half of the mean of the top five percentiles (46.5 €/MWh). Figure 2 visualizes the profile of hourly electricity prices over an average day. Comparing Figure 1, Panel (b), with Figure 2 further shows that over the course of a typical day solar resources tend to be available when electricity prices are high. These diurnal patterns thus suggest that solar has a higher market value relative to wind.

Second, hourly marginal emissions vary substantially driven by the fact that base-load generation tends to be more carbon-intensive relative to generation in hours with high demand, e.g. the mean for the two bottom quartiles (0.87 tons of CO₂/MWh) is more than twice the mean of the top five percentiles (0.31 tons of CO₂/MWh). Figure 2 visualizes the hourly profile of marginal emissions over an average day. The daily pattern suggests that there is scope to differentiate RE subsidies based on heterogeneous environmental values for wind and solar: the high availability of wind compared to solar during night, morning, and evening times coincides with a relatively high CO₂ intensity of electricity generation. In addition, the availability of wind compared to solar is much higher during winter and fall (see Figure 1). Thus, for the given modelled system of the German electricity market, wind has a larger environmental value than solar.

Lastly, the technology mix in the unregulated outcome of the German market

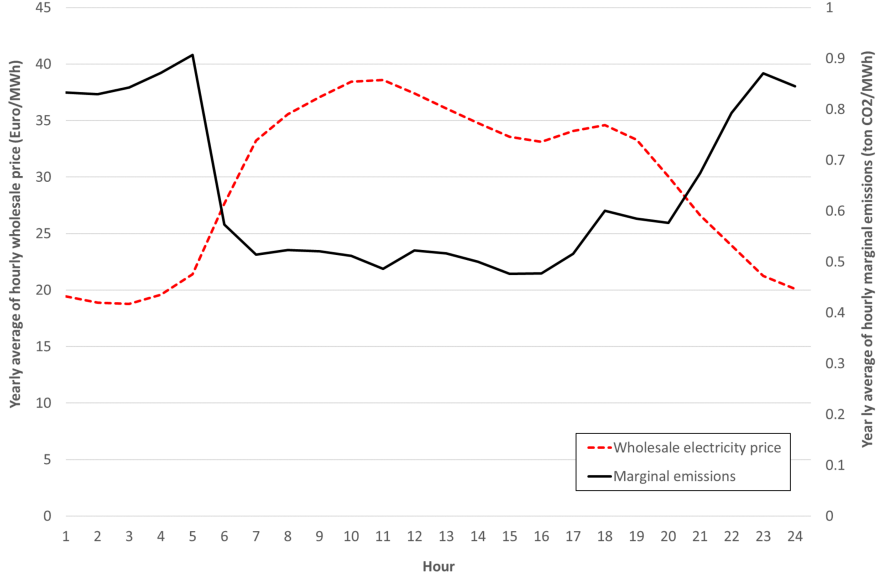


FIGURE 2. Hourly wholesale electricity prices and hourly marginal emissions rate over a typical day

highly relies on coal-fired electricity: 89% of CO₂ emissions derive from burning lignite and hard coal while only 11% stem from gas-fired generation (Table 5). Moreover, in the unregulated market there exist massive excess production capacities for natural gas (only 15.2% of the installed capacity for natural gas is used for electricity generation). Together, these points suggest that there is considerable scope for CO₂ abatement through switching from “dirty” to “clean” fossil fuels.

III. Main Simulation Results

This section compares the performance of optimal RE support schemes with regard to their ability to address the carbon externality.²⁴ We first assess RE support policies in terms of their welfare impact and investigate how particular features of policy design affect the welfare implications. We then depart from the perspective of optimal RE policies by analyzing the policy ranking in terms of cost-effectiveness, i.e. which RE policy can achieve a given emissions reduction target at the lowest possible cost.

²⁴All simulations in this section are based on the central-case parametrization of the model as laid out in Section II.D. More specifically, fuel prices, carbon coefficients, pre-installed production capacities, and empirically estimated marginal cost and emissions functions are specified according to Tables 3 and 4, and we assume intermediate values for the own-price elasticity of energy demand (i.e., $\epsilon = -0.15$) and the social cost of carbon (i.e., $\delta = 50\text{€}$ per ton of CO₂).

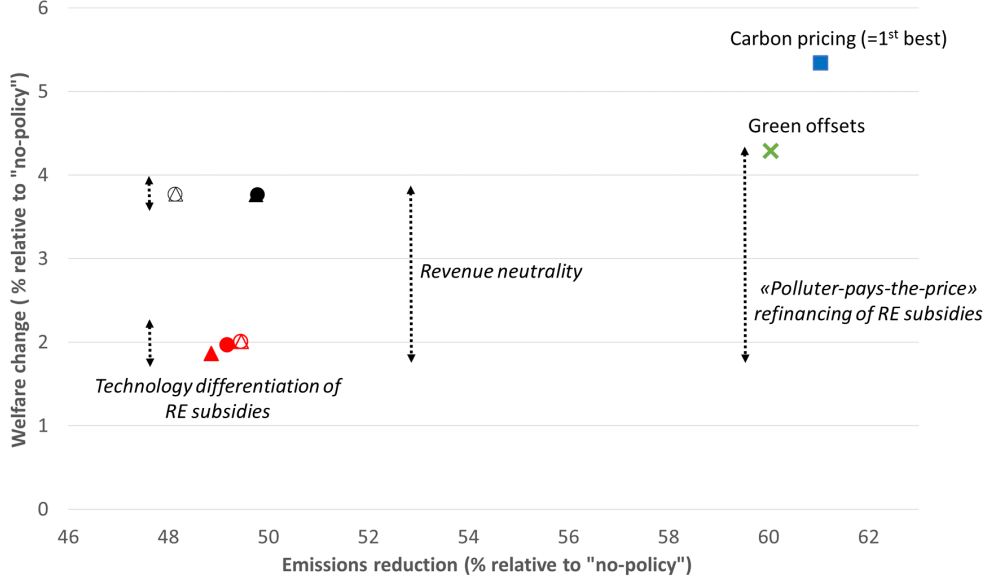


FIGURE 3. Comparison of efficient RE support policies

Notes: Assumes central case as specified in Section II.D. Legend: The “ Δ ” and “ \circ ” markers denote a feed-in tariff and market premium policy, respectively. Filled (hollow) triangles and circles refer to the case when RE subsidies are uniform (differentiated) across wind and solar technologies. “Red” symbols denote the case when RE subsidies are combined in a revenue-neutral manner with a non-optimal energy demand tax. “Black” symbols denote the case when RE subsidies are combined with an optimal energy demand tax.

A. Can RE policies approximate the social optimum?

Figure 3 summarizes the welfare and CO₂ emissions impacts (both measured relative to the unregulated market equilibrium) of the RE support policies which have been categorized in Table 1.²⁵ We compare constrained-optimal RE policies which entail constraints on the structure and financing of RE subsidies. It is straightforward to see that alternative regulatory designs can yield substantially different outcomes in an otherwise identical economy and given the same SCC. These differences stem from varying specific features of the RE support scheme: the structure of RE subsidies (uniform or technology-differentiated RE support), the financing of RE subsidies (demand tax vs. “polluter-pays-the-price”), and the way in which the expenses for RE subsidies and their financing are linked together (revenue-neutral support schemes or not).

First, carbon pricing achieves the highest welfare gain relative to the unregu-

²⁵In contrast to the theoretical analysis, we focus in our numerical analysis on the case of a time-constant energy demand tax. First, a time-varying hourly demand tax is likely to be unrealistic from a real-world policy perspective. Second, the computational burden to solve for an optimal hourly demand tax would be enormous.

lated market outcome—consistent with the result that such a policy implements the social optimum (see Proposition 1).²⁶ Second, RE support schemes which involve FIT or a market premium which are funded through a revenue-neutral tax on energy demand—marked by red triangles and circles—perform worst, yielding less than 40% of the welfare gains obtained under carbon pricing. Third, differentiating RE subsidies, under either a FIT or a market premium, only negligibly improves overall economic efficiency—comparing solid with hollow triangles and circles. Fourth, combining RE subsidies with an optimal demand tax to efficiently incentivize the energy conservation channel, and thereby relaxing the constraint that the energy demand tax is set to cover expenses for RE subsidies—comparing red with black triangles and circles—substantially enhances efficiency, yielding about twice the welfare gains relative to the revenue-neutral RE support schemes. However, such policies only achieve about 70% of the welfare gains associated with first-best carbon pricing. Fifth, changing the structure of refinancing of RE subsidies to one which charges conventional “dirty” energy producers in proportion to their emissions (i.e., “polluter-pays-the-price” financing), as would be the case under a green offset policy, yields an outcome that is fairly close to the social optimum (achieving 80% of the welfare gains from carbon pricing).

B. Quantifying alternative designs for RE support

What are the economic mechanisms triggered by particular choices in the design of RE support policies and how do they explain the (in)ability to approximate socially optimal outcomes? To compare policies, we define an index of abatement efficiency, \mathcal{E}^b , which expresses the welfare change for an RE support policy \mathbf{b} relative to the welfare change under the first-best carbon pricing policy:

$$(21) \quad \mathcal{E}^b = \frac{\mathcal{W}^b - \overline{\mathcal{W}}}{\mathcal{W}^{\text{Carbon pricing}} - \overline{\mathcal{W}}},$$

where $\overline{\mathcal{W}}$ denotes welfare in the unregulated market equilibrium. The closer \mathcal{E}^b is to unity, the better the RE support policy \mathbf{b} approximates the socially optimal outcome.

TECHNOLOGY-NEUTRAL RE SUBSIDIES.—RE support schemes based on a FIT or market premium with refinancing through energy demand taxes incentivize carbon abatement through two channels. First, by subsidizing investments into RE production capacity, they correct the relative prices between fossil-based and RE technologies. Second, the refinancing tax increases the price of energy thus contributing to energy conservation.

Table 6 shows that the two channels are, however, not exploited in an efficient manner. Tax-inclusive consumer prices increase only slightly (around 2%) leaving

²⁶In our comparative-static analysis, reported welfare changes refer to annual values. For example, the 5.33% in the case of carbon pricing corresponds to a welfare increase equal to €0.236 billion per year relative to the unregulated market outcome.

TABLE 6. Overview of key impacts for alternative efficient RE support policies.

	Abatement efficiency ^a \mathcal{E}^b	Change to unregul. market (%)		Generation share by technology category (%)				Subsidy rate for solar ^c
		Demand	Price ^b	Coal	Gas	Wind	Solar	
Unregulated market outcome	–	–	–	48	5	0	0	–
Carbon pricing	1	-12.7	88.3	26	13	14	7	0
<i>Support schemes based on explicit RE subsidies with refinancing via demand tax</i>								
Technology-neutral RE subsidies & revenue-neutral								
FIT	0.35	-0.8	2.1	30	0	18	15	1
Market premium	0.37	-0.8	2.2	30	0	20	13	1
Technology-differentiated market premium								
revenue-neutral	0.38	-0.9	2.7	31	0	22	11	0.93
optimal refinancing	0.71	-12.9	86.1	36	0	16	7	0.97
<i>Technology or intensity standards</i>								
RE quota	0.37	-0.8	2.2	30	0	20	13	1
Green offsets with RE subsidies paid as								
Market premium	0.72	-7.8	55.4	17	7	23	13	1
FIT	0.80	-13.0	89.7	24	13	13	7	1

Notes: Assumes central case as specified in Section II.D. Reported quantities (demand and generation) refer to annual values. ^aAbatement efficiency \mathcal{E}^b is defined in equation (21). ^bDemand-weighted annual average of hourly tax-inclusive consumer prices for electricity. ^cSubsidy rate relative to wind. A value of 1 indicates equal subsidy rates for wind and solar.

energy demand virtually unaffected (-0.8%). Consumer prices rise because of the refinancing tax for the subsidy paid to RE firms; at the same time, zero-marginal production cost of RE technologies means high marginal-cost fossil energy producers are driven out of the market implying a reduction in hourly electricity prices. The net effect is a small increase in consumer prices which is considerably smaller than under a first-best carbon pricing policy where on average consumers prices increase by 88.3% and energy demand reduces by 12.7%. As abatement cannot be achieved via the energy conservation channel, carbon abatement has to be achieved through an inefficiently high level of RE investments induced by the subsidy instrument: the combined generation share of wind and solar under a FIT or market premium is 33% compared to only 21% under carbon pricing.

While a FIT or market premium policy induces a substitution away from fossil-based generation toward renewables, they do not incentivize a fuel switch within fossil-based generation and thus fail entirely to exploit a major abatement channel: while the energy mix under (socially optimal) carbon pricing comprises a significant amount of natural gas (13%), under a FIT and market premium policy gas-fired generation is pushed out of the market and coal plants continue to produce at sub-optimally high levels.

A FIT is slightly less efficient than a market premium (i.e., $\mathcal{E}^{FIT} = 0.35$ and $\mathcal{E}^{Market\ premium} = 0.37$). The reason is that under a market premium RE firms sell electricity at the hourly wholesale price whereas a FIT guarantees a constant output price for every hour. This means that the uniform FIT, in contrast to the market premium, fails to take into account the market value of the resource. A

FIT thus creates incentives for over-investment in solar capacity which are particularly strong during periods of high demand (e.g., around noon) when electricity prices are high and solar availability is at its daily peak. Adding cheap solar energy, in particular around midday, implies that hourly wholesale electricity prices fall; RE firms, however, do not see these lower prices under a FIT scheme. In addition, a higher share of solar energy in total RE production under a FIT also means that in winter, when the availability of solar is considerably lower, peak energy demand is satisfied to a lesser extent with RE generation implying that more carbon-intensive fossil generation is used and, hence, less carbon is abated. Together, these two effects explain the slightly lower efficiency of a FIT as compared to a market premium.

TECHNOLOGY-DIFFERENTIATED RE SUBSIDIES.—Proposition 2 states that optimal subsidies for RE technologies should be differentiated according to the environmental value of the underlying resource. The relevant question for policy design, however, is: what order of magnitude for welfare gains can be achieved by optimally differentiating RE subsidies?

We find that improving policy design to reflect the environmental value of the underlying resource only produces minor efficiency gains (i.e., $\mathcal{E}^{Market\ premium}$ increases from 0.37 for technology-neutral to 0.38 for technology-differentiated RE subsidies; see Table 6).²⁷ The reason is that wind has a higher environmental value compared to solar over both daily and seasonal time scales (for the German electricity market; see the analysis in Section II.E). The optimal differentiation of RE subsidies therefore entails a lower support rate for RE firms producing electricity, i.e. the optimal subsidy rate for solar is 93% of the optimal subsidy rate for wind (see Table 6). Relative to the case of a technology-neutral RE support, optimally differentiated subsidies thus lead to more investment in wind and less investment in solar capacity.

COMBINING RE SUBSIDIES WITH AN OPTIMAL ENERGY DEMAND TAX.—An optimal RE support scheme based on a FIT or market premium generates through the refinancing tax revenues which exceed the expenses for RE subsidies, i.e. an optimal FIT or market premium support policy cannot be revenue-neutral (see Corollary 3). But how large is the efficiency gain when the revenue-neutrality constraint is relaxed?

We find that combining RE subsidies, in the form of a FIT or market premium, with an optimal energy demand tax yields sizeable improvements more than doubling abatement efficiency (i.e., $\mathcal{E}^{Market\ premium}$ increases from 0.37 for revenue-neutral to 0.71 for optimal refinancing; see Table 6). The optimal demand tax increases consumer prices to roughly the same levels as would be obtained under a carbon pricing policy, thus inducing similar abatement through the energy conservation channel. Importantly, we find that improving the refinancing of RE subsidies is more important than differentiating the subsidy rate by technology.

²⁷From Corollary 1, we know that the optimal FIT and market premium lead to the same allocation. We here focus on discussing our results in terms of the market premium.

While the abatement efficiency increases when revenue-neutrality is relaxed, it still is significantly below 1 because the demand tax does not affect the relative production costs of coal vs. gas-fired electricity producers leaving the fuel-switch abatement channel unexploited.

INTENSITY STANDARDS FOR RE SUPPORT.—Intensity standards are blending constraints which translate into implicit output subsidies for RE technologies and implicit input taxes on energy production to finance RE subsidies. As such, they are by construction revenue-neutral, and cannot implement the social optimum (see Proposition 5). Notwithstanding their undesirable property of revenue-neutrality, we show below that intensity standards can in principle yield an abatement efficiency fairly close to a first-best outcome depending on the structure of both (implicit) RE subsidies and the (implicit) input taxes to finance the RE support.

Under an RE quota an equal per-MWh tax on electricity is levied on all firms to finance the RE subsidies. By construction, such a policy is revenue-neutral and does not discriminate the subsidy rate across RE technologies. An RE quota is thus equivalent to a technology-neutral market premium policy which is financed through a revenue-neutral tax on energy demand. Consequently, the abatement efficiency of an RE quota is poor (i.e., $\mathcal{E}^{RE\ quota} = 0.37$; see Table 6).

We find, however, that changing how RE subsidies are financed can greatly enhance abatement efficiency. Under a green offset intensity standard, where demand for certificates is proportionally related to CO₂ emissions, abatement efficiency increases (i.e., $\mathcal{E}^{Green\ offsets}$ is equal to 0.72 and 0.80 when the support for RE firms is structured as a subsidy added to the market price or a guaranteed output price, respectively). With respect to the performance of a green offsets system, three main insights emerge.

First, regardless of how the RE subsidies are structured, there is an advantage for conventional energy producers with low emissions intensity due to the lower costs for buying offset certificates for each MWh of electricity produced. Specifically, this helps to exploit carbon abatement through the fuel-switch channel by incentivizing electricity generation from natural gas.

Second, when the subsidies for RE firms are structured as a market premium, the abatement efficiency of a green offset system is only slightly higher than under an optimal policy with technology-differentiated market premium and demand tax refinancing. The reason is that when the marginal damage of emissions is reflected through the implicit input taxes, the wholesale electricity price already reflects the external cost. There is thus no need to further subsidize RE investments, i.e. the subsidy rate for RE firms should be zero. This, however, is not what happens under green offsets policy: revenue neutrality implies that positive tax revenues translate into a positive subsidy rate which is added on top of the wholesale electricity price, thus yielding inefficiently high unit revenues per MWh of electricity produced from wind and solar resources. In addition, the inefficiently high subsidy rate dampens the price signal for energy conservation. We find that when RE subsidies are paid as a market premium, the advantage of implicitly

taxing CO₂ emissions under a green offsets system, which induces a partial fuel switch to natural gas, is almost entirely outweighed by too high investments into RE technologies and a too low energy demand reduction.

Third, as under a FIT investors do not receive the wholesale price, the abatement efficiency increases because the induced over-investment in wind and solar is much smaller as compared to a market premium. At the same time, the need for refinancing is higher when RE support is paid in the form of a guaranteed output price relative to a market premium. A higher need for refinancing, however, implies a stronger carbon price signal established through the implicit input taxes. This explains why the green offsets system with FIT can come closer to the socially optimal outcome obtained under carbon pricing.

C. Cost-effective RE support policies

Rather than choosing optimal RE support policies under an endogenous environmental target (and given information about the SSC), policymakers may also be concerned with the question which policy designs can achieve a given emissions reduction target at lowest economic cost. To scrutinize the cost-effectiveness perspective on optimal policy choice, this section considers a simplified version of the general problem of optimal regulation laid out in (4), or its numerical equivalent (11), by assuming that RE support policy has to achieve an exogenously determined and fixed level of emissions reductions, \hat{E} .²⁸

Figure 4 shows the percentage welfare change relative to the unregulated market outcome (i.e., $100 \times [\mathcal{W}^b/\mathcal{W} - 1]$) for different RE support schemes \mathbf{b} for different levels of emissions. Unsurprisingly, carbon pricing is the most cost-effective policy irrespective of policy stringency as it efficiently exploits all abatement channels. The “cost-effectiveness ranking” of RE support policies, however, varies largely depending on policy stringency. Generally speaking, the reason is that alternative policy designs exploit various abatement channels (see Table 2) differently while the relative importance of each abatement channel for total abatement varies depending on targeted emissions reductions.

Analyzing the policy ranking under cost-effectiveness considerations yields the following additional insights with respect to the performance of different RE support schemes. First, the technology differentiation of RE subsidies according to the heterogeneous environmental value of the underlying resource is empirically not important for policy design at any level of emissions reductions. This underscores the similar finding we obtained in the context of optimal RE policies with endogenous environmental quality.

Second, for high abatement levels (i.e., emissions reductions relative to the unregulated market outcome are in excess of 50%), it becomes crucial to link the

²⁸Specifically, we add the following constraint to the upper-level part of the optimal policy problem in (11): $\sum_{i,t} \int_0^{X_{it}} E_i(\bar{x}) d\bar{x} \leq \hat{E}$. This amounts to evaluating policy choices solely on the basis of economic surplus—while the differences in environmental benefits from averted pollution are muted across the policy options given a constant environmental quality.

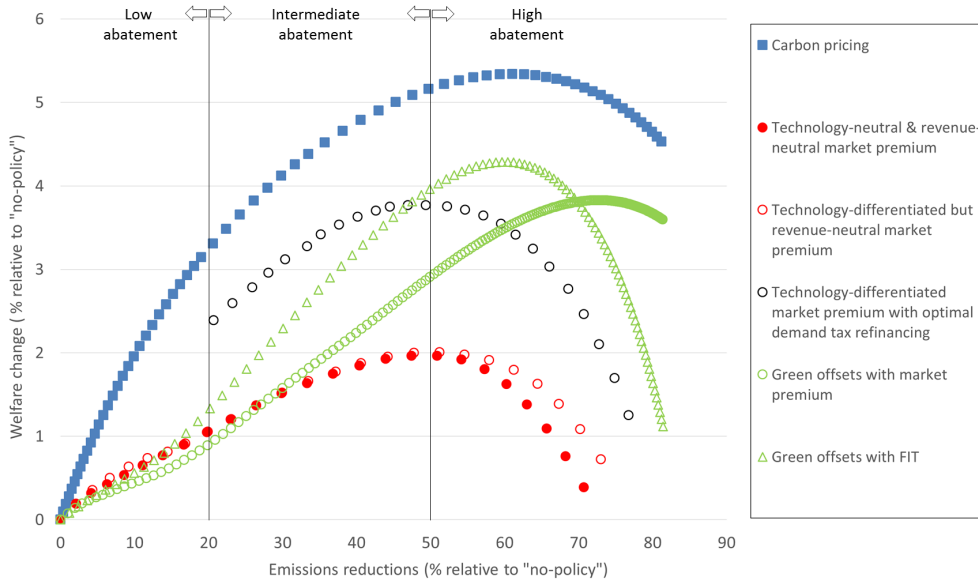


FIGURE 4. Cost-effectiveness of RE support under varying policy stringency

financing of RE support to carbon-intensive generation, for example, as achieved through an intensity standard with green offset certificates. The reason is that the higher policy stringency, the more important becomes CO_2 abatement through switching from coal to natural gas. As RE support schemes based on either a FIT or market premium fail to incentivize such a fuel switch, they perform poorly. This holds regardless of whether such policies are combined with an optimal demand tax for refinancing or not. With increasing policy stringency, green offsets with RE subsidies paid through a FIT outperform a green offset scheme with a market premium as a guaranteed output price under a FIT avoids over-investment in RE capacity (this is similar to the context of optimal RE support with endogenous environmental quality; see Section III.A).

Third, for intermediate abatement levels (between 20% and 50%), abatement is mainly achieved through RE capacity investments and reductions in energy demand; the switch with fossil-based technologies is not important. For this range of emissions reductions, RE subsidies with an optimal energy demand tax are thus the second-best policy (after carbon pricing). In particular, they outperform all policy designs which require revenue-neutrality between RE subsidies and refinancing. The reason is that the revenue-neutrality requirement limits the scope for exploiting abatement through the energy conservation channel. With increasing policy stringency, the green offset policies begin to outperform the RE support schemes with revenue-neutral demand tax refinancing as the efficiency gains from incentivizing a fuel-switch increase.

Fourth, for low abatement levels (less than 20%), cost-effective abatement under

a carbon pricing policy mainly occurs through energy conservation. The performance of revenue-neutral RE policies relative to , either directly as in the case of a FIT or market premium or indirectly under a green offset intensity standard, is therefore rather poor for low policy stringency as they entail inefficiently high incentives for RE investments averting abatement through energy conservation with to increase the consumer price.²⁹

IV. Robustness Checks and Model Extensions

Here we consider the sensitivity of results to parameters and model extensions affecting the relative importance of the different channels for abatement including the price responsiveness of energy demand, fuel prices and the composition of installed fossil-based production capacities, the social cost of carbon, environmental damages due to non-CO₂ greenhouse gases, and a higher temporal resolution.

A. Price responsiveness of energy demand

Columns (1)–(3) in Table 7 compare the abatement efficiency \mathcal{E}^b of the different RE support schemes for different assumptions about the price elasticity of energy demand ($|\epsilon|$). The stronger demand responds to price, the easier it is to induce abatement through the energy conservation channel for a given consumer price increase. Hence, the gap in abatement efficiency between carbon pricing and policies which subsidize RE technologies without refinancing rules that counteract too low energy prices, i.e. RE subsidies with revenue-neutral demand tax financing and RE quota, is larger (smaller) for the case of a high (low) $|\epsilon|$. In contrast, the abatement efficiency of RE support schemes which combine RE subsidies with an optimal demand tax depends positively on $|\epsilon|$ as such a policy can directly incentivize abatement through reductions in energy demand.

For a market where energy demand is relatively price-elastic, Table 7 shows that green offsets policies can closely approximate the socially optimal outcome (i.e., $\mathcal{E}^{Green\ offsets}$ equals 0.82 and 0.92 for the case of FIT and market premium, respectively). Intuitively, if the energy conservation channel is relatively important, the distortion induced by such policies—due to the fact the environmental damage is already reflected in electricity prices and that RE firms receive in addition a positive subsidy rate leading to abatement through an over-investment in RE capacity—becomes less important. On the other hand, the abatement efficiency of such policies can be poor, when $|\epsilon|$ is low.

B. Low natural gas prices and “monolithic” fossil-based energy supply

An important question is how our assessment of alternative policy designs for RE support changes when it becomes less important or even not necessary at all to

²⁹The case of the market premium with optimal demand tax refinancing is not shown for low abatement levels as this policy would essentially involve taxing energy demand with a zero subsidy rate for RE technologies.

TABLE 7. Sensitivity of abatement efficiency \mathcal{E}^b of different RE support policies^a.

	<i>Central case^b</i> (1)	Demand elasticity		<i>Low natural gas price^c</i> (4)	<i>Monolithic FE supply</i> (5)	<i>High SSC</i> $\delta = 100$ (6)
		$\epsilon = -0.05$ (2)	$\epsilon = -0.5$ (3)			
<i>Support schemes based on explicit RE subsidies with refinancing via demand tax</i>						
Technology-neutral RE subsidies & revenue-neutral						
FIT	0.35	0.44	0.26	0.23	0.42	0.67
Market premium	0.37	0.45	0.29	0.23	0.42	0.72
Technology-differentiated market premium						
revenue-neutral	0.38	0.46	0.30	0.23	0.42	0.75
optimal refinancing	0.71	0.63	0.76	0.68	0.94	0.81
<i>Technology or intensity standards</i>						
RE quota	0.38	0.46	0.30	0.23	0.94	0.75
Green offsets with RE subsidies paid as						
Market premium	0.72	0.66	0.82	0.50	0.06	0.97
FIT	0.80	0.69	0.92	0.55	0	0.85

Notes: ^a \mathcal{E}^b is defined by equation (21). ^bThe central-case values are: $\epsilon = -0.15$ and $\delta = 50$ € per ton of CO₂. ^cAssumes that the fuel price for natural gas is reduced from the central-case value of 21.16 €/MWh to 5 €/MWh.

switch from coal to natural gas in order to reach a social optimum. To explore this question, we analyze the two additional cases assuming (1) a substantially lower natural gas price (reducing central-case value of 21.16 €/MWh to 5 €/MWh) and (2) that all coal-fired (lignite and hard coal) capacity is rededicated as natural gas capacity.

Both perspectives are useful to reflect the conditions of current and likely future energy systems. First, the costs of supplying natural gas may decline further due to increased exploitation of shale gas resources and enhanced infrastructure and market integration due to liquified natural gas. Second, systems with “monolithic” fossil-based energy (FE) supply not only depict the current situation of a number of countries with abundant oil resources (for example, Middle Eastern countries such as Iran, Saudi Arabia, Egypt) but may also describe future electricity systems for countries where coal use has already been banned or where nuclear power in an otherwise zero-carbon generation mix will be replaced with natural gas (for example, Sweden and Switzerland).

In the case with a “*Low natural gas price*” (comparing columns (1) and (4) in Table 7), the technology mix in the unregulated market outcome, compared to the central case (see Table 6), is tilted towards natural gas (generation share of 29.7%) but coal is still part of the mix (generation share of 32.2%). While this reduces the scope for CO₂ abatement through a fuel switch between coal and gas, the important implication of low natural gas prices is another one: for the socially optimal policy with carbon pricing, the tax-inclusive fuel price of coal is higher than the one for natural gas. This implies that coal-fired plants become price-setting with the result that the increase in the consumer price of electricity is substantially larger than in a situation with high natural gas prices. Consequently, the abatement efficiency of RE support policies which do not exploit

the energy conservation channel relative to carbon pricing significantly worsens. The important implication for policy design is that as long as coal-based generation remains in the system, the efficiency loss associated with using RE support schemes, without modifying the financing structure to reflect the carbon intensity of fossil-based generation, may be substantial.³⁰

In contrast, when no fuel switch is needed, as is the case for systems with “*Mono-lithic FE supply*”, RE support schemes have the ability to closely approximate the socially optimal outcome obtained with carbon pricing. The extent to which this is possible, however, depends on whether the RE support scheme can trigger abatement through the energy conservation channel. If this is possible only to a limited extent, as under a revenue-neutral FIT or market premium system, the abatement efficiency remains poor (i.e., $\mathcal{E}^{FIT} = \mathcal{E}^{Market\ premium} = 0.42$). A policy combining optimal RE subsidies with optimal refinancing yields an abatement efficiency which closely approximates those obtained under first-best carbon pricing (i.e., $\mathcal{E}^{Market\ premium\ with\ optimal\ demand\ tax} = \mathcal{E}^{RE\ quota} = 0.94$). With an optimal time-varying hourly demand tax such policies would achieve the first-best solution (see Proposition 4); the remaining efficiency loss thus derives from constraining the optimal demand tax to be uniform over time.

C. Social cost of carbon

The higher the SCC, the higher is in general the abatement efficiency of RE support schemes, i.e. \mathcal{E}^b increases for all policies (comparing column (6) to column (1) in Table 7). The simple reason is that with higher SCC abatement mainly occurs through subsidizing RE investments and conserving energy demand while the importance of a fuel switch among fossil-based generation is diminished.

But even with high SCC, the question of policy design remains important. Support schemes that either establish incentives for energy conservation or are based on “polluter-pays-the-price” financing of RE subsidies can closely approximate socially optimal outcomes (i.e., the abatement efficiency exceeds 80%) whereas revenue-neutral FIT or market premium policies entail efficiency losses of around 30% (i.e., $\mathcal{E}^{FIT} = 0.67$ and $\mathcal{E}^{FIT} = 0.72$).

D. Non-CO₂ greenhouse gases

Motivated by the fact that CO₂ is the principal anthropogenic greenhouse gas (GHG) being emitted by the power sector, we have so far abstracted from other non-CO₂ GHGs relevant in the context of electricity generation such as methane (CH₄) and nitrous oxide (N₂O). The potential concern is that not accounting for other GHGs may underestimate the potential benefits from RE support schemes relative to carbon pricing policies. While a carbon pricing policy provides incen-

³⁰One exception is the RE policy which combines RE subsidies with an optimal demand tax. Here, the possibility to directly incentivize energy conservation somewhat dampens the efficiency loss (i.e., $\mathcal{E}^{Market\ premium\ with\ optimal\ demand\ tax} = 0.68$).

tives for removing coal, it potentially leaves a significant amount of natural gas, and hence methane emissions, in the system. In contrast, a stringent RE support policy provides incentives for removing fossil fuels altogether.

Although these GHGs are more potent than CO_2 , we find that including them explicitly in our analysis does not affect our main insights—and, in fact, only has small quantitative effects (for example, on abatement efficiency \mathcal{E}^b as our main metric for comparing policies). The robustness of our results with respect to the inclusion of non- CO_2 GHGs can be understood as follows. First, the amounts of non- CO_2 GHGs are several orders of magnitude smaller than for CO_2 . Second, the ordering of energy technologies in terms of emissions intensity is not altered. More specifically, for the case of CH_4 , the emissions coefficient for natural gas and different types of coal is roughly identical; for N_2O , natural gas has a lower emissions coefficient than coal.³¹

Consequently, including non- CO_2 GHGs in our model slightly increases, on average, the damage caused by a MWh of electricity produced. The upshot is that under all policies considered a higher level of abatement is optimal (as compared to ignoring non- CO_2 GHGs). As the ordering of energy technologies, including the costs due to environmental damage caused, does not change, the qualitative ranking among different regulatory designs for addressing the GHG externality are unaffected.

E. Temporal resolution

While we model electricity supply and demand decisions at the hourly level, we use for each season the hours of an average week to reduced computational complexity (rather than using all 8760 hours of a year). The potential concern is that this may smooth out some of temporal variation with respect to the availability of RE resources and energy demand. While solving the model for 8760 hours is computationally not feasible, we have carried out sensitivity analysis based on a model with 12 (instead of four) representative weeks. We find that this increases the temporal variation of marginal hourly emission rates thus potentially pronouncing the scope for technology-differentiated RE subsidies. We do find, however, that the optimal differentiation of the subsidy rate between wind and solar is only slightly affected, suggesting that four representative weeks are sufficient to capture the variability of resource availability and demand relevant for our analysis.

V. Conclusions

Public policies aimed at promoting clean energy from intermittent RE resources such as wind and solar are the most widely adopted form of actual low-carbon

³¹Using standard emissions coefficients and CO_2 -equivalence factors of global warming potentials for CH_4 and N_2 from the IPCC (see tables 2.2 and 2.14 in [Eggleston et al., 2006](#)), the emissions factors for coal and natural gas increase by only 0.5% and 0.09%, respectively.

policy—yet the question of how to best design support schemes for wind and solar has received surprisingly little attention. This paper aims to fill this gap by examining optimal support schemes for intermittent RE resources in the presence of a carbon externality. We have characterized optimal policies and the conditions under which RE support schemes can achieve socially optimal outcomes. To assess different policies in an empirically plausible setting and to derive additional quantitative insights, we have developed a numerical equilibrium framework of optimal policy design which incorporates a number of features relevant for analyzing real-world electricity markets.

We have emphasized three issues for policy design: the heterogeneity of intermittent natural resources, budget-neutral financing rules, and incentives for carbon mitigation. We show that optimal subsidies for wind and solar should be differentiated to reflect the heterogeneous environmental value of the underlying resource. We find, however, that the differentiation of RE subsidies is only of minor importance for policy design. Rather, the way RE subsidies are financed is critical: RE policies relying on “smart” financing by either using “polluter-pays-the-price” financing in the context of budget-neutral schemes (such as, for example, RE quotas and technology or intensity standards for clean energy) or by giving up budget neutrality can approximate socially optimal outcomes. We have further assessed the performance of RE policies under different market conditions (including the price responsiveness of energy demand and the composition of fossil-based supply) and assumptions about the social valuation of environmental damages (including the social cost of carbon and inclusion of non-CO₂ greenhouse gases). Overall, our analysis suggests that—when carbon pricing is unavailable due to political (and other) constraints—optimally designed RE support policies do not necessarily have to be regarded as a costly second-best option.

Some limitations of our analysis should be kept in mind. First, our analysis has focused on how to design RE support policies in the presence of a carbon externality. In doing so, we have deliberately abstracted from the positive externalities related to learning, technological innovation through R&D investments, and network effects (Jaffe, Newell and Stavins, 2005; Acemoglu et al., 2012; Bollinger and Gillingham, 2014) which may provide an important rationale for choosing RE support schemes over carbon pricing policies. Incorporating such positive effects would obviously play in favor of RE support policies. Second, these benefits would, however, have to be weighed against the additional system integration and back-up cost of intermittent RE generation (Borenstein, 2012; Marcantonini and Ellerman, 2014; Gowrisankaran, Reynolds and Samano, 2016). While it is beyond the scope of this paper to provide a comprehensive cost-benefit analysis, our estimates could be viewed as a first indication of how large the net benefits from other external effects would have to be to provide a rationale for decarbonization through RE support policies.

Notwithstanding these caveats, our analysis demonstrates that optimally designed policies to support RE from intermittent wind and solar resources, in par-

ticular with regard to the financing of RE subsidies, can substantially enhance the efficiency of decarbonization policies in the electricity sector. At the same time, this diminishes the importance of arguments relying on positive (and difficult to quantify) learning and technology externalities for rationalizing the public policy support for renewable energy.

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APPENDIX A: PROOFS

A1. Proof of Proposition 1

Let $t^e = \kappa_i, \forall i$, denote the uniform emissions tax. Maximizing the social surplus (2) with respect to κ yields the following first-order condition:

$$(A1) \quad \sum_t \left[S'_t \frac{\partial d_t}{\partial t^e} - G'_t \frac{\partial k_t}{\partial t^e} \right] = \sum_{i,t} (C'_{it} + \delta E'_{it}) \frac{\partial q_{it}}{\partial t^e}.$$

From the equilibrium conditions for conventional energy production (4b) and RE generation (4c), we obtain, respectively: $C'_{ct} \geq C'_{dt} = p_t - t^e E'_{dt}$ and $S'_t = G'_t = p_t$. Differentiating the market-clearing condition (4d) with respect to t^e yields: $\sum_i \frac{\partial q_{it}}{\partial t^e} = \frac{\partial d_t}{\partial t^e}$. Substituting terms into (A1) gives:

$$\sum_t p_t \sum_i \frac{\partial q_{it}}{\partial t^e} = \sum_t (p_t - t^e E'_t + \delta E'_t) \sum_i \frac{\partial q_{it}}{\partial t^e},$$

which can be simplified to yield:

$$t^e = \delta.$$

From comparing the conditions for the social optimum (3a) with the equilibrium conditions (4b) under the case of carbon pricing only (i.e., $s_t = \tau_t = 0$), it follows that a uniform carbon tax $\kappa_i = t^e = \delta, \forall i$, implements the social optimum. \square

A2. Proof of Proposition 2

We present the proof for the case of an RE support scheme consisting of a FIT and tax on energy demand. The proof for the case of a market premium proceeds analogously.

As we know from Proposition 3 that the clean technology does not enter the market, we can focus on the dirty conventional generation technology, i.e. we can simplify notation by dropping the index for conventional technologies. Differentiating the equilibrium conditions (4a)–(4d) for the case of a FIT with respect to the RE subsidy (s_t) yields:

$$\begin{aligned} \frac{\partial k_t}{\partial s_t} &= \frac{1}{G''_t} \\ \frac{\partial d_t}{\partial s_t} &= \frac{C''_t}{C''_t - S''_t} \frac{\partial k_t}{\partial s_t} \\ \frac{\partial q_t}{\partial s_t} &= \frac{S''_t}{C''_t - S''_t} \frac{\partial k_t}{\partial s_t} \\ \frac{\partial p_t}{\partial s_t} &= \frac{C''_t S''_t}{C''_t - S''_t} \frac{\partial k_t}{\partial s_t}, \end{aligned}$$

and with respect to a change in the energy demand tax (τ_t) yields:

$$\begin{aligned} \frac{\partial k_t}{\partial \tau_t} &= 0 \\ \frac{\partial d_t}{\partial \tau_t} &= \frac{\partial q_t}{\partial \tau_t} = \frac{1}{S''_t - C''_t} < 0 \\ \frac{\partial p_t}{\partial \tau_t} &= \frac{C''_t}{S''_t - C''_t} < 0. \end{aligned}$$

From the regulator's problem in (4), we can derive the following first-order conditions for optimal feed-in

tariffs (s_t) and energy demand taxes (τ_t), respectively, as:

$$\begin{aligned} S'_t \frac{\partial d_t}{\partial s_t} - (C'_t + \delta E'_t) \frac{\partial q_t}{\partial s_t} - G'_t \frac{\partial k_t}{\partial s_t} &= 0 \\ S'_t \frac{\partial d_t}{\partial \tau_t} - (C'_t + \delta E'_t) \frac{\partial q_t}{\partial \tau_t} - G'_t \frac{\partial k_t}{\partial \tau_t} &= 0. \end{aligned}$$

Since the RE firm only receives the feed-in tariff, the RE capacity k_t does not respond to a change in the demand tax, i.e. $\frac{\partial k_t}{\partial \tau_t} = 0$. Substituting the marginal private surplus, conventional cost, and marginal investment cost from the equilibrium conditions and using the partial derivatives of conditions (4d) for clearing of the energy spot markets with respect to the RE subsidy and demand tax yields:

$$\begin{aligned} (p_t - s_t) \frac{\partial k_t}{\partial s_t} + t_t \frac{\partial d_t}{\partial s_t} - \delta E'_t \frac{\partial q_t}{\partial s_t} &= 0 \\ (t_t - \delta E'_t) \frac{\partial d_t}{\partial t_t} &= 0. \end{aligned}$$

From the second equation above, the socially optimal level of the energy demand tax can be derived as:

$$\tau_t^* = \delta E'_t.$$

Inserting τ_t^* into the first equation above and using the derived terms for the equilibrium responses of k_t , d_t , and q_t with respect to RE subsidies s_t yields:

$$s_t^* = p_t + \delta E'_t.$$

□

A3. Proof of Corollary 2

Proof of parts (i) and (iii): A constant surplus function S_t implies that energy demand is constant over time. Hence, conventional energy production is constant over time, too. Given that cost function $C_{it}(q_{it})$ and the emissions function $E_{it}(q_{it})$ are time-invariant, this implies that the wholesale energy price and the emissions level do not change over time. From the formula for the optimal FIT in equation (8a) it then follows that the FIT rate has to be differentiated by t , i.e. across RE technology or RE resource. Similarly, if marginal costs (the emissions rate) are constant, the wholesale energy price (the emissions rate) takes on the same value for all t , implying that the optimal FIT is constant over time, i.e. $s_1^{FIT} = s_2^{FIT}$. The proof for the case of an optimal market premium proceeds analogously.

Proof of part (ii): With the same reasoning, if the surplus is constant in time or the marginal emissions rate is constant, the marginal social costs are constant in time and, thus the demand tax is constant in time, i.e. $\tau_1^* = \tau_2^*$. □

A4. Proof of Corollary 3

The revenues from an energy demand tax (weakly) exceed the expenses for an RE subsidy which is structured as a market premium if:

$$\sum_t \tau_t d_t \geq \sum_t s_t k_t$$

and for an RE subsidy which is structured as a FIT if:

$$\sum_t \tau_t d_t \geq \sum_t (s_t - p_t) k_t.$$

Using the respective optimal RE subsidy rate and demand tax from Proposition 2 yields:

$$\sum_t \delta E'_{dt} d_t \geq \sum_t \delta E'_{dt} k_t$$

which always holds since marginal emissions rates are positive and energy demand (weakly) exceeds the production of renewable sources. If the market penetration of RE is incomplete, i.e. $k_t < d_t$, the tax revenues under an optimal RE support scheme is strictly larger than the expenses for optimal RE subsidies. \square

A5. Proof of Proposition 3

We prove Proposition 3 for the case of a FIT.³² Differentiating the equilibrium conditions (4a)–(4d) under the case of a FIT (i.e., $\kappa_i = \tau_t = 0$) with respect to feed-in rates s_t and solving for the policy-induced changes in equilibrium quantities and prices yields:

$$\begin{aligned} \frac{\partial k_t}{\partial s_t} &= \frac{1}{G_t''} > 0 \\ \frac{\partial d_t}{\partial s_t} &= \frac{\partial d_t}{\partial k_t} \frac{\partial k_t}{\partial s_t} = \frac{\sum_i C_{it}''}{\sum_i C_{it}'' - S_t''} \frac{\partial k_t}{\partial s_t} = \frac{\sum_i C_{it}''}{\sum_i C_{it}'' - S_t''} \frac{1}{G_t''} > 0 \\ \frac{\partial q_{it}}{\partial s_t} &= \frac{\partial q_{it}}{\partial k_t} \frac{\partial k_t}{\partial s_t} = \frac{\sum_j C_{jt}''}{\sum_j C_{jt}'' - S_t''} \frac{S_t''}{C_{it}''} \frac{\partial k_t}{\partial s_t} = \frac{\sum_j C_{jt}''}{\sum_j C_{jt}'' - S_t''} \frac{S_t''}{C_{it}''} \frac{1}{G_t''} < 0 \\ \frac{\partial p_t}{\partial s_t} &= \frac{\partial p_t}{\partial k_t} \frac{\partial k_t}{\partial s_t} = \frac{\sum_i C_{it}''}{\sum_i C_{it}'' - S_t''} S_t'' \frac{\partial k_t}{\partial s_t} = \frac{\sum_i C_{it}''}{\sum_i C_{it}'' - S_t''} S_t'' \frac{1}{G_t''} < 0. \end{aligned}$$

The FIT thus implies an increase in demand and a reduction in the price of electricity. Moreover, it unambiguously increases generation from RE technologies and reduces output from the clean and dirty conventional technology. Recalling that the clean conventional technology is initially not in the market implies that it does not enter the market due to a FIT. The weaker statement of this result—if one were to relax the assumption that the clean technology is initially not in the market—is to say that the output of the clean technology decreases due to the introduction of a FIT. As long as the cost functions of the conventional technologies are convex and do not intersect, however, it holds that the FIT does not lead to a fuel switch between clean and dirty conventional technologies.

Similarly, equilibrium changes in response to a change in demand taxes are given by:

$$\begin{aligned} \frac{\partial k_t}{\partial t_t} &= 0 \\ \frac{\partial q_{it}}{\partial t_t} &= \frac{\prod_i C_{it}''}{S_t'' \sum_i C_{it}'' - \prod_i C_{it}''} \frac{1}{C_{it}''} < 0 \\ \frac{\partial d_t}{\partial t_t} &= \sum_i \frac{\partial q_{it}}{\partial t_t} < 0 \\ \frac{\partial p_t}{\partial t_t} &= \frac{\prod_i C_{it}''}{S_t'' \sum_i C_{it}'' - \prod_i C_{it}''} < 0. \end{aligned}$$

Applying the same argumentation as above, it is straightforward to see that a demand tax does not create a fuel switch between the two conventional technologies. \square

³²The proof for the case of a market premium proceeds analogously and is omitted for reasons of brevity.

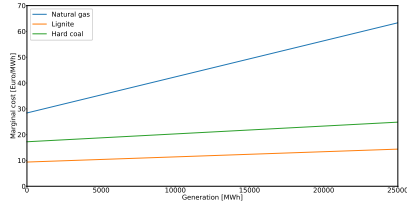
A6. Proof of Proposition 4

Suppose the social optimum does not require a fuel switch, that is, the cleaner conventional energy technology c does not enter the market following a direct or indirect RE support policy, i.e. $q_{ct} = 0$. From Proposition 3, it follows that the clean conventional technology never enters the market under an RE subsidy. Substituting the optimal RE subsidy, either for the case of a FIT or a market premium, as well as the optimal energy demand tax from Proposition 2 into the equilibrium conditions (4a)–(4d) yields:

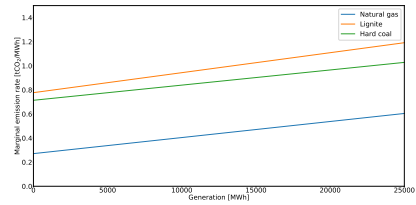
$$\begin{aligned}
 S'_t &= p_t + \delta E'_t && \forall t \\
 C'_t &= p_t && \forall t \\
 G'_t &= p_t + \delta E'_t && \forall t \\
 \Rightarrow S'_t &= C'_t + \delta E'_t = G'_t && \forall t
 \end{aligned}$$

which is equivalent to the conditions characterized by (3a) and (3b). In contrast, suppose the social optimum implements an allocation in which production of the clean conventional energy technology c is positive, i.e. $q_{ct} > 0$. From Proposition 3 technology c never enters the market under an RE subsidy; an RE subsidy therefore does not implement the social optimum.

APPENDIX C: ADDITIONAL FIGURES

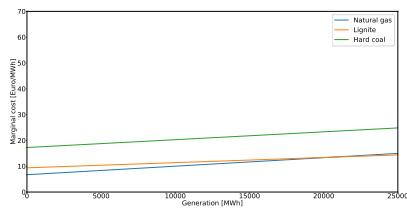


Marginal cost functions

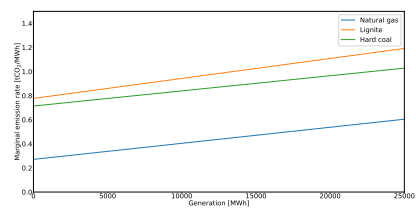


Marginal emission rate as function of output

FIGURE B1. Empirically estimated functions for marginal generation cost and marginal emissions rate by technology assuming central-case value for natural gas price (21.16 €/MWh).



Marginal cost functions



Marginal emissions rate as function of output

FIGURE B2. Empirically estimated functions for marginal generation cost and marginal emissions rate by technology assuming a low price for natural gas (5 €/MWh).

ONLINE APPENDIX: DOCUMENTATION OF COMPUTER CODES TO REPRODUCE QUANTITATIVE ANALYSES

This online appendix provides a brief documentation of computer codes—using the GAMS (General Algebraic Modeling System) and Python software—which can be used to reproduce the quantitative empirical analyses presented in Sections III and IV of the paper. All files, including model and data, can be downloaded [here](#).³³

The appendix is structured as follows. We first list the software programs and solvers needed to execute the computer codes. We then describe the folder structure, file names, and functionality of each program in the overall package.

Software prerequisites

The following solvers are needed to solve the GAMS routines:

- *PATH*: To solve the complementarity-based economic equilibrium problem.

The following Python packages are needed to implement the grid search for optimal policies:

- *GAMS API*: To interface GAMS and Python. Delivered with GAMS.
- *Numpy*: Used for numerical computations.
- *Pandas*: Used for data processing
- *Jupyter Notebook*: For calibration and result processing.

Folder structure and file names

The folder named “**model**” contains files of the core GAMS model:

- *main.gms*: Main file to run the model
- *dataload.gms*: Loads data files, calibration and assignment of model parameters.
- *policies.gms*: Defines parameters for policy implementation and assigns default values.
- *model.gms*: Definition and assignment of model equations and variables.
- *initialize.gms*: Initialization of variables depending on policy parameters.
- *report.gms*: Assignment of reporting parameters.

The folder named “**Iteration_parallel**” contains Python files to perform grid search for optimal policies using parallel processing.

- *iteration.py*: Main file to run grid search over optimal policies. Functions within the file are named after the scenario to solve, e.g., *solve_core_cases*, determines all optimal policies for the central results used in the paper.
- *scenarios.py*: Functions to implement policies and report results.
- *model.py*: Functions to run GAMS model using Python.
- *Process_results.py*: Reporting of model results in pivot-table friendly format.

³³The electronic version of this document contains a hyperlink. The address is: https://www.ethz.ch/content/dam/ethz/special-interest/mtec/cer-eth/economics-energy-economics-dam/documents/people/srausch/Online_Appendix_TheEconomics_of_RenewableEnergySupport.zip.

- *results*: Folder for model results.

The folder named “**data**” contains data input files for the GAMS model:

- *DE_season_average.xlsx*: Time series for electricity demand and generation.
- *Technology_data.xlsx*: Cost and generation characteristics of power plants.
- *Technology_data_elas0.05.xlsx*: Cost and generation characteristics of power plants. Case of low elasticity.
- *Technology_data_elas0.5.xlsx*: Cost and generation characteristics of power plants. Case of high elasticity.
- *Technology_data_cf_nofuelswitch.xlsx*: Cost and generation characteristics of power plants. Case of low natural gas price.
- *Technology_data_no_coal.xlsx*: Cost and generation characteristics of power plants. Case of no coal capacity.
- *investments_cost_res.xlsx*: calibrated parameters of investment cost function.

The folder named **calibrate_cost_curves** contains file to calibrate marginal cost and emission curves:

- *ipython/Calibrate_cost_curve.ipynb*: Jupyter notebook to calibrate cost and emission curves for the central case.
- *ipython/Calibrate_cost_curve_counterfactual.ipynb*: Jupyter notebook to calibrate cost and emission curves for the case of low natural gas prices.
- *ipython/Fit_Investment_Curves.ipynb*: Jupyter notebook to calibrate investment cost functions for wind and pv installations.
- *source_data/conventional_power_plants_DE.csv*: List of German power plants.
- *source_data/fuel_prices.csv*: Time series of daily fuel and emission prices.
- *source_data/RES_investment_curves.xlsx*: Cost characteristics, potential, and generation of wind and pv power in Germany used to calibrate investment cost curves.
- *figures*: Folder to store figures of cost and emission curves.

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