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Keywords: Feed-in-Tariff, Carbon Trust, Carbon Pricing, Supply-Side Dynamics, Green Paradox, Climate Policy

JEL Classification: Q4, Q52, Q54, Q58, D58, H21

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Renewable energy subsidies: Second-best policy or fatal aberration for mitigation?*

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Abstract

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*Supplementary material is available under: <http://www.pik-potsdam.de/~kalkuhl/SM/ren-policy.pdf>

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1 Introduction

Policies to promote renewable energy technologies have a long tradition in many OECD countries. Even before carbon pricing instruments (like the EU-ETS in 2005) were implemented to reduce carbon emissions, many countries had used subsidies, feed-in-tariffs (FIT) or public R&D spending to increase the share of renewable energy (IEA 1997). As concerns about global warming intensify due to new research results such as the latest IPCC (2007b) report and the Stern (2007) Review, politicians and economists are debating about the most effective mitigation policy. Many economists recommend putting a price on carbon in form of taxes or emissions trading schemes (ETS) to mitigate emissions at least costs (e.g. IPCC 2007a, p. 747). The academic popularity of carbon pricing has given rise to a controversial debate on how this instrument relates to renewable energy policies: Are both instruments necessary to achieve mitigation targets at least costs or does the policy mix increase compliance costs?

Basically, there are two strands of argumentations for implementing renewable energy specific policies: one is based on efficiency grounds, the other relies on pragmatic considerations promoting second-best policies that are politically more feasible (see Benneer and Stavins (2007) for a general discussion of the use of second-best instruments). The first argumentation claims that the energy sector is subject to multiple externalities like carbon emissions, local air pollution, innovation and learning spillovers, imperfect competition, network effects or energy security concerns (e.g. Fischer and Preonas 2010; Sorrell and Sijm 2003; Unruh 2000). If the regulator implements only Pigouvian carbon taxes, emissions will be higher than under the first-best optimum (Grimaud et al. 2010). Likewise, if the regulator seeks to achieve a certain emission target (by an ETS or by appropriate carbon taxes) without further policy instruments, compliance costs will be higher than socially optimal (Fischer and Newell 2008; Kalkuhl et al. 2011; Kverndokk and Rosendahl 2007). The second, pragmatic argumentation stresses that distributional concerns and missing stakeholder support for (efficient) carbon pricing may constitute political constraints which prevent the implementation of the first-best policy: High carbon prices reduce profits and income primarily in the fossil energy industry and lower-income households (Burtraw et al. 2009; Metcalf 2008; Parry 2004; Parry and Williams III 2010). Additionally, unilateral carbon pricing can induce relocation of energy-intensive industries (e.g. Markusen et al. 1993). A uniform global carbon tax or a global ETS solves the relocation problem, but might be Utopian in the short term as there is no practical experience how to negotiate and distribute rent incomes and cost burdens. Ideological attitudes against carbon pricing poli-

cies also play an important role: Carbon taxes face high opposition as taxes in general are unpopular in wide parts of the US society (Newell et al. 2005). The alternative to taxes, emissions trading, is criticized similarly by many environmentalists and developing countries as being institutionally infeasible or unfair. Distributional concerns and practical and information constraints for compensation may be the most important reason why carbon pricing has not yet been stringent if imposed at all. If exogenous constraints impede the implementation of the first-best instrument, a second-best approach can be a valuable alternative (Benneer and Stavins 2007). In particular, technology-optimistic considerations about the progress of the learning renewable energy technologies might lead to the perception that a temporary renewable deployment stimulus could be a more manageable way to foster mitigation.¹

It is difficult to estimate to what extent existing renewable energy policies are efficiency-based (i.e. addressing further externalities besides carbon pricing) or driven by pragmatic second-best considerations to reduce emissions. Nevertheless, existing renewable energy policies are also criticized by economists as being inefficient or ineffective. Nordhaus (2009) advocates to treat technologies and innovations in all sectors of the economy equally, i.e. avoid technology discrimination. He advises to concentrate on establishing a global carbon price. Sinn (2008b,a) criticizes ‘demand-side policies’ like renewable energy subsidies as they could lead to an accelerated fossil resource extraction. Generally, many economists recommend to favor an efficient first-best policy over an inefficient second-best approach – without quantifying the respective efficiency losses of the latter.²

This paper steps into this gap by considering second-best alternatives to carbon pricing and weighing (theoretical) efficiency against (practical) feasibility aspects. For this purpose, we assume that possible secondary market failures like innovation spillovers or network effects are completely internalized by firms or already addressed by additional first-best policies. Hence, renewable energy technologies are not subject to uncorrected additional market failures besides the climate target which rules out the implementation of renewable energy subsidies for efficiency reasons. Instead, we consider a second-best (i.e. the welfare maximizing) renewable energy subsidy when carbon pricing is missing, delayed or imperfect. We further analyze a second-

¹Farmer and Trancik (2007), for example, estimate that the “costs of reaching parity between photovoltaics and current electricity prices are on the order of \$200 billion” – which is 1.4% of U.S. GDP in 2009.

²Fischer and Newell (2008) are a notable exception as they calculate the costs of achieving certain emission reductions with second-best policies. Likewise, Galinato and Yoder (2010) focus on revenue-neutral second-best tax-subsidy combinations to reduce carbon emissions.

best feed-in-tariff system and carbon trust scheme where fossil tax income is used to cross-finance renewable energy subsidies. We evaluate these instruments with respect to their impact on welfare, resource rents and energy prices compared to an optimal carbon pricing scheme as efficient first-best benchmark. By calculating optimal second-best instruments we provide a valuable numerical estimation of the (optimistic) least-cost potential of these emission mitigation instruments. Furthermore, we assess the robustness of renewable energy subsidies and elaborate the risk of “green paradoxes” due to slightly mal-adjusted subsidies. One of the key findings of our paper is that permanent renewable energy subsidies are a very poor and risky substitute for missing or imperfect carbon prices. Mitigation costs increase by a multiple if no carbon price is available for variations in a wide range of plausible parameters. Additionally, subsidies that deviate only slightly from the optimal subsidy can lead to a severe increase in emissions or to high consumption losses. Hence, although high carbon prices are hard to establish in reality, permanent subsidies are no practical alternative. However, feed-in-tariff systems, carbon trusts or temporary subsidies combined with long-term carbon pricing can be designed in a way to ease distributional conflicts at reasonable additional costs.

We perform our analysis within an integrated policy assessment model described in [Kalkuhl et al. \(2011\)](#). The model provides a consistent and flexible framework to calculate optimal policies and to conduct a precise welfare analysis. [Sec. 2](#) introduces the economic sectors and the relevant basic equations. In our intertemporal general equilibrium model, we consider three stylized energy technologies: (i) a fossil energy technology causing carbon emissions, (ii) a renewable energy technology with high learning-by-doing potential, and (iii) a nuclear power technology as a capital-intensive non-learning carbon-free technology. An intertemporal fossil resource extraction sector is integrated to account for possible supply-side responses to climate policies as motivated by [Sinn \(2008b\)](#). The model is parameterized on a global-economy scale to reproduce business-as-usual and mitigation scenarios from typical integrated assessment models. The global dimension is crucial for appropriately considering the intertemporal supply-side dynamics of fossil resource owners. Although policies have to be implemented nationally, considering the global perspective gives a useful upper bound for the efficiency of second-best instruments. In contrast to [Kalkuhl et al. \(2011\)](#), we assume no additional market failures for learning technologies. Instead, we explore the potential of several renewable energy subsidies (presented in [Sec. 3](#)) to compensate for missing or suboptimal carbon prices in order to achieve ambitious mitigation targets. In [Sec. 4](#), the impact of these second-best policies on welfare, rents and energy prices is discussed. Subsequently, the sensitivity

and robustness of second-best subsidies is analyzed. Finally, we conclude our paper by summing up important insights and implications for climate policy.

2 The model

We use an intertemporal general equilibrium model that distinguishes a household, a production sector, fossil resource extraction and several energy sectors. In addition to energy generated by combustion of fossil resources, there are two carbon-free energy sources: a non-learning nuclear energy sector, and a more expensive yet learning renewable technology with a high cost-decreasing potential. A further sector extracts fossil resources from a finite resource stock. We assume standard constant elasticity of substitution (CES) production functions which are given in detail in the appendix. Fig. 1 gives an overview of the technology used.

The mitigation target is expressed by an upper bound for cumulative extraction. The government, which anticipates the equilibrium response of the economy, imposes policy instruments on the economy to maximize welfare subject to the mitigation target.

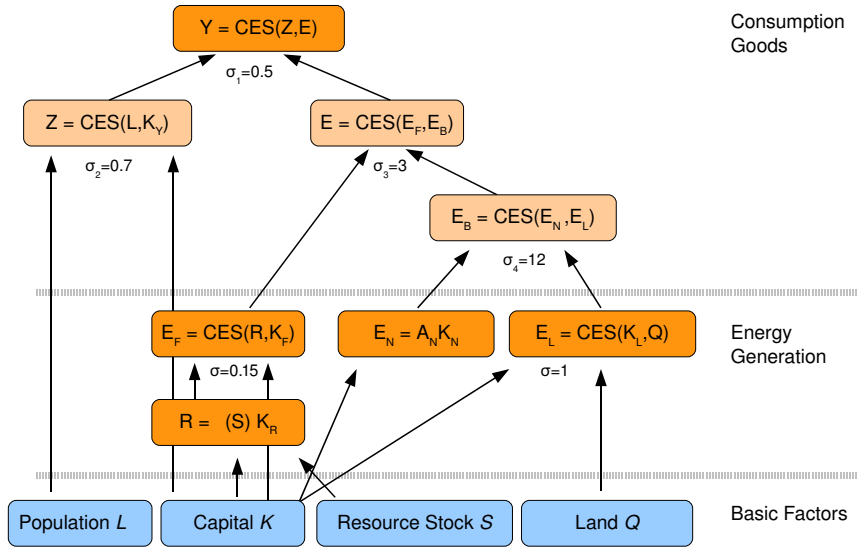


Figure 1: Technology of the model and key elasticities of substitution between production factors.

2.1 The economic sectors

In the following, we concentrate on a short description of the agents' optimization problem and the interplay with the government's policies. A detailed and more formal description of production technology, market equilibrium and parameter choices can be found in [Kalkuhl et al. \(2011\)](#).

The representative household

We assume a representative household with the objective to maximize the sum of discounted utility U , which is a function of per-capita consumption C/L :³

$$\max_{C_t} \sum_{t=0}^T (1 + \rho)^{-\Delta t} \Delta U(C_t/L_t)$$

The factor Δ denotes the length of a time period in years and ρ is the pure rate of time preference.

The household owns labor L , capital stocks K_j , and the firms, and therefore receives the factor incomes wL and rK_j , as well as the profits of all firms π_j , where $j \in \{Y, F, R, N, L\}$ enumerates the sectors (consumption good sector Y , fossil energy sector F , resource extraction sector R , nuclear energy sector N , renewable energy sector L). Wage rate w , interest rate r , profits π_j and lump-sum transfers from the government Γ are taken as given. The household is assumed to take the depreciation of capital at rate δ into account in its investment decision. The household therefore faces the following constraints:

$$C_t = w_t L_t + r_t K_t - I_t + \pi_t + \Gamma_t \quad (1)$$

$$K_t = \sum_j K_{j,t}, \quad I_t = \sum_j I_{j,t}, \quad \pi_t = \sum_j \pi_{j,t} \quad (2)$$

$$K_{j,t+1} = K_{j,t} + \Delta(I_{j,t} - \delta K_{j,t}), \quad K_0 \text{ given} \quad (3)$$

The production sector

The representative firm in the consumption good sector maximizes its profit π_Y by choosing how much capital K_Y and labor L to deploy, and how much energy to purchase from the various sources: fossil fuels, nuclear power and renewable energy (E_F , E_N , and E_L , respectively). It has to consider the production technology $\mathbf{Y}(\cdot)$ and the given factor prices for capital (r), labor (w),

³In the following, we often omit the time-index variables t in the main text to improve readability.

fossil (p_F), nuclear (p_N) and renewable (p_L) energy (the price of consumption goods is normalized to one). Furthermore, the production sector may need to consider government intervention in form of a subsidy on renewable energy τ_L or a feed-in tariff ζ_F . The latter takes the form of a subsidy but is cross-financed by a tax τ_F on energy from the fossil and the nuclear energy sectors.

$$\begin{aligned} \pi_{Y,t} = & \mathbf{Y}(K_{Y,t}, L_t, E_{F,t}, E_{L,t}, E_{N,t}) - r_t K_{Y,t} - w_t L_t - (p_{F,t} + \tau_{F,t}) E_{F,t} \\ & - (p_{L,t} - \zeta_{F,t} - \tau_{L,t}) E_{L,t} - (p_{N,t} + \tau_{F,t}) E_{N,t} \end{aligned} \quad (4)$$

The nested CES production function $\mathbf{Y}(\mathbf{Z}(K_Y, A_Y L), \mathbf{E}(E_F, \mathbf{E}_B(E_L, E_N)))$ combines the inputs capital-labor intermediate and energy, assuming an elasticity of substitution of σ_1 . Capital and labor are combined to an intermediate input Z using the elasticity of substitution σ_2 ; similarly, fossil energy and backstop energy are combined to final energy with the elasticity of substitution σ_3 . Finally renewable and nuclear energy are combined to an aggregate backstop energy E_B using the elasticity of substitution σ_4 .⁴ Population L and labor productivity A_Y grow at an exogenously given rate.

The fossil energy sector

The fossil energy sector maximizes profits π_F with respect to capital K_F and fossil resource use R , subject to the CES production technology \mathbf{E}_F and given factor prices for fossil energy, capital and resources (p_R). Additionally, it may consider a carbon tax τ_R :

$$\pi_{F,t} = p_{F,t} \mathbf{E}_F(K_{F,t}, R_t) - r_t K_{F,t} - (p_{R,t} + \tau_{R,t}) R_t \quad (5)$$

The fossil resource sector

The fossil resource sector extracts resources from an exhaustible stock S using capital K_R . Its objective is to maximize the sum of profits over time, discounted at the (variable) rate $r_t - \delta$:

$$\max_{R_t} \sum_{t=0}^T \pi_{R,t} \Delta \Pi_{s=0}^t [1 + (r_s - \delta)]^{-\Delta}$$

⁴We do not integrate fossil, renewable and nuclear energy on the same CES-level because we assume that substitutability between the two backstop energies E_L and E_N should be higher than between a backstop and a fossil energy E_B and E_F . This is due to the fact that in many integrated assessment models backstop energy is considered as part of the electricity sector while fossil energy covers electric as well as non-electric energy consumption. The substitutability between electric and non-electric energy technologies, however, is worse than between electric energy technologies (see also [Kalkuhl et al. 2011](#)).

Resource owners purchase the capital used in the extraction process at the market interest rate. The productivity of capital $\kappa(S)$ decreases with ongoing depletion of the exhaustible resource stock, implying increasing unit extraction costs (Rogner 1997; Nordhaus and Boyer 2000). The resource sector, therefore, has to take into account the following constraints:

$$\pi_{R,t} = p_{R,t}\kappa(S_t)K_{R,t} - r_t K_{R,t} \quad (6)$$

$$S_{t+1} = S_t - \Delta R_t, \quad S_t \geq 0, \quad S_0 \text{ given} \quad (7)$$

The renewable energy sector

The renewable energy sector maximizes profit π_L using capital K_L and a fixed amount of land Q . It considers the interest rate and renewable energy prices as given. The optimization problem of the sector reads:

$$\max_{K_{L,t}} \sum_{t=0}^T \pi_{L,t} \Delta \Pi_{s=0}^t [1 + (r_s - \delta)]^{-\Delta}$$

$$\pi_{L,t} = p_{L,t} \mathbf{A}_L(H_t) K_{L,t}^\nu Q^{1-\nu} - r_t K_{L,t} \quad (8)$$

$$H_{t+1} = H_t + \Delta(E_{L,t} - E_{L,t-1}), \quad H_0 \text{ given} \quad (9)$$

The productivity \mathbf{A}_L depends on cumulative output H according to $A_L = \frac{A_{L,max}}{1 + (\frac{\Omega}{H})^\gamma}$ and converges to $A_{L,max}$ when $H \rightarrow \infty$. This formulation is based on Arrows's learning-by-doing approach (Arrow 1962) and is widely used in energy economic models (e.g. Kverndokk and Rosendahl 2007; Fischer and Newell 2008). Ω is a scaling parameter, and γ is the learning exponent. The latter is related to the learning rate lr by $\gamma = -\ln(1 - lr)/\ln 2$, which measures by how much productivity increases when cumulative capacity is doubled.

The nuclear energy sector

The nuclear energy sector maximizes profit π_N subject to capital input K_N with an AK-technology function:

$$\pi_{N,t} = p_{N,t} A_{N,t} K_{N,t} - r_t K_{N,t} \quad (10)$$

2.2 The government

In this study, we are interested in optimal first-best and second-best policies and their impact on welfare. We therefore calculate the Stackelberg equilibrium where a welfare-maximizing government selects the optimal trajectory

of policy instruments from a pre-defined subset of available policy instruments given the implicit reaction functions of the economic sectors (see for example [Dockner et al. \(2000, p. 111\)](#)).

The first-order conditions (FOCs) of the previously described sectors (that are listed in detail in [Kalkuhl et al. \(2011\)](#)) define an intertemporal market equilibrium for given policy instruments. The government considers all technology constraints, budget constraints, equations of motion, and first-order and transversality conditions and chooses policy instruments (and not investment and extraction) to maximize welfare. Furthermore, the government balances income and expenditure at every point in time with households' lump-sum tax Γ .

$$\Gamma_t = \tau_{N,t}E_{N,t} - \tau_{L,t}E_{L,t} + \tau_{R,t}R_t + \pi_{B,t} \quad (11)$$

The mitigation target B is considered by a constraint on cumulative resource extraction:

$$\sum_{t=0}^T \Delta R_t \leq B \quad (12)$$

Considering the amount of cumulative emissions of the next decades is a robust indicator for achieving the two-degree target ([Meinshausen et al. 2009](#)). Hence, the government's optimization problem is described by:

$$\max_{\Theta} \sum_{t=0}^T (1 + \rho)^{-\Delta t} \Delta \mathbf{U}(C_t/L_t) \quad (13)$$

subject to Eqs. 1–12, 16–21, FOCs

Θ is the set of government policies and comprises all variables the government has direct access to, e.g. carbon taxes τ_R , renewable energy subsidies τ_L and fossil energy taxes τ_F . The description of concrete policies Θ used in this paper follows below (Sec. 3).

2.3 Calibration and implementation of the model

Model parameters are chosen from [Kalkuhl et al. \(2011\)](#). We use a carbon budget of 450 GtC as climate stabilization target for the mitigation scenario. This limits global warming to 2°C above the pre-industrial level with a probability of roughly 50 %.⁵ The endogenous fossil energy price starts

⁵The chosen carbon budget refers to the entire planning horizon. For $B = 450$, the resulting cumulative emissions for 2010–2050 are 337 GtC. Together with cumulative 2000–

at 4 ct/kWh in 2010 and increases up to 8 ct/kWh in 2100 (under business as usual) due to increasing extraction costs. The cost of nuclear energy is mostly constant at 15 ct/kWh which is at the upper bound of the IEA’s cost estimate (IEA 2010) that ignores external costs of nuclear power, e.g. external costs due to the limited accident liability for operators.⁶ For renewable energy we consider a 17% learning rate which leads to generation costs of 9 ct/kWh in 2100. Initially, the generation costs are around 28 ct/kWh. The chosen parameterization implies that renewable energy is the dominating backstop technology under an optimal mitigation policy while nuclear energy plays a limited role.⁷

In this paper, we focus on the costs of alternative policies to carbon pricing in the absence of additional externalities in the renewable energy sector. Hence, we assume perfect anticipation of learning and therefore neglect potential spillover externalities for learning technologies. The optimization problem as defined by (13) forms a non-linear program which is solved numerically with GAMS (Brooke et al. 2005).

3 Policy instruments and evaluation criteria

In the introduction we mention several arguments why an efficient carbon price – be it a carbon tax or an emissions trading scheme – may be difficult to implement in reality. Hence, policy makers might prefer to use renewable energy subsidies as a practical second-best alternative. In this section, we consider the optimal carbon tax as a benchmark and several second-best policies promoting renewable energy:

- Optimal carbon tax (mitigation benchmark) $\Theta = \{\tau_{R,t}\}$: The optimal carbon tax $\tau_{R,t}$ is the first-best instrument as it achieves the mitigation target at least costs and re-produces an economic outcome identical to a social planner economy if no further market failures exist (Kalkuhl et al. 2011). The carbon tax increases with the interest rate as it

2009 emissions of 77 GtC (Boden et al. 2010), 2000–2050 emissions are 414 GtC. Meinshausen et al. (2009) suggest that limiting cumulative emissions for 2000–2049 to 392 GtC yields a 50% probability of not exceeding the two-degree target. This probability increases to 75% if cumulative 2000–2049 emissions are lower than 273 GtC.

⁶Heyes and Heyes (2000) estimate the magnitude of the implicit subsidy to be 0.01–3.58 ct/kWh for nuclear reactor operators in Canada.

⁷If market failures distort the anticipation of future learning benefits in the renewable energy sector, however, nuclear energy becomes temporarily dominant (see Kalkuhl et al. (2011), where the same model framework is used).

resembles a Hotelling price for the scarcity of the carbon budget.⁸ The revenues are lump-sum transferred to households via Γ_t .

- Feed-in-tariff (FIT) $\Theta = \{\tau_{F,t}, \varsigma_{F,t}\}$: A tax $\tau_{F,t}$ on fossil and nuclear energy is used to cross-finance a subsidy $\varsigma_{F,t}$ on renewable energy and to limit fossil resource use. The FIT is implemented as income-neutral policy for the government due to $\varsigma_{F,t}E_{L,t} = \tau_{F,t}(E_{F,t} + E_{N,t})$. It is calculated to achieve the mitigation target at maximum welfare without an additional carbon price and lump-sum taxes ($\Gamma_t = 0$).
- Carbon trust $\Theta = \{\tau_{R,t}, \tau_{L,t}\}$: For this policy instrument, the revenues of carbon pricing $\tau_{R,t}$ are spent completely to subsidize renewable energy $\tau_{L,t}$, implying $\tau_{L,t}E_{L,t} = \tau_{R,t}R_t$ and $\Gamma_t = 0$.⁹ This instrument differs from the FIT only in that not fossil and nuclear energy but fossil resources (i.e. emissions) are taxed.
- Renewable energy subsidy $\Theta = \{\tau_{L,t}\}$: A subsidy $\tau_{L,t}$ on renewable energy is calculated that achieves the climate target at highest welfare. The subsidy is financed by lump-sum taxation Γ_t of the household. No additional carbon price or energy tax is employed.
- Subsidy with constant carbon tax $\Theta = \{\bar{\tau}_R, \tau_{L,t}\}$: An exogenously given, constant carbon tax $\bar{\tau}_R$ together with a welfare-maximizing subsidy on renewable energy $\tau_{L,t}$ is employed to achieve the climate target. Additional lump-sum transfers Γ_t are allowed.
- Temporary subsidy policy that is displaced by a carbon price: $\Theta_{t \leq t'} = \{\tau_{L,t}\}$ and $\Theta_{t > t'} = \{\tau_{R,t}\}$. Hence, for $t \leq t'$ there is no carbon price ($\tau_{R,t \leq t'} = 0$) and for $t > t'$ there is no subsidy ($\tau_{L,t > t'} = 0$). This instrument is appropriate if substantial carbon pricing is not politically feasible in the short run or if there is a long regulatory phase-in.¹⁰ In the long run, however, carbon pricing will be implemented and subsidies become obsolete.

⁸The optimal carbon tax is also equivalent to the permit price that evolves under a carbon bank which manages the carbon budget intertemporally (Kalkuhl et al. 2011).

⁹This instrument leans on the atmospheric trust proposal by Barnes et al. (2008). It considers an emissions trading scheme where the revenues from auctioning are partly used to promote renewable energy technologies.

¹⁰Such a gradual phase-in of regulation can be motivated by distributional concerns (Williams III 2010). Introducing the efficient level of Pigovian taxes immediately devalues past investments into physical and human capital that are related to fossil energy use. These investments had taken place under the prospect of missing Pigovian taxes.

- Finally, a business-as-usual (BAU) scenario is considered where the cumulative carbon budget constraint (12) is relaxed and government intervention is absent, implying $\Theta = \emptyset$.

These policies are evaluated with respect to their impact on (i) intertemporal welfare, (ii) fossil resource and renewable rents and (iii) energy prices. While the analysis of intertemporal welfare measures the efficiency of instruments to achieve the mitigation budget, the consideration of fossil resource and renewable rents and energy prices indicates possible distributional conflicts provoked by these policies. Usually, we will compare second-best policies with the first-best mitigation policy $\Theta = \{\tau_{R,t}\}$ (carbon pricing). However, it will also be interesting to compare second-best policies with the BAU outcome in order to identify policies making factor owners or energy buyers better off under the mitigation goal.

Intertemporal welfare In order to compare the intertemporal welfare of several policies we use *balanced growth equivalents* (BGE) as introduced by [Mirrlees and Stern \(1972\)](#). As we use a discrete time model, we adopt the modified calculation of [Anthoff and Tol \(2009\)](#). The BGE γ is defined as an exponentially increasing consumption path (with γ as initial consumption level and an exogenously given constant growth rate) that generates the same discounted utility as the original consumption path. Hence, we compare the relative BGE differences for the first-best policy Θ and the second-best policy Θ' according to the formula:

$$\Delta\gamma = \frac{\gamma(\Theta') - \gamma(\Theta)}{\gamma(\Theta)} = \begin{cases} \left(\frac{W(\Theta')}{W(\Theta)}\right)^{1/(1-\eta)} - 1 & \eta \neq 1 \\ \exp\left(\frac{W(\Theta') - W(\Theta)}{\sum_{t=0}^T (1+\rho)^{-\Delta t}}\right) - 1 & \eta = 1 \end{cases} \quad (14)$$

where $W(\Theta)$ denotes the resulting intertemporal welfare under policy Θ . By considering the relative difference $\Delta\gamma$ of the two BGEs for Θ and Θ' , the growth rate of the exponentially increasing reference consumption path becomes irrelevant (see [Anthoff and Tol \(2009\)](#) for an analytical derivation). In contrast to a discounted consumption measure that uses an exogenously given discount rate, the BGE does not change the welfare ordering of policy outcomes. It translates welfare losses into appropriate consumption losses which occur once and forever. In other words, the BGEs measure the costs of a policy like a (non-recycled) tax levied on consumption.

The welfare difference of a policy compared to the BAU scenario is denoted in the following as *mitigation cost*. The welfare difference of a second-best policy compared to the optimal first-best mitigation policy (carbon pricing) is denoted as *additional second-best cost*.

Rent dynamics Fossil resource rents are simply given by π_R from (6). The associated land rent π_Q for renewable resources is calculated by the product of land Q with the scarcity price for land $p_Q = p_L \frac{\partial E_L}{\partial Q}$, thus, $\pi_Q = p_Q Q$.¹¹

Energy prices As energy from different sources is imperfectly substitutable, prices for fossil and renewable energy differ. Therefore, we calculate an average energy price $\tilde{p}_{E,t}$ by the fraction of total energy expenditures and total energy consumption E_t :

$$\tilde{p}_{E,t} = \frac{p_{F,t}E_{F,t} + p_{L,t}E_{L,t} + p_{N,t}E_{N,t}}{E_t} \quad (15)$$

By comparing this average energy price, we analyze the impact of policies on energy prices.

4 Renewable energy subsidies in case an optimal carbon tax is not available

In the following we analyze the performance of mitigation policies that focus on renewable energy deployment. First, we study several second-best policies with respect to welfare, rent distribution and energy prices. Next, we consider how important key parameters influence the welfare losses of renewable energy subsidies (Sec. 4.2). Finally, we consider small deviations from the optimal second-best subsidy and their impact on welfare and emissions (Sec. 4.3).

4.1 Ranking of second-best policies

Impact on welfare

Fig. 2 shows the welfare losses of the policies described in Sec. 3 compared to the business-as-usual scenario without a mitigation target (BAU) and to the optimal first-best mitigation policy (optimal carbon tax). The mitigation costs under an optimal carbon pricing policy are 2.3%. Hence, introducing a carbon budget reduces the consumption level of a balanced-growth path by

¹¹The intertemporal learning-by-doing technology complicates the rent dynamics in the renewable energy sector. As the renewable energy price entails also the value of future cost reductions, it is lower than the current-period generation costs. Hence, negative profits arise in early decades. By considering the land rent π_Q only, we abstract from the difficult technological rent dynamics and focus on the rent of limited natural resources.

2.3%. These costs increase to 3.1% under a FIT and to 2.9% under a carbon trust. The higher mitigation costs occur because taxing fossil energy or fossil resource use always implies a significant subsidy for renewable energy by the cross-financing mechanism. This subsidy, however, is not necessary because further market imperfections (besides the mitigation target) are absent. Hence, the subsidy leads to distortions and reduces welfare – albeit the quantitative effects remain small. The FIT provokes higher welfare losses than the carbon trust because fossil and nuclear energy is taxed instead of fossil resource use and because not all cost-effective re-allocation possibilities in the fossil energy sector are exploited.¹²

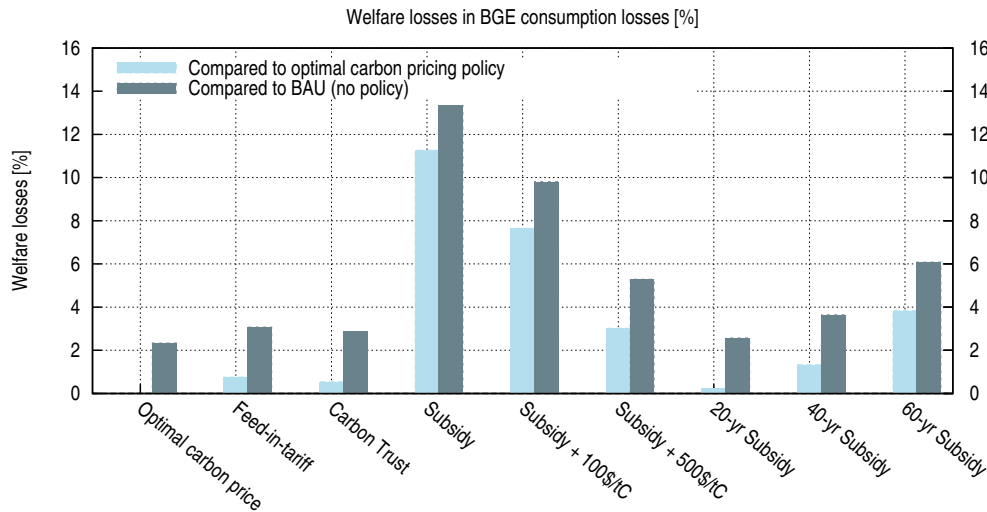


Figure 2: Welfare losses (in BGE) for several policies.

A pure subsidy policy, however, increases mitigation costs substantially to 15.4%. If a low constant carbon price is imposed consumption losses remain at high levels. High constant carbon taxes can decrease the additional second-best costs – although, for constant carbon taxes higher than 750\$/tC, consumption losses begin to increase. Finally, a temporary subsidy which is displaced by a carbon price in the long run provokes higher additional costs the longer carbon pricing is absent. If carbon pricing is implemented after 20 years, additional costs are marginal (0.2%). If, in contrast, carbon pricing is implemented after six decades, additional second-best costs become substantial (3.8%).

¹²In particular, the fossil energy tax fails to decrease carbon intensity in the fossil energy sector by higher capital input. Even without the cross-financing mechanism (i.e. $\zeta_F = 0$), mitigation costs of an optimal second-best fossil energy tax are 2.6% implying welfare losses of 0.3% relative to the optimal carbon price.

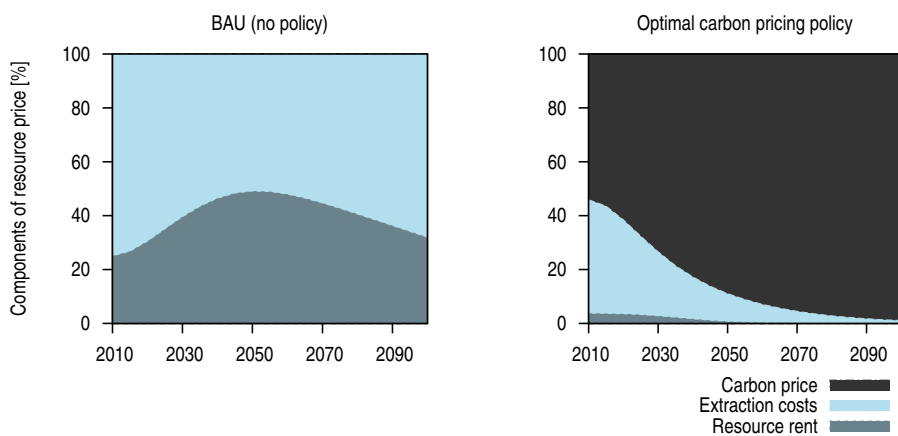


Figure 3: Decomposition of the net resource price under business-as-usual and under an optimal carbon pricing policy.

Impact on rents

Climate policy does not only affect the welfare of the representative household. It also changes rents and factor prices associated with the consumption of carbon and energy. In particular, mitigation lowers the rent associated with the scarcity of fossil resources because the scarcity of the atmospheric deposit becomes more severe due to ambitious mitigation targets. This can be seen very illustratively in Fig. 3, where the net fossil resource price is decomposed into its basic components. In the BAU scenario, the resource rent forms a significant part of the resource price the energy sector has to pay for. This changes under an optimal carbon pricing scheme; In the long run, the carbon price virtually determines the net resource price and, thus, demand for fossil resources. In the first decades – when the carbon price is low –, extraction costs also play an important role. Fossil resource scarcity rents, however, have only a marginal impact on the net resource price.

The mitigation policy decreases the rent per unit of extracted fossil resources as well as the amount of cumulative fossil resource extraction. Under a business-as-usual policy, the scarcity of fossil resources generates rents higher than one percent of GDP for resource owners (Fig. 4). In contrast, fossil resource rents shrink dramatically for optimal first-best as well as second-best policies. Interestingly, the revenue-neutral feed-in-tariff and the carbon trust policy lead to higher short-term fossil resource rents than the optimal carbon pricing policy: The cross-financing mechanism of the carbon trust initially leads to lower carbon taxes which imply a higher resource extraction in the early decades. Equally, temporary subsidies that are displaced by a

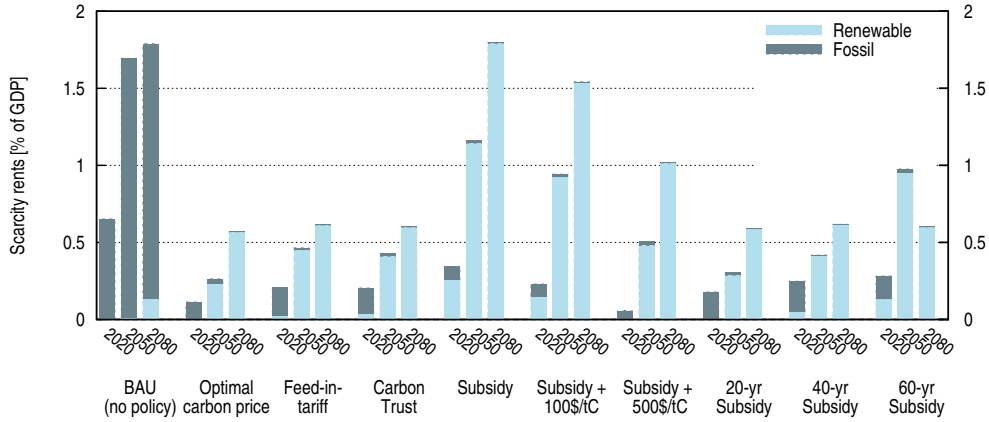


Figure 4: Fossil resource and renewable (land) rent for several policies for the years 2020, 2050 and 2080.

carbon price in the long-term lead to higher short-term rents. The prospect of future high carbon taxes can induce an accelerated resource extraction exceeding even the business-as-usual extraction for the initial period where no carbon price is implemented (cf. Sinn 2008b). The temporary subsidy, however, weakens this effect although the short-term resource extraction is higher than under the optimal carbon pricing policy. In contrast, permanent renewable energy subsidies that are financed by lump-sum taxes reduce fossil resource rents even to a greater extent than an optimal carbon price. Hence, the political economy argument that subsidies provoke less resistance because no firm takes a higher explicit financial burden is flawed. From the resource owners' perspective, a feed-in-tariff, a carbon trust or a temporary subsidy policy is preferable to an optimal carbon pricing policy – and carbon pricing is preferable to a permanent subsidy policy.

While owners of fossil resources lose under all mitigation policies, owners of land used for renewable energy generation profit substantially. Extensive renewable energy subsidies can more than double the land rent associated with renewable energy generation compared to a carbon pricing policy. If subsidies are only temporary, the gains for land owners are moderate and return to the level of the first-best mitigation policy after subsidies have been cut.

Impact on energy prices

As argued in the introduction, distributional concerns are one important reason for the high opposition against carbon prices. Beside resource rents, mitigation policies also change energy prices. First, carbon pricing and fossil

energy taxation (FIT) clearly increase fossil energy prices. On the contrary, subsidies on renewable energy decrease fossil energy prices (for an explanation see below). Hence, households and consumers using large amounts of fossil energy face less energy expenditures under a pure renewable energy subsidy policy. Secondly, renewable energy prices decrease for all mitigation policies (partly due to induced learning-by-doing, partly due to paid subsidies).¹³ While the cost decrease is smallest for an optimal carbon tax, it is most pronounced under a pure subsidy policy. Finally, the development of average energy prices is shown in Fig. 5. The efficient carbon tax leads to high energy prices – almost double as high as in the business-as-usual scenario. The FIT and the carbon trust imply lower energy prices, although higher than in the BAU scenario. Temporary subsidy policies can reduce energy prices near to or below business-as-usual prices as long as subsidies are paid. After replacing the subsidy by a carbon price, energy prices increase sharply up to the energy price under an optimal carbon pricing scheme. Thus, a temporary subsidy effectively delays the cost increase (and the associated distributional conflict). The permanent subsidy policy leads to energy prices that are always lower than without mitigation. Note that in the very long run, energy prices under carbon pricing policies are not substantially higher than in the BAU scenario.¹⁴ Constant carbon taxes increase the short term energy prices until subsidies have expanded to compensate for low carbon prices.

Hence, when firms or households cannot be compensated for higher energy prices resulting from mitigation targets, feed-in-tariffs, a carbon trust or a temporary subsidy policy might be a pragmatic alternative to an optimal carbon pricing policy.

4.2 What determines the second-best costs of renewable energy subsidies?

If no tax on carbon or fossil energy is available, renewable energy net prices have to become very low in order to crowd out fossil energy. It is important to note that the subsidy has to be higher than the difference between fossil and renewable energy prices due to the (i) extraction cost dynamics, (ii) the fossil resource rent dynamics and (iii) the imperfect substitutability between energy technologies: The less fossil resources are extracted, the lower are the

¹³Recall that fossil and renewable energy are good but not perfect substitutes. Prices therefore differ.

¹⁴First, fossil energy is more expensive in the BAU scenario because extraction costs increase due to high cumulative extraction. Second, learning-by-doing reduces the costs of renewable energy generation.

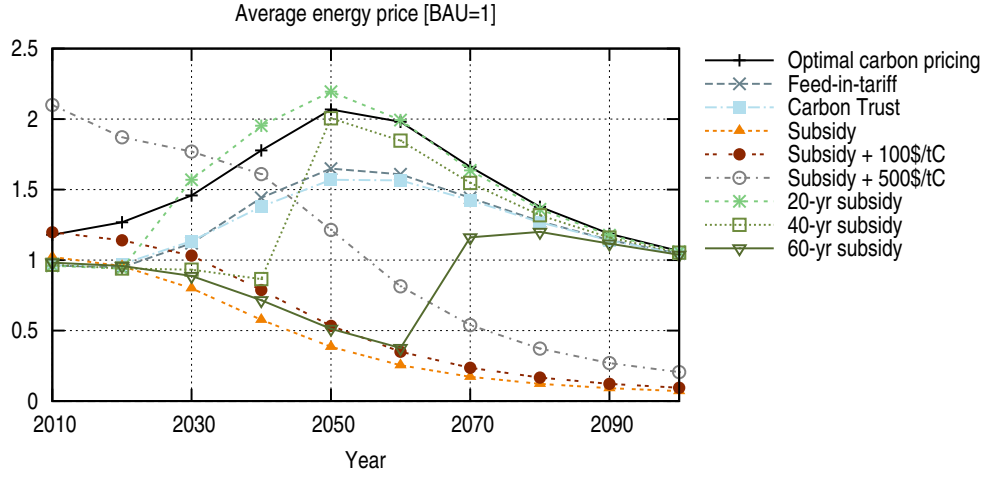


Figure 5: Average energy prices according to Eq. (15) under different policy regimes relative to BAU prices.

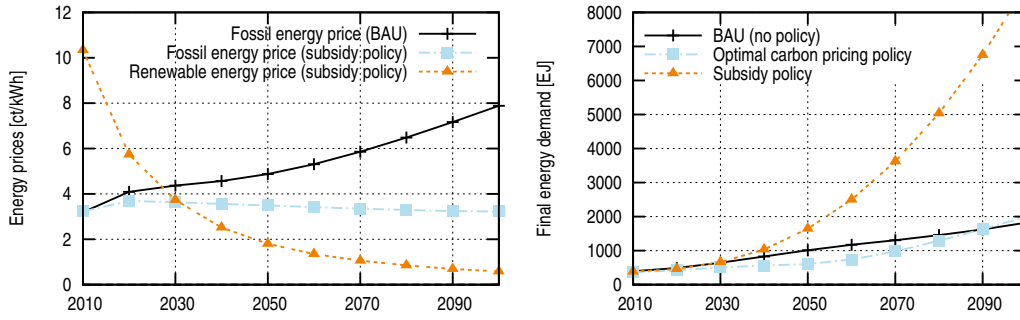


Figure 6: Impact of renewable energy subsidies on (a) fossil and renewable energy prices and on (b) fossil and renewable energy generation.

unit extraction costs as the capital productivity κ of the extraction industry decreases with cumulative extraction. Second, fossil resource owners receive a smaller scarcity rent per unit extracted resources (see Fig. 3) because fossil resources become abundant compared to the tight carbon budget under the mitigation policy. Fig. 6a indicates how renewable energy subsidies reduce fossil energy prices below BAU prices due to the supply-side dynamics of fossil resources. However, Fig. 6a also shows that the subsidy is so high that it pushes the renewable energy price far below the fossil energy price. This is necessary because both energy technologies are good, but not perfect substitutes: It is difficult, for example, to decarbonize the transportation sector by increasing renewable energy subsidies because fossil fuel is not always replaceable by energy from wind, solar or biomass. The fact that the renewable energy price has to be far below the BAU price of fossil energy

leads to an enormous energy demand (Fig. 6b). As a great part of the GDP is now shifted into the energy sector to generate immense amounts of renewable energy consumption falls dramatically which explains the high welfare losses in Fig. 2.

In order to analyze the sensitivity of the consumption losses of a pure renewable energy subsidy, we calculate the mitigation costs for an optimal carbon pricing policy and the additional second-best costs for a variation in several economic parameters. Tab. 1 lists the results for parameters describing fossil resource reserves (S_0), substitutability between fossil and backstop energy (σ_3) total energy demand ($A_{L,max}, \sigma_1$), backstop energy costs ($A_{L,max}, \nu, A_N$), normative parameters (η, ρ) and the mitigation target (B).

By varying all these parameters we find that the additional second-best costs due to the subsidy are in most cases higher than 5%. A lower fossil reserve size S_0 leads to higher resource extraction costs as resource sites that are difficult to access have to be exploited earlier (see also Eq. 22). Furthermore, resource rents increase due to the higher scarcity. With increasing extraction costs, the subsidy performs better as the fossil energy net price increases in a similar way than under carbon taxes. High fossil energy prices, however, require lower subsidies – which leads to fewer distortions. Additionally, a high substitutability σ_3 between fossil and backstop energy reduces the price gradient at which renewable energy crowds out fossil energy. An increase in labor growth productivity \hat{A}_Y implies a higher energy demand in the BAU scenario. This exacerbates the distortions created by the subsidy policy. In the BAU scenario and under the optimal carbon pricing policy a higher substitutability σ_1 between final energy and capital and labor reduces the energy demand as it becomes easier to substitute expensive energy by capital and labor. Large renewable energy subsidies, on the contrary, lead to a higher energy demand for higher σ_1 as labor and capital is substituted by cheap energy. Hence, the second-best costs of renewable energy subsidies increase in σ_1 .

If the generation costs of non-learning backstop energy are low (i.e. A_N is high), the technology forms a significant part of an optimal energy mix under an optimal carbon pricing policy. A pure renewable subsidy policy, however, favors renewable energy against both, fossil and nuclear energy. The discrimination against nuclear energy increases the additional second-best costs the cheaper the nuclear energy is. Low generation costs for renewable energy (high $A_{L,max}$ and ν) generally reduce the mitigation costs. As the cost difference for fossil and renewable energy decreases, lower renewable energy subsidies are necessary to achieve the mitigation goal. This implies lower additional second-best costs.

Normative preferences influence optimal investment and extraction deci-

Fossil resource stock [GtC] S_0	5000	4000*	3000	2000	1000	
Mitigation costs [%]	2.55	2.34	2.01	1.47	0.48	
Additional 2nd-best costs [%]	11.68	11.27	10.45	8.56	3.56	
Fossil-backstop substitutability σ_3	3*	4	5	6		
Mitigation costs [%]	2.34	2.63	2.78	2.85		
Additional 2nd-best costs [%]	11.27	9.19	8.05	7.31		
Initial labor productivity growth rate \hat{A}_Y	0.010	0.015	0.020	0.024	0.026*	0.028
Mitigation costs [%]	1.92	2.06	2.2	2.29	2.34	2.38
Additional 2nd-best costs [%]	7.39	8.42	9.54	10.51	11.27	14.27
(KL)–E substitutability σ_1	0.3	0.4	0.5*	0.6	0.7	
Mitigation costs [%]	3.75	2.96	2.34	1.84	1.45	
Additional 2nd-best costs [%]	8.58	9.99	11.27	12.5	13.73	
Nuclear energy productivity A_N	0.15	0.2*	0.25	0.3	0.35	
Mitigation costs [%]	2.37	2.34	2.22	1.99	1.69	
Additional 2nd-best costs [%]	11.18	11.27	11.48	11.79	12.12	
Renewable energy productivity $A_{L,max}$	0.6*	0.7	0.8	0.9	1	
Mitigation costs [%]	2.34	1.87	1.47	1.17	0.93	
Additional 2nd-best costs [%]	11.27	8.36	6.38	4.98	3.95	
Cobb-Douglas exponent for renewable energy ν	0.85	0.9	0.95*	1		
Mitigation costs [%]	3.46	3.14	2.34	1.56		
Additional 2nd-best costs [%]	41.96	21.47	11.27	6.04		
Pure social time discount rate ρ	0.01	0.02	0.03*	0.04	0.05	
Mitigation costs [%]	3.48	2.94	2.34	1.76	1.27	
Additional 2nd-best costs [%]	18.7	14.68	11.27	8.47	6.29	
Risk aversion η	1*	1.5	2	2.5	3	
Mitigation costs [%]	2.34	1.87	1.39	1.02	0.74	
Additional 2nd-best costs [%]	11.27	9.02	6.82	5.36	3.92	
Carbon budget [GtC] B	250	350	450*	550	650	750
Mitigation costs [%]	4.2	3.09	2.34	1.8	1.4	1.09
Additional 2nd-best costs [%]	18.45	14.32	11.27	8.92	7.07	5.6

Table 1: Mitigation costs (welfare losses of the optimal carbon pricing policy relative to the BAU scenario) and additional second best costs (welfare losses of the pure subsidy policy relative to the optimal carbon pricing policy) for several parameter variations. The asterisk is assigned to the value used for the standard parameterization.

sions of market agents as well as the policy trajectory and the performance of policies. A higher discount rate reduces mitigation costs because the costs of transforming the energy system are shifted into the far-distant future where they are heavily discounted: Extraction is accelerated and the deployment of learning technologies delayed which increases consumption in early decades at the expense of subsequent decades. This intertemporal re-allocation occurs under an optimal carbon price as well as under the second-best subsidy. As the higher far-distant costs are stronger discounted for higher discount rates, (discounted) welfare losses decrease in ρ . A higher elasticity of the marginal utility of consumption η penalizes an unequal distribution of consumption in time. Within our growth model, consumption grows even under the mitigation target, though growth rates are smaller. Mitigation mainly reduces future consumption (due to higher costs in the energy system) when the society became more productive. Therefore, limiting fossil fuel use reduces the inequality in the consumption trajectory. Hence, a higher η leads to lower welfare losses – both under an optimal carbon pricing as well as under a second-best subsidy policy. Finally, ambitious mitigation targets (implemented by a low carbon budget B) increase the second-best costs of the subsidy as higher renewable energy subsidies are required to crowd out fossil energy use.

Fig. 7 compares the (optimal) mitigation costs with the additional second-best costs of the renewable energy subsidy from Tab. 1. It becomes apparent that the second-best costs of the subsidy policy correlate positively with the mitigation costs – except for three parameter variations. The positive correlation implies that the costs of the subsidy policy are moderate when climate protection does not place a significant burden on the economy. In this case, carbon pricing has only marginal distributional impacts through increasing energy prices. The rationale for choosing renewable energy subsidies instead of the efficient carbon pricing policy becomes obsolete in this case. Only for three parameter variations, higher mitigation costs correlate with lower second-best costs of the subsidy policy. If final energy is to a smaller extent substitutable by labor and capital (low σ_1), if fossil energy and backstop energy are very good substitutes (high σ_3), and if the non-learning backstop energy generation is expensive (low A_N) the additional second-best costs of the subsidy policy could become small.

4.3 The risk of green paradoxes

Motivated by the green paradox of Sinn (2008b) we study the impact of suboptimal subsidies on emissions and consumption. Again, we assume the absence of a carbon price and calculate the optimal subsidy to achieve the

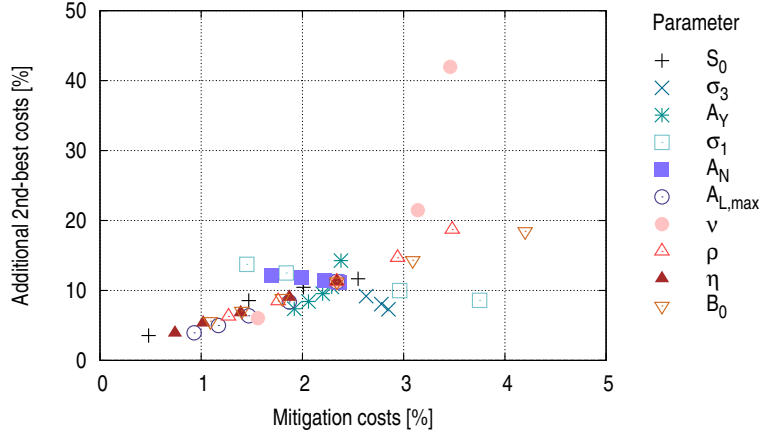


Figure 7: Sensitivity analysis for a renewable subsidy policy. The welfare losses of a pure renewable subsidy policy compared to an optimal carbon pricing policy (additional 2nd-best costs) are shown as well as mitigation costs of an optimal carbon pricing policy compared to the BAU scenario. Parameter variations correspond to Tab. 1.

450 GtC mitigation target. Next, we calculate subsidies that deviate slightly from the optimal subsidy by a fixed ratio, e.g. a ratio which is 1% lower than the optimal subsidy at each period in time. The optimal subsidy and the perturbations are shown in Fig. 8a. Finally, we impose the perturbed subsidies into the model (still without a carbon price) and compare the impact on cumulative emissions and welfare of these subsidies (Fig. 8b).

The numerical calculations show that the economy responds very sensitively on changes of subsidy levels. For a subsidy which is only 2% lower than the optimal subsidy, consumption increases by 2.4% and cumulative emissions even by 17.8% (compared to the 450 GtC carbon budget). In con-

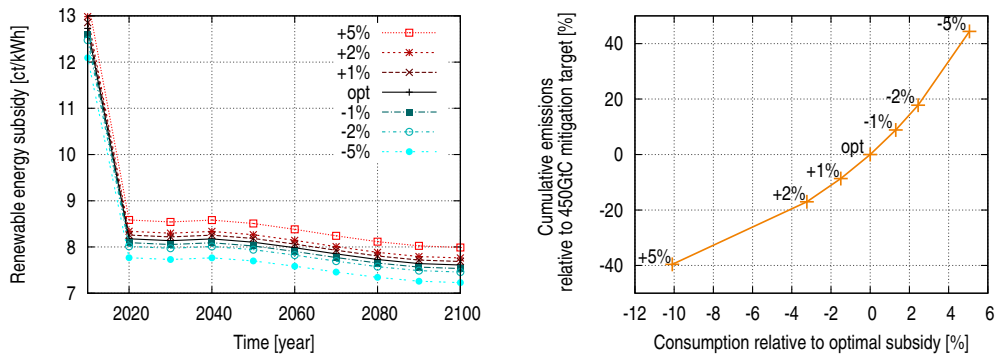


Figure 8: (a) Optimal subsidy and perturbations. (b) Impacts of perturbed subsidies on consumption and emissions.

trast, the implementation of a subsidy which is 2% higher than the optimal one, decreases consumption by 3.2% and cumulative emissions by 17.0%.

Hence, a slightly higher subsidy causes additional consumption losses and a slightly lower subsidy leads to far more emissions. Without any carbon price, the renewable energy subsidy is not only a very expensive instrument. It is also a dangerous instrument because it can provoke unintended side-effects on emissions if the regulator deviates only slightly from the optimal tax.

5 Conclusions

Our analysis provides some valuable information for policy makers struggling with introducing high carbon prices. For a wide range of parameters, using permanently renewable energy subsidies instead of carbon prices to achieve mitigation implies disastrous welfare losses: they are multiple times higher than first-best mitigation costs under a carbon price policy. Even if constant carbon prices are feasible, the subsidy cannot correct the suboptimal carbon price at low costs. Although renewable energy becomes cheaper due to subsidies and learning-by-doing, it is difficult to crowd out fossil energy supply. Resource prices decrease due to the supply-side dynamics of fossil resource extraction. And the good – but not perfect – substitutability between energy technologies requires to maintain a high price differential between renewable and fossil energy. Achieving the cost break-through is therefore not sufficient. If the substitutability between fossil and renewable energy is high, the second-best costs decrease substantially. Hence, a sectoral policy approach with renewable energy subsidies in the electricity sector (where technologies are almost perfect substitutes) and carbon taxes in the industry sector may decrease the second best-costs.

A low fossil resource base and low renewable energy generation costs reduce the second-best costs – though the mitigation costs fall dramatically in these cases and a carbon pricing policy only has a marginal impact on the economy. Distributional conflicts due to carbon pricing do not arise for these parameter settings. While renewable energy subsidies indeed lower energy prices even below the business-as-usual prices, the government has to raise taxes on households to finance these subsidies. Furthermore, fossil resource owners lose more rents under a renewable subsidy policy than under a carbon pricing policy. Hence, at a second glance, a subsidy-only policy may provoke even higher resistance of the fossil industry than a carbon tax. Permanent renewable energy subsidies are not only an expensive choice to reduce emis-

sions. They are also a very risky instrument because small deviations from the second-best optimum lead to strong responses in emissions and welfare. If the subsidy was set 2% below its optimal value, emissions would increase by 18%. In contrast, if the subsidy was set 2% above its optimal value, welfare would decrease by an additional 3% due to an over-ambitious emission reduction.

There are some attractive alternatives to a pure carbon pricing policy. The feed-in-tariff and the carbon trust policy cause only small additional costs. Even if no market failures besides the mitigation target exist, redirecting the revenues of a fossil energy tax (FIT policy) or carbon tax (carbon trust policy) to the renewable sector reduces consumption by 0.8% (FIT) and 0.5% (carbon trust) compared to the optimal carbon pricing policy. In this case, fossil resource rents are higher and energy prices lower than under efficient carbon pricing. If additional market failures in the renewable energy sector exist (like spillover externalities for innovations), the carbon trust may even be welfare-increasing compared to a pure carbon pricing policy. Finally, temporary subsidies delay or ease distributional conflicts provoked by high energy prices and low fossil resource rents due to carbon pricing. A subtle combination of short-term renewable energy subsidies and long-term carbon prices can achieve the mitigation target at moderate costs – although fossil resource owners may slightly accelerate resource extraction in the short term.

Renewable energy subsidies are an efficient policy instrument when they address market failures directly associated with renewable energy technologies or markets. However, if renewable energy subsidies aim to reduce carbon emissions because carbon prices are missing or too low, welfare losses can be substantial. In particular, if mitigation imposes a severe constraint on the economy – i.e. if fossil resources are abundant and cheaply available compared to renewable energy generation – a subsidy policy creates high additional consumption losses. The results of this paper show that without a careful policy analysis, pragmatic policy approaches may turn out to be a fatal aberration for mitigating global warming as costs explode. In order to achieve mitigation targets at low costs, there seems to be no way around direct or indirect carbon pricing – at least in the long run.

A Technology

The following functional forms for utility and production technology are used:

$$\mathbf{U}(C, L) = \frac{\left(\frac{C}{L}\right)^{1-\eta}}{1-\eta} \quad (16)$$

$$\mathbf{Y}(Z, E) = \left(a_1 Z^{\frac{\sigma_1-1}{\sigma_1}} + b_1 E^{\frac{\sigma_1-1}{\sigma_1}} \right)^{\frac{\sigma_1}{\sigma_1-1}} \quad (17)$$

$$\mathbf{Z}(K_Y, L) = \left(a_2 K_Y^{\frac{\sigma_2-1}{\sigma_2}} + b_2 (A_Y L)^{\frac{\sigma_2-1}{\sigma_2}} \right)^{\frac{\sigma_2}{\sigma_2-1}} \quad (18)$$

$$\mathbf{E}(E_F, E_B) = \left(a_3 E_F^{\frac{\sigma_3-1}{\sigma_3}} + b_3 E_B^{\frac{\sigma_3-1}{\sigma_3}} \right)^{\frac{\sigma_3}{\sigma_3-1}} \quad (19)$$

$$\mathbf{E}_B(E_L, E_N) = \left(a_4 E_L^{\frac{\sigma_4-1}{\sigma_4}} + b_4 E_N^{\frac{\sigma_4-1}{\sigma_4}} \right)^{\frac{\sigma_4}{\sigma_4-1}} \quad (20)$$

$$\mathbf{E}_F(K_F, R) = \left(a K_F^{\frac{\sigma-1}{\sigma}} + b R^{\frac{\sigma-1}{\sigma}} \right)^{\left(\frac{\sigma}{\sigma-1}\right)} \quad (21)$$

$$\kappa(S) = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{S_0 - S}{\chi_3} \right)^{\chi_4}} \quad (22)$$

$$\mathbf{E}_L(A_L, K_L, Q) = A_L K_L^\nu Q^{\nu-1} \quad (23)$$

$$(24)$$

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