Resource and Energy Economics 35 (2013) 217–234

Contents lists available at SciVerse ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

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

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ARTICLE INFO

Article history:
Received 16 September 2011
Received in revised form 27 January 2013
Accepted 30 January 2013
Available online xxx

JEL classification:
Q4
Q52
Q54
Q58
D58
H21

Keywords:
Carbon pricing
Carbon trust
Climate policy
Feed-in-tariff
Green paradox
Energy prices

ABSTRACT

This paper evaluates the consequences of renewable energy policies on welfare and energy prices in a world where carbon pricing is imperfect and the regulator seeks to limit emissions to a (cumulative) target. The imperfectness of the carbon price is motivated by political concerns regarding distributional effects of increased energy prices. Hence, carbon prices are considered to be temporarily or permanently absent or endogenously constrained by their effect on energy prices. We use a global general equilibrium model with an intertemporal fossil resource sector and calculate intertemporally optimal policies from a broad set of policy instruments including carbon taxes, renewable energy subsidies and feed-in-tariffs, among others. If carbon pricing is permanently missing, mitigation costs increase by a multiple (compared to the optimal carbon pricing policy) for a wide range of parameters describing extraction costs, renewable energy costs, substitution possibilities and normative attitudes. Furthermore, we show that small deviations from the second-best subsidy can lead to strong increases in emissions and consumption losses. This confirms the rising concerns about the occurrence of unintended side effects of climate

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Abbreviations: ETS, emissions trading scheme; FIT, feed-in-tariff; CES, constant elasticity of substitution; FOC, first-order conditions; BAU, business-as-usual; BGE, balanced growth equivalent; RE, renewable energy.

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http://dx.doi.org/10.1016/j.reseneeco.2013.01.002

policy – a new version of the green paradox. Smart combinations of carbon prices and renewable energy subsidies, however, can achieve ambitious mitigation targets at moderate additional costs without leading to high energy price increases.

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 research and development 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).

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.[1] 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., 2011). 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., 2012; 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). Boeters and Koornneef (2011) give further political arguments for the implementation of the EU renewable energy policy such as increase in energy security (through less imports of fossil resources), job creation and technology leadership, among others. 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 could solve 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 policies 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. Technology-optimistic considerations about the progress of the learning renewable energy technologies might further lead to the perception that a temporary renewable deployment stimulus could be a more manageable way to foster mitigation.[2]

The importance of a thorough investigation of the welfare effects of second-best policies is known from the more specific literature on ethanol fuel policies in the United States, where first-best policies are most likely not politically feasible but a second-best setting is given due to environmental externalities and energy security concerns. Vedenov and Wetzstein (2008), for example, compute the optimal ethanol subsidy for the United States. They stress that in particular rebound effects (i.e. increased fuel

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[1] Bennear and Stavins (2007) provide a general discussion on the use of second-best instruments.

[2] Farmer 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 US GDP in 2009.

consumption) have strong implications for the welfare analysis and consequently for the level of the optimal subsidy. Lapan and Moschini (2012) analyze the welfare performance of portfolios of subsidy, mandates, and fuel tax, showing analytically that mandates outperform subsidies, particularly when complemented by a fuel tax. Fischer and Newell (2008) calculate the costs of achieving low emission reductions (approx. 5%) in the US with carbon pricing and technology policies. They report that carbon prices are the most efficient stand-alone policy; renewable energy subsidies can double mitigation costs. Likewise, Palmer and Burtraw (2005) consider renewable portfolio standards (RPS), subsidies (renewable energy production tax credits) and cap-and-trade for reducing emissions in the US in 2020. The application of a comprehensive US energy market model shows that subsidies are the most expensive policy. Due to decreased energy prices, however, subsidies lead to the highest consumer surplus. Galinato and Yoder (2010) focus on revenue-neutral second-best tax-subsidy combinations to reduce carbon emissions. Finally, Boeters and Koornneef (2011) analyze the interplay of the existing EU ETS and the proposed renewable energy policies to increase the renewable energy share to 20% by 2020.

This paper contributes to the assessment of second-best policies by considering alternatives to carbon pricing for the energy sector and weighing (theoretical) efficiency against (practical) feasibility aspects. We conduct a cost-effectiveness analysis which takes a certain mitigation target as exogenously given. On the one hand, cost-benefit-analysis depends highly on the assumed damage function and probability distribution of uncertain parameters. As Weitzman (2010) elaborated, this may not only lead to a wide range of optimal temperature targets but may also make cost-benefit analysis impossible if probability distributions are fat-tailed. On the other hand, governments focus in international negotiations and national implementations often on temperature or emissions targets as they are less abstract than cost-benefit analysis.

We differ from the existing studies cited above by calculating (intertemporally) *optimal* second-best instruments that provide a valuable numerical estimation of the (optimistic) least-cost potential of these emission mitigation instruments. Existing numerical policy assessments of renewable energy policies focus usually on a medium-term horizon (e.g. emission targets in 2020) for a specific country or region (US or EU). The medium-term and regional scope is important for national governments but neglects two crucial characteristics of the climate problem: (i) Fossil resource markets are globally integrated; hence, domestic policies affect global resource prices (being exogenous in most models) that may trigger adverse supply-response reactions (green paradox). (ii) As a large fraction of carbon emissions remains for several centuries in the atmosphere, temperature stabilization requires to eventually achieve almost zero (net) emissions, which is a far more demanding goal than a rather ‘marginal’ reduction of emissions by 5–15%. Second-best policies that are tolerable for such moderate mitigation targets might turn out to be prohibitively expensive for achieving a zero-carbon economy in the long-term.

In order to focus on the welfare effects of second-best policies, we assume that possible secondary market failures like innovation spillovers or network effects are completely internalized by firms or already addressed by an efficient policy instrument. 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-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 and energy prices compared to an optimal carbon pricing scheme as efficient first-best benchmark. As the impact of climate policy on energy prices is a major concern and motivation for the analysis of second-best policies in the literature, we integrate this aspect explicitly: By formulating an energy price constraint (additionally to the emissions constraint), we can compare ad-hoc policy instruments (like feed-in-tariffs or renewable energy subsidies) with an optimal portfolio subject to emission *and* price constraints.

It is not obvious how second-best instruments affect the energy price: Fischer (2010) analyzes the effect of renewable portfolios standards on energy prices. This study offers an explanation why previous investigations of the effect delivered contradicting results. She shows that the effect of renewable portfolios standards (RPS) on energy prices is ambiguous (RPS simultaneously subsidize renewable while taxing non-renewable energy sources which has counteracting effects on the electricity price).

This is an important clue that combined subsidy/tax instruments may not have the intended effect on energy prices.[3]

One of the key findings of our paper is that renewable energy subsidies are indeed capable to lessen the energy price effect of mitigation at moderate costs – if implemented as an optimal portfolio together with carbon pricing. Permanent renewable energy subsidies, however, are a very poor and risky substitute for missing carbon prices *in the long-run*. 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. (2012). Section 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 (2008). 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. (2012), we assume no additional market failures for learning technologies. Instead, we explore the potential of several renewable energy policies to compensate for missing or suboptimal carbon prices in order to achieve ambitious mitigation targets. Section 3 elaborates the costs of optimal energy subsidies to reduce emissions by simultaneously considering an energy price constraint. In Section 4, the impact of several second-best policies on welfare and energy prices is discussed, with special emphasis on pure renewable energy subsidies. 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 that causes carbon emissions, 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 (see Fig. 1 for an overview of the technology used).

For our cost-effectiveness analysis, the mitigation target is expressed by an upper bound for cumulative extraction. In contrast to Kalkuhl et al. (2012), there is no emissions trading scheme or ‘carbon bank’ that provides a first-best carbon price according to the Hotelling rule. The government, which anticipates the equilibrium response of the economy, imposes policy instruments on the economy to maximize welfare subject to the mitigation target.

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. (2012).

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[3] The RPS policy in Fischer (2010) is equivalent to the feed-in-tariff policy in our deterministic setting (see Kalkuhl et al., 2012 for a formal proof).

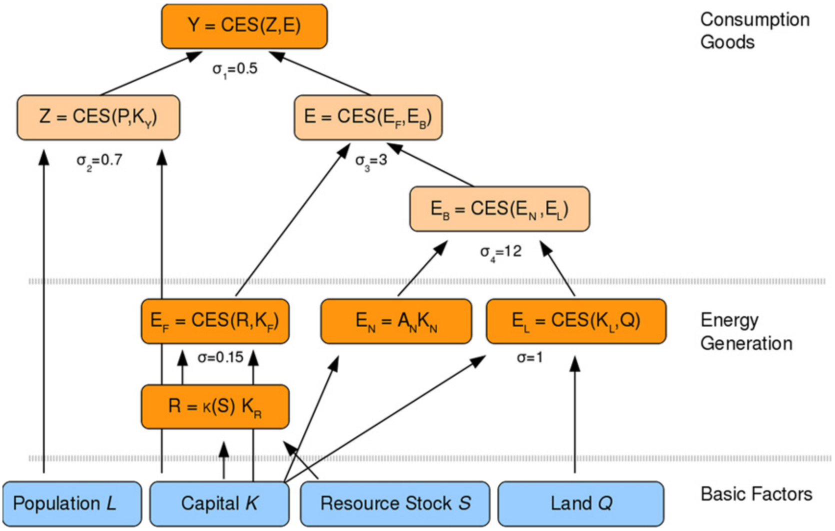

Fig. 1. Technology of the model and key elasticities of substitution σ_i between production factors.

2.1.1. 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 $U(C/P)=(C/P)^{1-\eta}/(1-\eta)$ with η being the risk aversion or (intertemporal) inequality aversion parameter.[4]

$$\max_{C_t}\sum_{t=0}^{T}(1+\rho)^{-t}P_t\mathbf{U}\left(\frac{C_t}{P_t}\right)$$

where ρ is the pure rate of time preference.

The household owns labor P, capital stocks K_j, and the firms, and therefore receives the factor incomes wP 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 capital stock changes due to investments I net of depreciation of capital at rate δ. The household therefore faces the following constraints:

$$C_t = w_tP_t + r_tK_t - I_t + \pi_t + \Gamma_t \tag{1}$$

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

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

2.1.2. 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), fossil (p_F), nuclear (p_N) and renewable (p_L) energy (the price of consumption goods is normalized to one). Furthermore, the

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

production sector may need to consider government intervention in form of a subsidy on renewable energy τ_L or taxes on fossil energy τ_F or nuclear energy τ_N (that are subsidies for negative values):

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

The nested CES production function $\mathbf{Y}(\mathbf{Z}(K_Y, A_Y P), \mathbf{E}(E_F, \mathbf{E}_B(E_L, E_N)))$ 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 carbon-free energy are combined to final energy with the elasticity of substitution σ_3. Finally renewable and nuclear energy are combined to an aggregate carbon-free energy E_B using the elasticity of substitution σ_4 (see also Fig. 1 for a condensed overview). Population L and labor productivity A_Y grow at an exogenously given rate.

2.1.3. 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:

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

2.1.4. 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 $r_t - \delta$:

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

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:

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

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

2.1.5. 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:

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

$$\pi_{L,t} = p_{L,t}\mathbf{E}_L(A_{L,t}, K_t, Q) - r_t K_{L,t} \tag{8}$$

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

with $\mathrm{E_L}(A_{L,t}, K_t, Q) = \mathrm{A_L}(H_t)K_{L,t}^{\nu}Q^{1-\nu}$. We employ Arrows's (1962) learning-by-doing approach for the renewable energy technology: The productivity $\mathbf{A}_L$ grows with capacity expansion (cumulative technology-level adjusted investments) H, implying $\partial A_L/\partial H > 0$, and converges to $A_{L,max}$ when $H \to \infty$.

2.1.6. The nuclear energy sector

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

$$\pi_{N,t} = p_{N,t}A_{N,t}K_{N,t} - r_tK_{N,t} \tag{10}$$

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. (2012)) 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.

$$\Gamma_t = \tau_{N,t}E_{N,t} + \tau_{F,t}E_{F,t} - \tau_{L,t}E_{L,t} + \tau_{R,t}R_t \tag{11}$$

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

$$\sum_{t=0}^{T} R_t \leq B \tag{12}$$

Considering the amount of cumulative emissions of the next decades is a robust indicator for achieving ambitious temperature targets (Meinshausen et al., 2009). Hence, the government's optimization problem is described by:

$$\max_{\Theta} \sum_{t=0}^{T} (1+\rho)^{-t} P_t \mathbf{U}\left(\frac{C_t}{P_t}\right) \text{subject to Eqs.}(1)-(12), \text{FOCs} \tag{13}$$

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, fossil and nuclear energy taxes τ_F, τ_N. The description of concrete policies Θ used in this paper follows below.

2.3. Calibration and implementation of the model

Model parameters are chosen from Kalkuhl et al. (2012). 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 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%

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[5] The 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 2000–2009 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.

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

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 carbon-free 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).

2.4. Evaluation of policy instruments

Policies Θ are evaluated with respect to their impact on intertemporal welfare and energy prices. While the analysis of intertemporal welfare measures the efficiency of instruments to achieve the mitigation budget, the consideration of energy prices indicates possible distributional conflicts provoked by these policies.

2.4.1. 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:

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

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.

2.4.2. Energy prices

As energy from different sources is highly but imperfectly substitutable, prices for fossil, nuclear 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:

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

By comparing this average energy price, we analyze the impact of policies on energy prices. For the subsequent analysis, two prominent reference points will often be considered to discuss and compare different mitigation policies:

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[7] If market failures distort the anticipation of future learning benefits in the renewable energy sector, however, nuclear energy becomes temporarily dominant (see Kalkuhl et al., 2012, where the same model framework is used).

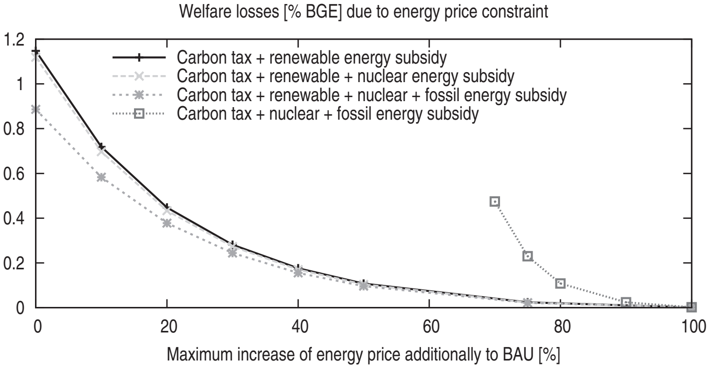

Fig. 2. Additional second-best costs of energy subsidies to reduce energy price increases due to carbon pricing.

- 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 economic costs and re-produces an economic outcome identical to a social planner economy if no further market failures exist (Kalkuhl et al., 2012). The carbon tax increases with the interest rate as it resembles a Hotelling price for the scarcity of the carbon budget.
- The business-as-usual (BAU) scenario is considered where the cumulative carbon budget constraint (12) is relaxed and government intervention is absent, implying $\Theta = \emptyset$.

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 mitigation benchmark (i.e. the first-best carbon pricing policy) is denoted as *additional second-best cost*. Usually, we will compare second-best policies with the first-best mitigation policy (carbon pricing) ignoring distributional (energy price) effects. However, it will also be interesting to compare second-best policies with the BAU outcome in order to identify the political economy implications regarding the implementation specific (second-best) mitigation policies.

3. Optimal climate policies with energy price constraints

As elaborated in Section 1, energy price effects are one of the most important political obstacles for implementing first-best carbon prices. As compensating lump-sum transfers are difficult to realize in practice, subsidies on energy generation may be a more pragmatic alternative. We therefore analyze how different sets of energy subsidies may counteract price increases.

Fig. 2 shows the additional second-best costs (in BGE) of a maximum constraint ν on energy prices, i.e. $\tilde{p}_{E,t} \leq (1+\nu)\tilde{p}^{\mathrm{BAU}}_{E,t}$. The considered policies are $\Theta = \{\tau_R, \tau_L\}$, $\Theta = \{\tau_R, \tau_L, \tau_N\}$, $\Theta = \{\tau_R, \tau_L, \tau_N, \tau_F\}$ and $\Theta = \{\tau_R, \tau_N, \tau_F\}$. If energy price increases are limited to 100% compared to BAU prices, almost no additional subsidies are necessary (and, thus, allowing for them will hardly increase costs). The less energy prices are allowed to increase, the higher the BGE losses for each policy. Thus, Fig. 2 visualizes the trade-off between energy price impacts and overall efficiency losses. As mitigation costs are 2.3% (i.e. the BGE losses of considering a climate target relative to the BAU economy ignoring energy price increases), the energy price constraint may increase the costs of climate policy by up to 50%. Limiting energy price increases to 50%, however, causes only very small additional costs.

If a carbon tax is not complemented by renewable energy subsidies, it becomes even infeasible to achieve the climate target with less than 70% energy price increases. The cheapest policy to consider the energy price constraint simultaneously with the climate target is a mix of subsidies for all three technologies. Complementing a carbon price by a renewable energy subsidy only, increases BGE losses by up to 0.2 percentage points (relative to the policy mix). Compared to the mitigation costs of 2.3% that add to all of the reported BGE losses in Fig. 2, the difference between the pure renewable subsidy and the more comprehensive policies seem to be rather small. While fossil and nuclear energy subsidies have only a small effect on BGE losses, renewable energy subsidies are indispensable.

The analysis indicates why renewable energy subsidies can be a useful complement for carbon pricing even if innovation market failures do not exist or have already been addressed: renewable energy policies, if designed appropriately, can dampen one of the politically most worrying negative side-effects of carbon pricing – the energy price increase – at relatively modest costs.

4. Renewable energy policies for climate change mitigation

In contrast to the optimal policy mix to account for the energy price constraint, there are other approaches focusing on renewable energy that have been implemented or that are considered for implementation. In the following, we assess several second-best policies that achieve a climate target by integrating a specific kind of renewable energy promotion. These policies are calculated without the energy price constraint because they are not always feasible for a tight constraints (due to the low degree of freedom) or because they achieve each price constraint 'by the way' (as it is the case for pure renewable energy subsidies, see below).[8] The selected policies are politically relevant as they are either already in place or debated for implementation:

- Feed-in-tariff (FIT) $\Theta = \{\tau_{F,t}, \tau_{N,t}, \tau_{L,t}\}$: A uniform tax $\tau_{F,t} = \tau_{N,t}$ on fossil and nuclear energy is used to cross-finance a subsidy $\tau_{L,t}$ on renewable energy and to limit fossil resource use. The FIT is implemented as income-neutral policy for the government due to $\tau_{L,t}E_{L,t} = \tau_{F,t}(E_{F,t} + E_{N,t})$. Hence, the costs of promoting renewable energy are entirely borne by the energy sector. It is calculated to achieve the mitigation target at maximum welfare without an additional carbon price and lump-sum taxes ($\Gamma_t = 0$).[9]
- 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 $\Gamma_t = 0$.[10] 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. The pure subsidy policy is considered as an extreme reference point which is sometimes advocated by environmentalists or experts that are skeptical of any form of carbon pricing.
- Temporary subsidy policy that is displaced by a carbon price: $\Theta_{t \le t'} = \{\tau_{L,t}\}$ and $\Theta_{t > t'} = \{\tau_{R,t}\}$. Hence, for $t \le t'$ there is no carbon price ($\tau_{R,t \le t'} = 0$) 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.[11] In the long run, however, carbon pricing will be implemented and subsidies become obsolete.

First, we study these second-best policies with respect to welfare and energy prices. Next, we consider how important key parameters influence the welfare losses of pure renewable energy subsidies as one extreme but popular tool to reduce emissions (Section 4.2). Finally, we consider small deviations from the optimal second-best subsidy and their impact on welfare and emissions (Section 4.3).

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[8] Income-neutral policies, for example, have to transfer all tax revenues to subsidy expenditures. Hence, extra-subsidies to decrease energy prices have to be financed by other energy taxes that, in turn, increase energy prices.

[9] The FIT is one of the most popular renewable energy policy as at least 45 countries implemented them already (Edenhofer et al., 2011, Chapter 11, p. 14).

[10] This 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.

[11] Such a gradual phase-in of regulation can be motivated by distributional concerns (Williams, 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.

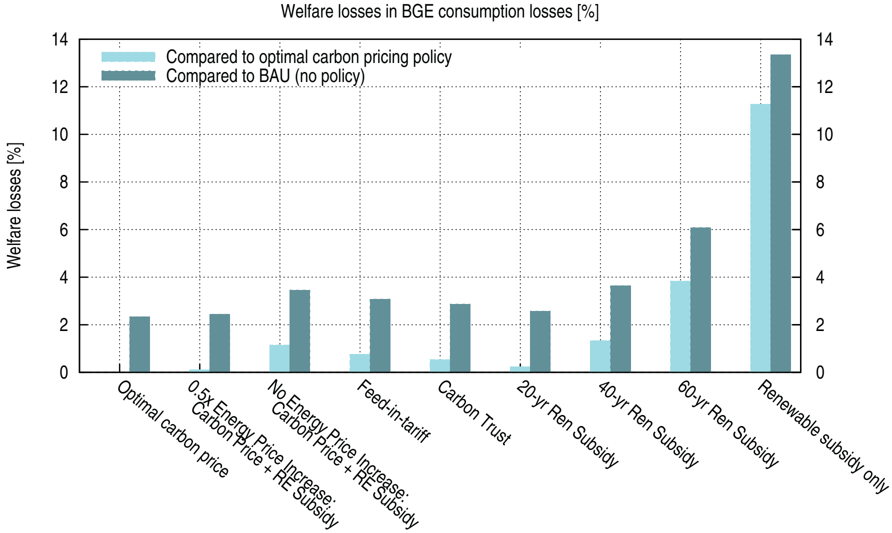

Fig. 3. Welfare losses (in BGE) for several policies.

4.1. *Assessment of second-best policies*

4.1.1. *Impact on welfare*

Fig. 3 shows the welfare losses of the policies described above (including two scenarios with energy price constraint) 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 of 2.3% 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]

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%). A pure subsidy policy, however, increases mitigation costs substantially to 15.4%. This is far higher than existing estimates who find that pure subsidy policies are approximately twice as expensive as carbon pricing (see (Fischer and Newell, 2008; Palmer and Burtraw, 2005), for moderate emission targets for the US).

4.1.2. *Impact on energy prices*

As argued in Section 1, distributional concerns are one important reason for the high opposition against carbon prices. 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. In contrast to fossil energy, renewable

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[12] In 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. $\varsigma_F = 0$), 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.

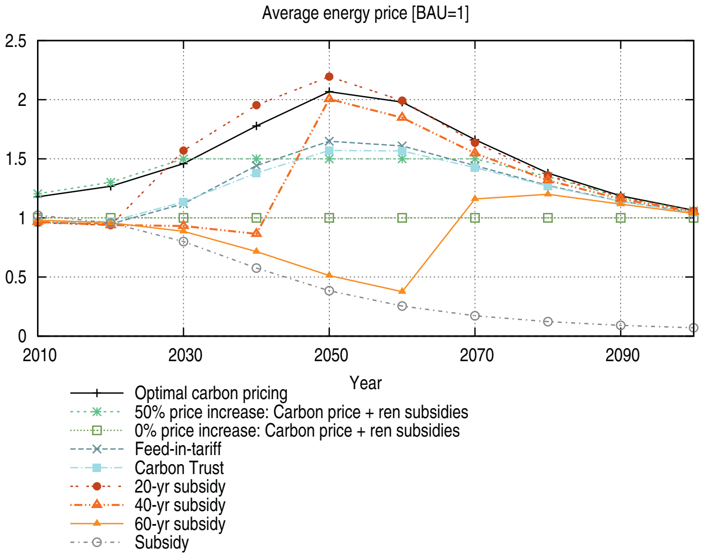

Fig. 4. Average energy prices according to Eq. (15) under different policy regimes relative to BAU prices.

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. Remember that in our model all feasible FIT or Carbon Trust policies raise the energy price. Thus while we observe a lower energy price in these scenarios compared to optimal carbon pricing, these policies are not able to maintain the business-as-usual energy price.

The development of average energy prices is shown in Fig. 4. 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. They peak increase is approximately 60%. 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 substantially lower than without mitigation. Note that in the very long run, energy prices under carbon pricing policies are not higher than in the BAU scenario.[14]

Hence, when firms or households cannot be compensated for higher energy prices resulting from mitigation targets, feed-in-tariffs, a carbon trust or additional renewable energy subsidies might be a pragmatic alternative to an optimal carbon pricing policy. A permanent renewable energy subsidy without further carbon prices, however, leads to extremely low energy prices and high welfare losses. The following section will explore the reasons for this and evaluate the role of economic parameters in determining the costs of the pure subsidy policy.

4.2. *What determines the second-best costs of a pure renewable energy subsidy policy?*

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

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

[14] First, 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.

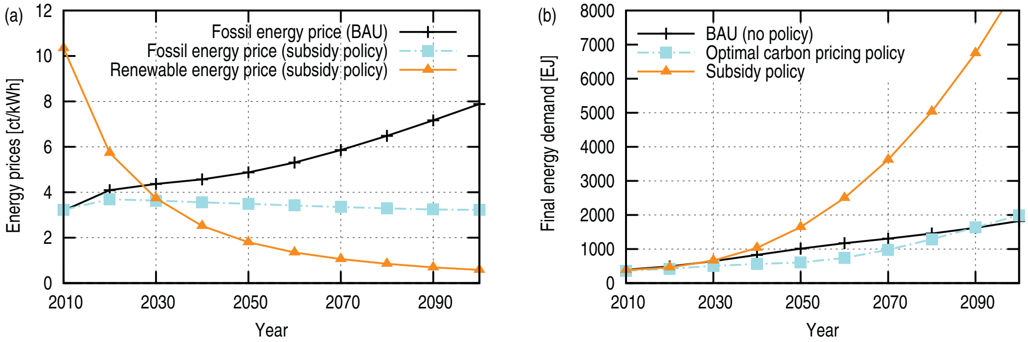

Fig. 5. Impact of renewable energy subsidies on (a) fossil and renewable energy prices and on (b) fossil and renewable energy generation.

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 unit extraction costs as the capital productivity κ of the extraction industry decreases with cumulative extraction. Fossil resource owners reduce further their scarcity rent mark-up per unit extracted because fossil resources become abundant compared to the tight carbon budget under the mitigation policy. Fig. 5a indicates how renewable energy subsidies reduce fossil energy prices below BAU prices due to the supply-side dynamics of fossil resources. However, Fig. 5a 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, also called rebound effect (Fig. 5b). 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. 3.

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. Table 1 lists the results for parameters describing fossil resource reserves (S_0), substitutability between fossil and carbon-free energy (σ_3) total energy demand ($A_{L,max}$, σ_1), carbon-free energy costs ($A_{L,max}$, ν, 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. 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 carbon-free 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 nuclear 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

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.

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–carbon-free energy 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	
Share parameter 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 (inequaltiy) 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

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 decisions 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

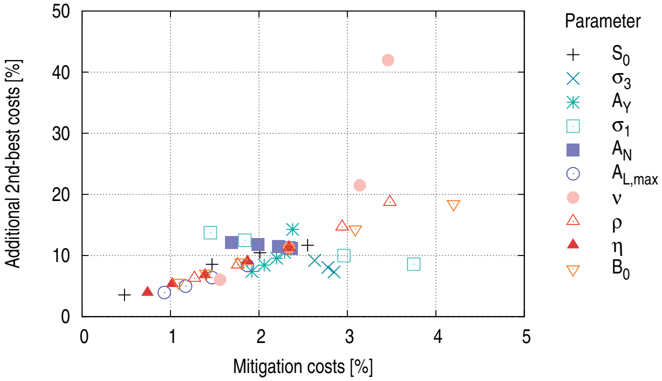

Fig. 6. Sensitivity analysis for a renewable subsidy policy. The welfare losses of a pure renewable subsidy policy compared to an optimal carbon pricing policy (additional 2nd-best costs) are shown as well as mitigation costs of an optimal carbon pricing policy compared to the BAU scenario. Parameter variations correspond to Table 1.

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. 6 compares the (optimal) mitigation costs with the additional second-best costs of the renewable energy subsidy from Table 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 rational 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 carbon-free energy are very good substitutes (high σ_3), and if nuclear 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 (2008) 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 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. 7a (subsidies are initially high to curb expansion which induces learning-by-doing; this makes, in turn, less subsidies necessary to crowd out fossil energy as renewable energy costs have come down substantially). 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. 7b).

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 contrast, 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.

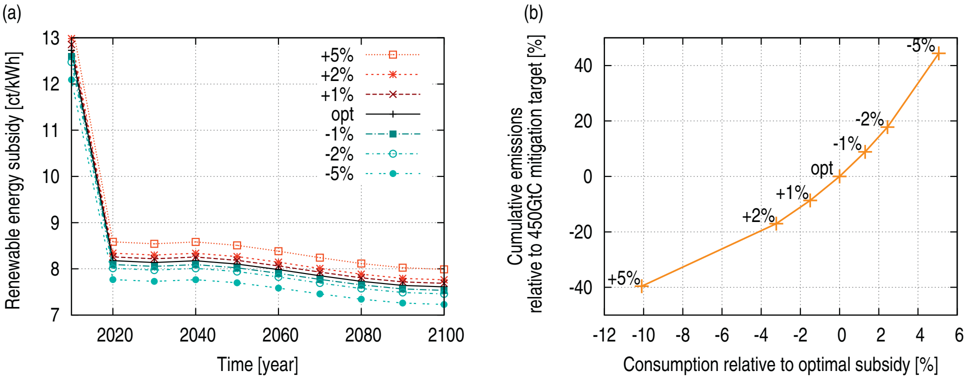

Fig. 7. (a) Optimal subsidy and perturbations. (b) Impacts of perturbed subsidies on consumption and emissions.

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.[15] 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. 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.

An extensive sensitivity analysis revealed that these high costs are not accidentally due to the chosen parametrization but prevail for a wide rage of parameter. It further shows that mitigation costs are correlated with the second-best costs of the renewable energy subsidy. For example, 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 has thus a marginal impact on the economy. The political economy concerns due to carbon pricing may therefore be low for these parameter settings.

Permanent renewable energy subsidies are not only an expensive choice to reduce emissions. 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, however, attractive alternatives to a pure carbon pricing policy. The feed-in-tariff and the carbon trust policy cause only small additional costs (0.8% and 0.6%, respectively) while they limit energy price increases – as side effect – to 60%. Relaxing the income-neutrality constraint of feed-in tariffs and the carbon trust policy, a freely adjustable renewable energy subsidy (that complements a carbon price) can reduce energy price increases to any desired level at even lower costs: A 50% maximum energy price increase can be achieved at 0.1% BGE losses and a 0% maximum price increase at 1.1% BGE losses.

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[15] These welfare losses remain almost unaffected if we allow for an additional nuclear energy subsidy promoting the second carbon-free energy technology in our model: In that case, welfare losses of the pure renewable energy subsidy policy decrease only by 0.3 percentage points.

Renewable energy subsidies are an efficient policy instrument when they address market failures directly associated with renewable energy technologies or markets.[16] This article emphasized that beside this aspect, renewable energy subsidies might be an important *additional* instrument to address the serious political concerns of carbon pricing regarding energy price impacts. However, if renewable energy subsidies aim to reduce carbon emissions because carbon prices are entirely missing, 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 some form of carbon pricing, pragmatic renewable energy policies 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.

Acknowledgements

We would like to thank two anonymous reviewers for the valuable comments that helped to improve the paper. We gratefully acknowledge funding by the “Pakt für Forschung und Innovation” of the Leibniz-Gemeinschaft Germany, and the German Federal Ministry of Education and Research (BMBF) in the Call “Economics of Climate Change” (funding code 01LA11020B, Green Paradox).

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[16] Compared to the social optimum, the welfare costs of pure subsidies does not change if innovation spillovers persist leading to an under-deployment of renewable energy. In this case, the pure carbon pricing policy benchmark would lead to approx. 0.5–2% additional BGE welfare losses (see Kalkuhl et al., 2012 for calculations within the same model approach), while the pure renewable subsidy policy would still entail welfare losses of 11% compared to the optimal combination of both policies. In case of 60% innovation spillovers, the welfare losses of feed-in-tariffs, reduce from 0.75 to 0.65% and the welfare losses of the carbon trust policy reduce from 0.54 to 0.41%.

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