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Subsidizing Renewable Energy: Higher Welfare by lower depreciation costs for fossil power plants?

Subsidizing Renewable Energy: Higher Welfare by lower depreciation costs for fossil power plants?

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Abstract

There is a broad agreement that renewable energy sources (RES) will play an important role to abate CO_2 emissions but there is a contentious debate about the economic sense to promote RES via subsidies. Many static analyses conclude that subsidizing RES ties up capital which could have been used more efficiently by other reduction strategies with lower marginal abatement costs (MAC). Dynamic models, in contrast, emphasize learning effects which lead to lower MAC of RES. In particular a start-up funding to induce an early market entry of RES may be advantageous to benefit from reduced MAC. To our knowledge there has been no attention so far to the effects of renewables' promotion to the necessary shut down of power plants based on fossil energy sources (FES). With respect to the achievement of a certain long-term reduction objective an early market entry of RES allows a longer transition from FES to RES. This also means more time to shut down fossil-based power plants which can reduce respective depreciation costs. We use an endogenous growth model to focus on the trade off between the described decrease of depreciation costs and the capital tie-up of a subsidization of RES. We find that subsidizing RES can indeed lead to a higher welfare solely because of reduced depreciation costs. We conclude that an optimal strategy to reduce emissions should consider both the increase of renewable and the decrease of fossil electricity generation.

Keywords Renewable Energy, Transition Period, Welfare Effects
JEL H23, O21, O44, Q42, Q43, Q48

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1 Introduction

The mitigation of anthropogenic climate change requires a massive reduction of atmospheric CO_2. This calls for enhanced reduction efforts in the electricity sector, since a significant share of emissions of most industrialized countries can be traced back to fossil-based electricity generation. Unfortunately there are physical limitations. Even the most efficient conversion of e.g. a piece of coal into electricity still emits CO_2. This leaves two possibilities to achieve ambitious reduction objectives: Either a part of fossil-based power plants is substituted by non-fossil electricity generation or CO_2 capture and storage (CCS) is used to prevent emissions to escape to the atmosphere. However, a necessary timely large-scale application of CCS in electricity generation is not very likely because of relatively high marginal abatement costs (Schröder *et al.*, 2013) and only few demonstration plants so far (Global CCS Institute, 2014). Thus, there is a broad agreement that at least a part of fossil electricity generation has to be substituted by renewable energy sources (RES)[1] in the future to meet necessary long-run CO_2 reduction objectives (e.g. Sanden and Azar, 2005).

Despite this general consensus there is a contentious debate about the sense of promoting RES via subsidies. Nordhaus (2009) for instance points out that the adequate pricing of CO_2 emissions is a sufficient climate policy. As an emissions trading system (ETS) potentially meets this requirement the promotion of RES is redundant and leads to a loss in cost efficiency (see e.g Pethig and Wittlich, 2009; Jensen and Skytte, 2003; Böhringer *et al.*, 2009; Böhringer and Rosendahl, 2010). Indeed, a perfect ETS-only regulation reduces emissions always using the technology with lowest marginal abatement cost (MAC). In such framework renewable energy is not used until physical restrictions in fossil-based electricity generation lead to increasing MAC, which finally makes renewables the cheapest mitigation option (De Jonghe *et al.*, 2009).

The continuous use of the technology with lowest MAC would be the optimal mitigation strategy if MAC could be interpreted as static supply curve. This interpretation implies to neglect dynamic effects. Frequently addressed with respect to dynamic analyses in this context, are learning effects of RES (Sorrell and Sijm, 2003; Edenhofer *et al.*, 2012) which eventually change the MAC curve. Unruh (2000) additionally points out the path dependency of mitigation strategies as a result of existing dominant technologies. Both arguments give a rationale for a promotion of renewable energy particularly as a start-up investment.

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[1] We focus on RES, although in principle a substitution of fossil energy sources by nuclear power plants is also possible, because disposal costs and modern safety requirements make nuclear power plants more expensive than renewables (Schröder *et al.*, 2013). Nevertheless, our analyses is also applicable to a substitution of fossil by nuclear power plants.

To our knowledge, so far no attention was paid on the dynamic effects caused by the interaction between an increase of renewable electricity generation and the necessary capacity reduction of power plants based on fossil energy sources (FES). Without subsidies renewable energy will enter the market later. With respect to the achievement of a long-term reduction objective at a certain point in time, this later market entry requires a faster transition to a RES-based electricity generation in the remaining time. As a consequence, the capacity of fossil power plants must decrease faster. This leads to higher depreciation costs if it exceeds the age-related exchange of power plants. The promotion of RES can lower depreciation costs, but it also leads to an early capital tie-up as CO_2 mitigation is not restricted to the strategy with lowest MAC. Thus, the promotion of RES creates a trade-off.

We use an endogenous growth model to focus on this trade off. The model economy is based on physical capital, labor force and energy. The regulator can choose between emission reduction with or without promotion of renewable energy. We find that a promotion of RES can lead to a higher welfare merely by reason of reduced depreciation costs. We further evaluate which parameters have an impact on this outcome and find that the result particularly depends on the harshness of the long-term reduction objective.

2 Model

The basis of the following analysis is an endogenous growth model of the Ramsey type. We assume a closed economy with perfect competition, identical rational agents with perfect information and constant returns to scale. For the electricity sector we assume an efficient promotion system for RES and an efficient coordination of promoted RES and the ETS. The model economy needs capital, labor and energy for production. The use of energy results in CO_2 emissions. These emissions can be reduced by a pricing of emissions inducing different measures to reduce CO_2. We assume a pricing mechanism which always induces CO_2 abatement with lowest MAC. This can be a perfect emissions trading system (ETS). In addition a promotion of RES is possible. We assume the simultaneous application of the ETS and the promotion of RES does not cause efficiency losses. The social planner thus perfectly considers emission reduction by RES in the emission cap. The ETS-only strategy without promotion of renewable energy serves as reference case (see Section 2.3). The accumulated discounted utility of this reference case is compared to the respective values with an additional promotion of RES.

2.1 General structure of the model

A social planner is maximizing welfare W which consists of the peoples' aggregated discounted utility from the starting point t_0 till infinity. Utility is obtained by per capita consumption C/L with L corresponding to the size of the (working) population. Consumption and utility are linked via a concave function to introduce a decreasing marginal utility. To keep things simple we use a logarithmic utility function yielding

$$W = \int_{t_0}^{\infty} L \ln \frac{C(t)}{L} \mathrm{e}^{-\rho t} dt \tag{1}$$

as objective function with ρ reflecting the time preference rate. L is normalized to a constant value of one, since it is not in the focus of our analysis. If desirable, population growth could be considered by a respective calibration of the model.

The economy produces the generic output Y which can be used for consumption as well as for investments. Thus, consumption C is given by the difference of the generic output Y and investments

$$C = Y - (I_K + RD_A + I_e). \tag{2}$$

Investments consist of investments I_K in physical capital, expenses RD_A for research and development in labor efficiency, and investments I_e in the mitigation of CO_2 emissions.

The generic output Y is produced with a CES production technology

$$Y = \Phi_Y[\xi_Y^A(u_A \cdot A)^{-\theta} + \xi_Y^E E^{-\theta} + \xi_Y^K(u_K \cdot K_A)^{-\theta}]^{-\frac{1}{\theta}} \tag{3}$$

introducing constant elasticity of substitution. A is the efficiency factor of labor which is multiplied with the working population $L = 1$. K corresponds to physical capital. In addition to these classical input factors production also requires energy E. Since electricity is both, a good substitute for other types of energy and the most important source of emissions in developed countries we treat E as electricity in the following. u_A and u_K are the shares of labor respectively capital which are used for the production of the generic output Y. The different factors $\xi_Y^A, \xi_Y^E, \xi_Y^K$ sum up to one and represent the relative factor shares of labor, electricity and capital. The substitution parameter θ is linked to elasticity of substitution σ by $\sigma = 1/(1+\theta)$. Following Edenhofer *et al.* (2012) we will choose $\sigma < 1$ to ensure that each factor is essential for production. Φ_Y is a scaling factor which allows the calibration of output if necessary.

Capital accumulation follows

$$\dot{K} = I_K - \delta_K K \tag{4}$$

reflecting that investments in physical capital I_K are depreciated with the rate δ_K. This corresponds to the standard Ramsey model.

The change of labor efficiency A is modeled according to Edenhofer *et al.* (2012)

$$\dot{A} = \alpha_A^{RD} \left(\frac{RD_A}{Y} \right)^{\gamma_A} A. \tag{5}$$

Labor efficiency is increased by investing a share of the generic output RD_A/Y. The parameter $\gamma < 1$ gives the function a concave shape to ensure a decreasing marginal product. This implies the realistic assumption that a higher learning level increases the possibility to forget. Eventually, investments in labor efficiency are the engine of growth in this model, since it is responsible for a constant positive growth rate in the long run. Thus, α_A^{RD} directly influences the long-run growth rate which allows a respective calibration if necessary.

The core of the model is the introduction of electricity in the production function (Eq. 3). Electricity itself is generated in power plants which are built by capital K and labor $A \cdot L$. In general, electricity is also necessary to build power plants but in comparison to the other factors it can be neglected. This avoids mathematical difficulties in the solution of the model. Following these considerations the generation of electricity may be described with a CES production function

$$\dot{E} = \Phi_E(\xi_E^A((1-u_A)A)^{-\tilde{\theta}} + \xi_E^K((1-u_K)K_A)^{-\tilde{\theta}})^{-\frac{1}{\tilde{\theta}}} - \delta_E E. \tag{6}$$

Since both necessary production factors are also used to produce the generic output Y, only the remaining parts $(1-u_A)$ and $(1-u_K)$ are available for electricity generation. This kind of modeling is analogous to the treatment of human capital in the model of Lucas (1988). The generation of electricity stresses power plants. This requires a continuous restoration process of power plants which is considered by the depreciation rate δ_E. The factor shares of labor and capital are given by ξ_E^A, ξ_E^K. They also sum up to one. In analogy to Φ_Y in the production function Φ_E is a scaling factor for calibration purposes.

Money which is spent for investments in emission reduction I_e cannot be used for other purposes. It is beyond the scope of this paper to find an optimal abatement path which determines the level of investments I_e at any time. Thus, we take a certain long-term objective for emission reduction as exogenously given. The regulator then defines intermediate objectives in order to achieve the long-term objective. In fact such an approach can be found for instance in the EU ETS. The long-term objective of the EU ETS is not only the result of scientific research but of a political process. This objective is regarded as given when intermediate objectives are chosen. Intermediate objectives are a compromise between necessary mitigation measures and the expected financial burden which is regarded as acceptable.

To follow this approach we model investments in emission reduction proportionally to electricity generation

$$I_e = \tau E \tag{7}$$

which gives direct access to a parametrization of the financial burden of emission reduction in two steps. First, τ is converging to a certain value τ_{max} after achievement of the long-run objective. This allows to choose τ_{max} as a parameter corresponding to estimated costs per electricity unit which must be covered to achieve the long-run objective. A reasonable parametrization is described in Section 2.5.4. Second, τ increases over time from 0 to τ_{max}. This is a plausible assumption as it reflects the expected behavior of the certificate price in the EU ETS with its tightening of the emissions cap. For simplicity, we model τ as linearly increasing over time till the long-term objective is achieved.

In principle τ can be interpreted as a tax rate of an electricity tax yielding, a certain level of emission reduction. However, we use τ only for described parametrization purposes while we implement a perfect ETS. That means emissions always comply with the emission cap and abatement measures are always carried out with the lowest MAC. The emission cap and the parameter τ are directly linked to each other by the MAC-curve assuming no uncertainty and perfect information (see Section 2.2.1 for details). There is no difference in our model to choose τ and τ_{max} yielding a certain emission reduction, or to choose an emission cap yielding a certain value for τ and τ_{max}. Thus, the described parametrization of τ and τ_{max} is synonymous with setting an emission cap.

The Hamiltonian of the maximization problem is given by

$$\mathcal{H} = \ln(Y_A - (I_K + RD_A + I_e)) + \lambda_K \dot{K} + \lambda_A \dot{A} + \lambda_E \dot{E} \tag{8}$$

with E, K, A as state variables, I_K, RD_A, u_A, u_K as control variables, and $\lambda_K, \lambda_A, \lambda_E$ as co-state variables. The respective maximum conditions and Euler equations are given in Appendix A.

2.2 Emissions and their mitigation

Emissions e arise proportionally to fossil-based electricity generation E_{FES} leading to

$$e = \epsilon E_{FES} \tag{9}$$

with ϵ as emission factor. In contrast, electricity from renewable energy sources does not emit any CO_2.

Consequently, there are two possible strategies to reduce emissions on the production side. On the one hand a decrease of the emission factor ϵ may be induced, on the other hand electricity which is generated by FES may be substituted by electricity from RES. According to

$$E_{FES} = E - E_{RES}, \tag{10}$$

E_{FES} decreases if E_{RES} increases more than total electricity E.

2.2.1 Cost structure of emission reduction

We assume that both strategies to reduce emissions are necessary to achieve the long-run reduction objective with lowest costs. This is a result of the assumed underlying cost structure of emissions' abatement which is described in the following.

To deduce reasonable assumptions for the cost structure, we look at a single fossil power plant at first. Initial easy efficiency gains will decrease the emission factor ϵ at very low cost. The more the power plant's emissions are already reduced, the more difficult it is to obtain further reductions because of physical limitations. Therefore, more expensive mitigation measures have to be executed. In other words, assuming a constant electricity output of the power plant, an emission reduction of 20 % causes costs more than double when compared to a reduction of 10 %. This means increasing MAC, which is a standard assumption in environmental economics (see e.g. Nordhaus, 2009). To keep things simple we assume linearly increasing MAC. Nevertheless, other functional shapes could be implemented if necessary.

For the next step in analysis we assume that the mitigation measures of the single power plant are installed in other comparable power plants as well. The multiplication of mitigation measures is predominantly subject to economies of scales. This also applies for the substitution of fossil power plants by RES which is mainly the multiplication of the same mitigation measure (e.g. building more wind or solar power plants).[2] Economies of scales are considered to be one of the main reasons for learning effects of RES because RES-based power plants do not exist in large numbers so far. This might justify increasing economies of scales. Nevertheless, we assume constant economies of scale as conservative assumption for both mitigation strategies therewith neglecting learning effects. This allows a focus on the impact of a reduced depreciation of FES-based power plants.

In light of the above considerations we assume constant MAC for the substitution of fossil power plants by RES because constant economies of scale predominate the substitution process. In contrast, we assume linearly increasing MAC, starting from zero, for CO_2 abatement within the existing fossil power plant fleet. Thus, for a relatively low CO_2 abatement the substitution of fossil-based power plants by RES faces much higher MAC than a CO_2 abatement within the fossil sector. This could be observed after the ETS was introduced in the EU in 2005. The EU ETS has not induced investments in RES so far.

The difference in MAC also has an effect on possible regulations to achieve emission reduction. A pricing of emissions by an ETS for instance always incentivizes abatement measures with lowest MAC. That is, at first emission abatement within the fossil power plant fleet is induced. On the contrary, a promotion of RES directly addresses the substitution of FES by RES. Therefore, the different MAC of the two described abatement strategies can be assigned to different regulations, too. Böhringer *et al.* (2009) also distinguish MAC assigned to the ETS (MAC_{ETS}) and the promotion of RES (MAC_{RES}).

The occurrence of separate MAC_{ETS} and MAC_{RES} may change with tighter future emission caps leading to higher CO_2 abatements and certificate prices. If we take, for example, the long-run emission objective of the EU with a reduction of 80 – 95 % with respect to 1990 (Council of the EU, 2009) it is very likely that for a high level of abatements the substitution of FES by RES becomes the cheapest abatement strategy. Then MAC_{RES} and MAC_{ETS} are identical. The described situation is illustrated in Fig. 1 with the intersection of MAC_{RES} and MAC_{ETS}.

Since we assume constant MAC_{RES} and linear increasing MAC_{ETS}, the determination of the intersection of MAC curves is sufficient to characterize MAC curves. Any other shape of MAC can be implemented in the model, too. Only the necessity of RES in the long run is a necessary condition. It entails the necessary intersection of MAC_{RES} and MAC_{ETS} in our model. Maximal MAC are equal to τ_{max} because a growing

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[2] Beside economies of scale the increase of fluctuating RES may also induce higher grid costs or storage costs. We assume that these effects play a minor role when compared to economies of scale.

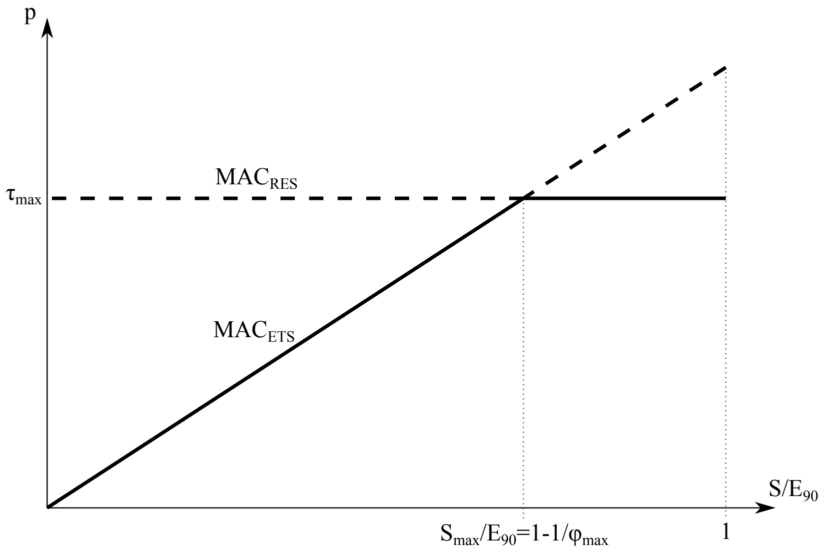

Figure 1: Schematic illustration of MAC_{ETS} and MAC_{RES}. Dashed lines illustrate the assumed further process of MAC_{ETS} without RES respectively the assumed further process of MAC_{RES} without emission reduction within the fossil sector. The solid line corresponds to the indeed MAC. Emission savings are given in savings S per emissions of the reference year 1990 E_{90}. S and E_{90} are both in electricity units while conversion to emission units follows Eq. 9 using the emission factor of the reference year $\epsilon^{'}$. This figure is based on the electricity demand of the reference year because changes in the electricity output do not influence MAC but they are subject to assumed constant economies of scale. Therefore, the abscissa is limited to 1. Maximal MAC are equal to τ_{max}. 1-1/φ_{max} characterizes the intersection of MAC_{ETS} and MAC_{RES}.

economy with growing electricity demand must more and more substitute FES by RES in order not to exceed the constant long-run objective. Since in the long-run τ_{max} equals the available money per electricity unit for emission reduction, it is also equal to long-run MAC. In addition, the intersection of MAC curves depends on the maximal emission abatement in the fossil sector, before substitution by RES becomes the dominant strategy.

To allow a reasonable parametrization of the model, we introduce the efficiency factor φ_{max}. It specifies how much more electricity can be generated with a fixed amount of emissions in comparison to the reference year. For example, if four times more electricity can be generated with the same amount of emissions compared to 1990 φ_{max} would be equal to four. This is an emission reduction of 75 % under a constant electricity output. Thus, the intersection of MAC curves is characterized by 1-1/φ_{max} and τ_{max} as depicted in Fig. 1. As stated above, changes in the electricity output do not influence MAC but they are subject to assumed constant economies of scale.

2.2.2 Emission reduction induced by the ETS

Emission savings induced by the ETS (S_{ETS}) depend on the investments into abatement measures I_e and MAC_{ETS}, which determine abatement costs. This yields

$$\begin{aligned} \int_0^{S_{ETS}} MAC_{ETS} \mathrm{d}S \frac{E_{FES}}{E_{90}} &= I_e(1 - X_{RES}) \\ \Leftrightarrow \int_0^{S_{ETS}} \frac{\tau_{max}}{\left(1 - \frac{1}{\varphi_{max}}\right) E_{90}} S \mathrm{d}S \frac{E_{FES}}{E_{90}} &= I_e(1 - X_{RES}) \\ \Rightarrow S_{ETS} &= \sqrt{\frac{2 I_e E_{90}^2 \left(1 - \frac{1}{\varphi_{max}}\right)}{\tau_{max} E_{FES}} (1 - X_{RES})} \end{aligned} \tag{11}$$

whereas the left hand side of Eq. 11 corresponds to abatement costs and the right hand side indicates necessary investments. Abatement costs consist of an integral over MAC_{ETS} and the scaling factor E_{FES}/E_{90}.

The scaling factor considers a change in electricity generation with constant economies of scale as discussed above. That is, abatement costs of e.g. a 10 % emissions reduction will double if electricity generation doubles, too.

S_{ETS} corresponds to unscaled emission savings in electricity units. The product of S_{ETS} and the scaling factor thus results in emission savings in electricity units. The product of S_{ETS} and the constant emission factor of the reference year ϵ' yields the unscaled emission reduction while additional multiplication with the scaling factor yields emissions savings.

Abatement costs (left hand side of Eq. 11) have to be covered by respective investments which are given on the right hand side of the equation. While total investments in CO_2 reduction are given by I_e a share X_{RES} of these investments may be put aside for the promotion of RES in addition to the ETS. This results in a share $1 - X_{RES}$ for emission reduction induced by the ETS.

The second line of Eq. 11 specifies MAC_{ETS} as linearly increasing with the slope $\frac{\tau_{max}}{\left(1 - \frac{1}{\varphi_{max}}\right) E_{90}}$ (see Figure 1). Rearrangement of Eq. 11 finally yields S_{ETS}.

Since the ratio S_{ETS}/E_{90} is the relative emission reduction with respect to the reference year it allows the calculation of the emission factor

$$\epsilon = \left(1 - \frac{S_{ETS}}{E_{90}}\right) \epsilon' \tag{12}$$

which determines emissions according to Eq. 9. Without ETS S_{ETS} equals zero yielding a constant emission factor $\epsilon = \epsilon'$. Consequently the bracket in Eq. 12

indicates the remaining share of emissions with respect to the reference year.

2.2.3 Emission reduction induced by the promotion of RES

In the following analysis we regard the promotion of RES and the ETS as independent of each other. That is to assume perfect coordination of the two policy instruments. Then the amount of electricity generated by renewable energy E_{RES} depends on the subsidy for renewables and does not decrease emission savings by the ETS. To calculate E_{RES}, we need to examine whether MAC_{ETS} is lower than or equal to MAC_{RES}. As long as MAC_{ETS} is lower than MAC_{RES} there is no incentive from the ETS to invest in RES. In this case an additional subsidization is necessary to build RES-based power plants. Less money is available for investments into mitigation with lowest MAC, while RES-based electricity generation is subsidized with a share X_{RES} of total investments in emission reduction I_e. This yields

$$\int_0^{E_{RES}} MAC_{RES}\mathrm{d}E = I_e X_{RES} \tag{13}$$

$$\Rightarrow E_{RES} = \frac{I_e}{\tau_{max}} X_{RES} \qquad \forall MAC_{ETS} < MAC_{RES} \tag{14}$$

assuming an efficient promotion system for RES allowing emission reduction at costs equal to MAC_{RES}.

If MAC_{ETS} equals MAC_{RES} savings in the fossil sector are at their maximum. This implicitly means to assume that the long-run objective is achieved with a maximum of emission reduction within the fossil sector until MAC_{ETS} equals MAC_{RES}. Referring to Fig. 1 it means to follow MAC_{ETS} from zero till 1-1/φ_{max}. The promotion of RES can, however, result in a share of renewables exceeding this optimum (starting to follow MAC_{RES} before 1-1/φ_{max}). Schäfer (2018) describes how these additional costs can be limited.

Since we assume savings in the fossil sector are at their maximum for MAC_{RES} equals MAC_{ETS}, all further investments will increase the number of RES-based power plants as they are the mitigation strategy with the lowest MAC. This yields

$$\int_0^{E_{RES}} MAC_{RES}\mathrm{d}E = I_e - \tilde{I}_e \tag{15}$$

$$\Rightarrow E_{RES} = \frac{I_e - \tilde{I}_e}{\tau_{max}} \qquad \forall I_e \geq \tilde{I}_e \tag{16}$$

whereas $\tilde{I}_e$ corresponds to the critical value of investments which is sufficient to exactly cover costs allowing maximal emission savings in the fossil sector S_{ETS}^{max}. According to

Eq. 11, this results in

$$\begin{aligned}\tilde{I}_e &= \int_0^{S_{ETS}^{max}} MAC_{ETS} \mathrm{d}S \frac{E_{FES}}{E_{90}} \\ &= \frac{\tau_{max}}{2} \left(1 - \frac{1}{\varphi_{max}}\right) \frac{1}{1 - X_{RES}} E_{FES}\end{aligned} \tag{17}$$

with $S_{ETS}^{max} = \left(1 - \frac{1}{\varphi_{max}}\right) E_{90}$ (see Section 2.2.1 and Fig. 1).

2.3 The reference scenario

Section 2.2 describes how we model emissions and their mitigation. This allows to illustrate different mitigation strategies in respective scenario calculations. In a first step we have to define the common basis for all scenarios. We assume an economy without any abatement of emissions ($\tau_{max} = 0$). No abatement is the optimal strategy as long as nobody knows about the consequences of CO_2 emissions. After the regulator finds out about these consequences he or she introduces an abatement strategy. We assume that the economy was on the balanced growth path between 1990 and 2005. In 2005 the regulator introduced an abatement strategy which leads to a long-run emission objective in 2050. We chose these dates following the example of the EU that started the EU ETS in 2005 and introduced a long-run emission objective for 2050. With the introduction of an abatement strategy the economy is not in the equilibrium anymore but converges to the new equilibrium if all control variables are chosen optimally.

Our reference scenario restricts emission reduction to the ETS as single mitigation strategy without any promotion of RES ($X_{RES} = 0$). Mitigation is always executed with lowest MAC in such a scenario. Therefore, a transition from FES to RES only takes place after MAC_{ETS} has reached MAC_{RES} (see Section 2.2.1 with Fig. 1).

The transition to RES induces capacity reductions for power plants which are based on FES. The depreciation rate resulting from this process can be approximately calculated by

$$\delta_{FES}(t) \approx \frac{1}{\Delta t} \frac{E_{FES}(t) - E_{FES}(t-1)}{E_{FES}(t)}. \tag{18}$$

If δ_{FES} exceeds the usual depreciation rate δ_E, the economy faces additional costs as it means that power plants, which are not completely depreciated, are shut down. Taking into account the ratio of fossil to total electricity generation we can calculate an adjusted depreciation rate for total electricity generation

$$\begin{aligned}\tilde{\delta}_E(t) &:= \underbrace{(\max\{\delta_{FES}(t), \delta_E\} - \delta_E)\frac{E_{FES}}{E}}_{:=\Delta\delta_E} + \delta_E \\ &= \Delta\delta_E + \delta_E \qquad (19)\end{aligned}$$

which considers the described additional capacity reductions in the fossil sector.

2.4 Promotion of renewable energy

The additional depreciation described in Section 2.3 can be reduced by the promotion of RES since it prolongs the transition phase in which fossil-based capacity is reduced. However, this means to leave the reduction path with minimal MAC. Thus, subsidizing renewables either results in higher CO_2 emissions if, in comparison to the reference scenario, τ is kept constant, or the other way round, in higher τ if emissions remain the same. To keep things comparable, we ask for equal emissions at any point in time in each scenario. That is the regulator retains the emission cap at any time.[3]

Assuming initially τ to be constant resulting emissions e of each time step in a scenario with promotion of RES can be compared to respective emissions of the reference scenario $\tilde{e}$ without promotion of RES. Additional emission reduction with lowest MAC (induced by the ETS) can eliminate excess emissions. Eqs. 9 and 12 with $(X_{RES} = 0)$ can be used to calculate the necessary additional emission reduction ΔS_{ETS} allowing identical emissions $(e = \tilde{e})$ at every point in time

$$\begin{aligned}E_{FES}\left(1 - \frac{S_{ETS} + \Delta S_{ETS}}{E_{90}}\right) &= \tilde{E}_{FES}\left(1 - \frac{\tilde{S}_{ETS}}{E_{90}}\right) \\ \Leftrightarrow \Delta S_{ETS} &= E_{90} - S_{ETS} + (\tilde{S}_{ETS} - E_{90})\frac{\tilde{E}_{FES}}{E_{FES}} \qquad (20)\end{aligned}$$

with the tilde indicating values of the reference scenario. The additional emission reduction requires extra investments $\Delta I_e := I_e(S_{ETS} + \Delta S_{ETS}) - I_e(S_{ETS})$. Rearrangement of Eq. 11 with respect to I_e and inserting of $I_e(S_{ETS} + \Delta S_{ETS})$ and $I_e(S_{ETS})$

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[3] In general it would be sufficient to keep accumulated emissions stable till the long-run objective is achieved because the long life time of CO_2 in the atmosphere (Houghton *et al.*, 1996, p. 15) makes this the decisive factor. The restriction of identical emissions at every point of time in each scenario may cause a slight overestimation of costs in the scenarios with promotion of renewable energy. On the other hand it keeps things simple because an optimization with respect to the emission path is not necessary.

yields

$$\begin{aligned}\Delta I_e &= \frac{\tau_{max}}{2\left(1-\frac{1}{\varphi_{max}}\right)E_{90}^2}\left[\left(S_{ETS}+\Delta S_{ETS}\right)^2 - S_{ETS}^2\right]E_{FES} \\ &= \frac{\tau_{max}}{2\left(1-\frac{1}{\varphi_{max}}\right)E_{90}^2}\Delta S_{ETS}\left(2S_{ETS}+\Delta S_{ETS}\right)E_{FES}.\end{aligned} \tag{21}$$

This allows to calculate

$$\Delta\tau = \frac{\Delta I_e}{E}. \tag{22}$$

Since Eq. 20 – 22 contain state variables, the reduction of additional depreciation by a promotion of RES changes the stable path to the equilibrium. This introduces an iterative calculation process. The result is a change in utility when compared to the reference case.

2.4.1 Strategies to promote renewable energy

In the following we implement two different promotion strategies to examine their impact on extra cost caused by additional depreciation of fossil-based power plants. First, the regulator uses a certain share X_{RES} of investments I_e to promote RES. Second, the regulator actively tries to reduce additional depreciation costs.

The first promotion strategy with a fixed share of investments is implemented in the model by X_{RES}. X_{RES}=0.1 for instance means to take 10 % of total investments for emission reduction I_e for the promotion of RES.[4] This promotion strategy does not directly address extra costs, which are caused by additional depreciations. A reduction of depreciation costs is only a side effect.

In contrast, extra cost of additional depreciation can be directly addressed if the promotion of RES is appropriately regulated. Additional depreciation costs for instance could be completely avoided if the reduction of fossil capacity did not lead to a depreciation rate higher than δ_E. That is $\delta_{FES}(t) \leq \delta_E$. To check if this restriction can be fulfilled we need to know $E_{FES}(t = 2005)$, since the ETS is introduced in 2005 and $E_{FES}(t = 2050)$, as the long-run objective shall be achieved in 2050. $E_{FES}(t = 2005)$ is known because it is the starting point of the simulation. $E_{FES}(t = 2050)$ is determined by the long-run objective which restricts emissions to a certain share χ of the reference year. Considering the efficiency factor φ_{max}, which specifies how much more electricity can be generated emitting the same amount of emissions in comparison to the reference year, we receive $E_{FES}(t = 2050) = E_{90}\varphi_{max}\chi$. If we approximate the

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[4] X_{RES} is not the final share of investments for RES because the afterward compensation of emissions according to Eq. 20 and 22 slightly reduces this share.

depreciation of fossil capacity by an exponential function, $\delta_{FES}(t) \leq \delta_E$ is fulfilled if

$$E_{FES}(2005) \lesssim E_{90}\varphi_{max}\chi e^{\delta_E(2050-2005)} \tag{23}$$

holds.

For ambitious long-run emission objectives fossil generation capacity may decrease so much that Inequality 23 cannot hold. Nevertheless, depreciation costs can be reduced if we generalize Inequality 23 yielding

$$E_{FES} \lesssim E_{90}\varphi_{max}\chi e^{\delta_E + \Delta\delta_E \frac{E}{E_{FES}}(2050-t)} \qquad \forall t \leq 2050. \tag{24}$$

For $\Delta\delta_E$ equal to zero additional depreciation costs vanish, as Inequality 24 includes Inequality 23 in this case. If the regulator considers Inequality 24 as additional restriction, depreciation costs can be reduced. However, this requires lower E_{FES} which means more E_{RES} resulting in higher expenses. Therefore, Inequality 24 only holds if investments in RES do not exceed I_e. Thus, we restrict the effect of Inequality 24 demanding that investments in RES must not exceed I_e. This avoids a reduction of depreciation at any cost. Nevertheless, this is not a mandatory restriction.

2.5 Parametrization of the model

All parameter values which we used for the different scenarios are given in Table 3 in Appendix B. Parameters should be in a plausible range to allow meaningful results. Since a part of the basic structure of the model relies on the work of Edenhofer *et al.* (2012), it makes sense to use their parametrization if possible. This applies to parameters of the macroeconomic production function (Eq. 3), capital accumulation (Eq. 4) and investments in labor efficiency (Eq. 5).

With respect to the macroeconomic production function Edenhofer *et al.* (2012) suggest that all production factors should be essential. This requires an elasticity of substitution in the range between zero and one ($1 > \sigma = 1/(1+\theta) > 0$). Thus, Edenhofer *et al.* (2012) suggest a CES-production function with $\theta = 1.5$ as plausible choice while a Cobb-Douglas production function does not work in this framework. As we agree with this approach we take the same value.

2.5.1 Ratio of the multipliers Φ_Y, Φ_E

In contrast to Edenhofer *et al.* (2012) we do not aim at the calibration to real GDP data. Therefore, Φ_Y may have any positive value. However, the ratio of Φ_Y/Φ_E has two effects. On the one hand it influences the price elasticity of electricity demand. On the other hand it determines the share of electricity generation on total output.

The price elasticity of electricity demand is very inelastic because substitutes for electricity are difficult to find. The elasticity depends on the time horizon and the magnitude of the price variation. In literature we can find a huge range of elasticities for different regions. Paul *et al.* (2009) find short-term elasticities between -0.01 and -0.22 for different regions in the US while long-run elasticities vary from -0.02 to -0.56. For the Netherlands Boonekamp (2007) finds a price elasticity between -0.05 and -0.07 for a price increase of 100 %. For a ratio $\Phi_Y/\Phi_E = 100$ with Φ_E normalized to one we obtain an elasticity of about -0.09 for the introduction of τ_{max} equals two, which means a quasi tax rate on electricity of 200 %. This is within the plausible range of long-run elasticities.

For this ratio of Φ_Y and Φ_E we obtain a share of electricity generation on total output of a bit more than one percent (see Table 1). This result can be compared to empirical data of Germany as an example. For 2013 we find a German GDP of about 2,821 billion € (Federal Statistical Office, 2016). The gross value added for the electricity sector was 42.5 billion € (Federal Statistical Office, 2015). The result is a share of electricity generation on GDP of 1.5 %. This is higher than the share in the model, but we do not want to exactly calibrate the model to a certain economy. The share of electricity generation on GDP varies from economy to economy as discussed for the price elasticity. Thus, the ratio $\Phi_Y/\Phi_E = 100$ is in a plausible range when compared to data of real economies.

2.5.2 Time preference rate ρ

The pure time preference rate ρ is set to 0.02, although Edenhofer *et al.* (2012) use 0.01 instead, and we accept most of their parametrization. After publication of the *Stern Review* (Stern, 2007) there was a broad discussion about how results of the report were driven by the used near-zero time preference rate. Nordhaus (2007) argues for a time preference rate which leads, based on the Keynes-Ramsey-Rule, to an adequate rate on return. Based on this argument a pure time preference rate of 0.01 seems too low.

In addition to these considerations the effect of the time preference rate also justifies a higher value. The lower the time preference rate, the higher is the effect of the future on today's consumption. An extremely low time preference rate thus leads to an extremely high saving rate. We examine the benefits of an early investment in RES with respect to costs of the future decrease of fossil capacity. Thus, a low time preference rate would pronounce these benefits to a larger extent. Choosing a rather high time preference rate allows a conservative approach to evaluate the benefits of a promotion of RES.

2.5.3 Electricity generation

We assume capital and labor to be of equal importance for the generation of electricity, because further information is not available yet. The distribution parameters ξ_E^L, ξ_E^K are both set to 0.5. However, the substitution of labor and capital should be a bit easier than in the production function of the generic output Y because highly standardized processes in the electricity sector should allow an easier substitution of labor and capital.

Thus, we choose $\tilde{\theta} = 0.75$ what makes the production function a bit more Cobb-Douglas-like. Nevertheless, both input factors are essential since $1 > \sigma = 0.6 > 0$. In contrast to the depreciation rate of capital δ_K, which is set to standard five percent, we assume a depreciation rate of electricity δ_E of three percent. This is a concession to the long lifetimes of fossil power plants which are 40 years and more (Tidball *et al.*, 2010).

2.5.4 Reduction of CO_2 emissions

Electricity generation from FES was often based on coal power plants in the reference year 1990. These power plants emit about 800 to 1100 g CO_2 per kWh while power plants, which are fired with natural gas, only emit 350 till 550 g/kWh (Wagner *et al.*, 2007). A (theoretical) substitution of coal by natural gas could cut emissions by half. If heat is cogenerated with electricity, emissions could decrease more. All in all we assume that emissions in the fossil sector can be decreased by 75 % before renewable energy becomes the cheaper alternative. Thus, we set φ_{max} equal to four. This is a rather high estimate, which avoids an overestimation of renewables' necessity allowing conservative results with respect to the welfare impact of RES.

The EU agreed to cut emissions by 80 – 95 % of the 1990 level till 2050 (Council of the EU, 2009). This long-run emission objective is implemented in the model by χ which corresponds to the remaining long-run emission share with respect to 1990. We calculate four different scenarios with χ equals 0.05, 0.10, 0.15 and 0.20 to reflect the EU objective.

τ_{max} is set to 2 which means a convergence of the quasi tax rate to this value after the year 2050. It implies that an increase of the electricity price by 200 % would be sufficient to cover all costs for intended emission reduction. From 2010 till 2013 the spot market price for base load electricity in Germany was 44 €/MWh on average (Fraunhofer ISE, 2018). The feed in tariffs for wind power plants and big solar power plants as main renewables in Germany at this point already are below 90 €/MWh (Renewable Energies Act, 2017). Thus, a long-run price supplement of 200 % seems to be sufficient for the necessary development of renewable energy including grid and storage facilities.

2.6 Solution of the Model

We developed an endogenous growth model which is based on four control variables and three state variables associated with three co-state variables. This creates a problem in ten dimensions with six dynamic and four algebraic equations. The system is unfortunately too complex to find the balanced growth path analytically. This calls for a numerical solution. Trimborn *et al.* (2008) describe a matrix operation which allows to convert such a differential-algebraic system into an algebraic system in a first step. Nevertheless, the detection of the balanced growth path is still a challenging task because it means to find a root in ten dimensions.

The model is solved with the relaxation algorithm which was first applied for economic growth models by Trimborn *et al.* (2008). To apply this algorithm we first calculate the balanced growth path and the long-run growth rates on the stable manifold. This allows a coordination transformation to convert the infinite time horizon into a finite one. The relaxation algorithm itself calculates the optimal adjustment to the stable manifold. It makes a guess of the solution while resulting errors are minimized in an iterative process using respective gradients. The calculations are established with the help of a program code which is provided by Trimborn *et al.* (2008).

In contrast to the widespread backward shooting technique the relaxation algorithm allows the implementation of continuous time dependent shocks. This feature is essential for the solution of our model because the additional depreciation, which is caused by the decrease of fossil capacity, is a time dependent endogenous shock. Thus, δ_E is not a constant parameter anymore. The implementation of τ also requires an algorithm which can deal with time dependent shocks because τ is linearly increasing with time till the long-run objective is achieved and converges to the predetermined value τ_{max} in the long-run. Every change of δ_E and τ has an impact on the state variables and vice versa. Therefore, the solution of the model is an iterative process which requires the relaxation algorithm of Trimborn *et al.* (2008) many times and is thus very time consuming. Furthermore, we modified the relax algorithm to speed up and stabilize the calculation process. We made the first guess for a solution of the transition process based on the last iteration.

3 Results

The starting point of all scenario calculations is the moment before the regulator introduces an ETS and the promotion of RES. In our model this corresponds to the year 2005. We assume that the economy was on the balanced growth path (BGP) from the reference year 1990 until 2005. The state variables physical capital K, electricity E and labor efficiency A define the starting point. Assuming no abatement of emissions we can calculate a point on the balanced growth path which we define as the starting point. The calculated state variables are the starting values for all following scenario calculations (see Table 1).

Y	3,073.751
K	354.121
E	31.438
A	24.746
λ_K	$3.45 \cdot 10^{-4}$
λ_A	2.000
λ_E	0.018

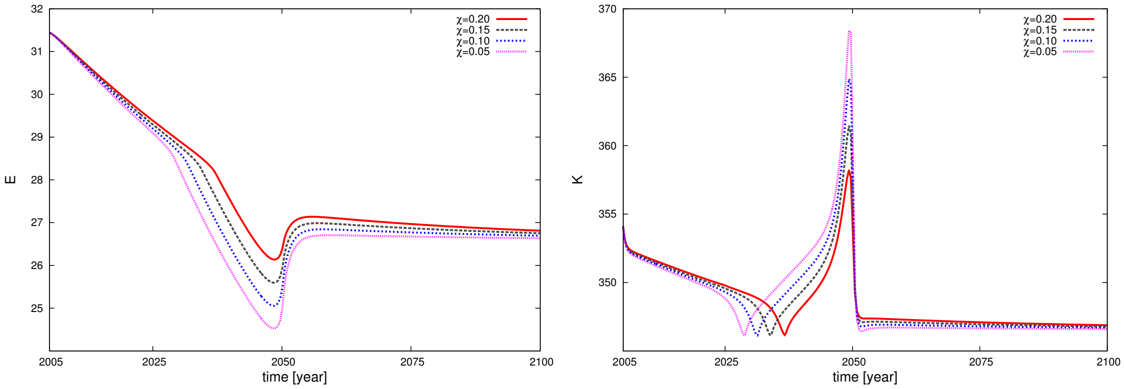
Table 1: Starting values (year 2005) of output Y, state variables capital K, electricity E, labor efficiency A and co-state variables (shadow prices).

The balanced growth rate is γ=2.1 % for each of the state variables. Since economy is assumed to follow the BGP at least since 1990 the starting point and the growth rate allow to calculate the amount of electricity which was generated in 1990 in our model economy yielding $E_{90} = E_{2005} \cdot \mathrm{e}^{-\gamma 15} = 23.07$. Since abatements do not start before 2005 the emission factor ϵ remains constant during this period.

The shadow prices indicate a very different shortage of the state variables. While labor efficiency A is the limiting factor of the economy, physical capital K is linked to the lowest shadow price indicating a rather low shortage.

3.1 The reference scenario

Our reference scenario corresponds to a perfect ETS-only-strategy which induces CO_2 abatement with the lowest MAC. We calculate scenarios with a remaining share of emissions χ equal to 5, 10, 15, and 20 % when compared to the 1990 emissions level. This reflects the long-run emission objective of the EU to reduce emissions by 80 – 95 % till 2050 with respect to 1990 (Council of the EU, 2009).



(a) Behavior of total electricity E from 2005 until the end of the century.

(b) Behavior of physical capital K from 2005 until the end of the century.

Figure 2: Impact of emission reduction on electricity generation and physical capital. Coordinates are scale-adjusted.

Figure 2 shows the development of electricity E and physical capital K after introduction of the ETS in 2005 until the end of the century in scale-adjusted coordinates. Transformation to non-scale-adjusted coordinates requires multiplication with $e^{\gamma t}$ whereas γ is the balanced growth rate of electricity and physical capital respectively. Scale-adjusted coordinates facilitate a comparison of the situation with and without an ETS because otherwise we find increasing graphs while the peculiarities almost vanish. Without introduction of an abatement policy the state variables would stay constant all the time in scale-adjusted coordinates.

We can see a decrease of total electricity generation when compared to the situation without emission abatement. The decrease becomes stronger the more stringent the long-run emission objective is (lower χ). This meets expectations as the abatement measures make electricity more expensive leading to reduced demand. Depending on the stringency of the objective, around 2030 – 2035 the decrease intensifies while after 2050 it significantly slows down. In the last years before achievement of the long-run objective we even see an increase of electricity. The reason for this behavior is that the quasi tax rate τ on electricity linearly increases till 2050 while it converges to a constant value thereafter. This means a lower growth rate for τ after 2050. It seems as if investments between 2030 and 2050 are postponed till τ grows with a lower rate.

Physical capital K also shows a decrease in comparison to the economy without emissions abatement. The decrease is weaker than the decline of electricity but similar to the behavior of electricity it also shows big changes between 2030 and 2050. Compared to the development of electricity we see a contrary behavior. After a decrease we see a strong increase of physical capital exceeding the starting level. A short time before 2050 we see a very sharp drop to a level which is only slightly decreasing thereafter.[5]

Figure 3 shows the development of the efficiency parameter A after introduction of the ETS in 2005 until the end of the century in scale-adjusted coordinates. In contrast to electricity and physical capital there is an increase of A. The introduction of CO_2 abatement has a lower impact when compared to the development of physical capital and electricity. The introduction of an abatement policy shifts investments from physical capital and electricity generation to research and development in order to achieve higher efficiency. This is a plausible reaction of the economy because it allows to use resources more efficiently.

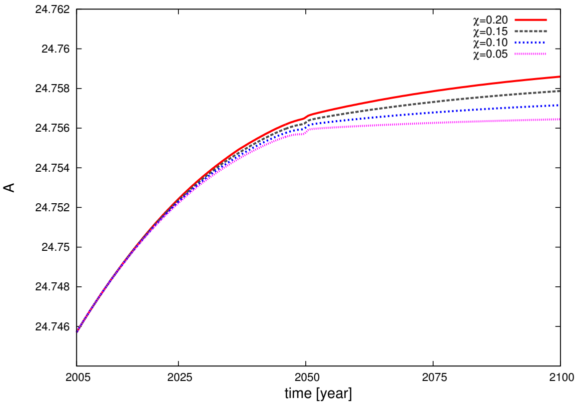


Figure 3: Behavior of the efficiency parameter A from 2005 until the end of the century.

Figure 4a shows the development of fossil electricity in non-scale-adjusted coordinates. First, we see an increase to cover increasing electricity demand. Around the year 2025 MAC_{ETS} obviously reaches MAC_{RES}. Emission reduction within the fossil sector thus reaches the maximum $S_{ETS}^{max} = \left(1 - \frac{1}{\varphi_{max}}\right) E_{90}$. Thenceforward CO_2 abatement is carried out only by substitution of FES by RES because it is the cheapest abatement measure. This leads to a strong decrease of fossil-based electricity after 2025. From 2050 the level of electricity from FES is constant because the long-run objective is achieved. We do not see further abatements in the fossil sector. The final level reflects the remaining share of emissions χ.

Figure 4b depicts the ratio of CO_2 emissions compared to CO_2 emissions in 1990. The

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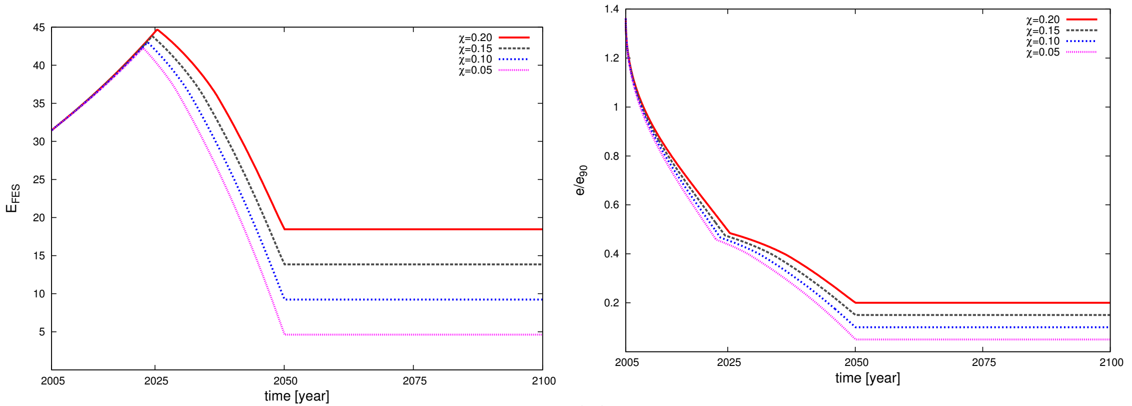
[5] This massive decline may even mean negative investments in physical capital which is not realistic. In the scenario with additional promotion of RES this effect vanishes. Thus, utility in the reference scenario is a bit overestimated when compared to an additional promotion of RES.



(a) Behavior of fossil electricity E_{FES} from 2005 until the end of the century

(b) Development of CO_2 emissions in comparison to the CO_2 emissions of the reference year 1990

Figure 4: Impact of emission reduction on electricity generation and CO_2 emissions. Coordinates are scale-adjusted.

graph is divided into two parts. Until circa 2025 emission reduction is based on abatement measures within the fossil sector while afterwards there is only a substitution of FES by RES. Therefore, the shape of the second part reflects the development of electricity generated from FES.

Money which is invested in emission reduction cannot be used for consumption. This means a welfare loss in our model because the damage which would occur from anthropogenic climate change if emissions were not reduced is not considered in the welfare function. Climate change is considered beyond welfare. The social planner wants to achieve the long-run objective because he or she expects the damage to be larger than the welfare loss due to lower consumption. It is beyond the scope of this chapter to evaluate if the long-run objective which is for instance established by the EU is optimal. According to Eq. 1, welfare corresponds to aggregated discounted utility with an infinite time horizon. The impact of investments in emission reduction on welfare is listed in Table 2.

χ	W	ΔW_{ref}	$\Delta W_{ref}/W$	W_{2050}	$\Delta W_{ref,2050}$	$\Delta W_{ref,2050}/W_{2050}$
1.00	450.18	-	-	270.76	-	-
0.20	449.58	0.60	0.13%	249.82	20.93	7.73%
0.15	449.55	0.64	0.14%	249.80	20.95	7.74%
0.10	449.51	0.67	0.15%	249.78	20.98	7.75%
0.05	449.47	0.71	0.16%	249.75	21.01	7.76%

Table 2: Welfare with emission reduction (χ<1) and without (χ=1) neglecting avoided damage of emissions. W_{2050} corresponds to welfare with a finite time horizon until 2050. ΔW_{ref} is defined by $W(\chi = 1) - W(\chi < 1)$ which applies analogously for $\Delta W_{ref,2050}$.

The relative impact of CO_2 abatement on welfare is around 0.1 % and, regarding a time horizon until 2050, around 8 %. The transition of the energy system is completed until 2050 because the model economy achieves the long-run objective until then. For this reason the impact of emission abatement on welfare is of hardly any consequence in an infinite time horizon whereas it becomes significant once welfare is considered only until 2050.

Table 2 shows that the welfare loss does not depend very much on the different remaining share of emissions χ. This might change for very high remaining shares of emissions because then objectives can be achieved without a relatively expensive substitution of fossil-based power plants. Nevertheless, renewables would enter the market after 2050 even for lax emission objectives because of an increasing demand for electricity. Since we chose $\chi \leq 0.2$ welfare losses do not vary very much with respect to χ.

3.2 Scenario with additional promotion of RES

In Section 2.4.1 we discussed two different strategies to subsidize RES. On the one hand the regulator may use a certain share X_{RES} of investments I_e to promote RES. On the other hand the regulator can actively try to minimize additional depreciation costs. To examine the impact of the two strategies we calculate the change in welfare $\Delta W = W(\chi, X_{RES\neq 0}) - W(\chi, X_{RES=0})$ to examine the impact of fixed investment shares X_{RES} and $\Delta W = W(\chi, \Delta\delta_E) - W(\chi, \Delta\delta_E = 0)$ for an active minimization of depreciation costs. While ΔW is not very meaningful the ratio $\Delta W/\Delta W_{ref}$ shows how much the welfare loss ΔW_{ref} is strengthened or weakened by a certain strategy to subsidize the use of RES.

Figure 5 shows the ratio $\Delta W/\Delta W_{ref}$ if the regulator decides to spend a fixed share X_{RES} of investments I_e for the promotion of RES. The share X_{RES} has a range from 0 to 1. $X_{RES} = 0.8$ for example means that 80 % of investments for abatement measures are directed to the promotion of RES. To keep emissions on the level of the reference scenario additional investments into abatement with lowest MAC may be required. Thus, the effective share of investments varies a bit over time and it is a bit lower than X_{RES} (see Section 2.4.1). The effective share of investments is not shown here since we are interested in the general impact rather than in details of fixed investment shares.

Figure 5 shows a ratio $\Delta W/\Delta W_{ref}$ which is mostly close to zero but always negative. This means the promotion of RES with fixed shares reduces welfare. Nevertheless, we find a local maximum for $X_{RES} \approx 0.9$. This indicates two things. First, a promotion of RES allows to decrease the additional depreciation of fossil-based power plants.

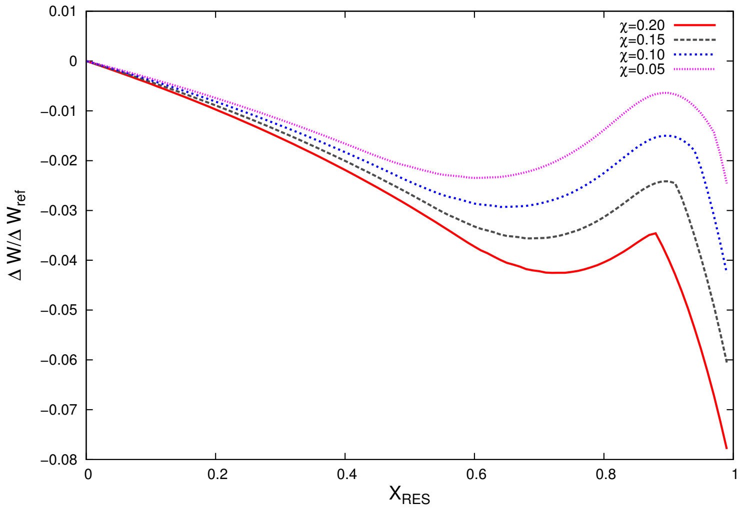


Figure 5: Scenario with a certain share X_{RES} of investments I_e to promote RES in comparison to the reference scenario. ΔW reflects the welfare change caused by the promotion of RES while ΔW_{ref} corresponds to the welfare change originated from emissions abatement in the reference scenario without subsidization of RES. The ratio $\Delta W/\Delta W_{ref}$ shows how much the welfare loss is strengthened or weakened choosing different shares X_{RES} of investments I_e. Negative values mean an increase of the welfare loss.

This has an impact on welfare. Second, this impact on welfare is higher for a stricter long-run objective (low χ). For $\chi = 0.05$ we almost find a compensation of the welfare loss induced by the early investment in RES.

Figure 6 shows the ratio $\Delta W/\Delta W_{ref}$ for a scenario in which the regulator actively tries to limit additional depreciation costs. $\Delta\delta_E$ in Figure 6 corresponds to the additional depreciation rate the regulator is willing to permit. However, $\Delta\delta_E$ may exceed this threshold level at specific dates because the regulator has to consider that investments in RES must not exceed $\tau \cdot E$. Thus, $\Delta\delta_E$ is the pursued threshold value under the restriction of the budget constraint. For instance $\Delta\delta_E = 0$ means the regulator tries to avoid any additional depreciation leading to $\tilde{\delta}_E = \delta_E = 0.03$.

In contrast to the scenario with fixed shares of investments (see Figure 5) the ratio $\Delta W/\Delta W_{ref}$ is also in the positive range (see Figure 6). This means a strategy which tries to actively reduce the additional depreciation of fossil-based power plants by a promotion of RES can lead to higher welfare than an ETS-only strategy. This statement applies for all long-run objectives which we analyze in this chapter ($\chi = 0.05$ – 0.20).

For stricter long-run objectives the welfare maximum is shifted to lower values of $\Delta\delta_E$. The reason for this behavior is the different intensity to shut down fossil-based power

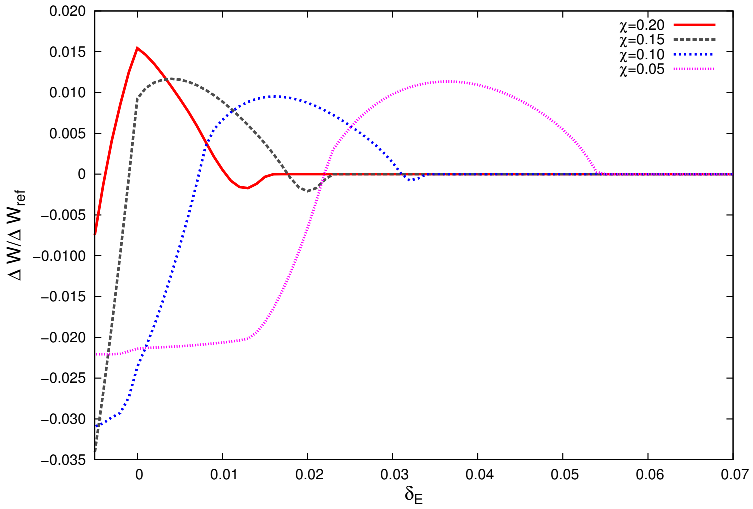


Figure 6: Scenario with additional promotion of RES to limit the depreciation of fossil-based power plants in comparison to the reference scenario. ΔW reflects the welfare change caused by the promotion of RES while ΔW_{ref} corresponds to the welfare change originated from emissions abatement in the reference scenario without subsidization of RES. The ratio $\Delta W/\Delta W_{ref}$ shows how much the welfare loss ΔW_{ref} is strengthened or weakened trying to limit additional depreciation to $\Delta\delta_E$. Negative values mean an increase of the welfare loss while positive values indicate a shrinking welfare loss.

plants. If there is a very strict long-run objective ($\chi = 0.05$) more fossil-based power plants need to shut down resulting in a higher depreciation rate $\tilde{\delta}_E$. Thus, the impact of a limitation of additional depreciation occurs already for higher $\Delta\delta_E$ the lower χ is.

According to Figure 6, the welfare maximum is not connected to a complete avoidance of additional depreciation, but depends on the long-run objective, too. On the one hand it never makes sense to limit depreciation below the assumed standard depreciation rate $\delta_E = 0.03$. Thus, $\Delta W/\Delta W_{ref}$ is always negative for $\Delta\delta_E < 0$. On the other hand the effort of a complete avoidance of additional depreciation may overcompensate its benefits. That is why we can see lower welfare although $\Delta\delta_E$ is still positive. It makes sense to avoid additional depreciation but not at any cost.

If the social planner tries to decrease depreciation costs this has an effect on fossil electricity generation E_{FES} when compared to the reference scenario (see Figure 7). In Figure 7 $\Delta\delta_E$ is chosen for each χ to maximize $\Delta W/\Delta W_{ref}$. Compared to the ETS-only scenario (see Figure 4a) the increase of fossil electricity is limited to a shorter period of time and the increase is weaker. As expected the deconstruction of fossil-based electricity is also weaker and starts earlier.

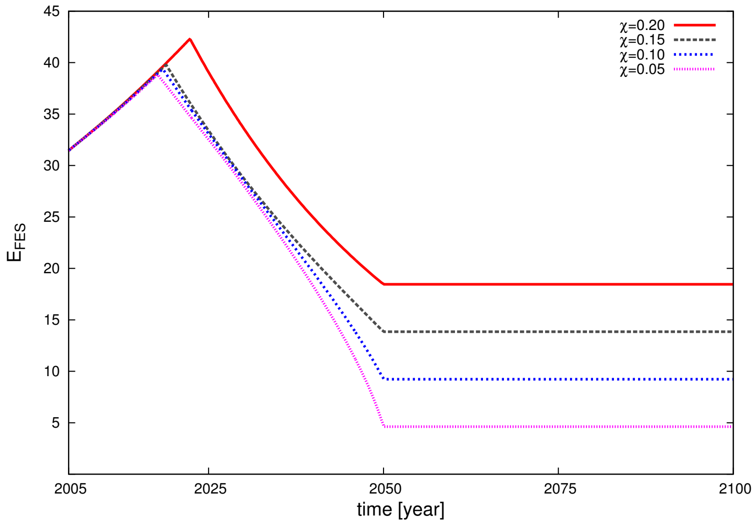


Figure 7: Development of fossil electricity E_{FES} from 2005 until the end of the century when the social planner tries to decrease depreciation costs by subsidizing RES. The graphs correspond to the value of $\Delta\delta_E$ which is assigned to the welfare maximum ($\Delta\delta_E(\chi = 0.05)$=0.036, $\Delta\delta_E(\chi = 0.10)$=0.016, $\Delta\delta_E(\chi = 0.15)$=0.004, $\Delta\delta_E(\chi = 0.20)$=0).

4 Conclusions

A promotion of RES allows their early market entry although other abatement methods face lower MAC. On the one hand this means a shift of costs to an early stage. This lowers welfare because present consumption is preferred to later consumption. On the other hand the early market entry of RES allows an elongated transition period in which fossil-based power plants are shut down and removed. This reduces additional depreciation costs.

We show that the positive effect of an elongated transition period can exceed the negative effect of the shift of costs. A promotion of RES can lead to a higher welfare than an ETS-only strategy. This result applies if the social planner specifically tries to reduce additional depreciation of fossil-based power plants. If instead an unspecific promotion of RES is introduced which means to spend a fixed share of investments for emissions abatement for the promotion of RES we find a welfare loss. However, we must take into account that our analysis focuses on the mitigation of additional depreciation while other dynamic effects (learning effects, path dependency), which may also lead to higher welfare by promoted RES, are neglected. Moreover, we assume perfect information of all market participants and no bailout of fossil generators by the social planner. Consequently there is a perfect reaction of fossil capacity reduction on renewable capacity increase in our model. Fossil-based power plants are thus shut down as soon as economically viable to minimize additional depreciation costs.

However, reality is much more complex. In Germany for example the promotion of RES has not led to the necessary shut-down of fossil-based power plants so far although RES have been already promoted since 1991. Rather, we see that excess electricity is exported (Working Group on Energy Balances, 2018) resulting in "distorted" prices at the spot market. Instead of using the chance for an optimal continuous reduction of fossil capacity as our model suggests more than 35 % of total capacity for electricity generation with hard coal was installed between 2008 and 2017 (Federal Network Agency, 2018). Only now the German government has installed a commission which will suggest a plan for a coal phase-out until the end of 2018 (CDU, CSU and FDP, 2018, p. 17, 142). It seems that this plan will also include payments for generators of fossil power plants to compensate additional depreciation costs (Federal Government, 2018).

This allows to conclude that additional depreciation has a higher impact on welfare than modeled in this chapter. The German case illustrates the difficulties to achieve the necessary reduction of fossil capacity although being in the comfortable situation of a long transition period. A shorter transition period will significantly reinforce these difficulties.

In reality we neither find a perfect ETS nor a perfect promotion of RES. In particular we do not find an omniscient social planner but rather little coordination on the way to a low carbon economy. Nevertheless, this chapter gives an insight which aspects are relevant for an optimal transition of the electricity system. It shows advantages of promoted RES as part of a comprehensive transition strategy. It underlines that the regulator must have both a strategy how to increase capacity of RES-based power plants and a strategy how to decrease fossil electricity generation. Otherwise welfare losses may occur. The question how to create incentives which allow a result as close as possible to the optimum described in this chapter is considered below as well as a question of further research.

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A Maximum conditions and Euler-equations

The maximum conditions of our maximization problem are

$$\frac{\partial \mathcal{H}}{\partial I_K} = -\frac{1}{Y_A - (I_K + RD_A + I_e)} + \lambda_K = 0 \tag{25}$$

and considering Eq. 25

$$\frac{\partial \mathcal{H}}{\partial (RD_A)} = -\lambda_K + \lambda_A \left(\frac{\gamma_A}{RD_A} \dot{A} \right) = 0, \tag{26}$$

$$\frac{\partial \mathcal{H}}{\partial u_A} = \Phi_A^{-\theta} \xi_A^L \left(\frac{Y_A}{u_A} \right)^{\theta+1} A^{-\theta} \lambda_K - \Phi_E^{-\tilde{\theta}} \xi_E^L \left(\frac{\dot{E} + \delta_E E}{1 - u_A} \right)^{\tilde{\theta}+1} A^{-\tilde{\theta}} \lambda_E = 0, \tag{27}$$

$$\frac{\partial \mathcal{H}}{\partial u_K} = \Phi_A^{-\theta} \xi_A^K \left(\frac{Y_A}{u_K} \right)^{\theta+1} K^{-\theta} \lambda_K - \Phi_E^{-\tilde{\theta}} \xi_E^K \left(\frac{\dot{E} + \delta_E E}{1 - u_K} \right)^{\tilde{\theta}+1} K^{-\tilde{\theta}} \lambda_E = 0. \tag{28}$$

The respective Euler-equations are given by

$$\begin{aligned} \dot{\lambda}_K = & \left[\rho + \delta_A - \Phi_A^{-\theta} \xi_A^K u_K^{-\theta} \left(\frac{Y_A}{K} \right)^{\theta+1} \right] \lambda_K \\ & - \Phi_E^{-\tilde{\theta}} \xi_E^K \left(\frac{\dot{E} + \delta_E E}{K} \right)^{\tilde{\theta}+1} (1 - u_K)^{-\tilde{\theta}} \lambda_E, \end{aligned} \tag{29}$$

$$\begin{aligned} \dot{\lambda}_A = & \left[\left(\Phi_A^{-\theta} \xi_A^L \gamma_A \left(\frac{Y_A}{u_A A} \right)^{\theta} - 1 \right) \alpha_A^{RD} \left(\frac{RD_A}{Y_A} \right)^{\gamma_A} + \rho \right] \lambda_A \\ & - \Phi_A^{-\theta} \xi_A^L (u_A)^{-\theta} \left(\frac{Y_A}{A} \right)^{\theta+1} \lambda_K - \Phi_E^{-\tilde{\theta}} \xi_E^L \left(\frac{\dot{E} + \delta_E E}{A} \right)^{\tilde{\theta}+1} (1 - u_A)^{-\tilde{\theta}} \lambda_E, \end{aligned} \tag{30}$$

$$\dot{\lambda}_E = (\rho + \delta_E) \lambda_E + \left[\tau - \Phi_A^{-\theta} \xi_A^E \left(\frac{Y_A}{E} \right)^{\theta+1} \right] \lambda_K. \tag{31}$$

B Parameter values

parameter	value
L	1
ρ	0.02
Φ_Y	100
ξ_Y^A	0.66
ξ_Y^E	0.04
ξ_Y^K	0.3
θ	1.5
δ_K	0.05
α_A^{RD}	0.024
γ_A	0.05
Φ_E	1
ξ_E^A	0.5
ξ_E^K	0.5
$\tilde{\theta}$	0.75
δ_E	0.03
τ_{max}	2
φ_{max}	4
X_{RES}	0 – 1
χ	0.05, 0.10, 0.15, 0.20

Table 3: Parameter values used in the model