Induced technological change and its importance for the energy transition

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Abstract

This thesis investigates the substitution of fossil energy by renewable resources. We compare two scenarios in which technological change is either endogenous - meaning that technological progress can be influenced - or exogenous, where technological change increases over time. We distinguish two states of the world. In the first state, no measures are taken against global warming (business as usual). This state is called the Market Equilibrium. In the second state, the Social Optimum, the negative impact on social welfare due to emissions as a side effect of fossil energy production is considered and action is taken against global warming. We find that in both the Market Equilibrium and the Social Optimum, the replacement of fossil with renewable energy is faster in the induced technological change scenario than the exogenous scenario. Moreover, this thesis shows that the costs of climate change mitigation have to be incurred for a shorter period of time when technological change can be influenced. Furthermore, the replacement of fossil energy is faster in the Social Optimum than in the Market Equilibrium, as in the Social Optimum the negative impact on social welfare due to emission generation is taken into account.

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1 Introduction

It is undisputed that climate change is one of the greatest threats to humanity to date. Due to anthropologically induced production of greenhouse gases, the average global temperature of our planet is increasing. International framework conventions are designed to drive climate change mitigation and promote incentives to reduce emissions. Currently, the most important framework agreement is the Paris Agreement (2015), which aims to limit average global warming to well below 2°C compared to pre-industrial levels, with the goal to limit the temperature increase to 1.5°C above pre-industrial levels. Significant global emission reductions are required to achieve this goal.

GHG[1]-emission reductions have the character of a public good, since they are non-excludable and non-rivalrous. This means that every other actor benefits from a reduction in GHG-emissions of one actor. No one can be excluded from the positive effect of reducing emissions, and reducing one actor's emissions does not limit another actor's reduction. This creates an incentive to free-ride, since an actor can benefit from the emission reductions of other actors without reducing emissions themselves. As a consequence, more emissions are emitted globally than would be beneficial to the global population.

One important solution to reduce GHG-emissions is technological change. Technological improvement can reduce the emissions that are emitted when the technology is used. In this thesis, we focus on technologies for energy production. Technology is not only a possible solution to combat global climate change, but also the cause of the problem (Jaffe et al. 2002). The combustion of fossil energy, for example by gasoline-powered cars, produces carbon dioxide emissions, the main greenhouse gas. These emissions can be reduced, for

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[1] Greenhouse Gas

instance through more energy-efficient combustion technologies or through the development of renewable technologies such as wind turbines and solar power. In addition, technologies such as air conditioning and changes in the construction of buildings can help the population adapt to climate change (Rip/Kemp 1998).

In the past, economists in the field of climate have included technological change in their models. However, most of these models do not consider that technological change itself can be influenced. These models deal with optimal climate policy under the assumption of exogenous technological change. This means that technological change increases over time without being influenced by human action. This assumption leads to an overestimation of the cost of emissions reductions because it does not account for the potential for technological change to reduce the cost of fossil-free technologies as progress is made in those technologies. The resulting policy recommendation should be interpreted with caution, as the impact on technology is not considered.

In reality, it is evident that technological change can be influenced by human action. Hence, technical progress is induced. Newer economic models studying climate change often include the assumption that technological change is induced. Different economic models already exist that include induced technological change in the context of the energy sector. However, our model differs from them in that it is kept as simple as possible and at the same time clearly illustrates the difference between exogenous and induced technological change. Our research question is formulated as follows:

> *How will induced technological change influence the energy transition and how strong must the political influence be to ensure that fossil energy production is replaced by renewable energies early enough to tackle the climate crisis?*

To answer this question, we construct an economic model that allows to compare exogenous and induced technological change. We look at the scenario where the negative externalities caused by emission production are not taken into account by the market participants. This scenario is called the Market Equilibrium and can be considered as the business-as-usual path. Then, the scenario is examined in which the negative effects of emissions are fully taken into account. This scenario is called the Social Optimum. By comparing those two scenarios, it is possible to determine the optimal climate policy (for example a carbon tax) to ensure that fossil energy production is replaced early enough to reach the 2°C-goal. In both scenarios, we show how the energy transition evolves if exogenous or induced technological change is assumed.

The thesis is structured as follows. Section 2 reviews the literature dealing with energy transition. Both the literature dealing with exogenous technological change and literature assuming induced technological change are considered. Section 3 explains the model economy and introduces two different fossil energy replacement paths. Section 4 explores and calculates the difference between exogenous and induced technological change in more detail. Section 5 presents our results in form of a numerical illustration. Furthermore, a sensitivity analysis is presented to show how the results change if the parameters change. Section 6 reviews the results and discusses the limitations of the model. Finally, Section 7 concludes the thesis.

2 Literature Review

In the past, technological change was largely treated as an exogenous process. One of the first integrated assessment models[2] was established by William Nordhaus (1994). In his model, he combines economic growth with the production of greenhouse gas emissions, concentrations in the atmosphere, and the resulting environmental damage. Essentially, the model leads to the optimal time path of economic growth, defined as the path that yields the greatest net present value of wealth. He assumes that technological change is unaffected by policy choices, hence it is exogenous. Nordhaus's model examines several approaches to climate policy: no controls, economic optimization, geoengineering, stabilization of emissions and climate, and a ten-year delay in implementing climate measures. We follow his approach, but only include two states in our model: no climate policy (Market Equilibrium) or optimal climate policy (Social Optimum).

Tahvonen (1997) studies the optimal exploitation of fossil fuels, while considering the negative impact the burning of fossil fuel has on the welfare function of the population. In his model there is an alternative energy source based on renewable resources which does not cause any damage. His results show that in an optimal energy consumption strategy, both energy sources are consumed simultaneously. The consumption of fossil fuels decreases over time and the consumption of renewable resources increases. But the paper neglects technological progress and the influence of market changes on technological change. Similar to Tahvonen, our model includes the damages to society from emissions, and there are two forms of energy, one based on fossil

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[2] An integrated assessment model combines scientific and socio-economic aspects in order to examine how human development and societal decisions interact with and influence the natural environment. These include the laws of physics, as well as the changing habits and preferences that drive human society. In order to combat climate change, these models can be very useful, especially for political decisions.

fuels and one based on renewable resources, whereas the damage to society only occurs in the production of the fossil fuel form of energy.

Van der Ploeg and Withagen (2014) examine the optimal climate policy in a model with exhausting oil reserves, an infinitely elastic supply of renewable energies, storage-dependent oil production costs and convex climate damage. They conclude that with a lower discount rate, less oil will be produced, and renewables will be introduced more quickly. They also show that subsidizing renewables (without a carbon tax) induces more oil to be left in the ground and a quicker transition to renewables, but oil is depleted more rapidly initially. In our model, an optimal carbon tax is introduced too. But we mainly compare the trajectory of the tax between the induced and exogenous scenarios.

Although many environmental economists do not consider the influence of human actions on technological progress in their models, it is evident that technological progress responds to human influences and does not simply increase with the passage of time. Human behavior can create economic incentives for more extensive research and development aimed at discovering new production techniques or improving existing techniques that produce less carbon. In addition, the use of the technology itself can also lead to improvements in the technology, as knowledge is automatically acquired through the usage. The importance of induced technological change on technical progress and the resulting emission reduction has already been examined in several studies.

One important paper for this thesis is the paper from Acemoglu et al. (2012), where they suggest that, under the condition that inputs are sufficiently substitutable, a combination of temporary research subsidies and carbon taxes can successfully redirect technological change towards clean technologies. They argue that these measures need only apply for a limited period of time, because once clean technologies are sufficiently advanced, research would be directed towards them without further government intervention. This thesis follows their results and shows that climate policy only needs to be implemented until fossil energy has disappeared from the market if no measures are taken against climate change. However, this study differs from Acemoglu's paper by comparing the exogenous and induced scenario of technological change. Therein, we show that measures against climate change need to be implemented for less time if the influence of human action on technological change is taken into account.

Moreover, Golosov et al. (2014) formulate a model that considers the world as a unitary region in which there is a global externality from emissions of carbon dioxide that arise as a by-product of fossil fuel use. The model provides a formula that shows how high the optimal tax on carbon emissions must be in order to follow the optimal path. The formula also indicates that the damage caused by emissions is proportional to current GDP, with the proportion depending on three factors: Discounting, expected damage elasticity (what percentage of output flow is lost to the atmosphere for an additional unit of carbon), and the structure of carbon depreciation in the atmosphere. They conclude that coal, not petroleum, poses the greatest threat to economic well-being, largely due to its abundance. They also find that the cost of inaction is particularly sensitive to assumptions about the substitutability of different energy sources and technological progress. Our model also assumes that the world is a unitary region in which there is an externality from emissions arising from the production of fossil energy. However, we do not examine how the damage on society changes with different conditions, but how the optimal replacement of fossil energy with renewable energy changes, if technological change is induced. We also examine how this pathway changes with different values of damage.

Another important paper for this thesis is the paper from Acemoglu et al. (2016), where they develop a microeconomic model in which clean and dirty technologies compete in production and innovation. If dirty technologies are more advanced from the start, the potential transition to clean technologies can be difficult because clean research has to overcome several stages to catch up with the dirty technology. Furthermore, this lag hinders research efforts directed towards clean technologies. Similar to Acemoglu et al., our model shows that the replacement of fossil energy by renewable resources is slower, if fossil energy has a higher market share in the beginning. But no matter which scenario is considered, fossil energy will be fully replaced by renewable energy at some point in time.

3 Model specification

We introduce a simple model of technology transition to analyze the difference between induced and exogenous technological progress.

3.1 Model economy

In the model economy, there are two representative firms, both producing energy. The firms operate under perfect competition. One firm produces energy with fossil fuel, while the other generates energy with renewable resources. The production of energy at time t is defined as X_t, where $X_{f,t}$ and $X_{r,t}$ represent the energy production in the fossil fuel and renewable sector. The production functions of the two different firms are defined as follows:

$$X_{f,t} = \phi_t {L_{f,t}}^u \tag{1}$$

$$X_{r,t} = \psi_t {L_{r,t}}^v \tag{2}$$

There is no capital stock in the energy production. The amount of energy output solely depends on the labor input. With a higher labor input, more energy can be produced in the respective sector. $L_{f,t}$ and $L_{r,t}$ represent the labor at time t in the fossil and renewable sector. The parameters u and v influence how much production output is generated with labor input. We assume that the relationship between labor input and fossil fuel production is linear. It follows that marginal returns are constant in the fossil fuel sector. For example, coal-fired power plants produce energy regardless of their location. When a new coal-fired power plant is built, the amount of energy produced should increase linearly with the number of coal-fired power plants. In contrast, the relationship between labor input and renewable energy production changes with different labor inputs. The marginal productivity of an additional unit of labor steadily decreases. The first wind turbines are installed at the windiest sites, and wind conditions are less ideal for additional wind turbines because the windiest sites are already occupied. This leads to diminishing marginal returns in the renewable energy sector. To include this assumption in the model, we set u to 1 and v to 0.5.

Moreover, more energy can be produced per unit of labor input if the respective production technology improves. We speak of technological progress when more energy can be produced per unit of labor input. The parameters ϕ_t and ψ_t denote the technological level at time t in the fossil, respectively renewable energy sector. If they increase, one unit of production needs less units of labor. Thus, the efficiency of production increases. How technological change proceeds, differs in the induced technological change scenario and the exogenous one. Assuming exogenous technological change, technical progress proceeds automatically with the passage of time. Consequently, progress cannot be influenced by production decisions and is taken as given. In the scenario of induced technological change, the more labor is invested in one sector, the more progress is generated in the according sector. With a higher labor input, there is a greater learning-by-doing effect. As Romer (1990) stated, technological change arises from intentional actions by people responding to market incentives. This does not mean that everyone who contributes to technological change is motivated by market incentives. For example, research by a university on a technology that is not induced by market incentives may improve the according technology. Nevertheless, market incentives play an essential role in the process of technology improvement because the actions of market participants can lead to technical progress without directly investing research in it. New knowledge can be acquired through the experience of using the technology. This learning-by-doing effect is considered in the induced technological change scenario through the fact that an increase in labor input leads to a stimulation of technological change and therefore to an increase in production.

In the model economy, there exists one representative household, which derives monotonically increasing utility from energy production. As energy is the only commodity in our economy, the household spends all income on purchasing energy. For the household, it does not matter if fossil or renewable energy is consumed. Consequently, the two forms of energy are perfect substitutes. The household provides labor to produce energy. The total amount of labor provided is standardized to 1, meaning that $L_{f,t} + L_{r,t} = 1$. This assumption simplifies the model and seems plausible since the amount of labor used in the energy sector does not change much over time. The household derives wage income for working in the two representative firms and the firms generate a profit by selling energy, whereas the two firms are owned by the representative household. Thus, the budget constraint of the household is characterized by:

$$p_t \phi_t {L_{f,t}}^u + p_t \psi_t {L_{r,t}}^v \leq w_t L_{f,t} + w_t L_{r,t} + \pi_{f,t} + \pi_{r,t} \tag{3}$$

The terms $\pi_{f,t}$ and $\pi_{r,t}$ determine the profit the fossil, respectively renewable firm earns from the sale of produced energy at time t. p_t stands for the market price for energy, where the price for fossil energy is the same as for renewable energy. This follows from the competitive market equilibrium, since the two forms of energy are perfect substitutes in our model. If the price of one energy form was higher, consumers would only consume the other energy because it is cheaper and provides them with the same benefit. As a result, the producers of the more expensive energy would lower the price until it is exactly the same as the price of the technology. Without loss of generality, we normalize the price p_t to 1, as this simplifies the calculation and interpretation. In addition, w_t represents the wages that workers receive for producing energy. Again, wages must be equal in both sectors, since if wages were unequal, all workers would want to work in the sector where the wage is higher and no workers would want to work in the sector with the lower wage.

Furthermore, we assume that there exists an end of time. This means time does not continue to infinity. We expect that the end of time is very far in the future and that this time has almost no value for today's population. We define this point in time as T, meaning that time runs from 0 to T and t can be every period in between. The difference between t and $t+1$ is called one period. We define one period as 5 years and set T to 90. Period 0 represents the year 2020. This means that the end of time will occur in 450 years. Since we are likely to phase out fossil fuels much sooner to avert the climate crisis, the time frame of 450 years seems sufficiently distant in the future.

3.2 Externalities

Three externalities appear in the model environment. One externality arises from pollution in the form of carbon emitted by the combustion of fossil fuels, which has a negative effect on the global population. We follow Golosov et al. (2014) and use the carbon budget approach, meaning that we consider total emissions generated since the industrial revolution until today. The damage to society from emissions production is a function of globally and temporally aggregated emissions. How the production of fossil fuel energy increases total global emissions is given in the following equation, whereas E_t is defined as total global cumulative emissions at time t.

$$E_t = E_{t-1} + \alpha \phi_t {L_{f,t}}^u \tag{4}$$

The term α represents carbon intensity and determines by how much total global cumulative emissions increase with an additional unit of produced fossil energy. How welfare decreases if emissions increase is determined by β.

The damage in period t is therefore given as $-\beta E_t$. The renewable sector generates no pollution because the production of renewable energy produces no carbon.

Another externality is the negative effect of a change in labor share between the sectors on total welfare. Certain skills are technology specific. For instance, a worker in a coal-fired power plant does not have knowledge about wind turbines. If labor input changes in both sectors, the generated costs are called structural change costs. Even though these costs occur in the Market Equilibrium and in the Social Optimum, they are only considered in the latter. Although we neglect capital in our model, the importance of capital is included in the structural change costs, since a change of labor in the sectors also entails capital losses for the firms. How structural change costs influence social welfare is given by $-\theta(L_{f,t} - L_{f,t-1})^2$, whereas θ indicates the intensity of the negative effect on welfare. A change in $L_{r,t}$ and $L_{f,t}$ means that the labor share changes in the sectors, which generates costs. If the difference between $L_{f,t}$ and $L_{f,t-1}$ differs from 0, this has a negative effect on the welfare of society. It is irrelevant whether we use $L_{f,t}$ or $L_{r,t}$ in the term, since we have defined $L_{f,t} = 1 - L_{r,t}$. As a consequence, the absolute difference between $L_{f,t} - L_{f,t-1}$ is the same as between $L_{r,t} - L_{r,t-1}$. Squaring the term $\theta(L_{f,t} - L_{f,t-1})$ results in a negative effect from the change in labor input in every case.

The third externality only occurs in the induced technological change scenario, as a change in labor input in a sector affects technological progress. If labor input in one sector is higher, technological change proceeds faster in that sector. Hence, it is a positive externality. In the exogenous change scenario, labor input has no effect on technological change. Consequently, no externality occurs. In chapter 4, this externality is explained in detail.

3.3 Market Equilibrium vs Social Optimum

In our model, we distinguish between the Market Equilibrium and the Social Optimum. The Market Equilibrium represents the path of replacement of the fossil by the renewable sector in the market without considering negative externalities arising from the combustion of fossil fuel or from structural costs (business as usual). In every period, firms in both sectors maximize their profits under the assumption that the market is perfectly competitive. The representative household maximizes its utility arising from the consumption of energy in every period. The price for energy is identical for fossil and renewable energy, because they are both perfect substitutes. The wage the household earns for producing energy is also the same in both sectors. Moreover, total labor demand needs to equal total labor supply in every period. The profit functions of the fossil fuel and renewable firm are defined as follows:

$$\pi_{f,t} = p_t \phi_t {L_{f,t}}^u - w_t L_{f,t} \tag{5}$$

$$\pi_{r,t} = p_t \psi_t {L_{r,t}}^v - w_t L_{r,t} \tag{6}$$

In the Social Optimum, there exists a social planner who maximizes total social welfare for the whole society. The externalities arising from the combustion of fossil fuel and from structural costs are included in the maximization problem. The social welfare is defined as the net present value of the discounted sum of per-period welfare and is indicated by W. The calculation of social welfare is determined as:

$$\begin{aligned} W = \quad & \textstyle\sum_{n=1}^{T} \delta^{t-1}[\phi_t {L_{f,t}}^u + \psi_t {L_{r,t}}^v - \beta E_t - \theta(L_{f,t} - L_{f,t-1})^2] \\ \text{with} \quad & E_{t+1} = E_t + \alpha \phi_t L_{f,t} \\ & L_{f,t} + L_{r,t} = 1 \end{aligned} \tag{7}$$

The term β indicates by how much social welfare decreases if cumulative emissions E_t increase by 1 unit. The discount factor δ specifies how strong the social planner devalues the next periods compared to today.

We analyze the Market Equilibrium and the Social Optimum with induced and exogenous technological change. This results in four cases:

	Market Equilibrium	Social Optimum
Exogenous technological change	Case 1	Case 2
Induced technological change	Case 3	Case 4

All four cases are investigated in our model. In the following section, first the Market Equilibrium under the exogenous and induced technological change scenario is explained, followed by the Social Optimum with both scenarios.

4 Exogenous vs induced technological change

In this section, we introduce the maximization problem of the firm and the social planner, and show how we calculate the optimal transition path from fossil to renewable energy.

4.1 Market Equilibrium

In the Market Equilibrium, producers maximize their profits of the energy production, not considering negative externalities for society arising from the combustion of fossil fuels and from structural change costs. The negative effect of structural change costs and the positive effect of the influence of labor on technical progress in the induced technological change scenario are also not taken into account. However, all three externalities occur in the Market Equilibrium as well. The fossil energy producing firm maximizes (5) with respect to $L_{f,t}$. Labor demand in the fossil sector is then given as:

$$L_{f,t} = \begin{cases} 0 & w_t > \phi_t \\ [0;1] & w_t = \phi_t \\ 1 & w_t < \phi_t \end{cases} \tag{8}$$

Since we have set u to 1, the profit function of the fossil firm is linear to labor input. Furthermore, as p_t is set to 1, the fossil firm only produces energy if $w_t \leq \phi_t$. As we assume a perfectly competitive market, it follows that w_t has to equal ϕ_t as long as the fossil firm generates energy.

The firm in the renewable sector maximizes (6) with respect to $L_{r,t}$. Labor demand in the renewable sector is given as:

$$L_{r,t} = \begin{cases} 1 & w_t > \phi_t \\ (\frac{v\psi_t}{\phi_t})^{1/1-v} & w_t = \phi_t \\ 0 & w_t < \phi_t \end{cases} \tag{9}$$

Total labor demand needs to equal total labor supply. Three possible scenarios arise: Only fossil energy or only renewable energy is produced, or both firms produce energy. As long as the fossil firm generates energy, it must be given that $w_t = \phi_t$. This case represents the short-term solution until only the renewable firm is generating energy in the market. Once the renewable firm is the only producer, the Market Equilibrium is in the long-term solution of the optimal labor division, because in the future fossil energies will have disappeared from the market. As long as both firms produce, labor inputs in the Market Equilibrium are as follows:

$$L^*_{r,t} = (\frac{v\psi_t}{\phi_t})^{1/1-v} \tag{10}$$

$$L^*_{f,t} = 1 - L^*_{r,t} \tag{11}$$

4.1.1 Exogenous technological change

In the scenario of exogenous technological change, we assume that ϕ_t and ψ_t increase automatically with the passage of time and are not influenced by the share of produced energy in the renewable or fossil fuel sector. Thus, they are not influenced by the labor share in one sector. We define the development of ϕ_t and ψ_t as follows:

$$\phi_t = \phi_{t-1}(1 + r_\phi)$$

$$\psi_t = \psi_{t-1}(1 + r_\psi)$$

The parameters r_ϕ and r_ψ are the per period rates of increase in technological change. They are determined such that reality is represented as closely as possible (section 5). The initial values ϕ_0 and ψ_0 are given. How those values are specified is explained in detail in chapter 5.1. By defining ϕ_t and ψ_t, we are able to calculate the labor shares in the renewable and fossil fuel sector in the Market Equilibrium in each period via equations (10) and (11).

4.1.2 Induced technological change

In accordance with the learning-by-doing assumption, we assume that ϕ_t and ψ_t are influenced through the labor shares $L_{f,t}$ and $L_{r,t}$ under the scenario of induced technological change. If more labor is invested into one sector, there is also a higher learning effect. Hence, technological progress increases to a greater extend. Through the fact that the value of technological change in one sector increases more if the labor share in the according sector is higher, the sector with a stronger increase of energy production benefits more from technical progress. We define the development of technical progress as follows:

$$\phi_t = \phi_{t-1} + \Delta\phi L_{r,t-1}$$

$$\psi_t = \psi_{t-1} + \Delta\psi L_{f,t-1}$$

Like in the scenario of exogenous technological change, the initial values ϕ_0 and ψ_0 are given. In the Market Equilibrium, labor share in the renewable sector in period 0 is given by: $L^*_{r,0} = (\frac{v\psi_0}{\phi_0})^{1/1-v}$. Consequently, the equilibrium labor share in the fossil fuel sector is given by $L^*_{f,0} = 1 - L^*_{r,0}$. In a next step, ϕ_1 and ψ_1 are determined through $L_{f,0}$ and $L_{r,0}$. This in turn allows ϕ_2 and ψ_2 to be calculated and so on.

4.1.3 Comparison of both scenarios

In order to compare the exogenous and induced scenario, it is necessary to consider what the difference them is. In the exogenous change scenario, technological progress constantly increases over time, while in the induced scenario, the labor input in the technology influences the progress in the respective technology. We exclude this influence in the induced scenario, such that technological change also increases at a constant rate over time. We then define $\Delta\phi$ and $\Delta\psi$ so that technological progress in both technologies is the same in both scenarios in the end of time. Thus, we ensure that technological progress is equal in both scenarios in the end of time when the influence of labor input is eliminated, meaning that ϕ_T and ψ_T have the same level. We remove the influence on technological progress in the induced scenario by setting $L_{f,t}$ and $L_{r,t}$ to $L_{f,0}$ and $L_{r,0}$:

$$\phi_t = \phi_{t-1} + \Delta\phi L_{r,0}$$
$$\psi_t = \psi_{t-1} + \Delta\psi L_{f,0}$$

Only the distribution of labor in the initial period and the technological change in the previous period influence the technological change at time t. In the exogenous technological change scenario, the levels of technical progress at time T are given by $\phi_T = \phi_0(1+r_\phi)^T$ and $\psi_T = \psi_0(1+r_\psi)^T$. In the induced scenario, if $L_{f,t}$ and $L_{r,t}$ have no effect on technical progress, the levels of technological change at time T are defined as $\phi_T = \phi_0 + T \cdot \Delta\phi \cdot L_{f,0}$ and $\psi_0 + T \cdot \Delta\psi \cdot L_{r,0}$. If technological change has to be equal in the last period, the following equations must hold:

$$\phi_0(1+r_\phi)^T = \phi_0 + T \cdot \Delta\phi \cdot L_{f,0}$$
$$\psi_0(1+r_\psi)^T = \psi_0 + T \cdot \Delta\psi \cdot L_{r,0}$$

The end of time T and the initial values of technological change are known. Therefore, it is possible to calculate $\Delta\phi$ and $\Delta\psi$. To conclude the Market Equilibrium, the values of labor share in both scenarios are determined as:

Exogenous technological change:

$$L^*_{r,t} = (\frac{v\psi_{t-1}(1+r_\psi)}{\phi_{t-1}(1+r_\phi)})^{1/1-v} \tag{12}$$

$$L^*_{f,t} = 1 - L^*_{r,t} \tag{13}$$

Induced technological change:

$$L^*_{r,t} = (\frac{v(\psi_{t-1} + \Delta\psi L_{r,t-1})}{\phi_{t-1} + \Delta\phi L_{f,t-1}})^{1/1-v} \tag{14}$$

$$L^*_{f,t} = 1 - L^*_{r,t} \tag{15}$$

4.2 Social Optimum

In the Social Optimum, the social planner maximizes social welfare, which is defined as the discounted sum of per-period welfare. The negative effects of CO_2-emissions and of structural change costs are taken into account. Also, the positive effect of labor input influencing technological change, which only appears in the induced scenario, is considered in the Social Optimum. In period 0, the division of labor in the Social Optimum is the same as in the Market Equilibrium: $L^*_{r,0} = (\frac{v\psi_0}{\phi_0})^{1/1-v}$ and $L^*_{f,0} = 1 - L^*_{r,0}$. Thereafter, the optimal division of labor is determined by the maximization of social welfare.

4.2.1 Exogenous technological change

In the scenario of exogenous technological change, the social planner takes the values ϕ_t and ψ_t in every period as given. The maximization problem is given as:

$$\begin{aligned} \max_{L_{f,t},L_{r,t}} \quad & \textstyle\sum_{t=1}^{T} \delta^{t-1}[\phi_t {L_{f,t}}^u + \psi_t {L_{r,t}}^v - \beta E_t - \theta(L_{f,t} - L_{f,t-1})^2] \\ \text{s.t.} \quad & E_{t+1} = E_t + \alpha\phi_t {L_{f,t}}^u \\ & \qquad L_{f,t} + L_{r,t} = 1 \end{aligned} \tag{16}$$

As described in Section 3, the social planner considers the negative effect from cumulative emissions in the welfare maximization. Furthermore, the cost of switching labor inputs between sectors is also included. The Lagrange-function has the following structure:

$$\begin{aligned} \mathcal{L} = & \sum_{t=1}^{T} \delta^{t-1}[\phi_t {L_{f,t}}^u + \psi_t {L_{r,t}}^v - \beta E_t - \theta(L_{f,t} - L_{f,t-1})^2 \\ & + \delta\lambda_{t+1}(E_t + \alpha\phi_t {L_{f,t}}^u - E_{t+1}) + \mu_t(L_{f,t} + L_{r,t} - 1)] \end{aligned}$$

The first-order conditions of the maximization problem of the social planner are the following:

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}L_{f,t}} = \delta^{t-1}[\phi_t - 2\theta L_{f,t} + 2\theta L_{f,t-1} + \delta\lambda_{t+1}\alpha\phi_t + \mu_t] \overset{!}{=} 0 \tag{17}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}L_{r,t}} = \delta^{t-1}[v\psi_t {L_{r,t}}^{v-1} + \mu_t] \overset{!}{=} 0 \tag{18}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}E_t} = \delta^{t-1}[-\beta + \delta\lambda_{t+1} - \lambda_t] \overset{!}{=} 0 \tag{19}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\delta\lambda_{t+1}} = \delta^{t-1}[E_t + \alpha\phi_t {L_{f,t}}^{u} - E_{t+1}] \overset{!}{=} 0 \tag{20}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\mu_t} = \delta^{t-1}[L_{f,t} + L_{r,t} - 1] \overset{!}{=} 0 \tag{21}$$

Analytically, we are not able to evaluate the first-order conditions for the optimal labor share $L^*_{r,t}$ and $L^*_{f,t}$. But the first-order conditions still provide us with some information. If in the first two FOCs μ_t is eliminated, the following equation results:

$$v\psi_t {L_{r,t}}^{v-1} = \phi_t + 2\theta(L_{f,t-1} - L_{f,t}) + \delta\lambda_{t+1}\alpha\phi_t \tag{22}$$

The term $v\psi_t {L_{r,t}}^{v-1}$ represents marginal returns of renewable energy production. Since marginal returns are decreasing with more labor input in the renewable sector, higher marginal returns signify lower renewable energy production. If ϕ_t is higher, meaning that technological change in the fossil sector is on a higher level, marginal returns of renewable energy increase as well. Thus, labor share in the renewable sector is lower. Furthermore, the term $2\theta(L_{f,t-1} - L_{f,t})$ states that if $L_{f,t}$ increases compared to the previous period, marginal returns of renewable energy production decrease, meaning that $L_{r,t}$ increases. The shadow price λ_{t+1} indicates how strong the negative impact on society is due to emissions generated by fossil fuel energy production. The impact on society is always negative, following that λ_{t+1} is negative. If the future is devalued with a higher factor given by δ, labor input in the renewable sector is higher, because society today cares more about the future generations. In addition, a higher parameter for carbon intensity specified by α leads to a higher labor share in the renewable sector.

4.2.2 Induced technological change

In the scenario of induced technological change, the social planner anticipates in the maximization problem that technical process can be influenced by the market participants. The influence of labor share on the values of technological change has the same appearance as in the Market Equilibrium:

$$\phi_{t+1} = \phi_t + \Delta\phi L_{f,t}$$

$$\psi_{t+1} = \psi_t + \Delta\psi L_{r,t}$$

The maximization problem of the social planner with induced technological change taken into account is almost identical to the exogenous scenario, except that the influence on ϕ_{t+1} and ψ_{t+1} is considered as well:

$$\begin{aligned} \max_{L_{f,t},L_{r,t}} \quad & \textstyle\sum_{t=1}^{T} \delta^{t-1}[\phi_t {L_{f,t}}^u + \psi_t {L_{r,t}}^v - \beta E_t - \theta(L_{f,t} - L_{f,t-1})^2] \\ \text{s.t.} \quad & \phi_{t+1} = \phi_t + \Delta\phi L_{f,t} \\ & \psi_{t+1} = \psi_t + \Delta\psi L_{r,t} \\ & E_{t+1} = E_t + \alpha\phi_t {L_{f,t}}^u \\ & L_{f,t} + L_{r,t} = 1 \end{aligned} \tag{23}$$

The Lagrange-function looks as follows:

$$\begin{aligned}\mathcal{L} = \sum_{n=1}^{T} \delta^{t-1}[&\phi_t {L_{f,t}}^u + \psi_t {L_{r,t}}^v - \beta E_t - \theta(L_{f,t} - L_{f,t-1})^2 \\ &+ \delta\lambda_{t+1}(E_t + \alpha\phi_t {L_{f,t}}^u - E_{t+1}) + \delta\mu^f_{t+1}(\phi_t + \Delta\phi L_{f,t} - \phi_{t+1}) \\ &+ \delta\mu^r_{t+1}(\psi_t + \Delta\psi L_{r,t} - \psi_{t+1}) + \xi_t(L_{f,t} + L_{r,t} - 1)]\end{aligned}$$

The first-order conditions are defined as:

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}L_{f,t}} = \delta^{t-1}[\phi_t - 2\theta L_{f,t} + 2\theta L_{f,t-1} + \delta\lambda_{t+1}\alpha\phi_t + \delta\mu^f_{t+1}\Delta\phi + \xi_t] \overset{!}{=} 0 \tag{24}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}L_{r,t}} = \delta^{t-1}[v\psi_t {L_{r,t}}^{v-1} + \delta\mu^r_{t+1}\Delta\psi + \xi_t] \overset{!}{=} 0 \tag{25}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}E_t} = \delta^{t-1}[-\beta + \delta\lambda_{t+1} - \lambda_t] \overset{!}{=} 0 \tag{26}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\phi_t} = \delta^{t-1}[L_{f,t} + \delta\lambda_{t+1}\alpha L_{f,t} + \delta\mu^f_{t+1} - \mu^f_t] \overset{!}{=} 0 \tag{27}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\psi_t} = \delta^{t-1}[L^v_{r,t} + \delta\mu^r_{t+1} - \mu^r_t] \overset{!}{=} 0 \tag{28}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\delta\lambda_{t+1}} = \delta^{t-1}[E_t + \alpha\phi_t {L_{f,t}}^u - E_{t+1}] \overset{!}{=} 0 \tag{29}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\mu^f_{t+1}} = \delta^{t-1}[\phi_t + \Delta\phi L_{f,t} - \phi_{t+1}] \overset{!}{=} 0 \tag{30}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\mu^r_{t+1}} = \delta^{t-1}[\psi_t + \Delta\psi L_{r,t} - \psi_{t+1}] \overset{!}{=} 0 \tag{31}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\xi_t} = \delta^{t-1}[L_{f,t} + L_{r,t} - 1] \overset{!}{=} 0 \tag{32}$$

It is not analytically possible to solve the model of the Social Optimum under the scenario of induced technological change for the optimal labor share. But also in the induced scenario, the first-order conditions give us some information. If ξ_t in the first two FOCs is eliminated, the following equation must hold:

$$v\psi_t {L_{r,t}}^{v-1} + \delta\mu^r_{t+1}\Delta\psi = \phi_t + 2\theta(L_{f,t-1} - L_{f,t}) + \delta\lambda_{t+1}\alpha\phi_t + \delta\mu^f_{t+1}\Delta\phi \quad (33)$$

The difference in the induced to the exogenous scenario are the terms $\delta\mu^r_{t+1}\Delta\psi$ and $\delta\mu^f_{t+1}\Delta\phi$. With a higher $\Delta\psi$, marginal returns of renewable energy production are lower, meaning that labor share in the renewable sector is higher. Consequently, if the impact of labor input on technological change in the renewable sector increases, also the amount of labor in that sector is higher. If $\Delta\phi$ is higher, marginal returns of renewable energy increase, resulting in a lower $L_{r,t}$. It follows that if the impact of labor input in the fossil fuel sector on technical progress is higher, the increase of labor in the fossil sector increases.

4.3 Optimal Tax

The social planner can impose a tax on fossil energy to achieve the Social Optimum. The tax increases production in the renewable energy sector and decreases production in the fossil fuel sector. If the tax is determined optimally, the labor share in the Market Equilibrium is equal to the one in the Social Optimum in each period. Consequently, energy production in the renewable and fossil sectors is also the same as in the Social Optimum. In this case, the imposed tax is called the optimal tax.

The tax reduces the producer price of fossil fuel energy in the Market Equilibrium. The producers thus pay a fraction to the state for each unit of energy sold. If a tax is imposed, the maximization problem of the fossil fuel firm is given as:

$$\max_{L_{f,t}} \quad \pi_{f,t} = (p_t - \tau_t)\phi_t {L_{f,t}}^u - w_t L_{f,t} \tag{34}$$

The variable τ_t represents the imposed tax on fossil fuel energy production in period t. It follows from the profit function of the fossil firm that labor input is determined as:

$$L_{f,t} = \begin{cases} 0 & w_t > (1-\tau_t)\phi_t \\ [0;1] & w_t = (1-\tau_t)\phi_t \\ 1 & w_t < (1-\tau_t)\phi_t \end{cases} \tag{35}$$

Due to the imposed tax, now the fossil firm only produces energy if $w_t \leq (1-\tau_t)\phi_t$. As we assume a perfectly competitive market, it follows that $w_t = (1-\tau_t)\phi_t$, which can be regarded as the short-term solution. The maximization problem of the firm in the renewable sector did not change, because the tax is only imposed in the fossil fuel sector. Thus, the renewable firm still maximizes (6) with respect to $L_{r,t}$. But the tax has an indirect effect on labor input because the wage has changed. Labor demand in the renewable sector is now given as:

$$L_{r,t} = \begin{cases} 1 & w_t > (1-\tau_t)\phi_t \\ (\frac{v\psi_t}{(1-\tau_t)\phi_t})^{1/1-v} & w_t = (1-\tau_t)\phi_t \\ 0 & w_t < (1-\tau_t)\phi_t \end{cases} \tag{36}$$

The scenario where both firms produce can only occur if $w_t = (1-\tau_t)\phi_t$. In that case, the optimal labor inputs $L_{r,t}$ and $L_{f,t}$ are as follows:

$$L^{*}_{r,t} = (\frac{v\psi_t}{(1-\tau_t)\phi_t})^{1/1-v} \tag{37}$$

$$L^{*}_{f,t} = 1 - L^{*}_{r,t} \tag{38}$$

Due to the fact that the imposed tax is always positive, $L^{*}_{r,t}$ is now higher and $L^{*}_{f,t}$ is lower compared to the labor input in the Market Equilibrium without tax. Consequently, the energy production in the renewable sector increases and the energy production in the fossil fuel sector decreases due to the imposed tax.

To achieve that the labor share in the Market Equilibrium is exactly the same as in the Social Optimum, we establish the following equation:

$$(\frac{v\psi_t}{(1-\tau_t)\phi_t})^{1/1-v} = L^{SO}_{r,t} \tag{39}$$

In the equation, $L^{SO}_{r,t}$ is defined as the optimal labor input in the renewable sector in the Social Optimum. To calculate how high the optimal tax must be, we transform the equation as follows:

$$\tau^{*}_t = 1 - (\frac{v\psi_t}{\phi_t})(L^{SO}_{r,t})^{v-1} \tag{40}$$

By implementing the optimal tax in the Market Equilibrium, the same fossil energy reduction path as in the Social Optimum is achieved. Even if three different externalities occur, the Social Optimum can be imposed with a single tax, because only one decision variable in the form of labor appears in our model. Since the allocation of labor among sectors is influenced by the optimal tax in such a way that the Social Optimum is achieved, a single tax is sufficient.

5 Numerical Illustration

In this section, we show how the parameters in our model are determined and we demonstrate our results from the Market Equilibrium and the Social Optimum under the scenario of exogenous and induced technological change. Moreover, a sensitivity analysis is conducted, examining how the results vary as the parameters change.

5.1 Parametrisation

Any numerical illustration of the model introduced in Sections 3 and 4 is dependent on the choice of parameters. A detailed empirical investigation to determine the exact values for the required parameters is beyond the scope of this thesis, but plausible values are used to illustrate the model numerically. The values for the parameters are presented in Table 1:

Symbol	Description	Value
α	Impact of fossil energy production on cumulative emissions	1
β	Impact of cumulative emissions on social welfare	0.1
θ	Impact of structural costs on social welfare	40
δ	Discount factor	0.95
ϕ_0	Parameter of technological change in fossil sector at time 0	1
ψ_0	Parameter of technological change in renewable sector at time 0	0.8
r_ϕ	per period rate of increase in technological change in fossil sector	0.01
r_ψ	per period rate of increase in technological change in renewable sector	0.025
E_0	Cumulative emissions	1

Table 1: *Choice of parameters*

In the model, the value of one unit of emissions or one unit of produced energy is not specified. Therefore, the carbon intensity given by α and cumulative emissions at time 0 given by E_0 are set to 1 without loss of generality. What is of importance, however, is how the cumulative emissions affect social welfare. Hence, how the value for β is determined. To do so, the global GDP and global emissions in 2019[3] are considered. Based on literature in this field, the social costs of carbon is specified as 200 USD per ton of CO_2-emissions. Emitted CO_2-emissions in 2019 were approximately 36.7 billion tons of CO_2. Furthermore, global GDP in the year 2019 was 87'610 billion USD. Hence, percentage loss of social costs compared to GDP was approximately 8.3%. The parameter beta is specified, such that in period 0 (representing the year 2020) the loss of social welfare relative to GDP lies around 8.3%.

With regard to the influence of structural costs on social welfare, it is assumed that a shift in labor of one percentage point leads to 0.5% GDP-loss. There is no useful literature to support this assumption. But if considering that 1% of total labor input in the energy sector is transferred from one sector to the other, it seems plausible that costs to society are not negligible. After all, structural costs do not only include the costs of training employees changing sectors, but also, for example, costs due to temporary unemployment or administrative costs incurred by the state, the company or the employee.

Moreover, regarding the discounting of time, it is assumed that the following year is discounted with the factor 0.99. Thus, one period is discounted with the factor 0.99^5, which is approximately 0.95. This parameter cannot be clearly defined either, as the discounting of time varies individually. Furthermore, the question arises whether it is at all justified that time is discounted,

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[3] The year 2019 and not 2020 was considered due to the lockdown caused by the COVID-19-crisis in the year 2020, which had an impact on global GDP and cumulative emissions.

since this means that less attention is paid to the next generations. However, because there is a point in time in the model at which the end of time is reached, it must be ensured that the value of this period is close to 0 from the perspective of the current period (period 0). As explained in Section 3.1, we define one period as 5 years and set T to 90. Period 0 represents the year 2020. With the assumption that the next period is devalued corresponding to a discount rate of 95% per period, the end of time is worth close to nothing for us (0.0099). Consequently, what happens in 450 years is almost irrelevant for today's population.

The initial values of the parameters of technological progress ϕ_0 and ψ_0 are specified such that the market share of renewables in period 0 equals the market share in the year 2019, which was approximately 27% (IEA 2021). Due to the fact that labor supply is standardized to 1 in the model, only the relative ratio between both values matters. Thus, without loss of generality, we define ϕ_0 as 1 and determine ψ_0 such that reality is represented as closely as possible. If ψ_0 is indicated as 0.8, the market share of renewable energy in period 0 is approximately 27%. Furthermore, it is predicted that the market share in the year 2025 (period 1) is predicted to be around 35% (IEA 2021). Also in the specification of the per period rates of increase in technological change, only the relative ratio matters. We set r_ϕ to 1% and determine r_ψ, such that the market share of renewables is close to the actual world. In reality, we live in an intermediate form between the Market Equilibrium and the Social Optimum, because measures against climate change are implemented, but not nearly to the extent to achieve the Social Optimum. In addition, many measures against global warming are still based on voluntary action. Therefore, the market share of renewables in the Market Equilibrium should be under 35% in period 1 and in the Social Optimum over 35%. To fulfill this condition, we define r_ψ as 2.5%.

5.2 Results

Using the parameters described in the previous section, this section presents the results of our model.

5.2.1 Labor input

In this section, the optimal labor inputs in the Market Equilbirum and Social Optimum under the exogenous and induced technological change scenario is illustrated. Figure 1 shows the path of labor share in all four cases. In the Market Equilibrium under the exogenous technological change scenario, the complete replacement of fossil energy occurs at the latest point in time, specifically in period 63, which corresponds to 315 years. Clearly, it is necessary to phase out fossil energy much sooner. In the Social Optimum under the exogenous technological change scenario, the replacement pathway progresses much faster, and fossil energy production ends in period 12, which corresponds to 60 years. Thus, if it is assumed that technological change is exogenously given, the optimal time for complete phase-out of fossil fuels is in 2080. Under the induced technological change scenario, the replacement path progresses faster than under the exogenous scenario in both cases. In the Market Equilibrium, fossil energy production ends in period 10, which corresponds to 50 years. This means that, under the assumption that technological change can be influenced and no measures are implemented to combat climate change, the phase-out of fossil energy occurs in 2070. In the Social Optimum, renewables completely replace fossil fuels the fastest. In period 5, fossil energy production ends, which means that from 2045 onwards, all energy production is already generated with renewable sources, provided that measures are taken to combat climate change.

From Figure 1 it follows that under the induced technological change scenario, the reduction path in the Market Equilibrium and Social Optimum proceeds faster than in the exogenous technological change scenario. Conse-

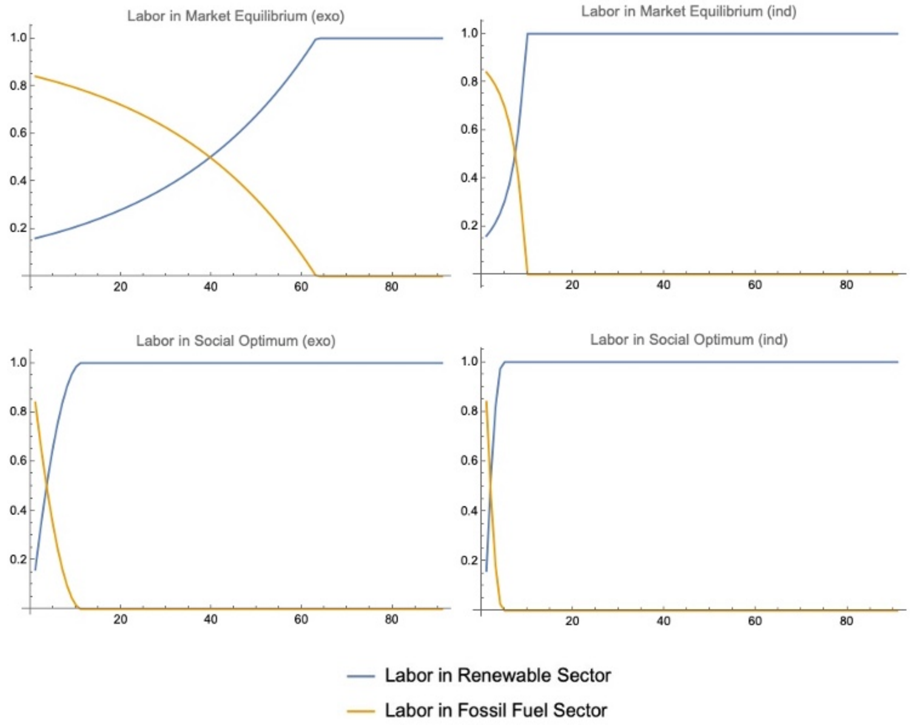


Figure 1: *Labor share in the renewable and fossil sector in the Market Equilibrium (top) and Social Optimum (bottom) under the exogenous (left) and induced (right) technological change scenario*

quently, the time of complete replacement of fossil fuels occurs faster under the induced scenario. This result comes from the fact that under induced change, technological progress is faster if labor input in a sector is higher. As the renewable energy sector grows, technical change in this sector increases. At the same time, technological progress in the fossil fuel sector grows at a lower rate as labor input becomes smaller. Moreover, the results in both scenarios clearly show that the fossil fuel replacement pathway progresses faster in the Social Optimum than in the Market Equilibrium. This result is as expected because in the Social Optimum, the negative impact of carbon emissions on society is taken into account, while in the Market Equilibrium, firms do not include the side effect of carbon production in their maximization problem. However, the negative externality of structural change costs are also incorporated in the Social Optimum, while they are ignored by the market participants in the Market Equilibrium. This externality slows down the replacement of fossil by renewable energy, because a change in labor input leads to costs for society. Furthermore, the third externality, which occurs through the influence of labor input on technological progress, leads to a stimulation of the replacement of fossil by renewable energy in the induced scenario. However, this externality does not occur in the exogenous technological change scenario. As can be seen in Figure 1, the replacement is faster in the Social Optimum compared to the scenario in which no externalities are taken into account.

5.2.2 Technological change parameters

The difference in the timing of total replacement of fossil energy by renewable sources between the exogenous and induced scenario is due to the different definition of the course of the technological change parameters, as described in section 4. In the scenario of induced technological change, the change in sectors is influenced by labor input. If labor input in one sector increases, the improvement of technology in that sector automatically increases. At the same time, labor input in the other sector decreases, since total labor supply is standardized to 1. This leads to less improvement in technology in the respective sector. Figure 2 shows the evolution of the parameters of technological change in the Market Equilibrium and Social Optimum under both scenarios. It is clearly visible that technological progress in the renewable sector compared to the fossil sector under the induced scenario is faster than in the exogenous change scenario. In the exogenous scenario, the processes of technological change is equal in the Market Equilibrium and Social Optimum, since progress occurs independently of labor input and increases with the passage of time. In the induced scenario, technological progress in the

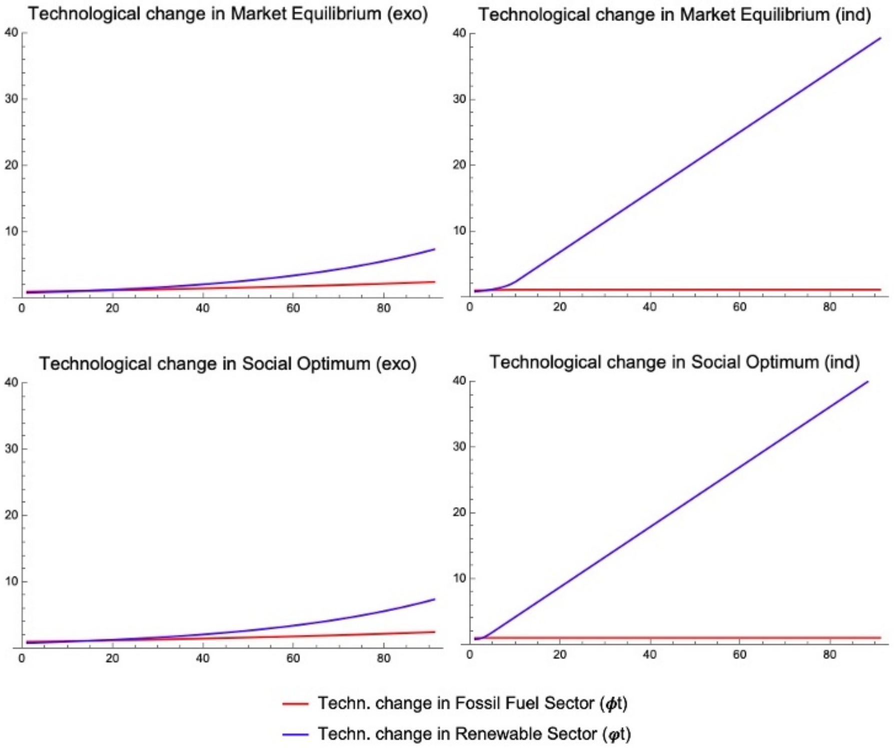


Figure 2: *Course of parameters of technological change in the Market Equilibrium (top) and Social Optimum (bottom) under exogenous (left) and induced (right) technical change scenario*

renewable sector is faster, if the negative effect of cumulative emissions on social welfare from fossil energy production is taken into account. Once the total replacement of fossil energy has occurred, the parameter of technological change in the fossil sector remains at the same level, since no more labor is invested in this sector. This process is reasonable, because no technology is developed further if there is no further use of the technology.

5.2.3 Optimal Tax

Through the results of labor share allocation in the Market Equilibrium and Social Optimum, the optimal tax in both scenarios is calculated. As explained in detail in section 4.3, the optimal tax is implemented in the Market Equilibrium and leads to the same replacement path of fossil by renewable energy as in the Social Optimum. Consequently, in the Market Equilibrium with tax fossil energy is completely replaced by renewable sources at the same time as in the Social Optimum. In Figure 2, the path of the optimal tax under the scenario of exogenous and induced technological change is illustrated. The path of labor input in the renewable sector in the Market Equilibrium is also included. Due to the influence of the optimal tax on labor share in both sectors, the path of labor input in the Market Equilibrium is now the same as in the Social Optimum. As soon as no fossil energy is produced in the Market Equilibrium with no tax, the tax can be canceled. Once the use of fossil energy has ended, without taking into account the negative externalities caused by CO_2-emissions on social welfare, the tax is ineffective, since fossil energy is no longer used in the market in any case. Consequently, no behavior of market participants can be influenced by the tax. In Figure 2,

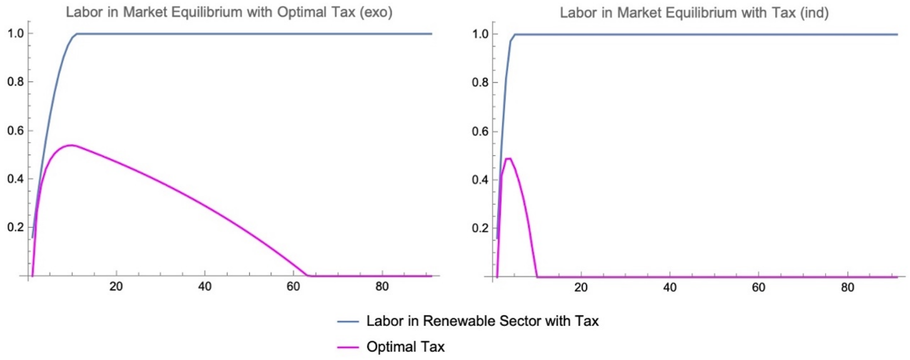


Figure 3: *Path of optimal tax and labor in renewable sector in Market Equilibrium with tax under the scenario of exogenous (left) and induced (right) technological change*

it is apparent that the tax needs to be levied for a shorter period of time if we assume that technological change can be influenced. This means that the costs of climate change mitigation disappear faster if technological progress is considered induced.

5.2.4 Cumulative Emissions

Furthermore, total cumulative emissions in the Market Equilibrium and Social Optimum under the scenario of exogenous and induced technological change are compared. In Figure 3, the path of cumulative emissions from period 0 to period 90 are shown. It can clearly be seen that in the Market Equilibrium under the scenario of exogenous technological change, cumulative emissions increase most and are at the highest level at the end of time. This difference is mainly due to the fact that fossil energies will not be completely replaced by renewables until period 63. Thus, the emissions increase until period 64 and then stagnate. In the Market Equilibrium under the scenario of induced technical progress, fossil energy production ends in period 10. Consequently, cumulative emissions stagnate in period 11. In the Social Optimum under the exogenous scenario, cumulative emissions stagnate in period 13, because fossil energy production stops in period 12. Even if fossil energy production is produced two periods longer (10 years) in the Social Optimum under the exogenous scenario compared to the Market Equilibrium under the induced scenario, cumulative emissions are higher in the latter. This result comes from the fact that the labor input in the fossil sector is relatively high in the Market Equilibrium until the total replacement has occurred in period 10, which can be seen in figure 1. In period 9, the labor invested in the fossil sector is still 0.206. In the induced scenario, a higher value of labor input in the fossil sector means that technological progress in this sector proceeds faster than if labor input was lower. Thus, the parameter of technological change increases more in the according sector. A stronger increase in the technical change parameter, in turn, means more energy pro-

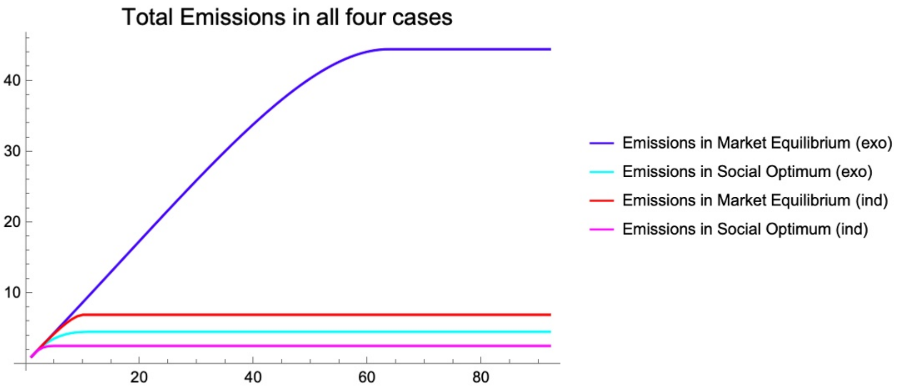


Figure 4: *Total cumulative emissions in the Market Equilibrium and the Social Optimum under the scenario of exogenous and induced technological change*

duction per labor input. More energy production in the fossil sector leads to more CO_2-emissions. In the Social Optimum under the exogenous scenario, on the other hand, technical progress proceeds with the passage of time and is independent of labor inputs. Moreover, the share of labor in the renewable sector reaches a high level faster than in the Market Equilibrium with induced change. Thus, the labor share in the fossil sector decreases faster, which in turn leads to less emission accumulation. Finally, in the Social Optimum under the induced change scenario, cumulative emissions are on the lowest level, because they already stagnate in period 6.

5.3 Sensitivity Analysis

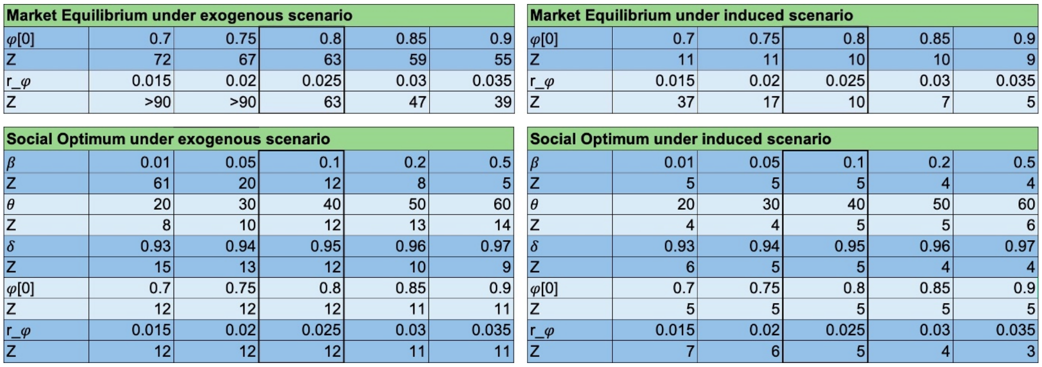
Since we cannot determine exactly which values the parameters have in the model, so that reality is fully represented, it is important to perform a sensitivity analysis. This section investigates how the replacement of fossil fuels by renewable sources changes if the parameters change. Furthermore, it is analyzed how cumulative emissions relative to emissions in the Social Optimum under the induced technical change scenario change with different parameters.

5.3.1 Time of full replacement

We investigate how the moment in which fossil energy is completely replaced by renewable sources changes with changed parameters. The time of full replacement is given by Z. In the Social Optimum, the parameters β, θ, δ, ψ_0 and r_ψ are considered. In the Market Equilibrium, β, θ and δ have no influence on the time of full replacement. Hence, only the parameters ψ_0 and r_ψ are considered. The parameters ϕ_0 and r_ϕ are not included, because only the relative ratio matters. In Figure 5, the time of full replacement with different values of the considered parameters in the Market Equilibrium and Social Optimum under the exogenous and induced scenario is illustrated. In the vertical center, surrounded in black, the values with the determined parameters in the model are shown.

Looking at the Market Equilibrium, the time when fossil energy is fully replaced differs under the exogenous scenario quite much if ψ_0, the initial value of technical progress in the renewable sector, is changed. However, in the induced scenario, the time of full replacement does not react much to a change in ψ_0. Considering r_ψ, the parameter of increase in technical change in the renewable sector, under both scenarios a clear change in the moment of full replacement is seen, whereas it seems that the change under the exogenous scenario is stronger.

Looking at the Social Optimum, a change in β clearly has a higher impact on the time of full replacement under the scenario of exogenous technological change. For instance, if we assume that β has the value of 0.01 (20 USD/tCO$_2$) instead of 0.1 (200 USD/tCO$_2$), the moment of full replacement in the Social Optimum under the exogenous scenario occurs in period 61,



Market Equilibrium under exogenous scenario					
φ[0]	0.7	0.75	0.8	0.85	0.9
Z	72	67	63	59	55
r_φ	0.015	0.02	0.025	0.03	0.035
Z	>90	>90	63	47	39

Market Equilibrium under induced scenario					
φ[0]	0.7	0.75	0.8	0.85	0.9
Z	11	11	10	10	9
r_φ	0.015	0.02	0.025	0.03	0.035
Z	37	17	10	7	5

Social Optimum under exogenous scenario					
β	0.01	0.05	0.1	0.2	0.5
Z	61	20	12	8	5
θ	20	30	40	50	60
Z	8	10	12	13	14
δ	0.93	0.94	0.95	0.96	0.97
Z	15	13	12	10	9
φ[0]	0.7	0.75	0.8	0.85	0.9
Z	12	12	12	11	11
r_φ	0.015	0.02	0.025	0.03	0.035
Z	12	12	12	11	11

Social Optimum under induced scenario					
β	0.01	0.05	0.1	0.2	0.5
Z	5	5	5	4	4
θ	20	30	40	50	60
Z	4	4	5	5	6
δ	0.93	0.94	0.95	0.96	0.97
Z	6	5	5	4	4
φ[0]	0.7	0.75	0.8	0.85	0.9
Z	5	5	5	5	5
r_φ	0.015	0.02	0.025	0.03	0.035
Z	7	6	5	4	3

Figure 5: *Change of time of full replacement (represented by Z) of fossil by renewable energy if the parameters are changed. The Market Equilibrium (top) and the Social Optimum (bottom) under the exogenous (left) and induced (right) technological change scenario are considered.*

which is already quite close to the moment in the Market Equilibrium with exogenous change. However, in the Social Optimum under the induced scenario, the time of full replacement is unchanged and still happens in period 5. Moreover, if we assume that β has the value of 0.5 (1000 USD/tCO_2), in the Social Optimum and exogenous scenario the full replacement occurs in period 5, whereas under the induced scenario, the replacement happens in period 4. Consequently, under the assumption of induced technological change, it does not matter so much how high the damage on society due to emissions is.

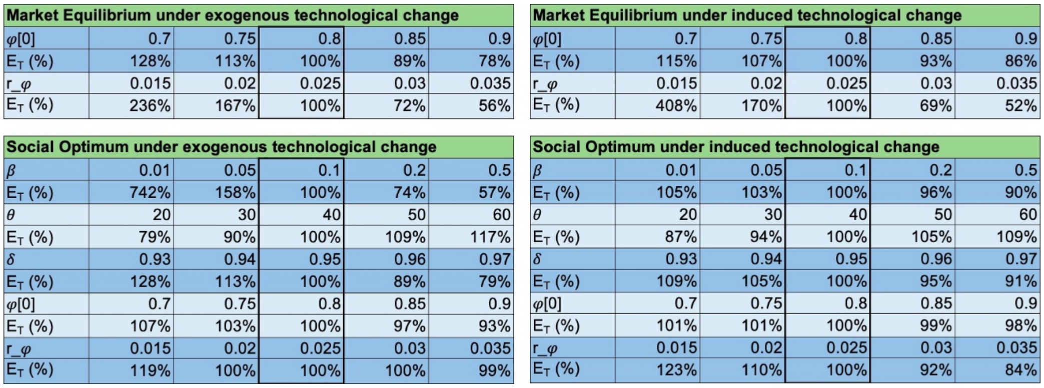
Considering structural costs occurring from a change in labor input between the two sectors, a change in θ leads to a higher change in the moment of full replacement in the Social Optimum under the exogenous scenario compared to the induced one. For instance, if we assume that θ has the value 20, the time when fossil energy is completely replaced occurs in period 8 in the Social Optimum with exogenous change. In the Social Optimum under the assumption of induced technological change, the transition is accomplished in period 4. As the structural costs of switching labour between sectors are lower with a lower θ, the replacement of fossil energy with renewable sources occurs faster. If θ has a higher value, the transition is happening at a slower rate. For example, if θ is set to 60, the transition in the Social Optimum with exogenous change is completed in period 14. In the Social Optimum under the induced scenario, fossil energy is fully replaced in period 6.

Regarding the discounting of time, a lower discount factor leads to a slower transition, because the future is valued less. Thus, people care less about the damage of cumulative emissions on social welfare in the future. If the discount factor is higher, the time of full replacement in the Social Optimum under both scenarios happens faster, whereas also here the reaction in the exogenous scenario is stronger. If the future is devalued with the factor 0.97 instead of 0.95, the full transition has occured in period 9 in the Social Optimum under the exogenous scenario. If we assume that technological change can be influenced, the time of full replacement happens in period 4 with a discount factor of 0.97.

Changing the initial value of the technological change parameter in the renewable sector has a similar impact on the Social Optimum in both scenarios, whereby the moment of full replacement with a changed value does not seem to vary much in either scenario. If the per period rate of increase in technical change in the renewable sector is changed, the reaction in the Social Optimum under the induced scenario seems to be stronger. The difference in reactions comes to some extent from the fact that a change in r_ψ has an influence on $\Delta\psi$. Given that r_ϕ does not change, if r_ψ is lower, $\Delta\psi$ has a lower value, because we define $\Delta\psi$ so that in the end of time, the parameters of technological change have the same value, if labor input has no impact in the induced scenario. A lower $\Delta\psi$ means that the influence of labor input on technological change is lower in the renewable sector. Consequently, the transition to renewable energies occurs at a lower rate. This explains why the reaction in the Social Optimum under the induced scenario is stronger compared to the Social Optimum with exogenous change, if r_ψ has a different value.

5.3.2 Cumulative emissions

In this section, we analyze how cumulative emissions relative to emissions with determined parameters change with different parameter choices. Although it is not specified in which unit emissions are measured, it is still possible to compare the different values of emissions, if they are in relative forms. The baseline emissions are the cumulative emissions in each scenario with the specified parameters. In Figure 6, relative emissions with changed parameters in the Market Equilibrium and Social Optimum under both scenarios are presented. Relative cumulative emissions are given by $E_T(\%)$. Emissions in the end of time are included, because we want to compare the total accumulated emissions over the entire time period. Cumulative emissions with the determined parameters are set to 100% in every scenario, because we want to consider the relation to those emissions with changed parameters.



Market Equilibrium under exogenous technological change					
φ[0]	0.7	0.75	0.8	0.85	0.9
E_T (%)	128%	113%	100%	89%	78%
r_φ	0.015	0.02	0.025	0.03	0.035
E_T (%)	236%	167%	100%	72%	56%

Market Equilibrium under induced technological change					
φ[0]	0.7	0.75	0.8	0.85	0.9
E_T (%)	115%	107%	100%	93%	86%
r_φ	0.015	0.02	0.025	0.03	0.035
E_T (%)	408%	170%	100%	69%	52%

Social Optimum under exogenous technological change					
β	0.01	0.05	0.1	0.2	0.5
E_T (%)	742%	158%	100%	74%	57%
θ	20	30	40	50	60
E_T (%)	79%	90%	100%	109%	117%
δ	0.93	0.94	0.95	0.96	0.97
E_T (%)	128%	113%	100%	89%	79%
φ[0]	0.7	0.75	0.8	0.85	0.9
E_T (%)	107%	103%	100%	97%	93%
r_φ	0.015	0.02	0.025	0.03	0.035
E_T (%)	119%	100%	100%	100%	99%

Social Optimum under induced technological change					
β	0.01	0.05	0.1	0.2	0.5
E_T (%)	105%	103%	100%	96%	90%
θ	20	30	40	50	60
E_T (%)	87%	94%	100%	105%	109%
δ	0.93	0.94	0.95	0.96	0.97
E_T (%)	109%	105%	100%	95%	91%
φ[0]	0.7	0.75	0.8	0.85	0.9
E_T (%)	101%	101%	100%	99%	98%
r_φ	0.015	0.02	0.025	0.03	0.035
E_T (%)	123%	110%	100%	92%	84%

Figure 6: *Change of cumulative emissions relative to emissions with specified parameters if parameters change. The Market Equilibrium (top) and the Social Optimum (bottom) under the exogenous (left) and induced (right) technological change scenario are considered.*

First, the Market Equilibrium is considered, which is illustrated in the upper part in Figure 6. As discussed in chapter 5.2.4, cumulative emissions in the end of time are much higher if we assume that technological change is exogenous compared to the induced scenario. But here, only the cumulative emissions in one scenario is compared. Thus, the comparison between scenarios is not possible. Under both scenarios, a change in the initial value of the technological change parameter in the renewable sector has a clear impact on relative cumulative emissions, whereas in the exogenous scenario, the influence is stronger. If ψ_0 is higher, under both scenarios emissions are lower, because technological change in the renewable sector in the first period is now on a higher level. Hence, the market share of renewable energy compared to fossil fuel is bigger, meaning that less fossil energy is produced, which results in lower emissions. It follows that with a lower value for ψ_0, cumulative emissions are higher.

Regarding a change in the per period rate of technological change in the renewable sector given by r_ψ, under both scenarios there is a clear difference in cumulative emissions, if the per period rate changes. If r_ψ increases, emissions are on a lower level, which makes sense, since the growth rate of technological change in the renewable sector is higher. Consequently, the transition to renewable energy occurs faster. It follows that with a lower r_ψ, the transition from fossil to renewable energy is slower. In the induced technological change scenario, the impact of a change in r_ψ is higher, because the definition of $\Delta\psi$ changes too (see section 4.1.3).

The bottom part in Figure 6 represents the sensitivity analysis in the Social Optimum regarding cumulative emissions. A change in damage on social welfare due to CO_2-emissions leads to a stronger change of cumulative emissions in the exogenous scenario. In the Social Optimum with exogenous change, relative emissions are 742% with a β of 0.01. In contrast, relative emissions are around 105% in the induced scenario with the same β. If β is set to 0.5, relative emissions in the exogenous scenario lie around 57%, whereas in the induced scenario they are 90%. Consequently, a change in damage on society leads to a higher change in relative emissions, if we assume that technological change is exogenous.

If the parameter θ representing structural change costs due to changing labor inputs between the two sectors changes, the relative change in cumulative emissions in the exogenous scenario is higher compared to the induced one. In the Social Optimum with induced change, relative emissions are 87% with a θ of 20. In the Social Optimum with exogenous change, on the other hand, with a θ of 20 relative emissions are approximately 79%. If θ is set to 60, relative emissions in the induced scenario lie around 109%, whereas in the exogenous scenario they are 117%. Hence, a change in structural change costs has a higher influence on cumulative emissions under the scenario of exogenous technical progress.

Furthermore, a change in discounting of time leads to a higher change in cumulative emissions in the Social Optimum under the scenario of exogenous technical progress compared to the induced one. In the exogenous scenario with a δ of 0.93, relative emissions are approximately 128%, whereas they are around 109% in the induced scenario. With a δ of 0.97, relative emissions are 79% in the exogenous scenario and 91% in the induced one. If the discount factor is higher, cumulative emissions are lower in both scenarios, because the future has a higher value. It follows that with a lower discount factor, emissions increase.

A change in the initial value of the technological change parameter in the renewable sector leads to a higher change of relative emissions in the exogenous technological change scenario. If ψ_0 is set to 0.7, relative cumulative emissions in the exogenous scenario are 107%, whereas regarding induced change, emissions lie around 101%. With a ψ_0 of 0.9, relative emissions in the exogenous scenario are 93% and 98% in the induced one. Hence, if the initial value increases, in both scenarios cumulative emissions are lower, because technological progress in the renewable sector is on a higher level in period 0. Consequently, a lower initial value of technological change in the renewable sector leads to higher cumulative emissions.

Moreover, a change in the per period rate of increase in technological change in the renewable sector leads to a higher percentage change in cumulative emissions in the induced scenario. If r_ψ is set to 0.015, in the Social Optimum with exogenous change relative cumulative emissions are 119%, whereas in the induced scenario emissions are 123%. With r_ψ set to 0.035, relative cumulative emissions in the exogenous scenario are 99% and 84% in the induced one. Hence, under both scenarios cumulative emissions increase, if r_ψ decreases. It follows that with a higher r_ψ, cumulative emissions are lower.

6 Discussion

The results of the numerical illustration have some interesting implications. It is important at this point to state that these results are not intended to be a quantitative projection of reality, but rather to provide an insight of the difference between exogenous and induced technological change. Our model generates three main findings. First, the optimal path to replace fossil with renewable energy is faster if the influence of labor on technological change is considered. Secondly, the cost of mitigating climate change - namely the cost of the carbon tax - is incurred for a shorter period of time when taking into account the impact of human behavior on technological progress. The third main finding is that the transition to fossil-free power generation is faster in the Social Optimum than in the Market Equilibrium, as the Social Optimum takes into account the negative externalities of emissions generation on social welfare.

Nevertheless, it is important to state that our model has some limitations. The specified parameters are difficult if not impossible to measure in the real world. For instance, how much the world population is affected by an additional unit of carbon is not clearly measurable. The damage caused by emissions production on the population varies strongly globally and temporally. Hence, β cannot be determined clearly. On top of that, the impact of one unit of emissions on social welfare is probably not linear, meaning that not every additional unit of carbon has the same impact on social welfare. For example, if more ice melts, less sunlight from the surface of the earth into the atmosphere is reflected, causing even more global warming. However, β always has the same value in our model. Thus, the negative impact on social welfare due to an additional unit of emissions is always the same, no matter how much emissions are already accumulated. Relevant to note, is that a change in β leads to a much stronger change in the time of full replacement and cumulative emissions in the scenario with exogenous technological change compared to the induced one. From this, it can be argued that even if β had a different value, the time of total replacement would change relatively less if the influence of labor input on technological change is taken into account.

Moreover, the negative effects of the costs of structural change on social welfare are not clearly measurable. The magnitude of the costs varies by energy sector, region, and timing. Consequently, θ cannot be clearly determined. Interesting though is, that a change in θ seems to have a much higher effect on the time of full replacement in the exogenous technological change scenario. Even if θ had a value differing strongly from the chosen value, the impact in the induced scenario is relatively small.

Another limitation in our model is that only two general types of energy forms are represented, renewable and fossil energy, while in reality there exist different types of fossil and renewable energy sources. Our model does not include certain market mechanisms. For instance, the competitive situation between the different forms of renewable energies or the spillover of technological progress from one technology to the others cannot be included. Our model only includes two types of energy sources. If we were to expand the model to include all groups of energy resources the results might differ slightly. However, whether we form two groups of energy sources or consider all forms of energy is unlikely to change our results significantly. Nevertheless, the interplay between renewable technologies and the market mechanism behind them is a very exciting area of research that would certainly yield interesting and important results.

Furthermore, we simplify our model by standardizing the number of workers in the energy sector to one unit. In reality, the amount of people working in the energy sector might change over time. But since it is not assumed that many more people will work in the energy sector in the future, this assumption seems plausible and should not affect our results.

Although our model has some limitations, it is still representative to show the difference between exogenous and endogenous technological change, as we do not want to provide exact figures of reality, but want to highlight that technological change with measures against climate change could be much faster than previously assumed.

7 Conclusion

In this thesis, we have constructed a model that is as simple as possible to demonstrate that the replacement of fossil energy by renewable resources occurs faster if we assume that technological change is influenced by market changes. In doing so, we have distinguished between the Market Equilibrium and the Social Optimum. We have not only shown that the replacement of fossil energy is faster with induced technological progress, but also that the costs of climate change mitigation need to be imposed for a shorter period of time. This result leads to the phenomenon that technological progress related to climate warming is underestimated. In reality, it appears that technological change is influenced through human actions. An actual example is the war between Russia and Ukraine, which is leading to higher prices for fossil energy. As a consequence, the use of renewable energies is more competitive and has a higher market share in energy production, which creates a greater learning-by-doing effect in the renewable sector, thus stimulating technological progress.

The exponentially increasing course of induced technological change, if market incentives in favor of renewable energies are implemented, gives reason to hope that the climate crisis can be slowed down in time. The greater awareness among the population that climate change is a real, man-made threat that must be stopped as quickly as possible reinforces this hope, as it stimulates the transition to renewable energy. Furthermore, the sensitivity analysis has shown that the replacement of fossil by renewable energy is much less responsive to a change in damage caused by CO_2-emissions when considering that technological change can be influenced. This justifies the optimal policy even if damage to society from emissions differs. Also, a change in structural change costs leads to a weaker change in the replacement pathway in the induced compared to the exogenous scenario. This provides a certain robustness to our results in the induced scenario.

However, our results show that we need to act now, as the exponential nature of induced technological progress will not be driven fast enough if no mitigation against climate change is undertaken. Political measures to slow down global warming are thus justified. The argument to wait for more efficient technologies before acting are weakened by our findings, because waiting neglects the impact of measures against climate change on technical progress in the renewable sector. Furthermore, the argument of immense costs due to mitigation policies is weakened, because under the assumption that technological change is induced, the costs of mitigating global warming need to be implemented for a shorter period of time and production costs of renewables decrease faster.

As a final conclusion, our results show that we should not give up in the fight against climate change, as the transition to a market economy without fossil fuels can occur faster than we can imagine. At the same time, we should not be under the illusion that fossil fuels will disappear from the market in time, even if no action is taken against global warming. If we are to succeed in limiting global warming while ensuring sufficient energy supply for the population, the world must use energy more efficiently and at the same time rely more on clean energy sources. Technological change has a key role to play in this regard. Currently, the transition from fossil to renewable energy cannot yet be fully achieved. However, with the right incentives and the right investments, energy production will be climate neutral in the future. How much we drive the technological transition of renewable energies today will be significant in preventing climate change.

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Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

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