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Avoiding Carbon Lock-In: Policy Options for Advancing Structural Change

Linus Mattauch[*], Felix Creutzig[†], Ottmar Edenhofer[‡]

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WORKING PAPER – *comments welcome*

Abstract

A major obstacle for the transformation to a low-carbon economy is the risk of a carbon lock-in: fossil fuel-based ("dirty") technologies dominate the market although their carbon-free ("clean") alternatives are dynamically more efficient. We study the interaction of learning-by-doing spillovers and the substitution elasticity between the clean and the dirty sector in an intertemporal general equilibrium model. We find that the substitution possibilities between the two sectors have an ambivalent effect: although a high substitution elasticity requires less aggressive mitigation policies than a low one, it creates a greater lock-in in the absence of regulation. The optimal policy response consists of a permanent carbon tax as well as a learning subsidy for clean technologies. A single policy instrument can also avoid high welfare losses, but a more stringent mitigation target can only be achieved at painful costs. We demonstrate that the policy implication of [Acemoglu et al. 2012] is limited in scope. Our numerical results also highlight that infrastructure provision is crucial to facilitate the low-carbon transformation.

Keywords : structural change, low-carbon economy, carbon lock-in, mitigation policies, learning-by-doing

JEL classification: O30, O38, Q54, Q55

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1 Introduction

Climate change threatens future well-being and economic stability. Its mitigation requires drastic cuts in emissions in the 21st century and necessitates a transformation from a fossil-fuel based to a decarbonised economy. Both empirical evidence and theoretical argument suggest that a main obstacle to this transformation is the likely possibility of a *carbon lock-in* [Unruh 2000, Schmidt and Marschinski 2009, Davis and Caldeira 2010, IEA 2011]: the economy remains in an equilibrium in which carbon-intensive ("dirty") technologies dominate the market although they are intertemporally inferior to low-carbon ("clean") alternatives.

Which policy options best advance structural change towards the low-carbon economy is less clear: few studies have examined policy responses that are sufficient to avoid a carbon lock-in [Fisher and Newell 2008, Gerlagh, Kverndokk and Rosendahl 2009]. Here we contribute to this task by studying the impact of the substitution elasticity between a dirty and a clean sector on appropriate policy responses. We find an ambivalent effect: A high elasticity creates a greater lock-in in the absence of regulation, but also requires less drastic policy intervention.

We use a two-sector intertemporal general equilibrium model to establish this result and solve it numerically to identify policy options that are sufficient to avoid high welfare losses. A common stylized setting is employed to depict structural change to a low-carbon economy: there is one 'clean' sector, without emissions, and one 'dirty', emitting greenhouse gases. This approach has been adopted for instance by [Acemoglu et al. 2012] (henceforth: AABH) and [Gerlagh and Hofkes 2002]. Our model set-up is similar to that of AABH in order to be comparable in terms of policy implications. However, while that study focuses on the effects of directed technical change for the transformation to a low-carbon economy, our work relies on the assumption of learning through spillover effects in the clean sector as its capacity is built up.

Such a learning-by-doing approach is well-established within energy economics [Kverndokk and Rosendahl 2007]: The cost of renewable technologies decreases with cumulative installed capacity at a stable rate [Fischedick et al. 2011, ch. 10.5.2]. It has moreover been demonstrated theoretically that in presence of learning-by-doing externalities optimal carbon pricing is insufficient to overcome a lock-in into mature low-carbon technologies in the energy market [Kalkuhl, Edenhofer and Lessmann 2012]. We discuss the differences between the assumptions of learning through increased capacity and directed technological change and their empirical plausibility (Section 2).

The carbon lock-in was originally examined from a systemic perspective highlighting the co-evolution of technology and institutions [Unruh 2000]: the technologically caused lock-in is exacerbated by institutional and policy failures. Our analysis focuses exclusively on the lock-in as a phenomenon of market failure and infrastructural barriers and leaves aside institutional issues. This permits to offer a clear economic perspective on that part of the carbon lock-in that can be treated quantitatively. In our model the lock-in arises through the combination of two externalities: First, learning spillovers that arise from building up capacities in the clean sector are unappropriated and are a stylized representation of positive externalities in the development of low-carbon technologies. Second, the negative effects of carbon-intensive production on utility through climate damages are ignored in the unregulated market outcome. The combination of the externalities can prevent the market from building-up the carbon-free sector and cause a delayed transition to the low-carbon economy. The model is described in Section 3.

The principal message of our study is that although a higher substitution elasticity requires less aggressive optimal mitigation policies, it creates higher welfare losses from a lock-in. This ambivalent role of the substitution possibility suggests to also examine second-best policy responses: We find that even if the only policy option available is a carbon tax, it can correct most of the welfare loss from the lock-in if the tax is set much higher. Furthermore, our results demonstrate that whether climate change mitigation requires a permanent or a merely temporary policy intervention depends primarily on the mechanism governing technological progress in the clean sector, and not on the value of the substitution elasticity. By contrast, the substitution possibilities crucially influence the feasibility of different policy options: we find that more stringent mitigation targets require a (much) higher carbon tax if the elasticity is low. This motivates a policy that increases the elasticity, particularly in the light of estimates that current substitution possibilities between clean and dirty sectors are very low [Hourcade, Pottier and Espagne 2011,Pelli 2011]. The simulation results are presented in Section 4.

We interpret the impact of the substitution elasticity for both the electricity and the transport sector. We conclude that in those sectors substitution possibilities can be mostly understood in terms of technology and infrastructure, although behavioral effects are important in the transport sector, too. This highlights the need for additional policy that increases the elasticity, for example financing appropriate energy infrastructure or fostering institutional changes towards intermodal transport (Section 5).

Our results are in contrast to the outcome of AABH's study on the impact of directed technical change in the chosen framework, which we demonstrate to be of limited scope. We find that the optimal policy suggested by AABH, which is temporary and triggers a sudden switch from the carbon-intensive to the low-carbon sector, does not reproduce the socially optimal outcome in our model. Instead, effective mitigation policies need to be permanent, regardless of the value of the substitution elasticity.

2 Two conceptions of technological progress

Technological progress that differs between the two sectors of an economy leads to different sectoral growth rates [Baumol 1967]. For the case of structural change towards the low-carbon economy AABH focus on endogenously determined sector-biased technological progress – *directed technical change* (DTC) [Acemoglu 2002]. Our approach is to assume a sector-biased technological change that is exogenously given, but inspired by empirical findings on the learning of low-carbon technologies. Here we compare the two approaches and discuss their relevance.

In the model of AABH, profit-incentives of workers in research and development ("scientists") determine whether technological progress proceeds in the clean or dirty sector. However, the numerical calibration of that model reveals that it exhibits "bang-bang" solutions: If the clean sector is significantly more productive than the dirty sector, no dirty output will be produced and the whole workforce will work in the clean sector and vice versa. This is due to the specific calibration of the direction of technical change: From Lemma 1 and Equations (11) and (24) of AABH as well as the specified calibration in Section V of that study one can deduce that if all innovation improves the technology of the dirty sector A_1 and none that of the clean sector A_2 :

$$A_{1,t} = 1.02A_{1,t-1} \text{ and } A_{2,t} = A_{2,t-1} \tag{1}$$

If instead all innovation benefits the clean sector A_2 :

$$A_{1,t} = A_{1,t-1} \text{ and } A_{2,t} = 1.02A_{2,t-1}. \tag{2}$$

The former is the case if the dirty sector is much more advanced than the clean sector. The latter happens if there are sufficiently high subsidies for the clean sector. The switch between these two possibilities is either immediate or happens within a time span of approximately 15 years in AABHs numerical simulation, depending on different parameter combinations.

By contrast, we examine the impact of a well-document stylized empirical fact about low-carbon technologies on policies for advancing structural change: a decline in cost per unit output through learning effects due to increased experience [Fischedick et al. 2011, Ch. 10.5.2.] [MacDonald and Schrattenholzer 2001]. While in our model there is an overall increase in total factor productivity that affects both sectors equally, technology in the clean sector $A_{2,t}$ depends positively on cumulative capacity H_t that represents the stock of experiences made with the low-carbon technology:

$$A_{2,t} = \exp(g_e t)\frac{\beta}{1 + (\frac{\omega}{H_t})^\gamma}. \tag{3}$$

Sector-unspecific total factor productivity is denoted by g_e, whereas β, γ and ω determine the shape of the learning curve for the clean technology. The level the clean technology converges to when it reaches maturity is given by β, thus determining the maximum productivity. The speed of the convergence to that level is determined by ω and γ. The three parameters together determine the learning rate of the technology. On this high level of generality the chosen learning curve of the clean technology in the model cannot correspond to actual data of the learning behavior of renewable energies. Yet the functional form employed is commonly used for the learning behavior of carbon-free technologies [Kalkuhl, Edenhofer and Lessmann 2012] and similiar modelling of learning-by-doing is very common in energy economics [Kverndokk and Rosendahl 2007,Edenhofer, Bauer and Kriegler 2005]. Examining the impact of learning-by-doing mechanisms in the structural change framework adopted by AABH has already been called for [Hourcade, Pottier and Espagne 2011].

Which conception of technological progress is more plausible for modeling structural change at this abstract level? While there is some evidence for the concept of DTC [Popp 2002], the decisive factor for understanding the risk of intertemporal lock-ins during the transition to the low-carbon economy is the learning behavior of renewable energies [Edenhofer et al. 2011]. Learning-by-doing is also the more comprehensive concept: It includes the migration of scientists and engineers to other sectors. Scientists and engineers need experiments to learn and need to build up capacities and equipment – this cannot be steered by huge research subsidy over a short time period as huge output of the clean technologies might not be profitable in a very short time span. The learning-by-doing approach thus stresses that the redirection of R&D-efforts is subject to path-dependencies in the careers of individuals, in the technological regulations and in the design and management of research institutions.

Our aim in this study is not to doubt the importance of DTC for understanding economic growth and structural change. We argue instead that the particular mechanism of DTC in the model of AABH represents a special case in the space of possible structural transformations towards the low-carbon economy, conflicting with empirical studies of the learning behavior of technologies. We identify an immediate switch between sectors as produced by AABHs model as corresponding to a very high learning curve in our model (4.4). Our study hence shows that focusing on the learning behavior of low-carbon technologies changes the picture of sensible policy responses to the carbon lock-in.

3 Model

We use a discrete-time intertemporal general equilibrium model that is similar to that of AABH except for the different conception of technological progress and the different role of government policy options. There are two sectors, one emission-intensive ("dirty") and one carbon-free ("clean"). Those sectors manufacture inputs used in the production of a final good that can be freely used for investment in each sector or for consumption. Households ignore the effect of global warming on their utility, which follows the heuristic approximation chosen in AABH. Technological progress in the clean sector is subject to a learning-by-doing effect based on its cumulative capacity, technological progress in the dirty sector is exogenously given.

The decentralized equilibrium contains two market failures: First, the environmental externality – dirty production decreases utility through damages of global warming – is not taken into account by the decentralized agents. Second, firms in the clean sector do not appropriate the intertemporal learning spillover resulting from their production.

3.1 The decentralized economy

We present the maximization problems of the agents in the economy and how policy instruments enter their choices. The derivations of the first-order conditions are given in Appendix A.

3.1.1 Demand

The representative household derives utility U_t from consumption C_t and the environmental quality, represented as the size of the carbon sink S_t :

$$U(C_t, S_t) = \frac{(\phi(S_t)C_t)^{1-\eta} - 1}{1-\eta} \tag{4}$$

with $\eta \neq 1$. The function $\phi(S_t)$ represents the impact of climate damages on utility including the possibility of an environmental catastrophe and is specified in Section 3.1.3. The household maximizes intertemporal utility, which is given by:

$$\max_{C_t, K_t} \quad \sum_{t=0}^{T} U(C_t, S_t) \frac{1}{(1+\rho)^t}. \tag{5}$$

It is assumed that the household ignores the effect of its investment decisions on S_t, thus representing climate change as an externality. The household owns labour L_t and capital K_t and faces the budget constraint

$$C_t + I_t = r_{1,t}K_{1,t} + r_{2,t}K_{2,t} + w_{1,t}L_{1,t} + w_{2,t}L_{2,t} + \Gamma_t, \tag{6}$$

with I_t denoting investment, $r_{i,t}$ the interest rate, $w_{i,t}$ the wage in sector $i = 1, 2$ and Γ_t the lump-sum transfer from the government budget to the household. The price of consumption is set to one as the final good is chosen as numeraire. The maximization is also subject to the dynamic constraint on the capital stock

$$K_{t+1} = I_t - (1-\delta)K_t \tag{7}$$

with depreciation rate δ. The household can distribute labour and capital arbitrarily between the sectors:

$$\bar{L}_t = 1 = L_{1,t} + L_{2,t} \tag{8}$$

$$K_t = K_{1,t} + K_{2,t}. \tag{9}$$

Labor is normalized to 1 for simplicity.

3.1.2 Supply

The economy produces a single good Y, which is composed of a carbon intensive intermediate good Y_1 and a low-carbon intermediate good Y_2. It is assumed that this final production is given by a CES function

$$Y = (Y_1^{\frac{\epsilon_t - 1}{\epsilon_t}} + Y_2^{\frac{\epsilon_t - 1}{\epsilon_t}})^{\frac{\epsilon_t}{\epsilon_t - 1}}. \tag{10}$$

in which $\epsilon_t > 0$ represents the elasticity of substitution between the clean and dirty goods. The higher the elasticity ϵ_t, the better substitutable are the clean and the dirty good. It may change with time exogenously. Intermediate good Y_i is produced from capital K_i and labour L_i according to a Cobb-Douglas production function:

$$Y_i = F_i(K_i, L_i) = K_i^{\theta}(A_i L_i)^{1-\theta}. \tag{11}$$

Final-good Producer The final good producer maximizes profits Π :

$$\max_{Y_1,Y_2} \quad \Pi = Y - (p_1 + \tau_1)Y_1 - p_2 Y_2$$

where p_1, p_2 are the prices of the clean and dirty goods and τ_1 is a tax on emission-intensive products *(carbon tax).*

Dirty sector Technological progress $A_{1,t}$ evolves exogenously in the dirty sector, reflecting an exogenous growth rate or total factor productivity g_e :

$$A_{1,t} = A_{1,0} \exp(g_e t) \tag{12}$$

The dirty firm maximizes profits Π_1 :

$$\max_{K_1,L_1} \quad \Pi_1 = p_1 Y_1 - r_1 K_1 - w_1 L_1$$

Clean sector In the clean sector, technological progress is endogenous and depends on the cumulative output of that sector through learning-by-doing. The cumulative output represents the stock of experiences made and is thus formalised as:

$$H_{t+1} = (Y_{2,t} - Y_{2,t-1}) + H_t, \tag{13}$$

H_0 denotes the inital stock of knowledge. The technology of the sector also depends on the total factor productivity g_e and is given by Equation (3), see Section 2 for a detailed explanation. It is additionally assumed that H_0 is small, so that technology in the dirty sector is initially much more advanced. Moreover, we posit $\beta > A_{1,0}$. Clean technology thus lags behind and takes more time to develop, but will eventually be more advanced than dirty technology. It is assumed for simplicity that spillovers in the clean sector are totally unappropriated by firms.

The clean firm maximizes profits Π_2 :

$$\Pi_2 = (p_2 + \tau_2)Y_2 - r_2 K_2 - w_2 L_2.$$

Here τ_2 is a *subsidy* on clean output.

No capital inertia in investments is assumed: in equilibrium wages and interest rates are equalized across sectors because production factors are perfectly mobile. Thus:

$$w_1 = w_2 \tag{14}$$

and

$$r_1 = r_2. \tag{15}$$

3.1.3 Climate damages

The climate externality caused by the production of the dirty sector and its negative impact on utility are modeled as in AABH[1]. In particular there is the possibility of an "environmental disaster" (zero utility) at very high temperatures. The size of the carbon sink S_t evolves as follows:

$$S_{t+1} = -\xi Y_{1,t} + (1+\zeta)S_t, \tag{16}$$

if the right-hand side is between 0 and the pre-industrial level $\bar{S}$. $S_{t+1} = 0$ if the right-hand side is negative, and $S_{t+1} = \bar{S}$ if the right-hand side is greater than $\bar{S}$.
S is now related to global mean temperature as follows: assume the standard approximation that if Δ is global mean temperature and C_{CO2} is carbon concentration in the atmosphere, then:

$$\Delta = 3\log_2\left(\frac{C_{\mathrm{CO2}}}{280}\right) \tag{17}$$

Assume further:

$$S = 280 \cdot 2^{\frac{\Delta_{\mathrm{dis}}}{3}} - \max\{C_{\mathrm{CO2}}, 280\}. \tag{18}$$

So Δ can be expressed as a smooth function of S if $C_{CO2} \geq 280$:

$$\Delta(S) = 3\log_2\left(2^{\frac{\Delta_{\mathrm{dis}}}{3}} - \frac{S}{280}\right). \tag{19}$$

Finally, define the function $\phi(S_t)$ introduced above as the argument of the utility function that gives utility the desired property of a possible environmental disaster and follows appropriate standard assumptions about climate damages for a moderate temperature increase (detailed in AABH, Sections I. and V A.):

$$\phi(S) = \varphi(\Delta(S)) = \frac{(\Delta_{dis} - \Delta(S))^{\lambda} - \lambda\Delta_{dis}^{\lambda-1}(\Delta_{dis} - \Delta(S))}{(1-\lambda)\Delta_{\mathrm{dis}}^{\lambda}}. \tag{20}$$

3.2 Equilibria of the Economy

We distinguish three types of equilibria: the social optimum, the laissez-faire equilibrium and the decentralized equlibirium with government intervention. We obtain our results by comparing different policy choices of the government with the social optimum and the laissez-faire equilibrium.

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[1] This climate module, due to AABH, has been critized as too optimistic concerning the regeneration capacity, the lifetime of CO_2 and the size of the carbon sink and thus as not in accordance with recent climate science. Furthermore, if a more realistic climate module is used in AABH's model, the policy implication of our study that the need for regulation is permanent has been confirmed [Hourcade, Pottier and Espagne 2011]. As the aim of our work is to make very general points without aiming for accuracy in calibration, we keep AABHs climate module in order to be directly comparable to that model.

3.2.1 Social Optimum

Determining the social optimum provides a benchmark for evaluating the effectiveness of policy options. The social planner determines the optimal allocation in the economy by maximizing intertemporal utility of the representative agent subject to the constraints on factors of production, the production technologies, the influence of environmental quality and the macroeconomic budget constraint. The social planner problem is thus:

$$\max_{C_t, K_{i,t}} \sum_{t=0}^{T} U(C_t, S_t) \frac{1}{(1+\rho)^t} \tag{21}$$

subject to the Equations (3), (7) – (13), (16) – (20) and the macroeconomic budget constraint $Y_t = C_t + I_t$.

The social planner hence recognizes both the negative impact of the carbon-intensive production on the household's utility through decreasing environmental quality as well as the productivity gains through learning-by-doing in the clean sector.

3.2.2 Decentralized equilibrium with government intervention

The first-order conditions following from the agents' maximization problems above (given in Appendix A) describe a market equilibrium with given policy instruments. The government anticipates the agents choices and sets the policy variables – the carbon tax and the learning subsidy – with the aim of maximizing social welfare. It redistributes taxes and subsidies lump-sum to the representative agent.

$$\Gamma_t = \tau_{1,t} Y_{1,t} - \tau_{2,t} Y_{2,t} \tag{22}$$

The maximization problem of the government is thus:

$$\max_{\tau_1, \tau_2} \sum_{t=0}^{T} U(C_t, S_t) \frac{1}{(1+\rho)^t} \tag{23}$$

subject to the the first-order conditions of the agents, the household's budget constraint, the technology constraints and the state of the carbon sink, that is subject to Equations (3), (6) – (20), (22) and (25) – (32).

3.2.3 Laissez-faire equilibrium

The laissez-faire equilibrium is a special case of the decentralized equilibrium with government intervention: the government's policy options are set to zero, implying unregulated markets.

3.3 Model calibration

The model is calibrated to be comparable with AABH. The time period of the numerical simulation corresponds to five years, intertemporal parameters are hence chosen with respect to that interval. The time horizon is T=175 years. Those parameters with values identical to the calibration of the model of AABH are displayed in Table

3 in Appendix B. Since the technological progress and capital dynamics are conceptualised differently from AABH in the present model, a standard rate of capital depreciation (0.03% per year, that is $\delta = 0.141$) is selected and the rate of exogenous technological progress is chosen to obtain a long-run growth rate of consumption of 1.8% per year. The remaining parameters for the technological progress in the clean sector are chosen such that the clean sector initially lags behind and eventually is more efficient than the dirty sector.

We deviate from the calibration of the state of the atmosphere from AABH in two respects. First, the initial value of CO2-concentration is updated to 389 ppm. Second, since AABH do not state precisely their employed values for the emission itensity ζ and regeneration rate ξ of the atmosphere, we compute our own emission intensity and regeneration rate with the values for current CO2 increase and dissipation given in [Rezai, Foley and Taylor 2011].

The optimisation problem of the social planner (21) and the government (23) form non-linear programs. These are solved numerically with GAMS [GAMS Development Corporation 2008].

4 Results

In this section the results of the numerical simulations of our model are reported. First the size of the lock-in is quantified (4.1), subsequently the optimal policy intervention is calculated as the welfare-maximizing tax paths (4.2). High welfare losses can be avoided even if only a single instrument is available to the government, providing a measure of the additional intervention due to the lock-in (4.3). The impact of a higher learning curve on the duration of the structural change is examined (4.4). Finally, the optimal policy is characterized when the social optimum is constrained by a two degree target (4.5).

Throughout, three cases for the substitution possibilites for clean and dirty production are considered and represented by values of the substitution elasticity ϵ. Two cases, $\epsilon = 3$ and $\epsilon = 10$, are equal to those in AABH's numerical simulation to make our findings comparable with that study. In addition a third case is examined in which ϵ increases linearly over time from initially $\epsilon = 3$ up to $\epsilon = 10$ eventually. These cases are labelled the “low”, “high” and “increasing” scenario below. Welfare losses resulting from sub-optimal or missing policy intervention are quantified in balanced-growth equivalents (BGE) [Mirrlees and Stern 1972, Anthoff and Tol 2009] as environmental quality enters utility directly.

All subsequent numerical results are very model specific and their rationale is to make general points only: the values of the various measures of the carbon lock-in should be understood as highly uncertain.

4.1 Lock-In

In the unregulated decentralized equilibrium the economy produces too much of the dirty good compared to the social optimum: The intertemporally inferior carbon-intensive technology dominates the market and a transition to the low-carbon economy occurs later than would be socially optimal. This lock-in into the dirty sector is quantified in three respects: (a) the aggregate discounted welfare losses over time are measured in BGE, (b) the delay of the structural transformation is given as the difference between the socially optimal and actual time of reaching a 50 % share of the clean sector and (c) the total and the additional amount of global warming compared to the social optimum is calculated. For the different substitution scenarios the simulations can be summarized as follows: The "high" scenario leads to a much greater lock-in compared to the "low" scenario on all scales, whereas the "increasing" scenario represents an intermediate case, see Figure 1. Figure 2 compares the socially optimal time paths with those of the unregulated market outcome for the share of the clean and the dirty sector and the state of the atmosphere. There are significant differences in the deviations of the decentralized paths from the socially optimal outcome: In the "low" case a share of the clean sector is missing that is approximately constant over time, while in the "high" case the switch from the dirty to the clean sector is delayed, the "high" scenario representing a middle case. The socially optimal amount of global warming is below 2°C for the "high" and "increasing" case and $2.9°C$ for the "low" case: due to the difficulty in substituting away from low-carbon production it is socially optimal to accept more global warming in order to have more consumption. However, the better the substitution possibilities, the higher is the additional amount of global warming produced by the externality.

4.2 First-best Policy Response

In the absence of policy intervention, severe welfare losses occur due to the combination of market failures that creates the lock-in. This motivates the subsequent analysis of policy responses that avoid it. To correct the externalities, a carbon tax and a learning subsidy are feasible policy instruments. The welfare-maximizing time paths of the policy instruments are computed for the three different substitution possibilities (Figure 3). In all cases, carbon prices are increasing with time, and after an initial period, subsidies are decreasing. Only for the "high" case of $\epsilon = 10$ an initially low learning subsidy is found that indicates that for such substitution possibilities the switch from one dominating technology to the other can be very fast. For the "low" case of $\epsilon = 3$ the optimal policy involves a substantially higher carbon price and a moderately higher learning subsidy than in the other cases. Except for an initially high learning subsidy, the "increasing" case requires policy instruments much more in the order of the "high" case than the "low" case. The optimal policy intervention for the structural change to avoid the lock-in is permanent for all scenarios and the subsidy, although it is decreasing, must last at least as long as no more learning can occur because the maximum productivity is reached.

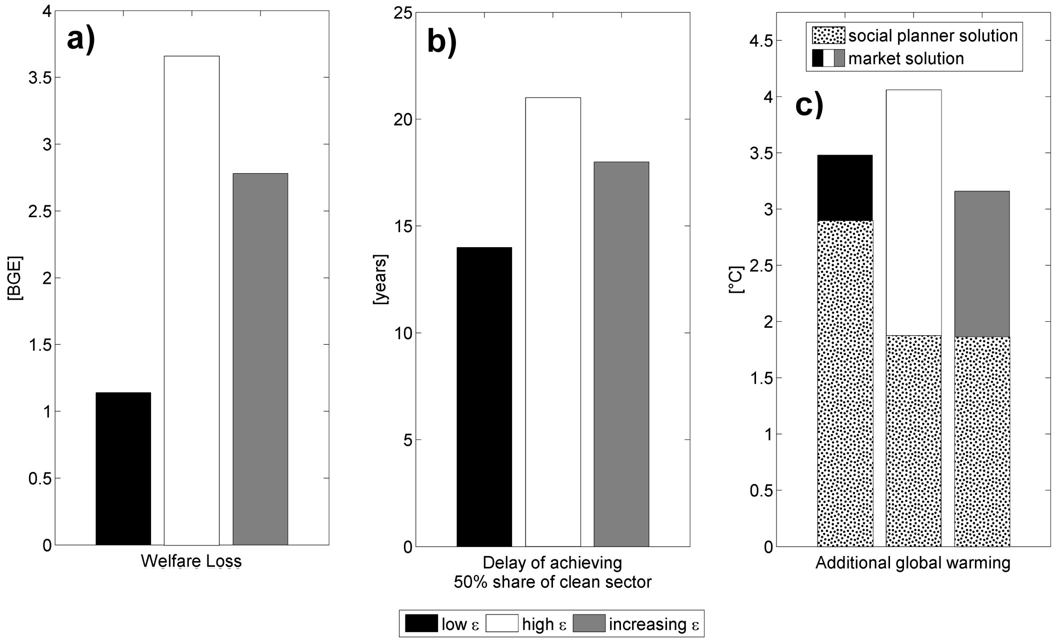

Figure 1: The lock-in of the unregulated market outcome for different substitution elasticities: comparison to the socially optimal outcome in terms of (a) welfare, (b) delay of clean sector and (c) (additional) global warming.

4.3 The size of the carbon lock-in as additional intervention: Second-best policy with a single instrument

In a second-best policy scenario the government has only a single instrument available to maximize welfare. Even in this case it can significantly improve the market outcome. This second-best intervention requires that the single instrument is set significantly higher compared to the optimal intervention. Results are close to the social optimum: numerical solutions show that for the different cases of elasticities the second-best optimum does not produce losses greater than 0.002 % BGE, even if the first-best production and consumption paths differ markedly. This is an unsurprising result: Both the climate and the learning externality impact the distribution of inputs to the dirty and clean sector. So one instrument set significantly higher than in the first-best optimum can correct much of the second externality.

This result is illustrated for the case that the *carbon tax* is the single instrument available to the government: Figure 4 displays the first-best (=Pigouvian) carbon tax $\tau_{1,t}$ compared to the single instrument carbon tax $\tau'_{1,t}$ for the three cases of the substitution possibility.[2] This comparison conveniently allows to quantify the

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[2] In the model the learning externality is very high because it is assumed for simplicity that spillovers are completely unappropriated. Thus the absolute magnitude of additional carbon tax due to the correction of the learning externality is not meaningful.

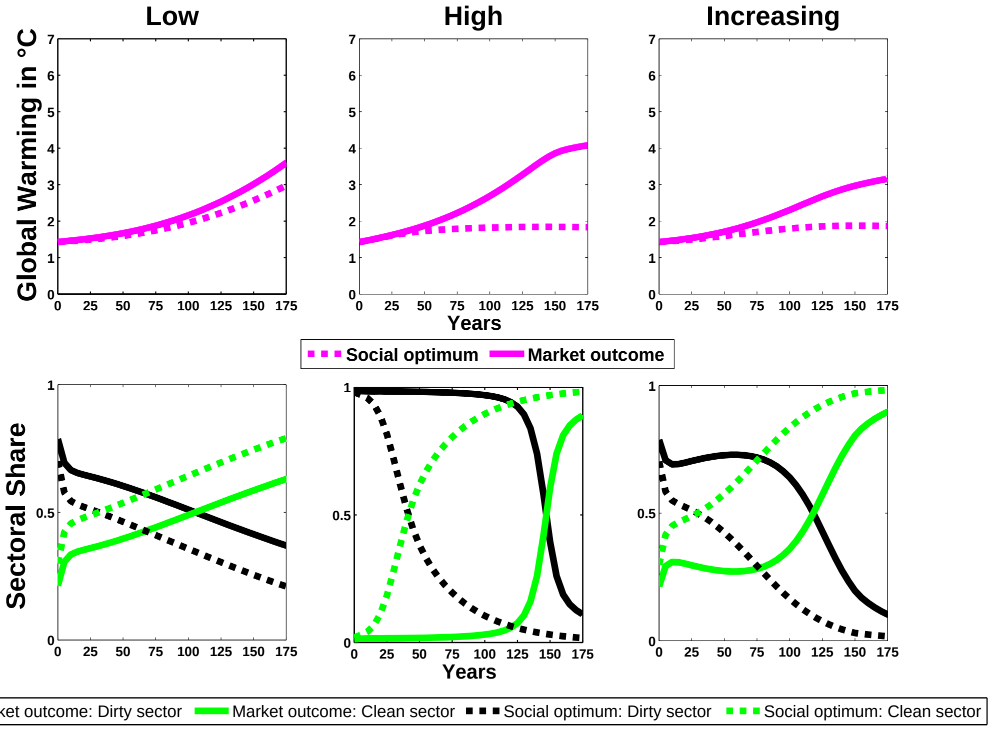

Figure 2: Comparison of the market and the social planner solution: The time paths of global warming and the share of the clean and dirty sector for the different cases of the substitution elasticity.

additional policy intervention that is specific of the lock-in and unrelated to the global warming externality per se. It takes into account that if substitution possibilities are poor, socially optimal mitigation is more difficult to achieve by policy intervention even if learning spillovers were appropriated. The additional cumulative carbon tax required by the lock-in is determined by calculating the additional policy intervention P_{Lock} as the cumulative difference between the two carbon tax paths ($P_{\text{Lock}} = \sum_{t=0}^{150}(\tau_{1,t} - \tau'_{1,t})$). Table 1 shows that the policy intervention that is required to overcome the lock-in beyond correcting the climate externality is highest if substitution possibilities are low.

This finding completes our thesis that substitution possibilities play an ambivalent role: While in (4.1) it was shown that in the unregulated outcome good substitution possibilities cause the highest welfare losses, the numerical results of (4.2) and (4.3) demonstrate that poor substitution possibilities require the highest policy intervention.

4.4 The impact of a high learning curve on the transition

This subsection provides an elementary consideration about the dependence of the structural change on the learning curve. “Transition time” denotes the time taken in

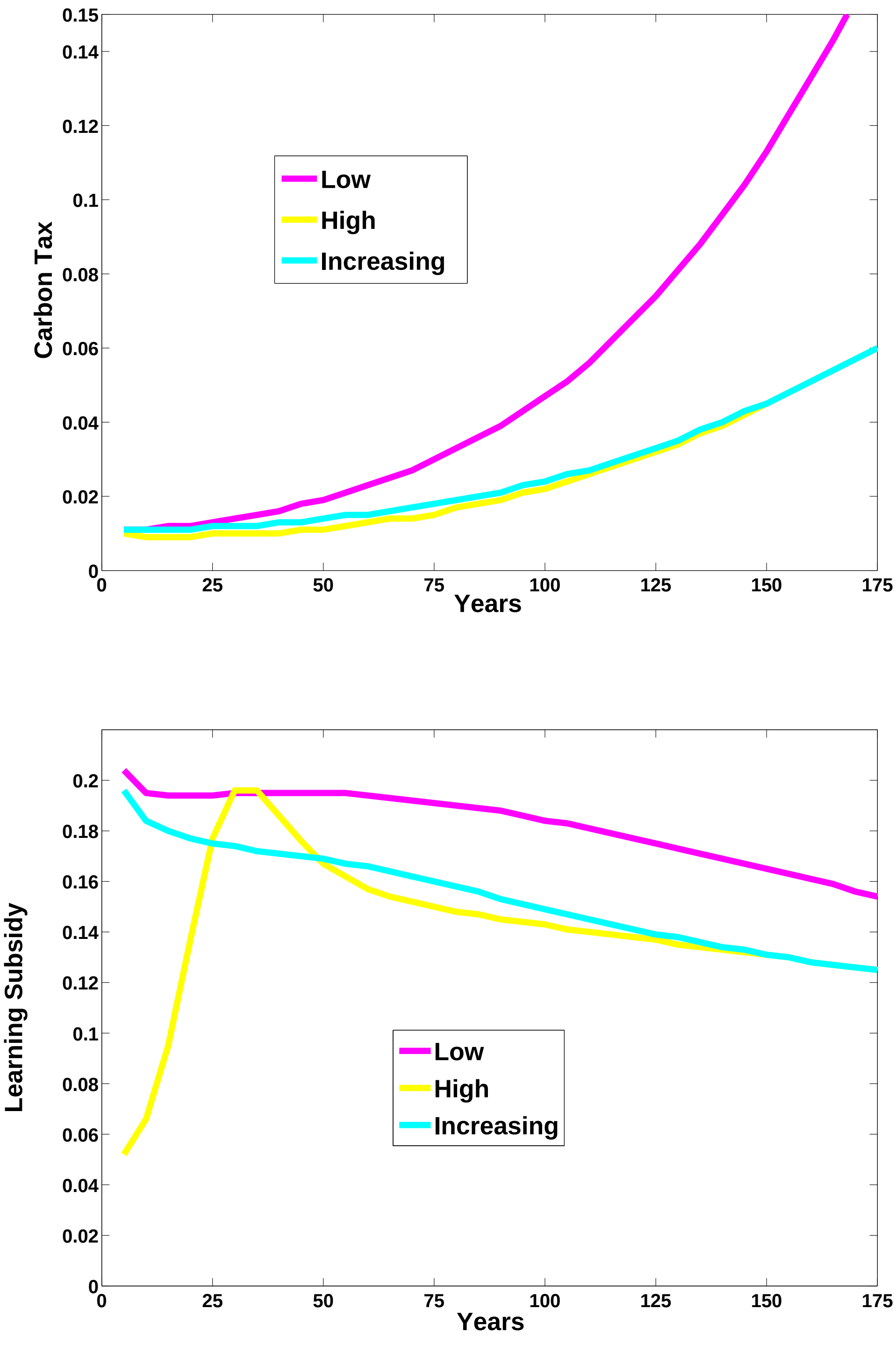

Figure 3: The optimal policy mix required to reproduce the social optimum.

	$\epsilon = 3$	$\epsilon = 10$	ϵ linearly increasing from 3 to 10
P_{Lock}	5.48	5.08	5.36

Table 1: Additional policy intervention that characterizes the carbon lock-in [price units]

	$\epsilon = 3$	ϵ linearly increasing from 3 to 10	$\epsilon = 10$
$\gamma = 0.27$	190	100	50
$\gamma = 0.2$	180	65	15
AABH[a]	70	–	15

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[a] Own estimations from Figure 1 of [Acemoglu et al. 2012]

Table 2: Transition time as a function of the learning rate and the substitution elasticity.

the social planner solution to reach a share of 80 % of the clean sector from at least a 20 % share of that sector. The transition time is calculated for two different learning curves for the clean technology. Besides the standard parametrisation of $\gamma = 0.27$ a low value of $\gamma = 0.2$ is considered that results in a higher learning curve (see Figure 5). Table 2 presents the values of the transition time for two different learning curves and three cases of the substitution elasticity. This measure characterizes the transition from the fossil-fuel based to the low-carbon economy as a gradual adjustment or an immediate switch: the higher the substitution elasticity, the shorter the transition time.

By comparison, the numerical solution to AABH's model contains a rather abrupt switch (see Figure 1 of AABH) due to the 'bang-bang behavior' of technological progress: In that model the transition time is 15 years for $\epsilon = 10$ and 70 years for $\epsilon = 3$ for the discount value of $\rho = 0.001$ (per year). We conclude that our analysis indicates that the conception of directed technical change propounded by AABH thus implicitly reflects a learning curve of sudden high competitivity.

4.5 Implications of a two degree target

Due to high uncertainties about economic damages and losses of human lives, standard cost-benefit-analysis is of limited normative cogency for evaluating policy responses to climate change. A more promising normative approach will seek to evaluate pathways of decarbonization taking a guardrail on climate damages as given. Limiting the most severe impacts from climate change requires keeping global mean temperature below 2°C [WBGU 2009, Lenton et al. 2008]. This two degree target

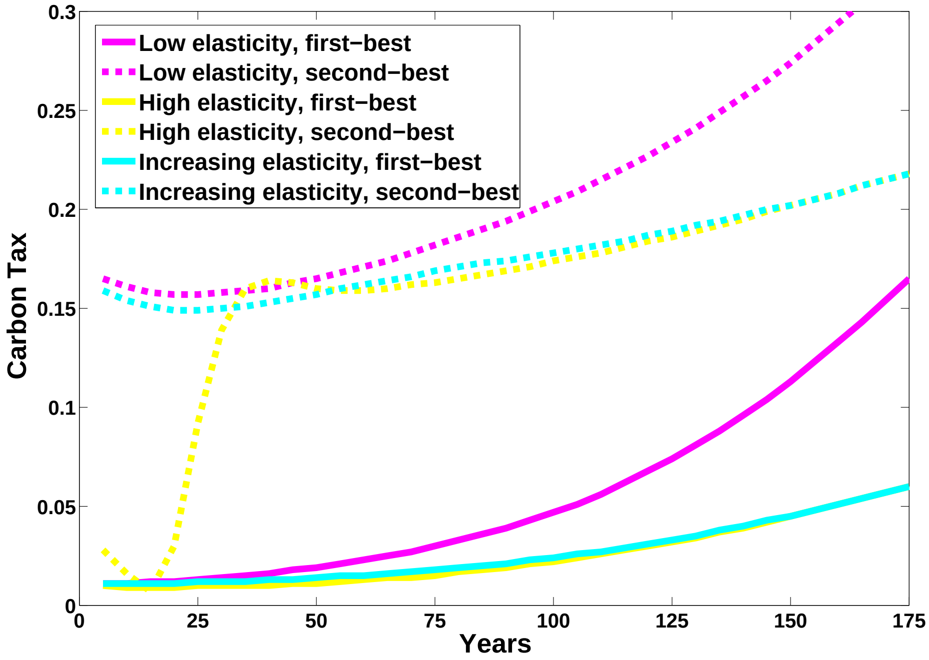

Figure 4: The second-best carbon tax $\tau'_{1,t}$ compared to the first-best tax $\tau_{1,t}$ for different substitution elasticities.

has become the focus of many political efforts to limit global warming and economic studies have demonstrated its feasibility [Edenhofer et al. 2009].

Under the unconstrained cost-benefit analysis of climate damages, the socially optimal amount of global warming is significantly above 2°C for low values of the substitution elasticity (see Figure 2) in our model: for $\epsilon = 3$ it is 2.9°C at t=175. For this case we compute the additional policy intervention necessary to comply with a two degree target. We find that the carbon tax for the two degree target is significantly – eventually about ten times – higher than the carbon tax from the first-best optimum of an unconstrained cost-benefit analysis (see Figure 6). Low substitution possibilities hence make ambitious mitigation very expensive and difficult to implement politically as they require aggressive carbon pricing towards the end of the decarbonization. This motivates our subsequent discussion of understanding substitution possibilities as non-constant over time and potentially subject to further policy intervention.

4.6 Comparison to the findings of AABH

AABH argue that a high substitution elasticity between the carbon-intensive and the carbon-free sector of the economy facilitates the structural change from a carbon-intensive to a low-carbon economy as it requires an immediate, but less comprehensive

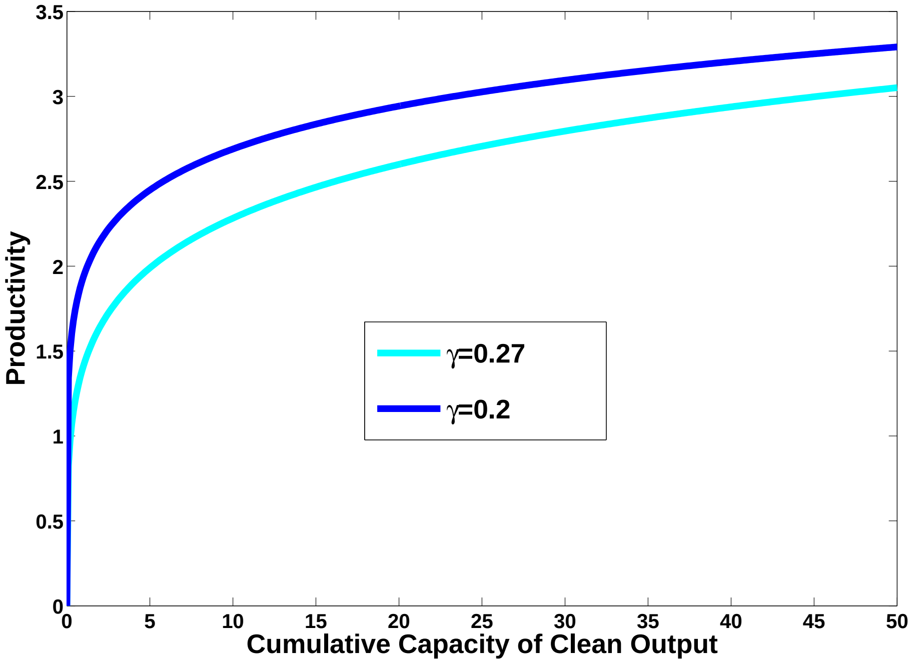

Figure 5: Two learning curves differing by the learning parameter γ for the clean technology.

and merely temporary policy intervention. We confirm this result with our model, but highlight that a high substitution elasticity also creates greater risks of a welfare loss from a lock-in. We disagree with AABH that an immediate, but temporary policy intervention is optimal: a permanent intervention is required if a more empirically plausible conception of advancing renewables is assumed. Our study can thus be seen as indicating that ABBH's policy advice for fostering low-carbon structural change is limited in scope: it depends on a particular calibration of technological progress in the framework of directed technical change, the normative assumption of an unconstrained cost-benefit-analysis, the restriction to finding the optimal policy response and an elasticity of substitution between sectors that is constant over time. The lesson for giving policy advice is that there is a high variability of trajectories for structural change according to particular assumptions – for which often no well-established empirical estimates exist; no clear-cut policy message based on one assumption-set is hence legitimate.

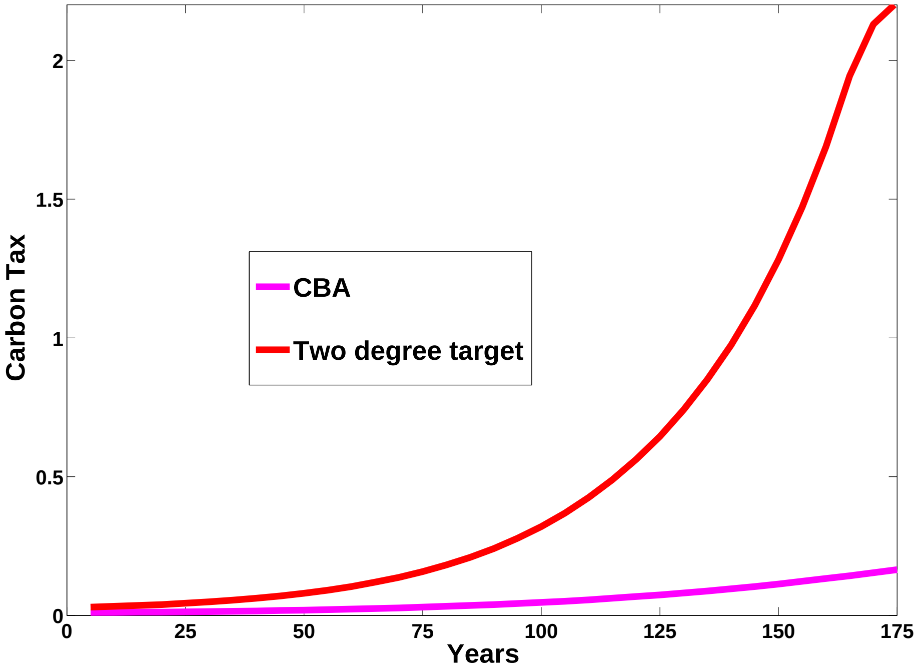

Figure 6: Comparison between a cost-benefit analysis and a two degree target of the optimal carbon tax paths for a low substitution elasticity $\epsilon = 3$.

5 Discussion: Substitution possibilities and infrastructure in real-world economic sectors

A substitution elasticity is not a natural constant, but an artifact of economic theory: the ease of using one technology or product instead of another one. We discuss our modelling results in the light of substitution possibilities from dirty to clean production for real-world sectors. We highlight three messages:

- Substitution possibilities are influenced by infrastructure in relevant sectors of the economy, as infrastructure crucially matters for enabling the use of a product. Yet behavioral and institutional factors can also influence substitutability.
- The substitution elasticity between clean and dirty production is currently not very high and the increasing case is the most plausible scenario for the coming decades.
- The substitution elasticity can be influenced by (infrastructure) policy; further research should study this additional policy measure formally.

We elaborate these messages concerning future substitution possibilities for two economic sectors: electricity and transport.

In the electricity sector the division between carbon-free and fossil-fuel based technologies is clear-cut. An estimate of the elasticity with the model of AABH in the electricity sector using historical output data finds that ϵ is around 0.5 for major countries in the last decades [Pelli 2011]. This contradicts the intuition developed in AABH's model that clean and dirty energy are good substitutes. It instead highlights the fact that in the 20^{th} century there was almost no energy infrastructure in place that was suitable for advancing carbon-free economic activities on a large scale.

Electricity is an almost perfectly homogenous good whether its generation is clean or dirty; however, the use as opposed to the generation of renewable energy is not straightforward and requires appropriate infrastructure. Consumers of electricity rarely have direct access to renewable energies: renewable energy production misaligns with electricity demand in time and space. Daily and seasonal fluctuations do not match demand and geographically advantageous generation capacity does not fit to load. Nevertheless infrastructure investments can enable renewable energy use in a way such that the misalignment across space and time is compensated for: Grid extensions allow large scale transfers of electricity from generation sites to load sites. If grid integration across large spatial scales ($>$ 300km) is substantial, weather and climate fluctuations can be averaged out. Storage and demand management attenuate temporal fluctuations. We suggest that the investments in these infrastructures can be interpreted as an increase in the substitution possibilities and that for the case of electricity, infrastructure is the decisive determinant of substitution possibilities. It thus seems likely that a) current substitution possibilities are *low* as electricity infrastructure is suited for large scale power generation near major demand sites and that b) there will be a considerable increase in the elasticity if substantial investments in electricity infrastructure towards the integration of renewables are carried out.

In the transport sector current infrastructure is focused on road vehicles with internal combustion engines [Schaefer et al. 2009]. Both at the level of local urban transport as well as for long-distance freight and passenger transport, existing infrastructure makes it difficult to substitute away from carbon-intensive transport modes. However, significant attempts are made to introduce a transport infrastructure suitable for the use of electric cars to facilitate the substitution [Andersen, Mathews and Rask 2009]. Furthermore, locally different infrastructures that are focused on non-motorized or public transport reveal that a high share in these other modes is possible: examples at the city level include Freiburg, Copenhagen, Hong Kong as well as high-speed (France, Japan) and freight rail (USA) networks for long-distance transport. In the urban context enhancing public transport infrastructure has been found to have an effect on the price elasticity of demand for carbon-intensive transport [Creutzig and He 2009]. Consumer preferences are also important to determine the elasticity between carbon-intensive and low-carbon modes in the case of transportation, since mode choice also involves important trade-offs in terms of security, privacy, comfort and health as well as being driven by habituation to a single mode. Yet easily usable indications of available (public) transport modes may facilitate switching between carbon-free and carbon-intensive modes. Currently the substitution elasticity between clean and dirty transport possibilities is supposedly low, but can be expected to increase with infrastructure projects and institutions promoting intermodal transport.

The previous discussion of the substitution possibilities in two sectors that are crucial for decarbonization of the economy suggests that the case of an increasing elasticity of substitution is a plausible scenario for the next decades. At least as far as substitution possibilities are driven by appropriate infrastructure, they can be changed by suitable policies. For instance, these may include to give other urban transport modes priority over cars or to adapt national power grids to the requirements of a high share of renewable energy generation.

Our modeling results demonstrate that the *timing* of such policy measures and their combination with taxes and subsidies matters. Enhancing the substitution possibilities at the right time during the phase of structural change may help the decarbonization and avoid a severe lock-in. According to our results, if infrastructure measures are taken up too late, mitigation requires high carbon pricing. If they are taken up too early, they may aggravate welfare losses from a lock-in if the other policy measures are insufficient.

The last point indicates a limitation of our interpretation of substitution possibilities in terms of infrastructures: these do not always influence the substitutability in both directions. In case substitutability is increased and the carbon-intensive technology is significantly more competitive, it will receive a larger share of production – implying high welfare losses if no tax against global warming is in place. However, some infrastructure measures do not act on substitutability in this way: tailoring urban transport infrastructure towards public and non-motorized modes facilitates substituting *away* from car transportation, but will not increase the share of the carbon-intensive mode if no other policy is in place. In future work, we intend to model explicitly which infrastructures influence the substitutability between clean and dirty production in both or only a single direction, while at the same time considering explicitly infrastructure investments as a policy instrument.

6 Conclusion

This paper discusses how substitution possibilities between carbon-intensive and low-carbon production influence which policy interventions are appropriate for avoiding a carbon lock-in. An ambivalent role for such substitution possibilites is identified: good substitutability increases the risk of a lock-in, but requires less drastic policy interventions to trigger structural change towards the low-carbon economy. A learning-by-doing approach for modeling technological progress in the clean sector with a conventional learning curve implies that a permanent intervention is necessary for structural change towards the low-carbon economy. The policy recommendation of AABH – based on directed technical change – that triggering the structural change requires a merely temporary intervention, is a special case in the parameter space of substitutability and learning of technologies. Characterising the full scope of the parameter space of learning behavior and substitution possibilities is however beyond the scope of this study.

Furthermore, the substitution elasticity between carbon-intensive and low-carbon production cannot be assumed to be constant over the next decades. We identify infrastructures as the main factor determining the substitutability and conclude that infrastructure investments can hence influence the substitution elasticity and be part of the policy response to the carbon lock-in. Disentangling different determinants of substitution possibilities in the major economic sectors that face decarbonization is beyond the scope of the paper, but an important question for future work.

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A First-order conditions of decentralized agents

Household The Lagrangian corresponding to the household's maximization problem is:

$$\mathcal{L}(C_t, K_t, \lambda_t) = \sum_{t=0}^{T} (U(\phi(S_t)C_t)) \frac{1}{(1+\rho)^t} \\ + \lambda_t (r_t K_t + w_t L_t + \Gamma_t - C_t - K_{t+1} + (1-\delta)K_t)) \quad (24)$$

The optimal choice for the household is thus characterised by the following first-order conditions (with $\mu_t := \lambda_t \frac{1}{(1+\rho)^t}$) :

$$\frac{\partial \mathcal{L}}{\partial C_t} = \frac{\partial U}{\partial C_t}(C_t) - \mu_t = 0 \quad (25)$$

and

$$\frac{\partial \mathcal{L}}{\partial K_t} = \mu_t (r_t + (1-\delta)) - \mu_{t-1}(1+\rho) = 0. \quad (26)$$

Final-good Producer The usual equilibrium price conditions apply including the carbon tax:

$$p_1 + \tau_1 = \frac{\partial Y}{\partial Y_1}, \quad (27)$$

$$p_2 = \frac{\partial Y}{\partial Y_2}. \quad (28)$$

Dirty Firm The usual static equilibrium conditions for the interest rate and the wage apply:

$$r = p_1 \frac{\partial Y_1}{\partial K_1}, \tag{29}$$

$$w = p_1 \frac{\partial Y_1}{\partial L_1}. \tag{30}$$

Clean Firm The standard static equilibrium conditions apply including the learning subsidy:

$$r = (p_2 + \tau_2) \frac{\partial Y_2}{\partial K_2} \tag{31}$$

$$w = p_2 \frac{\partial Y}{\partial L_2}. \tag{32}$$

B Parameter choices for numerical solution

Parameter	Significance
$\eta = 2$	intertemporal elasticity of substitution
$\epsilon = 3, 10$	elasticity of substitution between clean and dirty sector
$\rho = 0.00501$	discount rate
$\theta = \frac{1}{3}$	factor intensity in production
$\bar{S} = 280 \cdot (2^{\frac{\Delta_{\text{dis}}}{3}} - 1) \approx 1098,9$	pre-industrial CO2-concentration: 280 ppm
$S_0 = 280 \cdot 2^{\frac{\Delta_{\text{dis}}}{3}} - 389 \approx 989,9$	current CO2-concentration: 389 ppm
$\Delta_{\text{dis}} = 6.9°$	disaster temperature
$\lambda = 0.3492$	damage scale parameter

Table 3: Parameters as assumed by AABH

Parameter	Significance
$\delta = 0.141$	depreciation of capital
$g_e = 0.07$	general productivity growth
$\beta = 8$	maximum productivity
$\omega = 300$	scaling parameter
$\gamma = 0.27$	curvature of learning curve
$\zeta = 1.7$	regeneration capacity of atmosphere
$\xi = 0.00137$	emission intensity
$K(0) = 5$	initial value of capital stock
$H(0) = 0.3$	initial value of knowledge
$L(t) = 1$	normalized size of labor force over all time periods

Table 4: Additional parameters calibrated to match stylized facts

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