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Energy Transition, Technological Spillovers and Elasticity of Substitution

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Abstract

Countries such as Germany and Switzerland have included the energy transition in their policy programs, setting specific targets in terms of energy production from renewables. However, the energy transition has a cost, which so far has been partly covered by subsidizing the clean production. This has produced an adverse effect, leading to overproduction in the clean sector and negative prices in the electricity spot market. An excessive subsidy, which does not takes into account technological spillovers and the elasticity of substitution, might be the cause. We use endogenous growth theory to study how the cost of the energy transition - proxied by a subsidy - is affected by these two channels. We provide a numerical solution to the model to give an insight into the magnitude of the effect considered. The main findings are: (1) technological spillovers reduce the cost of the energy transition and the subsidy becomes negative after a threshold value of relative spillover intensities; (2) a higher elasticity of substitution between the two sectors increases the cost of the energy transition.

Keywords: Energy transition, Negative electricity prices, Technological spillovers, Elasticity of substitution, Market size effect.

JEL classification: O33, O44, Q42, Q58

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1. Introduction

The need to limit emissions in order to avoid undesirable consequences of climate change is now widely recognized. Identifying opportunities to cut emissions of greenhouse gases (GHG) requires a clear understanding of the main sources of those emissions. The energy sector, including fuels consumed to generate, transmit and distribute electricity and heat generation, is responsible for about 40% of global emissions according to the International Energy Agency (IEA)'s estimates. Moreover, the energy sector, contributes to approximately 35% of global emissions of CO_2, which accounts for more than 80% of total greenhouse gas emissions globally (IEA, 2015). Given these numbers, an energy transition - defined as a long-term structural change in energy systems, encompassing a shift from a system dominated by fossil-based energy towards a system using a majority of renewable energy sources - can play a fundamental role in mitigating climate change (Sims et al., 2007). As a consequence, countries such as Germany, with the *Energiewende*, and Switzerland, with the *Energy Strategy 2050*, have started to define goals in terms of energy produced from clean sources. Legislative support for the *Energiewende* was passed in late 2010 and includes greenhouse gas reductions of 80-95% by 2050 (relative to 1990) and a renewable energy target of 60% by 2050. The *Energy Strategy 2050* includes technology and energy efficiency measures aimed at reducing energy consumption, increase energy efficiency and promote renewable energies. In particular, it states that the percentage of energy produced from renewable sources must be increased by 5400 GWh in 2030 compared to the value in 2000 and by 11400 GWh in 2035. However, these measures have costs (e.g. in terms of new technologies development or infrastructures construction) that has been so far been mostly covered by subsidizing the clean sector. Indeed, policy support is crucial to trigger the energy transition and can affect the direction of technical change, encouraging firms to adopt a cleaner path (Smulders & de Nooij, 2003). In this paper, we investigate how the cost of the energy transition, proxied by a subsidy, is affected by technological spillovers and by the elasticity of substitution between sectors. We use a model of endogenous growth with substitutable clean and dirty sectors and we introduce technological spillovers from broad capital. The stylized fact which captured our interest and led us to study how the subsidy is affected by technological spillovers and by the elasticity of substitution between sectors is the realization of negative prices in the german electricity spot market. We think this can be at least partly attributed to an excessive subsidy and the latter may be the consequence of incorrect or lacking expectations about the impact of spillovers and of the elasticity between sectors.

Our work is motivated by the goal of providing possible explanations to the negative electricity prices observed in countries that have adopted measures to promote the production from renewable sources. We consider in particular the case of Germany, where renewable power producers receive guaranteed feed-in payments for every kilowatt-hour they produce. As their power is sold at the electricity market (either by transmission grid operators or directly by renewable marketeers) part of this feed-in remuneration is covered from the market price for power. However, the choice to subsidize clean production has turned out to have a potential adverse effect, leading to overproduction in the renewable sector and negative prices in the electricity spot market. The phenomenon rarely occurs in Germany but it is on the rise since a larger number of renewable sources are feeding into the grid. Since 2008 more than 10 hours with negative prices have occurred at the day-ahead market at the electricity exchange for the German market area, EPEX-Spot, every year. After, the number of hours rose to 71 in 2009 and then it fell again. In 2011 the renewable energy sector was expanded further and the number of negative price hours rose. Between 2012 and 2014 a total of 10 intervals with negative electricity prices which lasted for at least 6 hours occurred. Production of power was higher than initial demand during 126 hours in

2015. As shown in Figure 1, the german electricity spot market displayed several days of overproduction in 2017, which has translated in negative prices (EPEX-Spot, 2017).

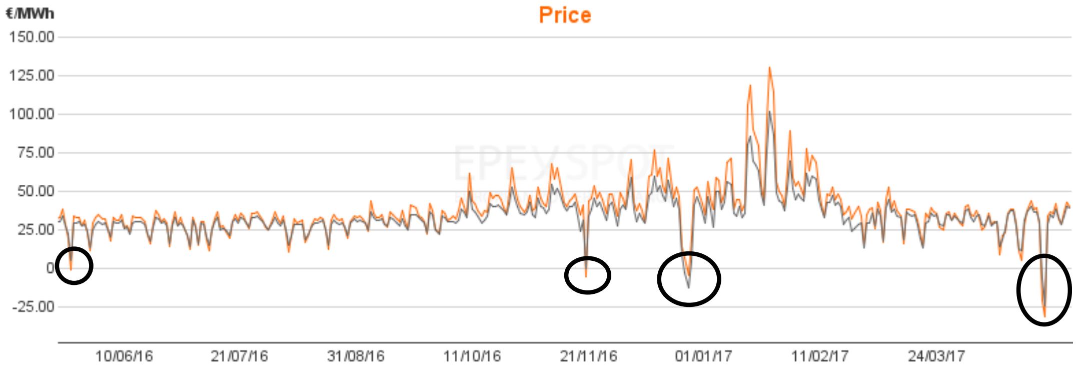


Figure 1: Spot energy price in Germany in 2017. Baseload (*grey*), peakload (*orange*). *Source*: EPEX-Spot

Apart from the inflexible power generation, which cannot be shut down and restarted in a quick and cost-efficient manner, negative prices can be attributed to the subsidy received by the renewable sector: when this is higher than the one needed to meet demand, it leads to overproduction. The facts reported above show that subsidizing the renewable sector excessively can generate a double cost. On one side, consumers have to finance the subsidy scheme; on the other side, producers have to sell electricity at negative prices or at least to reduce their profits. The excessive subsidy can be due to the government's lack of correct information on the intensity of technological spillovers in the economy and on the elasticity of substitution between clean and dirty sectors. As a consequence, we think it is important to investigate the impact of these channels on the subsidy, even though this is not the only component involved in the cost of an energy transition. We show that including the impact of technological spillovers and of the elasticity of substitution can explain the negative prices observed in the electricity market.

Although the link between global economic output and energy-related GHG emissions weakens (Bretschger et al., 2015), a transformation in the energy system is required in order to stabilize GHG concentrations at low levels (Dasgupta, 2015). The long-term transition to an energy system consistent with the 2°C climate goal, entails fostering the development of new technologies, which are the more convincing tool to face the increasing demand for energy and, at the same time, satisfy the sustainability constraint (Stern, 2007).

Technological innovation potentially leading to an energy transition can occur by means of three, non-exclusive, processes: (1) Learning-by-doing; (2) Research and development (R&D) investments that lead to the improvement of the technology; and (3) Technological spillovers.

The learning-by-doing effect refers to the increasing experience in the development of the technologies and to the innovative activity that results from knowledge gained from operating experience (Taylor et al., 2005). Indeed, technological development is characterized by a process of learning such that countries and firms can rely on already accumulated knowledge to further improve their production processes and reduce their costs (Jamasb, 2007). A widely used method to describe technology cost reduction is the learning curve approach (also known as experience curve), which was first introduced by Wright (1936), who originally observed this relationship for airplane manufacturing.

R&D is one of the basic driving force of technological progress: R&D contributes to expand the knowledge base, which in turn can stimulate further technological innovation and reduce the costs of production (Azevedo et al., 2013). R&D is also one of the variables that government policies might affect and in the case of energy system it constitutes a fundamental factor for the successful introduction of new, more efficient and clean technologies (Barreto & Kypreos, 2004).

Technological spillovers refer to the flow of knowledge from one country or industry to another and to the positive impact that this can have on technological improvement and innovation in the recipient country or industry (Yeh & Rubin, 2012). It is widely recognized that knowledge spillovers exist on a national as well as an international level, that is, knowledge originating in one country or in a sector transcends its boundaries and contributes to productivity growth and technological progress in other countries or sectors (Grossman & Helpman, 1990). In particular, there is empirical evidence that a country's innovative performance in the renewable energy sector depends positively on the knowledge stocks of the other countries in the same sector (Garrone et al., 2014). However, it is not clearly understood how innovation spillovers or transfer between technologies, sectors and countries take place (Yeh & Rubin, 2012). Given the potential of spillovers to increase the productivity in the sectors receiving them, this mean of technological innovation is particularly relevant to analyze the cost of the energy transition and this is why we decided to focus on them in our model.

Next to the three channels identified above, technological innovation is fostered by both demand-pull instruments, which affect the size of the market for a new technology, and technology-push instruments, which influence the supply of new knowledge. Demand-pull policies can be devised as market based instruments such as tradable permits, feed-in tariffs, production and tax credits and control regulation inducing demand through standard setting (Dechezleprêtre & Glachant, 2014). Demand-pull instruments have both a direct and an indirect effect: they promote the diffusion of new technologies, and they have a positive effect on the innovative activity causing, indirectly, more R&D or more learning by doing (Taylor et al., 2005; Taylor, 2008). Technological innovation occurs also by means of supply-push policies such as R&D funding, leading to knowledge accumulation and improvement in the technologies. Technology-push policy instruments influence the supply of new knowledge and, in this case, a supply side driven process occurs from research to development and diffusion of a technology (Dosi, 1988).

In this paper, we consider an economy in which a final good is produced with a clean and a dirty intermediates, which benefit from clean and dirty spillovers respectively. Since spillovers are recognized to have a role in technological change, we want to start from this fact and focus on how they affect the cost of the technological shift needed for an energy transition. We also analyze the impact of the elasticity of substitution between sectors and of the market size effect on the cost of the energy transition. We use our findings about the interactions between these two parameters and the subsidy to explain the negative prices observed in the german electricity spot market. The objective of the theoretical model is to shed light on the trade-offs at work in the economy and to help understanding through which channels energy policies can operate. We then provide a numerical solution to the model to give an insight into the magnitude of the effects considered.

1.1. Relation to the Literature

Our paper is related to the literature in several ways. We refer to the literature on the drivers of technological diffusion; we introduce technological spillovers from capital into a model of endogenous growth formalizing the determinants of productivity growth (Romer, 1990; Rebelo, 1991; Aghion & Howitt, 1992; Helpman, 1992). We also build on the literature on technological spillovers (Eaton & Kortum, 1999; Keller, 2001). The work is particularly close to Bretschger et al. (2016), which shows that knowledge spillovers mitigate the negative impact on welfare from environmental policies. However, we consider technological spillovers and we focus on the impact of the elasticity of substitution between sectors instead of the impact of the elasticity between different types of knowledge. As for the role of spillovers in technological innovation an important contribution is provided by Dechezleprêtre & Glachant (2014), which shows that technology improvements respond positively to policies both at home and abroad, but the marginal effect of domestic policies greater because the influence of foreign polices is reduced by barriers to technology diffusion.

Acemoglu (2002) introduces directed technical change in an economy where final output is obtained by means of two factors. The respective rates of technical progress are determined by the relative profitability of developing factor-specific innovations, so that the direction of technical change is determined endogenously. Our paper differs because we focus on sectors rather than on factors of production. This allows us to determine the relative productivity of sectors and hence their market shares. Bretschger (1998) studies the substitution possibilities between man-made inputs and natural resources in order to determine the conditions for long term sustainable development. In a one sector economy, growth is sustainable only if the elasticity is larger than one. In a multisector economy a small value of the elasticity is favorable for growth; on the oppposite, a too high elasticity between factors may harm long-term growth. Our results are in line with these findings even though we consider the cost of switching from the clean to the dirty sector. Bretschger & Smulders (2012) found that low values of the elasticity between natural resources and other inputs are not necessarily detrimental for sustainable growth; low values can foster structural change and research investments. We build on their results adding that low values of the elasticity are also not detrimental for the achievement of an energy transition. An empirical investigation of the determinants of directed technical change at the firm level in the electricity generation sector is provided by Noailly & Smeets (2013).

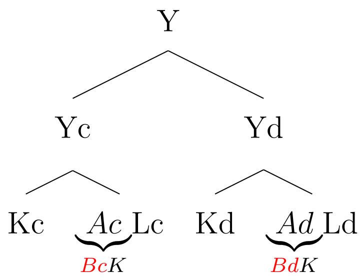
Our paper is also close to the literature on climate policies and growth. Among the others Michel & Rotillon (1995), presents an endogenous growth model including an aggregate capital stock which implies a learning-by-doing effect and a pollution flow proportional to production; they show that in this case the optimal policy is to tax capital. Differently from us, they only consider one sector in their analysis. Acemoglu et al. (2012) shows that depending on the degree of substitution between inputs, taxes and subsidies aiming at redirecting innovation towards the clean sector must be temporary or permanent. Bretschger & Schaefer (2017) studies the impact of economic policies on energy transition, considering history and expectations, and Acemoglu et al. (2015) characterizes the optimal policy path in the transition from dirty to clean technologies. This paper differs because we include technological spillovers in the analysis. Finally, Johnstone et al. (2010) provides an analysis of how energy prices and various policy instruments affect innovation in different renewable energy technologies and shows that more costly energy technologies such as solar power need targeted subsidies.

To the best of our knowledge, this is the first paper which tries to explain the negative electricity prices encountered in countries experiencing an energy transition, such as Germany. As we think that this adverse effect can depend on a excessive subsidy generating overproduction in the clean sector, we try to reproduce the trade-offs at work in the economy to investigate how the subsidy needed to achieve a given target in terms of production from clean sources varies depending on the intensity of technological spillovers and on the elasticity of substitution between sectors. Lacking or incorrect expectations about the values of these parameters might lead to the choice of a subsidy higher than the one needed.

We develop the theoretical model for technological spillovers and for the energy transition in Section 2. In Section 3 we solve the model numerically and we discuss the results in Section 4. Section 5 concludes and introduces possible future lines of research.

2. Model

In this section we present the theoretical model in the spirit of Romer (1986). We consider a closed economy that produces a single final consumption good (Y) and the production process is divided into two stages. The final good sector uses, as inputs, the outputs from a clean (Y_c) and a dirty (Y_d) intermediate production sectors. The second stage of production defines the production functions for these intermediate goods, which combine capital (K_i) and labor (L_i) augmented by a productivity term (A_i), where $i = \{c, d\}$. The productivity term depends on technological spillovers due to capital accumulation ($B_i K$, where B_i is an intensity or productivity parameter and K is broad capital).



The final good is produced according to a CES specification such that the clean and dirty intermediates are imperfect substitutes. The price of the final good is normalised to one. Hence, we may write:

$$Y = \left[\gamma Y_c^{\frac{\sigma-1}{\sigma}} + (1-\gamma) Y_d^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

$\gamma \in (0, 1)$ denotes the distribution parameter and $\sigma \in (0, \infty)$ is the elasticity of substitution between inputs. If $\sigma > 1$ the two factors are gross substitutes whereas if $\sigma < 1$ the two factors are gross complements. The case of substitutes appears as the more empirically relevant benchmark, as established in the literature (Papageorgiou et al., 2017). Hence, in the numerical solution, we will focus on the case of substitutable inputs. In the theoretical model, however, we consider both cases; Acemoglu et al. (2012) shows that results are very different depending on whether goods are substitutes or complements.

Final output can be used for consumption (C) and investment (I)

$$Y = C + I$$

The production technologies for clean and dirty intermediates are symmetric. The two inputs are produced within a perfect competition market structure, using sector-specific labor augmented by a productivity index and physical capital. The two factors of production are combined in a Cobb-Douglas fashion

$$Y_c = K_c^{\alpha}(A_c L_c)^{1-\alpha} \tag{2}$$

$$Y_d = K_d^{\alpha}(A_d L_d)^{1-\alpha} \tag{3}$$

where A_i, with $i = \{c, d\}$, are the sector specific productivity indexes; output is increasing in the productivity term as a greater level of A_i signals an improvement in technology. Capital is assumed to be perfectly mobile across sectors. Without loss of generality, we assume that labor is fixed across sectors [1] and no population growth.

By market clearing, in equilibrium,

$$K_c + K_d = K \tag{4}$$

where K is total capital in the economy.

The resource constraint of the economy is given by

$$\dot{K} = I - \delta K \tag{5}$$

[1] This assumption is made for tractability matters, but it does not affect the results, as it will be made clear afterwards.

where $\dot{K}$ is the derivative of K with respect to time.

Clean and dirty productivity indexes are defined in a symmetric way; they depend on technological spillovers from broad capital

$$A_c = B_c K \tag{6}$$

$$A_d = B_d K \tag{7}$$

where B_i, with $i = \{c, d\}$, are productivity parameters representing the intensity of spillovers.

We impose the condition that the clean sector is initially backward relative to the dirty sector

$$B_c < B_d$$

Given our definition of spillover in (6) and (7), sectoral output can be expressed as

$$Y_i = \left(\frac{K_i}{K}\right)^{\alpha} K \tilde{B}_i$$

where $\tilde{B}_i = (B_i L_i)^{1-\alpha}$. This term indicates which sector is more productive; otherwise, everything else is equal between sectors.

For convenience, we define $\frac{K_c}{K} \equiv \zeta$ the share of capital allocated to the clean sector and $\frac{K_d}{K} \equiv 1 - \zeta$ the share of capital allocated to the dirty one. Notice that the share of capital allocated to a sector determines the market size of that sector. In our model, when the elasticity of substitution is sufficiently high, the market size effect implies that more capital will be allocated to the larger sector, increasing its production. This effect is strengthened by an increase in the elasticity of substitution[2].

[2]Following the literature of directed technical change, when the elasticity of substitution is sufficiently high (above a threshold value between 1 and 2), the market size effect implies that innovation

2.1. Insights

In this subsection, we look at how expenditure shares (s_i) affect the final solution of the model depending on the sectors' growth rates and on the elasticity of substitution between inputs in final production. Expenditure shares in each sector are given by:

$$s_c = \frac{p_c Y_c}{Y} = \gamma \left(\frac{Y_c}{Y}\right)^{\frac{\sigma-1}{\sigma}}$$

$$s_d = \frac{p_d Y_d}{Y} = (1-\gamma) \left(\frac{Y_d}{Y}\right)^{\frac{\sigma-1}{\sigma}}$$

where the equality follows from the profit maximizing behavior of final good producers and p_i are the prices in the clean and dirty sector respectively.

Since the markets are competitive

$$Y - p_c Y_c - p_d Y_d = 0 \quad \rightarrow \quad s_c + s_d = 1$$

By manipulating the expressions above we can show

$$\dot{s}_c = s_c(1-s_c)\frac{\sigma-1}{\sigma}(\hat{Y}_c - \hat{Y}_d)$$

Since expenditure shares are constant in steady state, $\dot{s}_c = 0$. Hence, denoting by $\hat{X}$ the growth rate of a variable, there are two possible solutions in our model:

1. If $\hat{Y}_c = \hat{Y}_d$, $s_c \in (0,1)$: if both sectors grow at the same rate they are both active.

2. If $\hat{Y}_c \neq \hat{Y}_d$, $s_c = 0$ or $s_c = 1$ and the outcome depends on the elasticity of substitution between the two inputs. In particular if $\hat{Y}_c > \hat{Y}_d$ and inputs are

will be biased towards the more abundant factor.

substitutes, then $s_c = 1$, because $\dot{s}_c$ is increasing over time. If instead, inputs are complements, $s_c = 0$ because $\dot{s}_c$ is decreasing over time.

2.2. Firms

Solving the maximization problem in the final sector where Y is given by (1) yields

$$\frac{p_c}{p_d} = \frac{\gamma}{1-\gamma}\left[\frac{\tilde{B}_c}{\tilde{B}_d}\left(\frac{\zeta}{1-\zeta}\right)^{\alpha}\right]^{-\frac{1}{\sigma}} \tag{8}$$

The firms in the two intermediate sectors $i = \{c, d\}$ do not take into account technology spillovers and solve

$$\max_{K_i, L_i} \pi_i = p_i Y_i - RK_i - w_i L_i$$

where Y_i is given from (2) and (3) respectively, R is the rental rate of capital and w_i is the wage in each sector. Solving the maximization problem yields

$$R = \alpha p_i \left(\frac{K_i}{K}\right)^{\alpha-1} \tilde{B}_i \tag{9}$$

where $\tilde{B}_i = (B_i L_i)^{1-\alpha}$.

Hence we can compute relative prices

$$\frac{p_c}{p_d} = \frac{\tilde{B}_d}{\tilde{B}_c}\left(\frac{\zeta}{1-\zeta}\right)^{1-\alpha} \tag{10}$$

By equating (8) and (10) we can find the share of capital, $\zeta \in (0, 1)$, that goes to the clean sector

$$\zeta = \frac{1}{1 + \left(\tilde{\gamma} \tilde{B}_R^{\frac{\sigma-1}{\sigma(1-\alpha)+\alpha}} \right)^{-1}} \tag{11}$$

where $\tilde{\gamma} \equiv \left(\frac{\gamma}{1-\gamma} \right)^{\frac{\sigma}{\sigma(1-\alpha)+\alpha}}$ and $\tilde{B}_R \equiv \frac{\tilde{B}_c}{\tilde{B}_d}$. The fraction of capital that is allocated to each sector is increasing in the sector productivity level if $\sigma > 1$, whereas it is decreasing in the sector productivity level if $\sigma < 1$. ζ determines the level of production in each sector and is constant.

2.3. Households

The representative household in each sector $i = \{c, d\}$ maximizes utility

$$U_i = \int_0^\infty e^{-\rho t} \frac{c_i^{1-\theta} - 1}{1-\theta} dt$$

where ρ is the rate of time preference and θ is the degree of relative risk aversion. The standard flow budget constraint is

$$\dot{a}_i = r a_i + w_i - c_i + T$$

where a are assets; r is the risk-free market rate of return on assets and T are transfers collected by the government in a lump-sum way. We assume that the No-Ponzi game condition applies, preventing paying debt with new higher debt, ad infinitum. This yields the standard optimality condition for the rate of change of consumption (Keynes-Ramsey rule)

$$g_c^* = \frac{1}{\theta}(r - \rho)$$

which shows that if the rate of time preference, is lower than the net marginal product of capital, per capita consumption will be increasing.

Since there is no uncertainty and a depreciation rate of δ, the market rate of return on assets will be given by

$$r = R - \delta$$

Hence, the growth rate of consumption in equilibrium becomes

$$g_c^* = \frac{1}{\theta}\left[\alpha\gamma\zeta^{\frac{\sigma(\alpha-1)-\alpha}{\sigma}}\tilde{B}_c^{\frac{\sigma-1}{\sigma}}\tilde{B}^{\frac{1}{\sigma}} - \delta - \rho\right] \tag{12}$$

where $\tilde{B} = \left[\gamma(\tilde{B}_c\zeta^{\alpha})^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(\tilde{B}_d(1-\zeta)^{\alpha})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$ ((A.2) in the Appendix). The growth rate only depends on the parameters of the model. If the sectors are substitutes, the growth rate is increasing in the intesity of the spillovers received by the sector and in the share of capital going to that sector. If the sectors are complements, the growth rate is decreasing in the intesity of spillovers received by the sector and in the share of capital going to that sector.

2.4. Balanced growth path

We know that ((A.2) in the Appendix) output grows at the same rate of capital

$$\hat{Y} = \hat{K}$$

where $\hat{X}$ denotes the growth rate of a variable. Dividing (5) by K we get

$$\hat{K} = \frac{Y}{K} - \frac{C}{K} - \delta$$

In equilibrium $\hat{K}$ is constant. Since $\frac{Y}{K}$ is constant and δ is constant, $\frac{C}{K}$ has to be constant as well. Therefore, in equilibrium, all the variables grow at the same constant rate.

2.5. Energy Transition

To reproduce the policies aiming at triggering an energy transition in our model, we assume that in order to trigger an energy transition output in the clean sector to be at least $x\%$ larger than output in the dirty sector, where $x > 1$. Considering the economy in which no policies are at work, we find the share of capital that has to be allocated to the clean sector ($\bar{\zeta}$) in order for output in the clean sector to be $x\%$ larger than output in the dirty sector

$$Y_c = xY_d \quad \Longrightarrow \quad \bar{\zeta} = \frac{1}{1 + x\tilde{B}_R^{\frac{1}{\alpha}}} \tag{13}$$

This value is different from (11) where we did not impose any restrictions to the economy and will be used as a benchmark for policy recommendations. Also notice that, in (13), the share allocated to the clean sector is decreasing in the sector productivity: this is because the larger the productivity of the sector, the lower the share needed to achieve the target.

2.6. Cost of the energy transition: the subsidy

For the economy to rely more on the clean than on the dirty sector, policies covering the cost of the energy transition are required. In this work, we assume that the cost of the energy transition can be proxied by a subsidy, although this is not the only component of such cost.

Suppose that the government can subsidize production in the clean sector using a proportional profit subsidy and that all proceeds are financed lump sum, such that revenues are raised in a non distortive way. Denoting this subsidy by q profits in the clean sector become

$$\max_{K_c, L_c} \pi_c = (p_c + q)Y_c - RK_c - w_c L_c$$

it is clear that a sufficiently high subsidy can increase relative production in the clean sector. Notice that now we are not imposing any restriction on the magnitude of output in the two sectors.

Solving the maximization problem in the clean sector yields

$$g_c^* = \frac{1}{\theta}\left(\alpha\gamma\zeta_s^{\frac{\sigma(\alpha-1)-\alpha}{\sigma}}\tilde{B}_c^{\frac{\sigma-1}{\sigma}}\tilde{B}_s^{\frac{1}{\sigma}} + \alpha q\zeta_s^{\alpha-1}\tilde{B}_c - \delta - \rho\right) \tag{14}$$

The growth rate is equal to the one in (12), but for the different share of capital going to the clean sector and for the additional term due to the presence of the subsidy. The clean and dirty sectors grow at the same rate, but the level is higher in the clean one because of the subsidy.

Relative prices in the intermediate sector are now given by

$$\frac{p_c}{p_d} = \left(\frac{\zeta_s}{1-\zeta_s}\right)^{1-\alpha}\frac{\tilde{B}_d}{\tilde{B}_c} - \frac{q\left((1-\zeta_s)^{\alpha}\frac{\tilde{B}_d}{\tilde{B}_s}\right)^{\frac{1}{\sigma}}}{(1-\gamma)} \tag{15}$$

in contrast to (10).

In the final output relative prices are still given by (8), but ζ is different in the economy with the subsidy

$$\frac{p_c}{p_d} = \frac{\gamma}{1-\gamma}\left[\frac{\tilde{B}_c}{\tilde{B}_d}\left(\frac{\zeta_s}{1-\zeta_s}\right)^{\alpha}\right]^{-\frac{1}{\sigma}} \tag{16}$$

By equating (15) and (16), we find ζ that is allocated to the clean sector in the economy with the subsidy (ζ_s), without imposing the restriction that output in the clean sector has to be $x\%$ higher than output in the dirty sector

$$\left(\frac{\zeta_s}{1-\zeta_s}\right)^{1-\alpha}\frac{\tilde{B}_d}{\tilde{B}_c} - \frac{q\left((1-\zeta_s)^{\alpha}\frac{\tilde{B}_d}{\tilde{B}_s}\right)^{\frac{1}{\sigma}}}{(1-\gamma)} = \frac{\gamma}{1-\gamma}\left[\frac{\tilde{B}_c}{\tilde{B}_d}\left(\frac{\zeta_s}{1-\zeta_s}\right)^{\alpha}\right]^{-\frac{1}{\sigma}} \tag{17}$$

Given (13) and the solution from (17), we equate them to find the subsidy that closes the gap between the clean and dirty sector.

$$\bar{\zeta} = \zeta_s \tag{18}$$

We know that for any subsidy above the level found from this equality, production is larger in the clean sector and hence we have an energy transition.

Since we cannot find an analytical solution to equation (17), we proceed numerically.

3. Numerical Solution

In order to provide an insight into the magnitude of the effects considered, we solve the model numerically. We focus on the impact of technological spillovers and of the elasticity of substitution between clean and dirty sectorson on the cost of the energy transition.

We set parameter values in accordance with the literature [3]. In particular, the share of capital in input production is set to $\alpha = 0.3$. We also assume that the target is to have clean sector production 50% higher than dirty sector production, that is $x = 1.5$. We let the share parameters γ to be equal for the two intermediates.

The more important parameters to our analysis are the intensity of spillover - the productivity levels of the two sectors - and the elasticity of substitution.

[3] See, for example, Acemoglu et al. (2012).

In the benchmark case, we set the productivity level to be the same in the two sectors. Then, given that the subsidy depends on the ratio of productivities in the two sectors, we look at how the cost of the energy transition changes when we disturb the productivity of the clean sector keeping the productivity of the dirty sector fixed.

As for the elasticity of substitution, we focus on the case of substitutable clean and dirty production ($\sigma > 1$) as it is the more established in the literature (Papageorgiou et al., 2017); hence, we increase the value of the elasticity to analyze the impact of this parameter on the results. However, we also provide an insight for the case of complement sectors ($\sigma < 1$) to support our results. Where not specified, the findings refer to the case in which the two sectors are substitutes.

4. Results

The main findings of the model are (Figures 3 and 4):

1. Regardless of the elasticity of substitution, the subsidy needed to increase production in the clean sector up to a x percentage of the dirty sector is decreasing with the relative intensity of the spillovers received by this sector. Moreover, for values of the clean spillover intensity larger than those of the dirty spillover intensity, the subsidy becomes negative.

2. For higher productivity level of the dirty sector, the subsidy needed to increase production in the clean sector up to a x percentage of the dirty sector is increasing with the elasticity of substitution between the sectors.

The first finding (see Figure 3) is that an increase in the clean sector productivity for a constant elasticity of substitution, generates an increase in the share of capital (ζ) that goes to the clean sector. Given that the share of capital allocated to a sector determines production in that sector, a larger share of capital allocated to the clean sector implies that the subsidy needed to increase its production up to a certain target is lower (Bretschger et al., 2016). This result is in line with the weak induced-bias hypothesis presented in Acemoglu (2002), which states that, irrespective of the elasticity of substitution between factors (as long as it is not equal to 1), an increase in the relative abundance of a factor creates some amount of technical change biased towards that factor. We found that, for equal productivities of the two sectors, the subsidy becomes zero and then negative when the clean sector is more productive. This means that a subsidy set without taking into account the impact of technological spillovers, might be excessive and generate overproduction in the clean sector, leading to negative prices in the electricity market. By way of example, in May 2016 (Figure 2) Germany produced so much electric power from clean energy sources that prices were actually negative for several hours. This implied commercial customers were being paid to consume electricity. Germany's power surplus showed the system is still too rigid for power suppliers and consumers to respond quickly to price signals. However, another reason for overproduction can be found in the excessive subsidy provided to the clean sector. The choice of such a high subsidy can depend on the lack of the inclusion of technological spillovers in the determination of the value of the subsidy. An excessive subsidy generates costs both for consumers and producers; hence, episodes as the one described above show that policy makers should take into account that the more a sector benefit from spillovers, the less it should be subsidize.

The second finding is more surprising and shows that an increase in the elasticity of substitution when the dirty sector is more productive, generates a decrease in the share of capital allocated to the clean sector (Figure 4), because more capital is allocated to more productive dirty sector. Given that production in the dirty sector is now higher, the subsidy that is required for clean sector to be some percentage of the dirty sector is larger (Bretschger, 1998; Bretschger & Smulders, 2012). This result is due to the strong

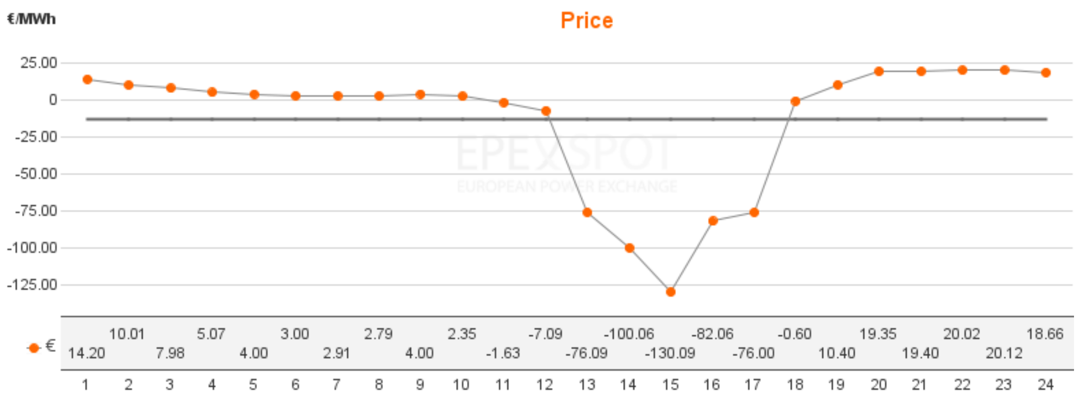


Figure 2: Spot energy price in Germany on 8^{th} May 2016. *Source*: EPEXSPOT

induced-bias hypothesis. This states that if the elasticity of substitution is sufficiently large (greater than a threshold betwee 1 and 2), the induced bias in technology causes the market size effect to dominate both the price effect and the substitution effect and to increase the relative reward to the factor that is more abundant. Not considering the value of the elasticity of substitution can lead to the choice of a wrong value for the subsidy: for instance, the excessive subsidy adopted in Germany could be due to an elasticity of substitution between clean and dirty energy production higher than the one expected.

In our model the price and market size effects determine the relative profitability of the sectors and hence the share of capital that is allocated to each sector, so we can define our model as a model of endogenous market size. To show how the market size effect works, we assume that productivity is the same in the two sectors as a benchmark case. That is, we switch off the market size effect; in this case, the share of capital that goes to each sector is the same (0.5) and it is not affected by the elasticity of substitution.

We also consider the case of complementary sectors and we find that an increase in the productivity of the clean sector increases the share of capital allocated to the dirty. Hence, the share allocated to the clean sector is decreasing with the sector productivity. This happens because, given the complementarity of the two sectors, an increase in the productivity of the clean sector increases the demand for the dirty sector by more than the demand for the clean. Similarly, in Acemoglu (2002), when the factors are complements the price effect is stronger than the market size effect and technical change is directed to the less abundant factor.

Notice that introducing endogenous technical change in the model, the higher market share allocated to the dirty sector would imply more innovation in this sector, further increasing the gap between the two sectors. However, this would not contradict our results: the only implication would be that the subsidy needed to achieve the target is higher.

Another finding is that the subsidy is decreasing with the amount (x) of which we require the clean sector to be larger than the dirty sector. Although this might seem counterintuitive, it is again an outcome of the market size effect mechanism. Indeed, when the market size of the clean sector increases, the profitability of this sector increases as well, reducing the subsidy needed to lift up production in this sector. Moreover, increasing the percentage of which we want the clean to be larger than the dirty shifts the model to a new balanced growth path. However, the model does not analyze the transition path so it can be that increasing x the subsidy jumps up and then it decreases to its new (lower) value in the new balanced growth path.

A final remark is that relaxing the assumption of fixed labor in the two sectors, the results do not change. What happens in this case is that when output increase in the clean sector because of the subsidy, not only more capital, but also more labor will be allocated to the clean sector. This means that production will be higher in the clean sector as compared to the case in which labor is fixed. As a consequence, the value of the subsidy needed for any productivity parameter and for any value of the elasticity of substitution will be lower; however, the shape of the curves presented in Figures 3 and 4 will not be affected by the relaxation of the assumption of fixed labor.

Figure 3: The share of capital that goes to the clean sector (ζ) is increasing with the relative intensity of spillover $\left(B_R = \frac{B_c}{B_d}\right)$; as a consequence, the subsidy (q) is decreasing with the intensity. Notice that when productivities in the two sectors are the same, the share of capital that goes to each is sector is 0.5. The horizontal dotted red line reminds that ζ is a share so it cannot be larger than one. Moreover, when the intensities of the spillover in the two sectors are equal, the subsidy is zero, and it becomes negative for clean spillover intensit larger than the dirty one.

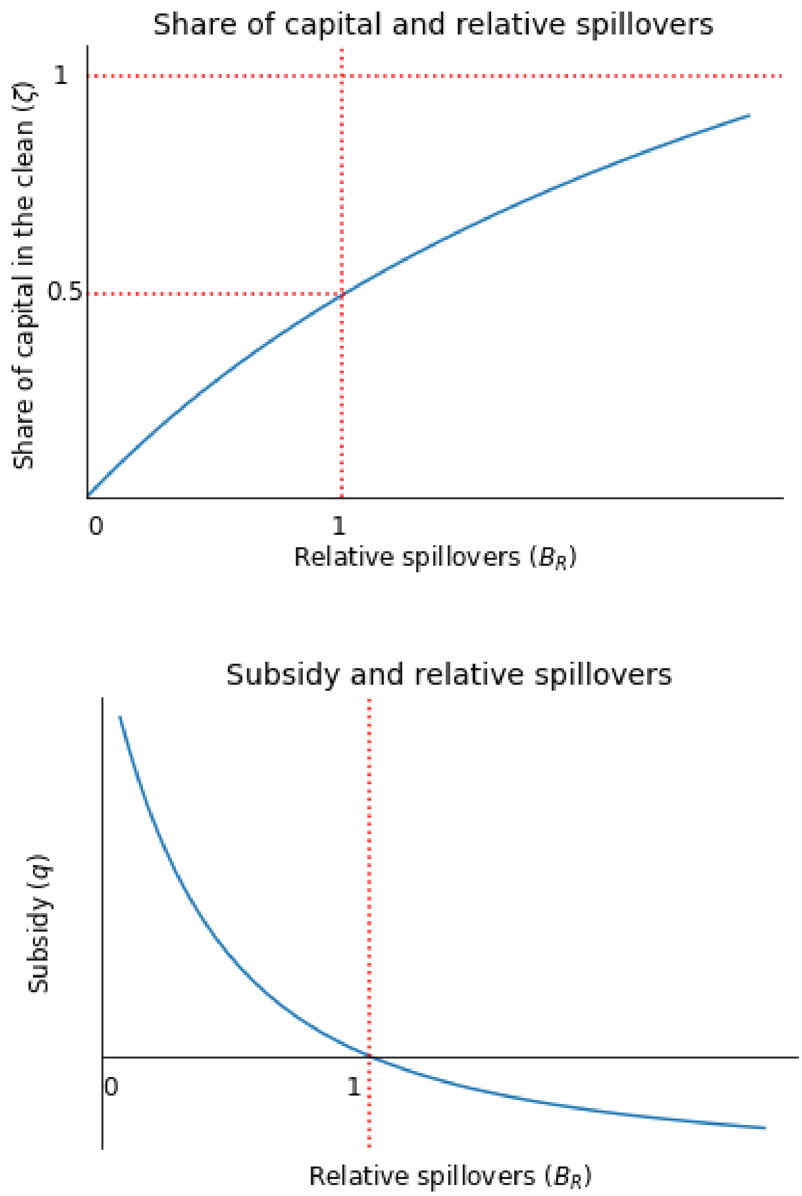
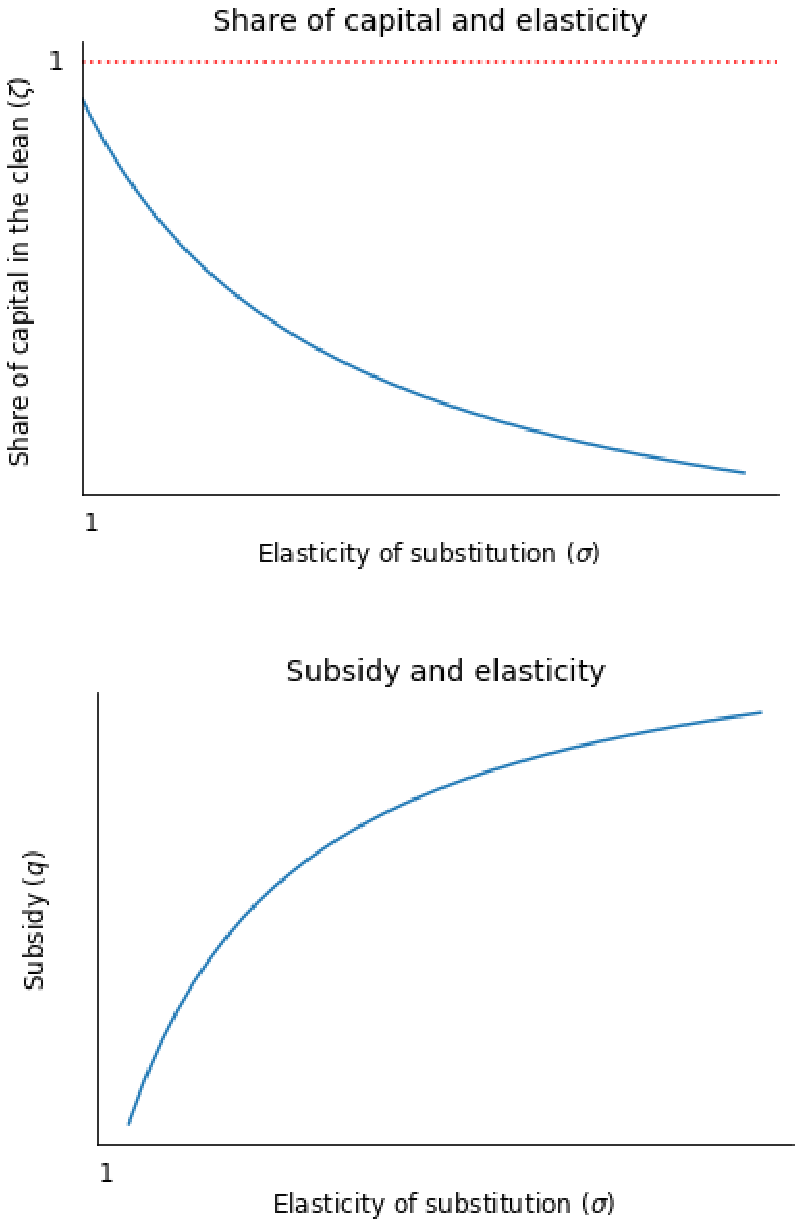


Figure 4: The share of capital that goes to the clean sector is decreasing with the elasticity of substitution; as a consequence, the subsidy is increasing with the elasticity of substitution.



5. Conclusions

We observe that countries such as Germany, that have decided to strongly subsidize the renewable energy production, have encountered an adverse effect due to overproduction and leading to negative electricity spot prices. This is definitely due to the lack of flexibility in the power generation system, but also to the excessive subsidy received by the clean sector. Hence, we try to investigate what elements can lead the value of the subsidy to be above the one needed to meet demand. We argue that the exclusion of technological spillovers from broad capital and of the elasticity of substitution between sectors in the determination of the subsidy play a role.

We use a model of endogenous growth to study the influence of technological spillovers and of substitution possibilities on the cost of the energy transition, which we proxy with the subsidy that has to be provided to the clean sector to achieve a given target in term of relative production of the two sectors. The model represents an economy that uses clean and dirty intermediates to produce a final good. These intermediates goods, in turn, use capital and labor in their production; labor is augmented by a productivity index which is due to technology spillovers from broad capital. We then provide an insight into the magnitude of the effects considered by solving the model numerically. The main findings of the work are: (1) technological spillovers reduce the cost of the energy transition; moreover, the subsidy becomes negative when the intensity of the clean spillover is larger than the one of the dirty; (2) when the sectors are substitutes, the market size effects dominates the price effect and, given that the dirty sector is initially more advanced, a higher elasticity of substitution between the two sectors increases the cost of the energy transition.

The policy relevance of our results is to show how the subsidy needed to achieve a given target changes, taking into account the interactions between spillovers, the market size effect and the elasticity of substitution. This allows us to provide rec-

ommendations in terms of the policies to be adopted. On one hand, the presence of spillovers helps the energy transition: when the intensity of spillover is higher, for a given elasticity of substitution, the subsidy that has to be provided to the clean sector is lower. It is worth notice that an excessive subsidy might generate overproduction in the renewable sector and, consequently, negative prices in the electricity sector. Ignoring this aspect would lead to misjudgments in the decision process and negative effects on economic growth. In these circumstances, in addition to the cost beared by consumers to finance the subsidy scheme, there is a cost on producers, who have to sell electricity at negative prices, as it has happened in Germany in the last years.
The other aspect that policy makers should take into account is the impact of the elasticity of substitution: the cost of the energy transition is increasing with the substitability between sectors because this implies that a greater share of capital is allocated to the more productive dirty sector, reducing production in the clean sector further. Hence the subsidy required to raise production in the dirty sector is larger, when the elasticity of substitution is higher. Similarly to the case of spillovers, a wrong expectation about the value of the elasticity of substitution can lead to the choice of a too high or too low subsidy.

Overall, the model shows that the possibility to increase production of a given sector depends on relative productivities and on the elasticity of substitution. What emerges is that spillovers and their impact on productivity on one hand and substitution and market size on the other hand should be linked to the effect of the subsidy when designing an energy transition.

Several extensions of the model presented are possible. First, it would be interesting to add the negative impact of pollution generated from the dirty intermediate to the utility function. Second, we could compute the social planner solution and use it as a benchmark to derive the optimal policy. Third, targets could be set in terms of CO_2

emissions instead of intermediate sector shares. Fourth, in the paper we assume the elasticity of substitution to be exogenous; however, it would be reasonable to consider that policies can have an impact on the extent to which dirty energy production can be substituted by energy produced from renewable sources. Finally, storage possibilities could be introduced in the model to see how this affects the results. All these aspects are left to future research.

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Appendix A.

Appendix A.1. Firms

In the final sector, the producers solve

$$\max_{Y_c, Y_d} \; Y - p_c Y_c - p_d Y_d,$$

where Y is given by (1). Solving the maximization problem yields

$$p_c = \gamma \left(\frac{Y_c}{Y}\right)^{-\frac{1}{\sigma}} \quad , \quad Y_c = \left(\frac{\gamma}{p_c}\right)^{\sigma} Y \tag{A.1}$$

$$p_d = (1-\gamma) \left(\frac{Y_d}{Y}\right)^{-\frac{1}{\sigma}} \quad , \quad Y_d = \left(\frac{1-\gamma}{p_d}\right)^{\sigma} Y$$

Hence, relative prices are given by

$$\frac{p_c}{p_d} = \frac{\gamma}{1-\gamma} \left(\frac{Y_c}{Y_d}\right)^{-\frac{1}{\sigma}}$$

which shows that the relative marginal product of inputs is decreasing in their relative abundance. Moreover, it can be seen that the elasticity of the relative price response is the inverse of the elasticity of substitution between the two inputs.

Substituting the expressions for sectoral output and the definitions for sectoral capital shares yields (8).

The firms in the two sectors $i = \{c, d\}$ do not take into account technology spillovers and solve

$$\max_{K_i, L_i} \pi_i = p_i Y_i - R K_i - w_i L_i$$

where Y_i is given from (2) and (3) respectively and R is the rental rate of capital.

The FOC with respect to capital is

$$\frac{\partial \pi}{\partial K_i} = 0 \implies \alpha p_i \frac{Y_i}{K_i} = R$$

In equilibrium we can substitute the expressions for spillovers and we get (9). By the no-arbitrage condition, the rate of return has to be the same in the two sectors, so

$$\alpha p_c \zeta^{\alpha-1} \tilde{B}_c = R = \alpha p_d (1-\zeta)^{\alpha-1} \tilde{B}_d$$

which implies (10).

The FOC wrt labor is

$$\frac{\partial \pi}{\partial L_i} = 0 \implies (1-\alpha) p_i \frac{Y_i}{L_i} = w_i$$

and we can compute relative wages as

$$\frac{w_c}{w_d} = \frac{\tilde{B}_d}{\tilde{B}_c} \left(\frac{\zeta}{1-\zeta} \right)^{1-\alpha} \frac{B_c}{B_d}$$

which shows that the ratio of wages is given by the ratio of marginal productivities of labor in the two sectors.

Appendix A.2. Equilibrium

Because of the no-arbitrage condition, what holds for one intermediate sector holds for the other as well. Hence, we can consider the clean sector only. Then,

$$g_c^* = \frac{1}{\theta}(\alpha p_c \zeta^{\alpha-1}\tilde{B}_c - \delta - \rho)$$

and we can derive p_c as follows: first, we substitute sectoral production into the expression for final output and we get

$$\begin{aligned} Y &= \left[\gamma(\tilde{B}_c\zeta^\alpha K)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(\tilde{B}_d(1-\zeta)^\alpha K)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \\ &= \tilde{B}K \end{aligned} \tag{A.2}$$

where $\tilde{B} = \left[\gamma(\tilde{B}_c\zeta^\alpha)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(\tilde{B}_d(1-\zeta)^\alpha)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$. Then, we can be rewrite (A.1) as

$$p_c = \gamma\left(\zeta^\alpha\frac{\tilde{B}_c}{\tilde{B}_s}\right)^{-\frac{1}{\sigma}} \tag{A.3}$$

Hence, the growth rate of consumption in the decentralized equilibrium becomes (12).

Appendix A.3. The Government

The government is introduced in a minimal fashion. We abstain from public consumption or public production goods; instead, all revenue is redistributed to the household in a non distorting lump sum manner. The government flow budget constraint is given by

$$D = G - T$$

where D is deficit, G is the government expenditure and T is tax revenues. We assume that the government does not issue bonds and hence it is forced to run a balanced budget in every period.

Appendix A.4. The cost of the energy policy: the subsidy

Denoting this subsidy by q, profits in the clean sector becomes

$$\max_{K_c, L_c} \pi_c = (p_c + q)Y_c - RK_c - w_c L_c$$

while profits in the dirty sector are still given by

$$\pi_d = p_d Y_d - RK_d - w_d L_d$$

The solution to the maximization problem in the clean sector is

$$R = \alpha(p_c + q)\frac{Y_c}{K_c}$$

which in equilibrium becomes

$$R = \alpha(p_c + q)\zeta_s^{\alpha-1}\tilde{B}_c$$

In the economy with the subsidy final output can be written as

$$Y = \tilde{B}_s K$$

following the same procedure as before.

Given (A.3), the growth rate is given by (14). By the no arbitrage condition we have

$$\alpha(p_c + q)\zeta_s^{\alpha-1}\tilde{B}_c = R = \alpha p_d(1-\zeta_s)^{\alpha-1}\tilde{B}_d$$

hence, relative prices are given by

$$\frac{p_c}{p_d} = \left(\frac{\zeta_s}{1-\zeta_s}\right)^{1-\alpha}\frac{\tilde{B}_d}{\tilde{B}_c} - \frac{q}{p_d} \tag{A.4}$$

Substituting the optimal $p_d = (1-\gamma)\left(\frac{Y_d}{Y}\right)^{-\frac{1}{\sigma}} = (1-\gamma)\left((1-\zeta_s)^{\alpha}\frac{\tilde{B}_d}{\tilde{B}_s}\right)^{-\frac{1}{\sigma}}$ into (A.4) we get the price ratio in the economy with the subsidy as in (15).

References

Acemoglu, D. (2002). Directed technical change. *The Review of Economic Studies*, *69*, 781–809.

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *Am Econ Rev.*, *102*, 131–166.

Acemoglu, D., Akcigit, U., Hanley, D., & Kerr, W. (2015). Transition to clean technology. *Bank of Finland Research Discussion Papers*, .

Aghion, P., & Howitt, P. (1992). A model of growth through creative destruction. *Econometrica*, *60*, 323–51.

Azevedo, I., Jaramillo, P., Azevedo, E. R., Rubin, E. S., & Yeh, S. (2013). Modeling technology learning for electricity supply technologies, .

Barreto, L., & Kypreos, S. (2004). Endogenizing r&d and market experience in the bottom-up energy systems eris model. *Technovation*, *24*, 615 – 629.

Bretschger, L. (1998). How to substitute in order to sustain: knowledge driven growth under environmental restrictions. *Environment and Development Economics*, *3*, 425–442.

Bretschger, L., Lechthaler, F., Rausch, S., & Zhang, L. (2016). Knowledge diffusion, endogenousgrowth, and the cost of global climate policy, . Working Paper.

Bretschger, L., Rausch, S., Lechthaler, F., & Zhang, L. (2015). Knowledge diffusion, endogenous growth, and the costs of global climate policy, . Available at SSRN: http://ssrn.com/abstract=2705001 or http://dx.doi.org/10.2139/ssrn.2705001.

Bretschger, L., & Schaefer, A. (2017). Dirty history versus clean expectations: Can energy policies provide momentum for growth? *European Economic Review*, .

Bretschger, L., & Smulders, S. (2012). Sustainability and substitution of exhaustible natural resources. how structural change affects long-term r&d-investments. *Journal of Economic Dynamic & Control*, *36*, 536–549.

Dasgupta, S. (2015). Dirty and clean technologies. *Journal of Agricultural and Applied Economics*, *47*, 123–145.

Dechezleprêtre, A., & Glachant, M. (2014). Does foreign environmental policy influence domestic innovation? evidence from the wind industry. *Environmental and Resource Economics*, *58*, 391–413.

Dosi, G. (1988). Sources, procedures, and microeconomics effectsof innovation. *Journal of Economic Literature*, *26*, 1120–1171.

Eaton, J., & Kortum, S. (1999). International technology diffusion: Theory and measurement. *International Economic Review*, *40*, 537–570.

Garrone, P., Piscitello, L., & Wang, Y. (2014). Innovation performance and international knowledge spillovers: Evidence from the renewable energy sector in oecd countries. *Industry and Innovation*, *21*, 574–597.

Grossman, G. M., & Helpman, E. (1990). Trade, knowledge spillovers, and growth. *NBER Working Paper No. 3485*, .

Helpman, E. (1992). Endogenous macroeconomic growth theory. *European Economic Review*, *36*, 237–267.

IEA, R. (2015). Energy and climate change. *World Energy Outlook Special Report*, .

Jamasb, T. (2007). Technical change theory and learning curves: Patterns of progress in electricity generation technologies. *The Energy Journal*, *28*, 51–71.

Johnstone, N., Hascic, I., & Popp, D. (2010). Renewable energy policies and technological innovation: Evidence based on patent counts. *Environmental and Resource Economics*, *45*, 133–155.

Keller, W. (2001). International technology diffusion, .

Michel, P., & Rotillon, G. (1995). Disutility of pollution and endogenous growth. *Environmental and Resource Economics*, *6*, 279–300.

Noailly, J., & Smeets, R. (2013). Directing technical change from fossil-fuel to renewable energy innovation: an application using firm-level data. *The Graduate Institute Geneva Research paper 24*, .

Papageorgiou, C., Saam, M., & Schulte, P. (2017). Substitution between clean and dirty energy inputs: A macroeconomic perspective. *Review of Economics and Statistics*, *99*, 281–290.

Rebelo, S. (1991). Long-run policy analysis and long-run growth. *The Journal of Political Economy*, *99*, 500–521.

Romer, P. M. (1986). Increasing return and long-run growth. *Journal of Political Economy*, *94*, 1002–1037.

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, *98*, 71–102.

Sims, R., Schock, R., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H., Schlamadinger, B., Torres-Martnez, J., Turner, C., Uchiyama, Y., Vuori, S., Wamukonya, N., & Zhang, X. (2007). Energy supply. in climate change 2007: Mitigation. contribution of working group iii to the fourth assessment report of the intergovernmental panel on climate change. *Cambridge University Press*, .

Smulders, S., & de Nooij, M. (2003). *The impact of energy conservation on technology and economic growth*. Other publications TiSEM Tilburg University, School of Economics and Management.

Stern, N. (2007). The economics of climate change: the stern review. *Cambridge University Press*, .

Taylor, M. (2008). Beyond technology-push and demand-pull: Lessons from california's solar policy. *Energy Economics*, *30*, 2829–2854.

Taylor, M., Rubin, E. S., & Hounshell, D. (2005). Control of so2 emissions from power plants: A case of induced technological innovation in the us. *Technological Forecasting and Social Change*, *72*, 697–718.

Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, *3*, 122–128.

Yeh, S., & Rubin, E. S. (2012). A review of uncertainties in technology experience curves. *Energy Economics*, *34*, 762 – 771.

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