STRATEGIC DYNAMIC CLIMATE POLICY: THE ROLE OF CCS[1]

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ABSTRACT

The paper examines the role of carbon capture and storage (CCS) technology first in an exogenous, and then, in an endogenous growth model with environmental constraints. In the first part, we investigate the activity of the CCS systems given an exhaustible resource constraint and limited CO_2 storage capacity under climate stabilization targets. In the second section, we look at the activity of the CCS technology and corresponding research and development (R&D) investments. Our findings indicate that the CCS technology is welfare improving but its level of activity is highly affected by resource and storage constraints. Given the low amount of resources allocated for CCS R&D, it can be considered that learning-by-doing (LbD) is more relevant for the CCS technology. This is because all components of CCS systems exist and are in use today by the fossil fuel extraction and refining industries. Yet, CCS has not been applied at scale to a large and operational commercial fossil fuel power plant, indicating that the technology can significantly benefit from LbD. Uncertainties in the political will towards tax rates, and leakage possibilities of the stored CO_2 are issues that are left for further research.

Key Words: Carbon Capture and Storage, Fossil Fuel Energy, Exogenous Technical Change, Endogenous Technical Change, Climate Change

JEL Classification: H23, O31, Q43, Q54, Q55

STRATEJİK DİNAMİK İKLİM POLİTİKASI: KYD'NİN ROLÜ

ÖZ

Çalışmada, karbon yakalama ve depolama (KYD) teknolojisin öncelikle dışsal ve sonrasında da içsel bir büyüme modelindeki rolü çevresel kısıtlar göz önünde bulundurularak incelenmektedir. İlk bölümde, enerji kaynaklarının tükenebilirliği ve yakalanan karbondioksidin depolanma kapasitesi göz önünde bulundurularak, KYD sistemlerinin faaliyetleri 450 ve 550 ppmv denge ve istikrar hedefleri doğrultusunda araştırılmaktadır. İkinci bölümde, KYD teknolojisinin aktivite derecesine ve ilgili

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araştırma ve geliştirme (AR-GE) harcamalarının etkinliğine bakılmaktadır. Bulgularımız, KYD teknolojisinin kullanımının refah düzeyini arttığını göstermekle beraber bu teknolojinin tükenebilir kaynak seviyesinden ve depolama kısıtlamalarından oldukça etkilendiğini ortaya koymaktadır. Sonuçlardan hareketle, KYD'nin AR-GE harcamaları için ayrılan düşük kaynak miktarı göz önüne alındığında, yaparak öğrenmenin (LbD'nin) KYD teknolojisi için daha uygun olduğu görülmektedir. Bunun basilica nedeni olarak KYD sistemlerinin tüm bileşenlerinin günümüzde mevcut olması ve fosil yakıt çıkarma ve rafine etme endüstrileri tarafından kullanılması gösterilebilir. Bununla birlikte, KYD, henüz büyük ölçekli, faal ve ticari faaliyet içerisinde olan bir fosil yakıtlı enerji santraline tam anlamıyla uygulanmamış olduğundan, teknolojinin LbD'den önemli ölçüde faydalanma potansiyeli gözükmektedir. Karbon vergisi oranlarına yönelik siyasi belirsizlikler ve depolanan karbondioksidin atmosfere sızma olasılıkları gibi konular daha ileriki bir araştırmaya bırakılmıştır.

Anahtar Kelimeler: *Karbon Yakalama ve Depolama, Fosil Yakıtlar, Dışsal Teknolojik Değişim, İçsel Teknolojik Değişim, İklim Değişikliği*

Jel Sınıflandırması: *H23, O31, Q43, Q54, Q55*

1. INTRODUCTION

Fossil fuels account for a major share of global anthropogenic greenhouse gas (GHG) emissions and still supply over 80% of all primary energy needs (IEA, 2014). According to U.S. Energy Information Administration, fossil fuels will remain the primary energy source for the decades to come (IEA, 2013). In the absence of specific actions, however, CO_2 concentration in the atmosphere will continue to grow, which can prove catastrophic for the generations to come (UNEP, 2006). Therefore, there is a demand for new technologies that can help with the fight against climate change.

One example for such technologies is carbon capture and storage (CCS). It is considered as a vital technology that can contribute significantly to the efforts in limiting emissions. CCS can be used by large stationary point sources, such as a coal-fired power plant, and emission- intensive industrial facilities, such as cement production. Its main goal is to prevent CO_2 emissions of a power plant from entering the atmosphere. Rates of CO_2 emissions that are captured can get as high as 85-95% (Metz et al., 2005).

As of today, there exist three methods for capturing CO_2 emissions. Post-combustion removes the CO_2 after combustion takes place. In this process, CO_2 is separated from the flue gases by using a liquid

solvent. In pre-combustion, the fuel is converted into a mix   of CO_2 and hydrogen. The latter gas is then burned to produce electricity. The burning of fuel is basically the reaction of fuel with oxygen in the air. Yet, in the oxy-fuel combustion process, the fuel is burned by pure oxygen. The result is a flue stream of CO_2 and water vapor. Because there is no nitrogen present in the flue gas, CO_2 can be easily captured in this process. (Golombek et al., 2011; Metz et al., 2005).

The CCS technology is envisaged to be a fundamental part of the lowest-cost GHG mitigation policy. In its Technology Roadmap, the International Energy Agency (IEA, 2009, p.4) concludes that without the technology the overall cost to reduce emission to 2005 levels by 2050 increases by 70%." Furthermore, CCS can provide 15% to 55% of the cumulative mitigation effort up to 2100 (IPCC, 2005, p.12).

We observe that high-income oil and gas producing countries in Europe and North America use resources on R&D of CCS technologies. Tjernshaugen (2008) shows that fossil fuel reserves and their extraction activities are the main variables that explain R&D funding for CCS. Among these countries, Canada and Norway show the strongest contributions. The shares of R&D budgets to the total R&D spending in 2005 were 38.79% and 6.23% for Nor- way and Canada, respectively (Tjernshaugen, 2008). Nevertheless, there are still questions regarding the economics of CCS and the uncertainties that surrounds the technology.

It is therefore important to show the feasibility of CCS activity and its R&D from the perspective of a benevolent planner, and see how much this overlaps with the contemporary global political agenda. For this purpose in Section 2, we present a growth model initially with exogenous and then endogenous technical change. The technology for the final good is labor augmenting, while the technology for CCS is capital augmenting. R&D investments are made using a portion of the final good. In this section we also present the first order conditions and an evaluation of them. In Section 3 we do the calibration. Section 4.1 presents the results for exogenous technical change under different scenarios including constraints like a ceiling on the volume of CO_2 in the atmosphere, limited resource stock and limited storage space for injecting the CO_2 captured. Section 4.2 presents the results with endogenous technical change. In Section 5 we conclude.

2. MODEL STRUCTURE

The analysis will be from a social planner's perspective. Hence, we are not going to deal with issues like imperfect appropriability of R&D efforts etc. There is a representative agent, representing the whole population. Final good, Y_t, represents the global gross domestic product (GDP). There are three factors

of production for the final output: a capital good (capital), exhaustible resource stock (equivalent to energy here), and labor. The final good production technology exhibits constant returns to scale.

CCS is a capital-intensive technology. Therefore, labor is omitted as a factor of production for CCS. Without loss of generality, we assume the technology is constant returns to scale in its capital infrastructure.

CO_2 stock in the atmosphere increase due to net emissions $a(E_t − Y_{At})$, where E_t and Y_{At} denote CO_2 emissions and CCS at time t, and a represents the uptake of emitted CO_2 by the atmosphere. Furthermore, δ_S represents the depreciation for atmospheric CO_2. Additionally, we have

$$Y_t = \Omega_t K_{Yt}^{\alpha} E_t^{\beta} (A_{Yt}L_{Yt})^{1−\alpha−\beta} \quad (\lambda_t) \tag{1}$$

$$Y_{At} = A_{At}K_{At} \quad (\lambda_{At}) \tag{2}$$

$$C_t + K_{Yt+1} + K_{At+1} − (1 − \sigma N)(K_{Yt} + K_{At}) = Y_t − qE_t \quad (\lambda_{Ct}) \tag{3}$$

$$S_{t+1} = (1 − \delta_S) S_t + a (E_t − Y_{At}) \quad (\lambda_{St}) \tag{4}$$

$$L_{t+1} = L_t + \gamma_L L_t (1 − L_t / L_{max}) \tag{5}$$

$$A_{jt+1} = A_{jt} + \gamma_j A_{jt} (1 − A_{jt}/A_{max}), \ j = Y, A \tag{6}$$

$$Y_{At} \geq 0 \ (\nu_{At}) \ \text{and} \ Y_{At} \leq E_t \quad (\nu_{CCSt}) \tag{7}$$

Production uses labor, capital and energy as inputs, and state of technology in the final good sector is represented by a labor productivity parameter A_{Yt}. Output can be used for consumption (C_t), net investments, or energy production costs, where K_{Yt} is the capital employed in the final good production, K_{At}, is the capital used for CCS, N is the number of years per period, σ is the capital depreciation per period, and q are the energy production costs (fossil fuel extraction costs). Furthermore, $\Omega_t = e^{−\delta_y S_t/S_0}$ is the multiplicative-damage function as a function of the atmospheric CO_2. Here, δ_y is a positive constant and S_t is the level of CO_2 in the atmosphere at time t. A_{At} is the CCS capital productivity parameter. Labor and technological growths are represented by the logistic growth functions (see Eqs. 5 and 6). Additionally, we impose two constraints on CCS. The first one is the non-negativity constraint. The other constraint imposes that the level of CCS cannot be more than the current emissions from fossil fuel use. Therefore, there can be no capture of CO_2 from the air. Lastly, the variables in parentheses on the right hand side (see Eqs. 1–7) represent the shadow prices (or the value of the Lagrange multipliers).

The first order conditions are presented below:

$$(K_{Yt+1}): \ r_{t+1} + N\delta_S = \alpha \ Y_{t+1}/K_{Yt+1}, \tag{8}$$

(K_{At+1}): $r_{t+1} + N\delta_S = \alpha\, Y_{At+1}/K_{At+1},$ (9)

(E_t): $q + a\tau_t - \hat{v}_{CCSt} = \beta Y_t/E_t,$ (10)

(Y_{At}): $p_{At} = a\tau_t + \hat{v}_{At} - \hat{v}_{CCSt}$ (11)

where r_{t+1} is the real interest rate defined by λ_t/λ_{t+1}, $\tau_t \equiv \lambda_{st}/\lambda_t$ is the unit tax on emissions, and $p_{At} = \lambda_{At}/\lambda_t$ is the marginal cost of CCS (in units of the final good). Furthermore, $\hat{v}_{At} \equiv v_{At}/\lambda_t$ and $\hat{v}_{CCSt} \equiv v_{CCSt}/\lambda_t$.

When $v_{At} > 0$ and $v_{CCSt} = 0$, $p_{At} > a\tau_t$; that is, the marginal cost of CCS is higher than the unit tax on energy, and there would be no CCS. On the other hand, when $v_{At} = 0$ and $v_{CCSt} > 0$, $p_{At} < a\tau_t$; that is, the marginal cost of CCS is lower than the unit tax on energy. Therefore, it is optimal to capture and store all current emissions. Lastly, when $p_{At} = a\tau_t$, the rate of emissions would be between 0% and 100% of the current emissions.

We also evaluate the effects having resource and storage constraints in the economy. The reason for having such constraints is to have conclusions that are more relevant for the real life. As this is a simplification of the real world economy we are not aiming for deriving numbers that are perfectly accurate. Rather, we would like to see the implications of having such constraints on the resource use, economic growth, climate change and CCS.

2.1.   Calibration And Data For Numerical Analysis

The time horizon we are working on is 600 years (60 periods with one period consisting of 10 years). The model is calibrated for the year 2010. The data used for the calibration is provided in the following table:

N	Number of years per period	10
L	Population in 2010	6.9 bn
g_L	Population growth	0.12 per decade
q	Fossil fuel costs	50 T€/TtCO$_2$
Nδ	Capital depreciation	0.7 per period
s	Gross savings rate	0.3
S$_0$	Preindustrial level of atmospheric CO$_2$	275 ppmv
a	CO$_2$ uptake rate	0.587
K$_{Y0}$	Initial capital stock in the final good sector	185 T€
α	Capital share	0.3549
β	Energy share	0.0249

ρ	Utility discount rate	0.256 per decade
A_{Y0}	Final good technology level in the initial period	240.6
L_{max}	Maximal population	11 billion
$A_{j,max}$	Maximum technological level	2406
γ_L	Population growth	0.322 per decade
γ_j	Rate of innovation; j= Y, A	0.178 per decade
δ_S	CO_2 depreciation per period	0.0763 per decade

Table 1

Furthermore, $\delta_Y = 0.027$. We calibrate the initial technology level for CCS, A_{A0}, as follows. The first order condition given by Eq. 9 can equally be shown as

$$A_{At+1} = (r_{t+1} + N\delta)/p_{At+1}.$$

Assuming that the interest rate equals the factor of social time preference initially (.256 in the module; constituting to 2.5% yearly), and assigning 31.7 €/CO_2, which approximately constitutes to 40.8\$/tCO_2 or 150\$/tC (Gerlagh, 2006), we calculate that $A_{A0} = 0.03$. To begin with, we assign as zero value for the initial CCS capital. This overlaps with the current observation that there is no large and fully operational commercial fossil fuel power plant with CCS.

The fossil fuel resource enters the economy as follows:

$$R_{Et+1} = R_{Et} - aE_t. \tag{12}$$

The reason for having the emissions, but not the level of resource use in the model is due to incorporating the amount of resource in terms of its carbon content. Doing such thing can be more in line with the model we have here. According to the IPCC Third Assessment report Climate Change 2001 -Working Group III: Mitigation, there is an estimated 5 TtC fossil fuel reserves in the ground (Converted to CO_2, this amounts to 18.350 TtCO_2). The storage data for CO_2 is taken from The Bellona Foundation - Fact sheet: CO_2 Storage. According to the estimates, global storage capacity is the sum of 675-900 GtCO_2, which can be stored in oil and gas fields, 3-200 GtCO_2 in unminable coal seams and 1000-10000 GtCO_2 in deep saline formations. To calculate the number to use in the numerical analysis, I take the average of these estimates, which gives 6340 GtCO_2 of storage space. However, I needed to adjust these numbers to the model. The reason is when you look at the annual global emissions data for 2004, which is 0.26 TtCO_2 (IEA, 2006). This number compared to what we have in the calibration,

0.179 TtCO$_2$, is higher. Hence I adjusted all the data by multiplying them with $\frac{17.96}{26} = 0.69$. After adjustments, the resource stock is 12.676 TtCO$_2$ and the available storage space for CCS is 6.340 TtCO$_2$.

3. EXOGENOUS TECHNICAL CHANGE

In this section we assume that population and technologies follow exogenous paths (see Eqs. 5 and 6), and run six different scenarios. BAU represents Business as usual, CBA represents the planner solution, 550 ppmv and 450 ppmv are the planner solutions with limits on atmospheric emissions concentrations.1 Reslimit is the planner solution with a resource constraint for the exhaustible resource, while Storlimit represent storage limitation for the emissions capture through carbon capture and storage.

Atmospheric CO$_2$ concentration

In the BAU scenario where climate change policy is absent, we see in Figure 1 that the atmospheric CO$_2$ concentration is continuously growing. In the two stabilization scenarios, atmospheric CO$_2$ concentrations are stabilized at 450 ppmv and 550 ppmv. The CBA, Reslimit and Storlimit scenarios result in quite similar concentration trajectories until the storage limit is reached in the Storlimit scenario.
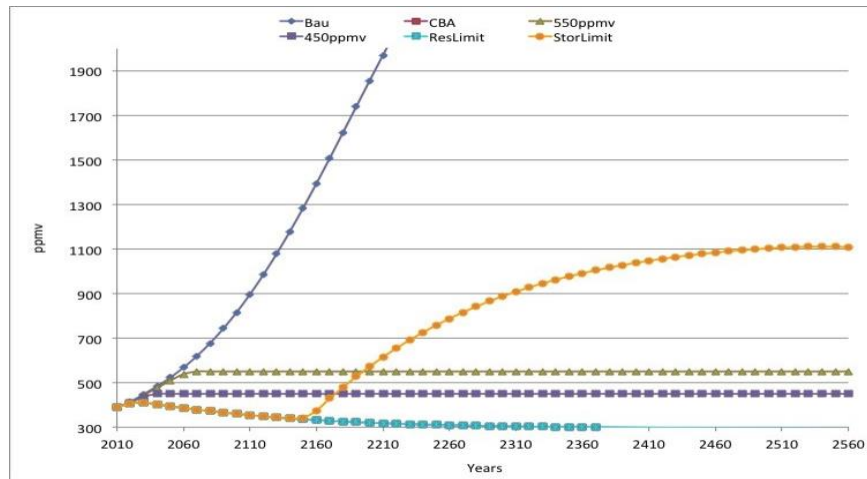
Figure 1

Carbon capture and sequestration

At a first glance we see the role CCS plays once it is available. In every scenario we see that it is optimal to capture and store carbon. In the stabilization scenarios, CCS has a smaller role to play. In the Storlimit case, the available storage for CO$_2$ vanishes around year 2150; therefore CCS cannot be

active anymore after this point. Although the ratio of CCS seems high in Reslimit case, the level is getting smaller in time due to diminishing levels of the exhaustible resource. The graph for CCS with the levels is given in Figure 3.
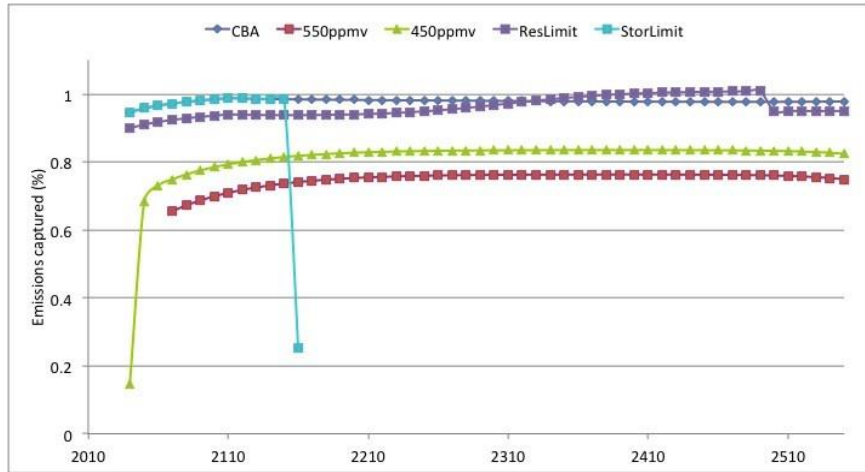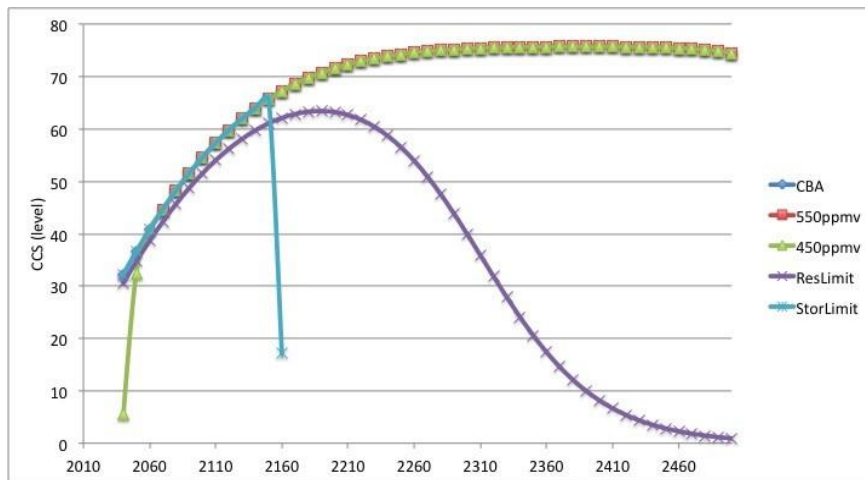

Figure 2

Figure 3

Tax rate

As is seen in 4 the tax on the final good is increasing continuously. For the stabilization scenarios the tax is lower as emissions cannot pass the stabilizers of 450 and 550ppmv. Within the limited resource case, we see that the tax gets lower than the corresponding   trajectories coming from the CBA and Storlimit scenarios as the resource use diminishing, resulting in lower emissions.
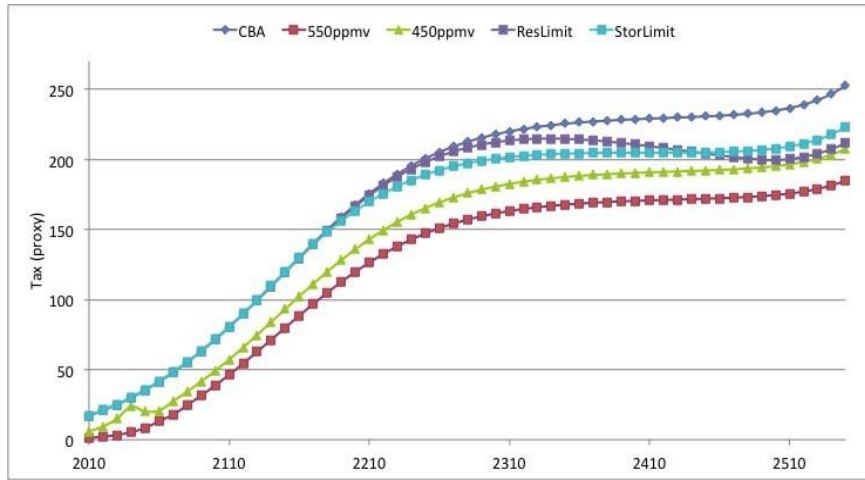
Figure 4

Output growth, consumption and welfare

There is a downward trend in the growth rates in the economy. This is a natural result of the fact that there is no non-carbon technology to switch to; hence the only way forward is to emit as low emissions as possible by contracting the economy or do as much CCS as possible (which will also put a burden on the growth rates). A closer look at Figure 5 reveals that the growth rates are quite similar except the BAU case, where the growth is relatively higher initially but gets lower in a short period of time.
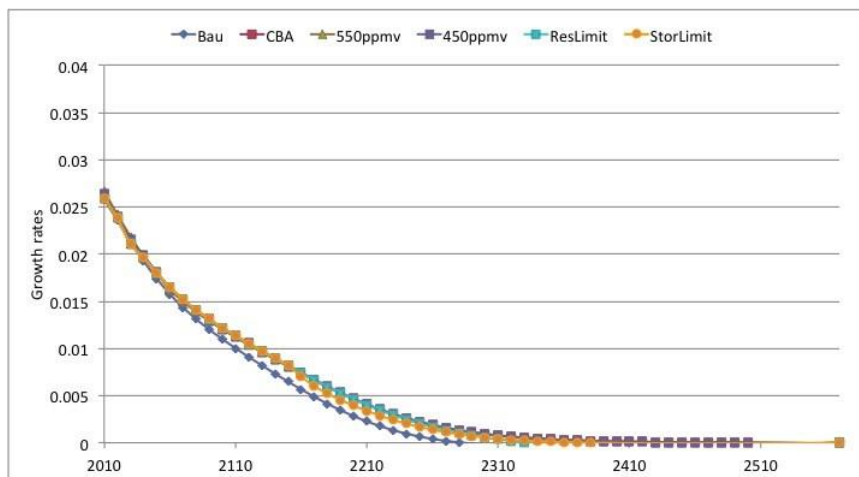
Figure 5

The consumption levels show rather a clearer picture in terms of the differences. We see the long run effect of the exhaustible resource constraint, which results in lower consumption. The limited storage case is also causing lower consumption though the level manages to get higher than the limited

resource case in the very long run. The consumption level is hit hard in the BAU case due to high damages coming from global warming.
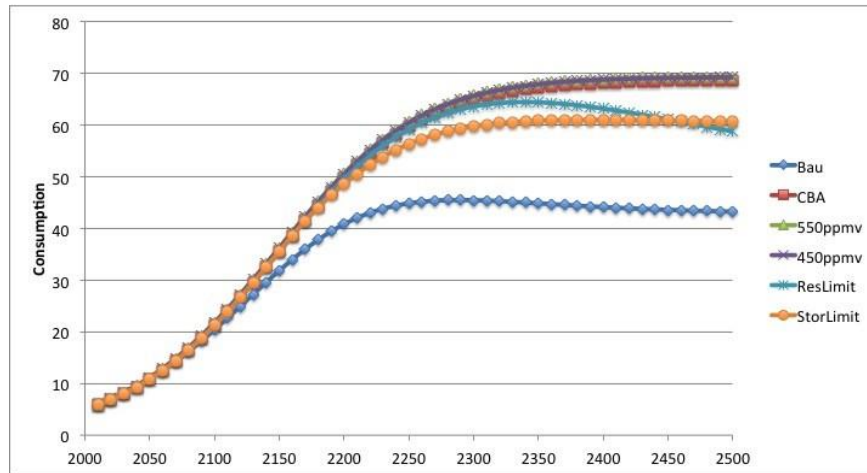

Figure 6

The welfare levels show a similar pattern to consumption levels. The ranking for the total welfare among the scenarios is as follows: $W_{BAU} < W_{StorLimit} < W_{ResLimit} < W_{CBA} < W_{450ppmv} < W_{550ppmv}$. The intuition for Storlimit giving the second lowest total welfare is related to the unavailability of CCS in the long run. For this reason, more sacrifice in growth needs to be made relative to other scenarios except BAU. The results also show that the limited resource has a smaller adverse effect than the limited storage case, which we find rather surprising.
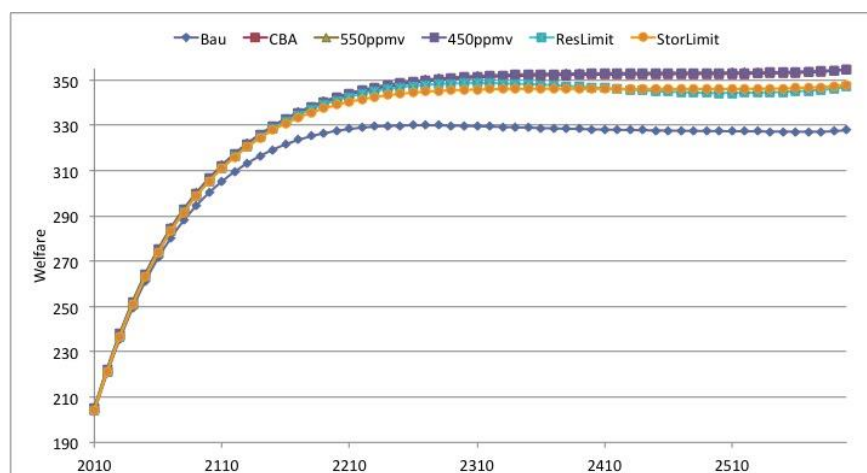

Figure 7

4. ENDOGENOUS TECHNICAL CHANGE

In this section we abstract from scenarios such as limited exhaustible resource and storage capacity. Instead, we focus on the role of endogenous technical change given the CCS technology and the two CO_2 stabilization targets. The source of endogenous technical change comes from R&D investments in labor-augmenting and CCS technologies, RY and RA, respectively. As a result the total R&D spending, R, is the total of these two R&D investments,

$$R_t = R_{Yt} + R_{At}. \qquad (\lambda_{Rt})$$

R&D expenditures determines the knowledge level in the next period

$$A_{jt+1} = A_{jt} + \frac{\theta+1}{\theta} R_{jt}^{\frac{\theta}{\theta+1}}, \ \ j = Y, A \quad (\mu_{jt})$$

The new budget equations is,

$$C_t + K_{Yt+1} + K_{At+1} + R_t - (1 - \sigma N)(K_{Yt} + K_{At}) = Y_t - qE_t \quad (\lambda_{Ct})$$

First order conditions with respect to R&D investment and accumulated knowledge levels, R_{jt} and A_{jt+1} respectively, are

$$(R_{jt}): \ \lambda_t = \mu_{jt} R_{jt}^{-\frac{1}{\theta+1}},$$

$$(A_{Yt+1}): \ \mu_{Yt} = \mu_{Yt+1} + \lambda_{t+1} Y_{t+1}/A_{Yt+1},$$

$$(A_{At+1}): \ \mu_{At} = \mu_{At+1} + \lambda_{At+1} Y_{At+1}/A_{At+1},$$

We display five different scenarios in the following figures. The first one is the BAU scenario with exogenous technical change. Then we have the first-best solution given exogenous technical change (CBAExo). Following this we have the first-best solution with endogenous change (CBAEndo). The last two scenarios are the ones with the 450 and 550 ppmv stabilization targets.

Atmospheric CO_2 concentration

The surprising result here is that the lowest concentration of CO_2 occurs in CBAExo. This is due to the consumption - climate change trade-off. A stronger growth due to endogenous technological change may make it more beneficial to produce more and at the same time emit more CO_2. Though, this needs further evaluation and this is what we are going to do in the following.

Carbon capture and sequestration

In Figure 9 we see that the level of CO_2 captured do not differ significantly between different scenarios. However, what cause the difference between the scenarios in Figure 10 are the emission
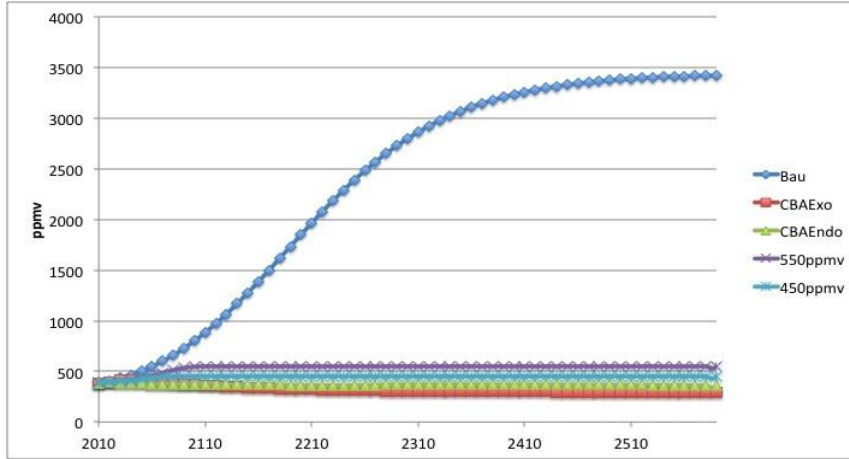
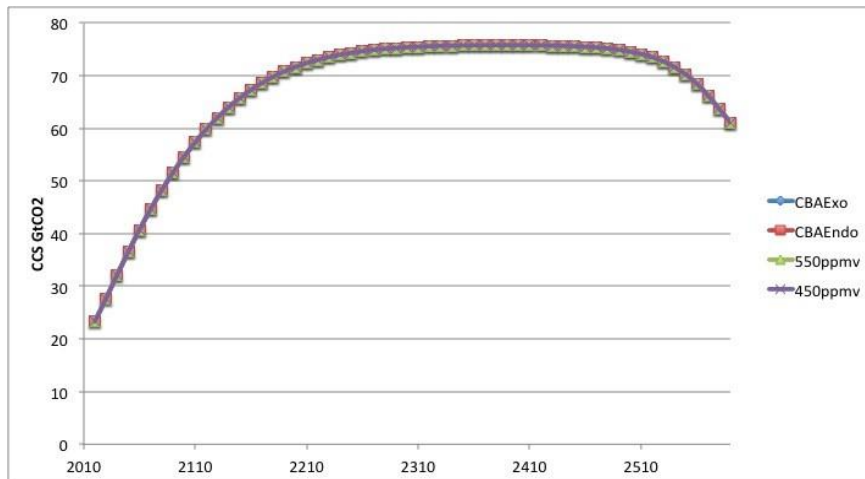trajectories (see Figure 11).

Figure 8

Figure 9

In Figure 11 we see that a strong presence of green paradox exists: the stabilization targets result in emissions to rise in the early periods. In the exogenous technical change scenario, the ratio of CCS to emissions is rather high but stable. We do see a weaker presence of green paradox in CBAEndo as there are no predetermined atmospheric CO_2 ceilings.
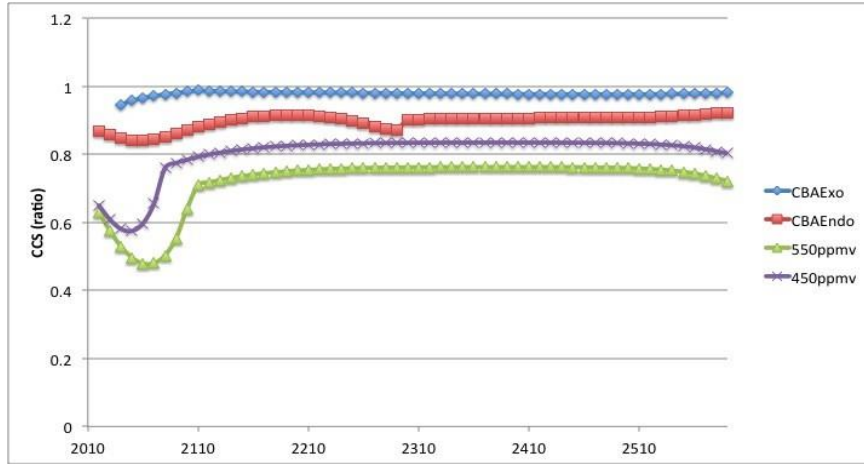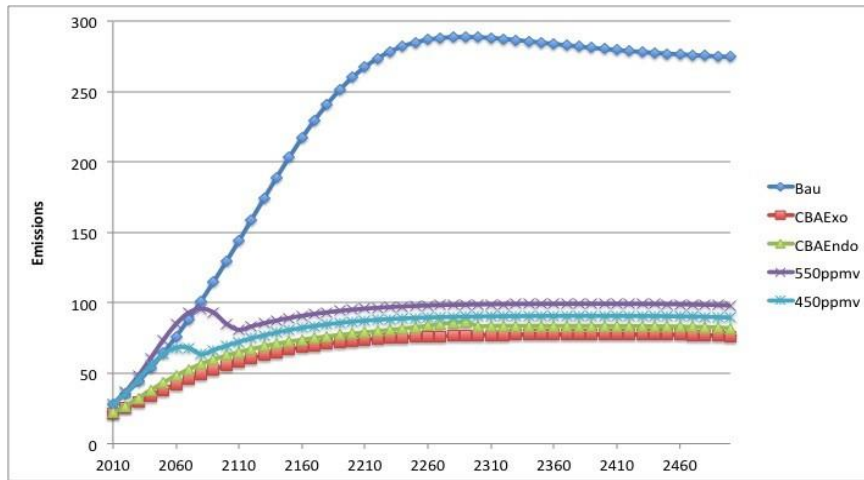
Figure 10

Figure 11

Tax rates

We see a stronger downward effect on taxes in the endogenous technical change case. Ac- cording to this, the tax on final good stays almost constant after 2270. This can be easily seen from stable emission levels and high carbon capture and storage activity corresponding to these emissions. The tax levels are slightly lower than the corresponding tax levels in the first section.
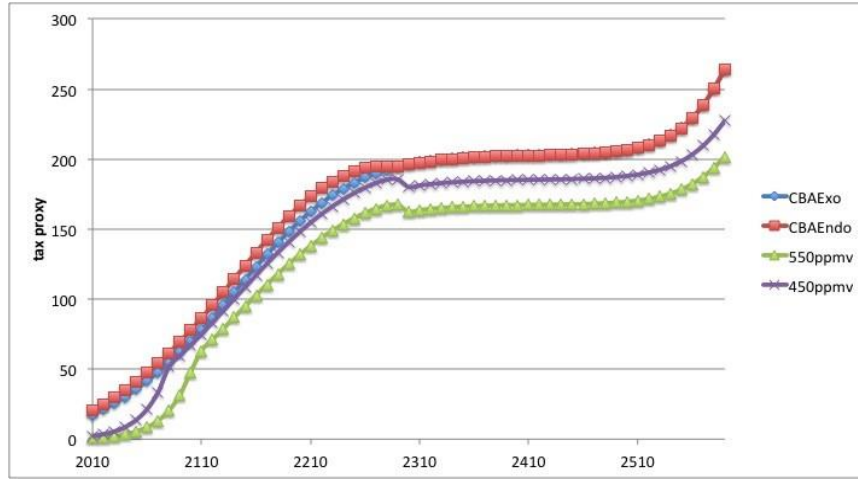
Figure 12

Output growth, consumption and welfare

The striking part is coming from the differences in growth rates and consumption levels. We witness strictly higher levels of growth for all the endogenous growth scenarios. This implies the importance of R&D activity and hence the endogenous growth.
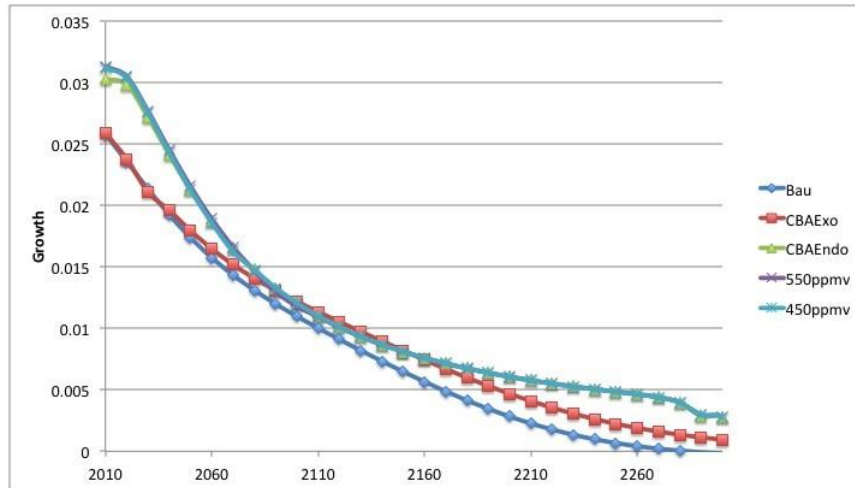

Figure 13

When we look at the levels of consumption (Figure 14) we observe that the optimal levels of consumption for the endogenous growth scenarios are twice the amount of the optimal consumption level in the exogenous growing technologies case. All of the scenarios give much higher levels of consumption compared to the BAUscenario.
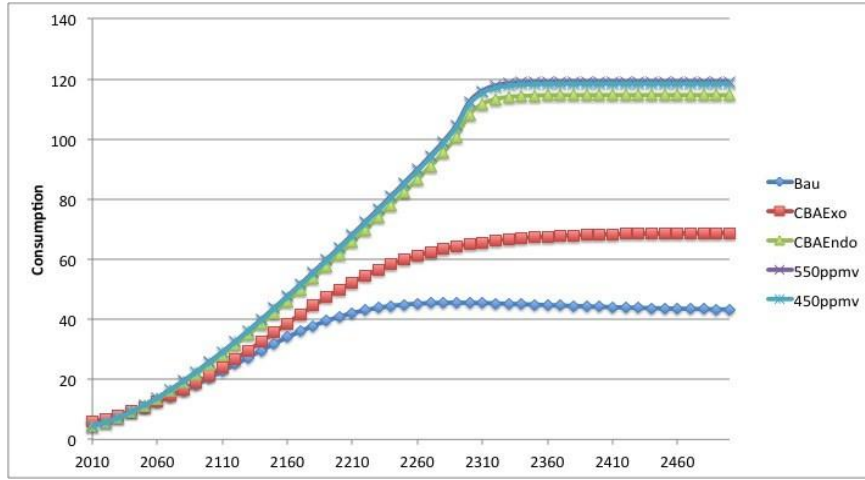
Figure 14

In Figure (15), we almost see the reflection of consumption levels; though the levels are scaled downward due to the logarithmic utility function
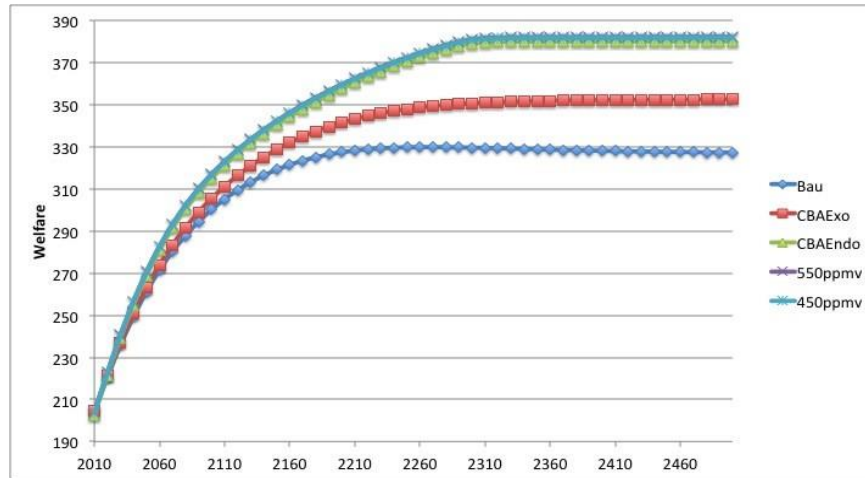

Figure 15

5. CONCLUSION

In this paper, we attempted to evaluate CCS technology both in exogenous and endogenous growth models with environmental constraints. According to the findings, the level of CCS is not significantly affected by the fact that technology is taken exogenous or endogenous. This may actually imply that instead of focusing on R&D spending for the technology, we may focus on the effects of learning-by-doing on the technology. As the technology is not productive (i.e., does use the final good),

it may be of relevance to focus on perfecting the process itself. (This is actually the case in reality. Given their experiences, people working on CCS say that experience, rather than R&D investments, play a bigger role in making the technology cheaper). This may explain the reason why the technology receives so little R&D investments in the results we have. Moreover, in all of the scenarios, we witnessed that CCS was employed. Therefore, there is no question about its welfare enhancing effect. In the exogenous growth case, all the results are as expected although it is rather hard to interpret the increasing atmospheric concentration of CO_2 when storage availability for CO_2 runs out. We did witness the presence of the green paradox in the endogenous growth case, although this effect is not present for the exogenous growth counterpart.

Before we had started working on this study, we had different research questions in mind. One was related to the political will of holding on to the optimal tax rates. Hence the question was about the effect of future uncertainties in tax rates on today's investments and activities in CCS. Although the trajectories in both the exogenous and endogenous technological change (exotech and endotech)) cases look similar for CCS, we do actually see differences in emission levels.   For example, in 2300 the emissions in in exotech and endotech are 76.9 and 83.5 $GtCO_2$, respectively. Depending on different scenarios, CCS rates start from 75% and gets higher, implying significant contribution to the abatement efforts. As the economies are, from an empirical point of view, more in favor of technical changes induced by prices, un- certain future tax rates can have significant effects on use of and investments made in CCS. Therefore, we believe this issue needs a closer look. Moreover, the storage issues for CO_2 captured may have some relevance. We think Figure (1) deserves a better understanding for this case. Besides, leakage possibilities can be discouraging for the technology. As we have also showed in the first section, there is a highly significant effect of an exhaustible resource on the level of CCS activity. This brings with it the question why there is so much investments going on for a technology that is dependent on an exhaustible resource.

In conclusion, uncertainty in the future political wills towards CCS, storage problems and limited resource availability may require further investigation for the technology. As being a carbon-free technology, and hence has the potential to compete with other carbon-free technologies, the analysis can become more interesting to look at these problems in a bigger model with more technological choices, different factors of production and a more detailed description of the environment. However, if we think that the very strong dependence on fossil fuels will carry on, the results we have in this study can have important policy implications.

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