Capital inertia and the timing of energy transition

Kevin Genna[1]

[1] AMSE, Aix marseille Université, CNRS,EHESS & centrale Marseille

November 2, 2019

Abstract

I use a multi-sector vintage capital model *à la* Krusell (1998) with climate economics to study timing of optimal energy transition. I include an exogenous technology differential between renewable and fossil, that will be the engine of growth. The vintage structure is used to modelize embodied technical change and carbon lock-in as it is mentioned in Unruh (2000), a situation in which we are trapped by carbonized energies and by slow transition. Economy being mainly fossil driven, about 82% of the energy mix, it creates inertia in energy capital sector that cannot be solved by technology, in the short run. Because capital unit are long-lived and technology is embodied, energy transition faces frictions to occur quickly. Preliminary results show a slow transition, with a ratio of renewable technologies that should remain below the 20% level in 2050. The second part of the paper tries (not in this version of the paper) to confront theoretical result to the data using a bayesian vector auto-regressive model (BVAR) on energy capital investments. This part relies on the "power plant tracker" dataset, from Enerdata. Econometric forecast would validate (or not) the theoretical model and measure the importance of capital inertia in the energy transition process.

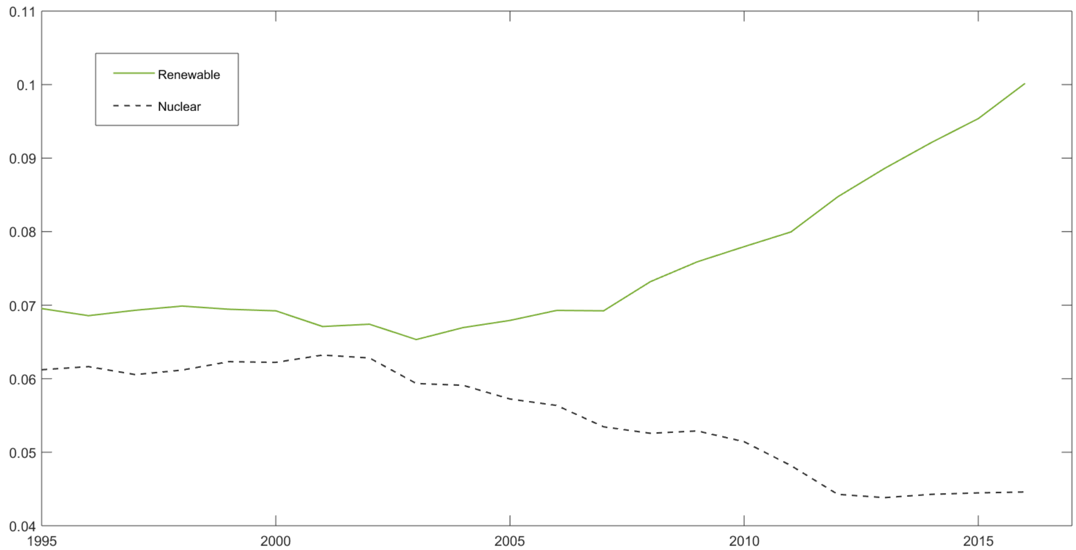
Keywords: *Energy transition, vintage capital, exogenous growth, climate economics*

Journal of Economic Literature Classification Numbers: C61, O41, Q43.

1 Introduction

Long-term climate policies are targeting a carbon neutral economy at horizon 2050, at least for European Union. This objective is of first importance to mitigate the global warming below 1.5^oC and protect environment from catastrophic event and biodiversity reduction. The task is not easy and requires time and investment at all levels of the economy, in this paper I will focus on the energy sector. When it comes to energy the problem is twofold, first we need to reduce carbon emission from our actual production, by producing more efficiently or by reducing carbon emission of energy production. Secondly, there is still a huge part of the world, mainly subsaharian Africa, which is lacking of proper energy access. We have to find a way to increase energy production at the world level, to improve quality of life in less developed countries, and at the same time to reduce absolute greenhouse gas emissions, because carbon hurts the environment in an absolute manner, we cannot target relative improvements only.

This paper focuses on energy mix and the timing of energy transition, and will deal with the particular issue of capital inertia as an explanation of our slow transition (see figure 1). I define capital inertia as a situation of great frictions in the capital sector: any transitional process is long due to the type of investment needed. In occurrence for energy it is the construction of long-lived power plant. To replace a unit of capital we have to wait the decommissioning of the first one. Additionally, technology is embodied in each unit so current improvement cannot enhance past power plants, or just slightly. A second source of frictions is the network already installed and experience gained from past use of older technologies, for example gas stations for Internal Combustion Engine (ICE) cars, which are still more numerous than facilities for electric cars. In this case the network slow-down the process of energy transition especially from consumer point of view. This way of exploration could be one of the reason for carbon lock-in, as mentioned in Unruh (2000). We are trapped in a carbonized world, as Unruh explains in his paper, and this is due to an institutional and technological co-evolution along the XX^e century.



source: BP statistical review of world energy

Figure 1: Share of renewable and nuclear energies in world energy mix

In this context of capital inertia I chose to use a vintage capital model *à la* Krusell (1998) with embodied technical change, which is the closest representation of capital inertia in a macroeconomic model. This framework allows me to investigate the question of capital inertia impact on optimal energy transition. In a frictional situation, what will be the timing of transition ?

I will try to answer to this question into a perfect foresight model, very simple, with a vintage capital model *à la* Krusell (1998) with 2 capital sectors, clean and dirty, and with exogenous growth. It will be specified in details further but it is a non-classical way to express growth in this framework, I use a technology differential between the 2 sectors. Clean sector begins with a delay in technology, back into the XX^th century, it was cheaper to invest in fossil fuels and renewable technologies were not that efficient. I introduce a variable q in clean capital accumulation function which is the actual performance of renewable capital compare to fossil one, I set $q_0 < 1$ to be sure that in a first time, fossil technologies are more efficient and then calibrate the quantitative part to match last years trends. To the best of my knowledge there is only one paper that use embodied technical change in the case of energy, this is Lennox and Witajewski-Baltvilks (2017). But they focus on optimal taxation and do not provide analytical solution to the problem.

The model is built to behave as expected, the interest is in the quantitative part when we explore the timing of energy transition. I begin with a very basic model without any frictions, and then I will add climate economics close to Golosov et al. (2014), with utilization of dirty inputs that reduces output production. Possible explanations for damages dues to pollution can be found in Graff Zivin and Neidell (2012) with pollution accumulation reducing workers productivity, or in all the existing literature around damage function in climate economics Nordhaus and Boyer (2000), Nordhaus (2014b) or Pindyck (2017) among others. I will also add a government sector in a next step to investigate some policy implications of taxation, subvention, quotas, etc...

The analysis will be kept at an aggregate level with only two sectors. The two intermediates inputs are combined through a CES function to give the final amount of capital used in the final good production. Elasticity of substitution is larger than one as it was shown in Papageorgiou et al. (2017), clean and dirty inputs are substitutable and the elasticity will be between 1 and 2. With exogenous technological progress in favor of clean sector and substitutable inputs there is no doubt that structural change will be in favor of the clean sector, but we have to wonder if it will be sufficient to reach a carbon neutral economy at 2050 horizon. However, transition is not the only objective because it is a relative measure and pollution is accounted in absolute terms. We can have a dominance of clean technologies in 30 years with an higher pollution level, this is why policies should target absolute objective and not only relative ones.

Preliminary results show that energy transition is a long process to occur and largely depends on technological progress value. For the moment the calibration is clearly non robust and need to be justified, but with a non irrealist calibration, fixing the share of clean technologies at 7%, like in 1995, it ends at 16% of clean energies in 2050, and this is without any friction, without any taxes or subventions and with constant rate of technology improvement. It is worthless to say that such a case is not the objective we want to reach.

Then, results with climate economics are qualitatively the same but transition speed is affected by two effect. In one hand, pollution damages GDP reducing savings and resulting by a lower level of investment, in both sector. In a second hand, because damages are due to the stock of dirty capital it creates incentives to speed-up energy transition. These two effects are contradictory but have no effect on the asymptotic behavior of the model, compare to the one without climate economics. For now, I am not able to conclude if incorporation of future damages in the social planner maximization will ends with a faster transition.

The last theoretical part I want to add is an economy with a government that can raise carbon taxes to set an optimal taxation scheme for the topic of energy transition. However, I will not try to proxy global warming with this model, the framework used is too simple for such a complex task. My belief would be, the faster the transition, the safer we are.

The second part of the paper would be dedicated to the empirical part of the same problem. I will ask the same question and I will confront theoretical simulations to econometric forecast, as a robustness check, to validate the theoretical findings in terms of policy recommendations.

For this purpose I will use data on electricity power plants provided by Enerdata. This dataset contains all the electricity generator in the world with their date of commissioning, the energy they use, in which country they are settled and how many power they deliver. Separating the power plant in 2 categories, fossil and renewable, and computing the power delivered each year by both of the category, I will be able to obtain my capital variables of the theoretical values. Then it seems important to integrate governement R&D spending data in the energy sector, from IEA, and also the number of patent applications in energy as a proxy for private R&D. It seems also consistent to add fossil fuels prices in the econometric specification.

The main issue with this econometric model is the number of observations, because some data start in the early 70's, we will have only 40 to 50 annual observations for each variables. And this brings the problem of overspecification of the model. My first idea to make some robust estimation is to use a Bayesian VAR. Problem with bayesian econometrics is that the choice of the prior is at the modeller discretion, but as we already have a theoretical model with a closed structure the prior will be chosen quite naturally. In this context I a thinking about using SSVS methods to select only the relevant variable and then avoid overspecification issue.

The paper is organized as follow, part 2 will be a non-exhaustive literature review about vintage capital, directed technical change and energy economics. Part three will describes the baseline model, without any frictions, and its transitional and asymptotic behavior. In the fourth section I add climate economics and government intervention in opposition to the baseline model. Section 5 is dedicated to the empirical work. And section 6 provides the conclusion.

2 Literature review

This paper is built at the crossroad of two different literature, the first one is on vintage capital, with the seminal paper of Solow et al. (1960) where he first built a model with embodied technical change. This paper was at the heart of the embodiment controversy" in the 60's, and at some extent to the Cambridge-Cambridge controversy about capital aggregation. These different philosophical controversies and technical difficulties linked to these models, made that vintage capital models were not extensively studied at that time, economist having a preference for the second Solow model: Solow (1957) with exogenous growth. A renewal for vintage models came in early 90's with Benhabib and Rustichini (1991) and pursue during this decade with Boucekkine et al. (1997), Jovanovic (1998), Gilchrist and Williams (2000) or the one we use in this paper Krusell (1998). And then, quite recently some papers began to investigate the link between resource management and vintage capital as in Bréchet et al. (2013), Boucekkine et al. (2014) or Azomahou et al. (2012). Because of the replacement problem and embodied technical change, growth is tackled differently in the vintage theory and fits to the study of energy production. The questions raised around power plant are often "which technology we will use ?" and "when we will decommissioning this power plant ?", and I think vintage theory can be of first interest to answer these questions.

The second literature linked to this paper is the one about optimal energy transition, also called directed technical change because the aim is to redirect technology and investment to renewable (or green) sectors. Acemoglu et al. (2012), Acemoglu et al. (2016) or Golosov et al. (2014) are important contributions in this field, these papers look on which policy tools can be used, and at which level, to redirect technology for a cleaner world. Mechanisms to enhance transition are mainly carbon tax and research subsidies. The question of carbon tax is of first importance in this literature and several contributions have been made Li et al. (2016) or Van Der Ploeg and Withagen (2014) among other, with the will, since DICE and RICE models Nordhaus and Boyer (2000), to estimate the social cost of carbon van den Bijgaart et al. (2016) or Nordhaus (2014a) in order to set the correct taxation scheme.

Two others papers are out of the scope of these literature, Mattauch et al. (2015) tackles the same problem of carbon lock-in and how to avoid it but with the learning-by-doing perspective compare to our vintage capital approach. And Lennox and Witajewski-Baltvilks (2017) which is the closest paper to this one, they use Acemoglu et al. (2012) model with embodied technical change *à la* Krusell (1998). To the best of my knowledge this is the only paper about energy transition that features embodied technical change.

3 Model

Based on the paper by Krusell (1998), we build a continuous version of this vintage capital model to study the impact of capital inertia on pollution emissions and dynamic efficiency. Our focus will be on the production sector, modelization of preferences will be kept simple.

3.1 Household

The representative household will maximizes along her lifetime:

$$U = \max \quad \int_0^\infty u(c_t, l_t)e^{-\rho t}dt \tag{1}$$

With ρ the discount factor and c_t the instantaneous consumption and l_t the labor. The household is endowed with L units of time and labor has a negative effect on utility.

For simplicity, $u(c_t, l_t) = ln(c_t) - \chi ln(l_t)$

3.2 Production sector

Production function for the final good is a classical Cobb-Douglas, it will differs in next section with the addition of climate economics.

$$Y_t = L_t^{1-\alpha} K_t^\alpha$$

L_t is labor used in tre prodcution and K_t is an aggregate of "dirty" and "clean" capital, using a CES function.

$$K_t = (K_{ct}^\sigma + K_{dt}^\sigma)^{\frac{1}{\sigma}}$$

K_{ct} and K_{dt} are respectively clean and dirty capital that are produced from a vintage accumulation function *à la* Krusell (1998). Dirty capital will be the variable included into the damage function at the next section, that is the only source of pollutant. The production function can be written as:

$$Y_t = L_t^{1-\alpha} \left(K_{ct}^{\sigma} + K_{dt}^{\sigma}\right)^{\alpha/\sigma} \tag{2}$$

Accumulation of capital is described by these dynamic equations:

$$\dot{K}_{dj} = i_{dt} - \delta K_{dt} \tag{3}$$

$$\dot{K}_{cj} = q_t i_{ct} - \delta K_{ct} \tag{4}$$

The law of motion of capital is the one consider by Greenwood and Jovanovic (2001), i_j is the amount invested in new machines for sector j=c,d. δ is the depreciation rate of capital and q in the clean sector is the efficiency differential between clean and dirty capital. Behind this q there is the idea that the same amount invested will not have the same productive power according to the sector in which investment is made Today it is cheapest to produce energy from fossil fuels, it is formally represented by $q < 1$. However there are more progress in the renewable sector, which reduces the gap between the two sources of energy. Efficiency differential is determined by the following equation:

$$\dot{q}_t = \gamma q_t \tag{5}$$

Final good is used to buy machine in a one-one relation, Household budget constraint is :

$$c_t = y_t - i_{dt} - i_{ct}$$

By imposing some restriction on q_0 we allow existence of both capital at the same time. We capture capital inertia of energy sectors by imposing capital specific hypothesis. Such an assumption is in line with the length of capital life in energy production: if you construct a coal-fired power plant it lives for several decades, with huge scrapping cost. I believe that this inertia hypothesis is one of the explanations for carbon lock-in and we want to modelize it properly and investigate its impact on energetic transition.

3.3 Social planner

In the centralized economy, a social planner will maximize the utility of the representative agent. In the first baseline, the social planner is not necessary because we do not consider any threat to the environment, but in a second time we will introduce environmental externality which we will need to correct.

$$\begin{aligned}
&\max_{l_t, i_{ct}, i_{dt}} \quad \int_0^{+\infty} \left(ln(c_t) - \chi ln(l_t)\right) e^{-\rho t} dt \\
&s.t. \quad (2) - (5) \text{ and} \\
&\qquad\quad c_t = y_t - i_{ct} - i_{dt}
\end{aligned} \tag{6}$$

We solve the Hamiltonian in current value:

$$\begin{aligned}
\mathcal{H} &= ln(Y - i_c - i_d) - \chi ln(L) + P[l^{1-\alpha}\left(K_c^\sigma + K_d^\sigma\right)^{\alpha/\sigma} - Y] \\
&+ P_d[i_d - \delta k_d] + P_c[q i_c - \delta k_c]
\end{aligned}$$

First order conditions give the following:

$$Y = \frac{\chi}{(1-\alpha)P} \tag{7}$$

$$P = P_d = qP_c = \frac{1}{Y - i_c - i_d} \tag{8}$$

First order conditions with respect to state variable give dynamic equations:

$$\frac{\dot{P}_c}{P_c} = \rho + \delta - \alpha q K_c^{\sigma-1} \frac{Y}{K_c^\sigma + K_d^\sigma} \tag{9}$$

$$\frac{\dot{P}_d}{P_d} = \rho + \delta - \alpha K_d^{\sigma-1} \frac{Y}{K_c^\sigma + K_d^\sigma} \tag{10}$$

Using these equilibrium properties we can show that the model is governed by the following dynamic system:

$$\begin{aligned}
\frac{\dot{K}_c}{K_c} &= \frac{qi_c(q, K_c, K_d, P_c)}{K_c} - \delta \\
\frac{\dot{K}_d}{K_d} &= \frac{i_d(q, K_c, K_d, P_c)}{K_d} - \delta \\
\frac{\dot{P}_c}{P_c} &= \rho + \delta - (1-\alpha)K_c^{\sigma-1}\frac{\chi}{(1-\alpha)P_c(K_c^\sigma + K_d^\sigma)}
\end{aligned}$$

As q is a completely exogenous variable that depends on its initial value, dynamic is represented by a three dimensions system with three variables. Behind this apparent simplicity, deriving properties for this model is not straightforward and the full dynamic is difficult to obtain because of the way states equations are built. To avoid computational weight, intermediate computations are not provided.

In order to go further in the analysis I introduce the ratio κ such that

$$\kappa \equiv \frac{K_c^\sigma}{K_c^\sigma + K_d^\sigma}$$

This ratio will be our proxy for energy transition, as one can see the closer from 1 κ will be, the higher the share of clean energy in energy mix will be. Calibration of the model will match with the renewable share in energy mix.

3.4 Steady growth path

We will focus here on the steady growth rate of the economy by assuming that asymptotically every variable grows at a constant rate, which means

$$g_{\dot{P_c}} = g_{\dot{P_d}} = 0$$

Using this for (9) and (10) gives the following results

$$g_{K_c} = \gamma + \frac{\dot{\kappa}}{\kappa} + g_Y \quad (11)$$

$$g_{K_d} = g_Y - \frac{\dot{\kappa}}{\kappa}\frac{\kappa}{1-\kappa} \quad (12)$$

We see that both of the growth rate depends on the output growth and on the clean ratio growth, obviously the technical progress present in the clean sector and κ has a negative impact on dirty capital. Note that structural change occurs in favor of the dirty sector only if $-\frac{\dot{\kappa}}{\kappa}\frac{\kappa}{1-\kappa} > \frac{\dot{\kappa}}{\kappa}$

If we differentiate the expression of κ we obtain the following result

$$\frac{\dot{\kappa}}{\kappa} = \sigma(1-\kappa)(g_{K_c} - g_{K_d})$$

We integrate (11) and (12) in this expression to obtain the rhythm of structural change

$$\frac{\dot{\kappa}}{\kappa} = \frac{\sigma}{1-\sigma}\gamma(1-\kappa) \quad (13)$$

Since the two capital inputs are substitute, we have $\sigma > 0$, the direction of structural change makes no doubt, it is in favor of clean capital, as one may have expected. We find a similar result of structural as in Acemoglu and Guerrieri (2008). This is a two stage transition that occurs, in a first round prices of clean and dirty capital reach their steady growth path ($g_{\dot{P_c}} = g_{\dot{P_d}} = 0$) which allow me to derive 13. And then there is a second round in which capital and GDP are adjusting to reach the Non-Balanced Growth Path (NBGP) described below.

κ growth rate depends on $(1-\kappa)$, it is straightforward that asymptotically κ will tend to 1, and its growth rate will tend to 0. We have $\kappa^* = 1$ as asymptotic condition. When $t \to \infty$ the clean technology will be the dominant one on the energy market, it does not mean that dirty technologies will disappear but they will be non significant in the energy mix. Their existence will be discussed below and is of first importance when it comes to the energy sector. Here we do not consider any climate economics, use of dirty inputs has no consequence on environment and on production facilities. Structural change occurs, production becomes relatively more green but if we continue to buy new dirty inputs, it will not reduce greenhouse gas emissions.

Using the clean capital ratio result, we are able to derive the other growth rates of the economy. The Non Balanced Growth Path (NBGP) is detailed in theorem 1.

Theorem 1 *Under the condition $\sigma > 0$, the set of Non Balanced Growth Rates (NBGR) of this model are as follow:*

$$\begin{aligned} g_Y &= \frac{\alpha\sigma\gamma}{1-\alpha\sigma} \\ g_{K_c} &= \gamma + g_Y \\ g_{K_d} &= g_Y - \frac{\sigma\gamma}{1-\sigma} \\ g_{P_c} &= -g_Y - \gamma \\ g_{P_d} &= -g_Y \\ g_{i_c} &= g_Y \\ g_{i_d} &= g_{K_d} \end{aligned}$$

The first thing to point out is decreasing steady growth rate of dirty capital. When $t \to \infty$ the capital stock of dirty capital is decreasing, ater a long enough period of time, we will be in a 100% green economy. But here, we are not interested in long-term behavior of the model but about short term behavior, because in our actual world we need the transition to speed-up and be partially achieved at 2050 horizon, in 30 years.

3.5 Preliminary simulation

In a very preliminary simulation exercise we will draw the evolution of κ across time. The calibration here is arbitrary and will be more robust in a further version. We set $\alpha = 0.33$ as it is standard in macroeconomics literature. For the elasticity of substitution we will base our calibration on the paper by Papaeorgiou et al. (2017) which demonstrates that dirty and clean inputs are substitutable, elasticity of substitution is larger than one and lower than 2. We will choose an elasticity of 1.5 which leads in our case to $\sigma = 0.33$. And then we need to set the value of γ, the growth rate of technology catch-up. We will use different values for this parameter to observe the role of technology on transition.

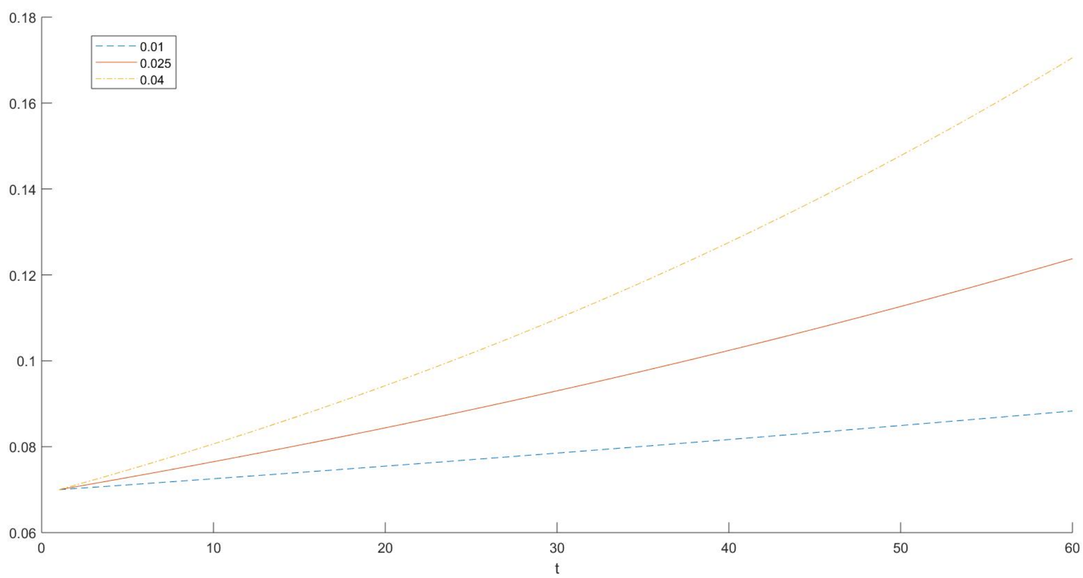


Figure 2: Share of clean technologies in the energy mix for different value of technology differential

The closest graph to figure 1 is the one with $\gamma = 0.04$, when technology increase at a 4% rate each year. And we see that in this configuration the transition is really slow because at horizon 2050 we reach 17% of renewable technologies in the energy mix. Even if it do not reflect the dirty capital stock in absolute terms, it is not very encouraging regarding carbon neutrality objectives.

4 Model with climate economics

For this part of the paper I use exactly the same model but I add a simple damage function to the production function. I will use a damage function inspired by Golosov et al. (2014), but the damage will focus on dirty capital and not on pollution stock. For the sake of simplicity I have decided to focus only on damages from flow pollution instead of stock pollution. It is possible to focus on stock but it will ends-up with 1 more state equation, so 2 mores dimensions and the qualitative results would be more difficult to extract. But as it is still a preliminary version, I keep the possibility to add damages from stock pollution.

4.1 New production function

As mentioned early, use of dirty capital hurts the global production as it is mentioned in the large literature about climate economics and damage functions. As we will only focus on flow pollution, it is the variable K_d that creates pollution emissions. And based on Golosov et al. (2014) I have $1 - d(t) = e^{-\theta K_{dt}}$, with $d(t)$ damages to GDP from pollution. I will consider now the following production function:

$$Y_t = l_t^{1-\alpha} \left(K_{ct}^{\sigma} + K_{dt}^{\sigma}\right)^{\alpha/\sigma} e^{-\theta K_{dt}} \tag{14}$$

This new production function slightly changes optimization results, and using the same methodology than previously we have only one modification for equation (10) that now becomes:

$$\frac{\dot{P}_d}{P_d} = \rho + \delta - \alpha K_d^{\sigma-1} \frac{Y}{K_c^{\sigma} + K_d^{\sigma}} + \theta Y \tag{15}$$

What we see here is the fact that damages θ are taken into account for price path of dirty capital. Pollution damages are internalized into the dynamic equation of dirty capital price, it increases its price and try to discard use of this type of input.

4.2 Steady growth path

I use the same methods than previously to reach the steady growth path, but with the damage function I obtain this formula for clean capital share in the economy:

$$\frac{\dot{\kappa}}{\kappa} = \frac{\gamma\alpha(1-\kappa)}{\frac{\alpha(1-\sigma)}{\sigma} + \theta K_d} + \frac{\theta K_d(g_{K_c} - \gamma)}{\frac{\alpha(1-\sigma)}{\sigma} + \theta K_d} > 0 \tag{16}$$

Regarding equation (11) and the fact that GDP will grow because of the exogenous growth characterized by $\frac{\dot{q}}{q} = \gamma$, we can conclude that (16) is always positive.

Secondly, we can divide this growth rate in two parts. The left part is the one observed in te previous case, because if you set $\theta = 0$, no damage, you have the same result as (13). But with climate economics, it lowers the growth rate because of the negative impact of pollution you can observed on GDP. The right part is new and characterize the incentive to invest in the clean sector, because of pollution. $\theta K_d(g_{K_c} - \gamma)$ is the expression of damages that cannot be corrected by technology only and asks for more investment in the clean sector and a faster transition.

In conclusion, there are two effect that goes in different directions, at this stage of the paper I am not able to say if the incorporation of climate economics would be enough to speed-up energy transition, because of the negative effect on GDP and carbon lock-in starting point in the economy.

As in the previous case we will obtain $\kappa \to 1$, which means that asymptotically $K_d \to 0$. In the long run, dirty capital disappear from the economy and we have only clean capital. In the end, steady growth path is the same than in the previous part because dirty capital stock collapses and there are no more damages. Everything I said about steady growth in the model without climate economics is true for this section too. Our concern is not about long term behavior but about short term transition, and the more important will be to see the differences with the previous model, and on the timing of energetic transition and also the absolute emissions on pollutant in the atmosphere.

Again we are facing this double transition scheme, with this two steps NBGP. But still, transition is subject to low speed because of capital inertia and we have seen that two opposite effects are at stake in this context with climate economics. We now have to rely on a quantitative exercise to determinate the transition speed which will need to be based on the full dynamic because of presence of K_d in (16). Full dynamic and robust calibration would help to conclude if taking into account local pollution speed-up transition.

5 Empirical work

This section is dedicated to the empirical side of the problem. We will try to confront the theoretical results to the data, and ideally, using bayesian estimation, we would be able to simulate the same variables than the theoretical model.

The main problem here is we have not a lot of observations for each variable, we are talking about annual data with quite recent concerns, we will have at most 50 observations per variable.

Using the "power plant tracker" from EnerData we aim to study the evolution of energy transition. To do so, the dataset gives access to the number of power plant with their year of commissioning and decommissioning, the energy they use and how much power they develop. Once with have separate each plant in 3 categories, renewable, nuclear and non renewable, we can extract the ratio of renewable weight in the new installed capacities, each year. It will be our proxy for accomplishment of energy transition.

The research question aims at studying the impact of capital inertia on the timing of energy transition. As one may know, capital units in energy sector are long living, between 40 and 50 years in mean for renewable, fossil or nuclear power plants. In this context, construction of coal fired power plants today will push forward the realization of carbon reduction objectives because of its lifetime and of the cost to stop it, both the opportunity cost of non producing energy and the non cover of the huge fixed costs.

This question has already been studied in the theoretical model presented before, here we will confront our theoretical findings to the data.

5.1 Data

Enerdata power plant tracker, IEA government budget in energy R&D, patents data as private R&D, fuel prices.

I need data about installed capacity to track the effect of investment, of fossil fuel prices and their persistence effect on clean technology ratio.

5.2 Model selection

The main issue for this econometric exercise is the low amount of data and the number of parameters to estimate. As mentioned there are a lot of frictions in the energy sector, ergodicity should be of high level and we will face problem of overparametrization. To deal with it, I can use SSVS or LASSO methods to shrink model dimension and allow to produce robust estimations.

Selection of the prior would be obvious regarding the structural model we have from theoretical part. And there is still a lot to be done in this empirical part.

5.3 Estimation

5.4 Forecast

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *American economic review*, 102(1):131–66.

Acemoglu, D., Akcigit, U., Hanley, D., and Kerr, W. (2016). Transition to clean technology. *Journal of Political Economy*, 124(1):52–104.

Acemoglu, D. and Guerrieri, V. (2008). Capital deepening and nonbalanced economic growth. *Journal of political Economy*, 116(3):467–498.

Arrow, K. J. (1971). The economic implications of learning by doing. In *Readings in the Theory of Growth*, pages 131–149. Springer.

Azomahou, T. T., Boucekkine, R., and Nguyen-Van, P. (2012). Vintage capital and the diffusion of clean technologies. *International Journal of Economic Theory*, 8(3):277–300.

Benhabib, J. and Rustichini, A. (1991). Vintage capital, investment, and growth. *Journal of economic theory*, 55(2):323–339.

Boucekkine, R., Germain, M., and Licandro, O. (1997). Replacement echoes in the vintage capital growth model. *Journal of economic theory*, 74(2):333–348.

Boucekkine, R., Hritonenko, N., and Yatsenko, Y. (2014). Optimal investment in heterogeneous capital and technology under restricted natural resource. *Journal of Optimization Theory and Applications*, 163(1):310–331.

Bréchet, T., Hritonenko, N., and Yatsenko, Y. (2013). Adaptation and mitigation in long-term climate policy. *Environmental and Resource Economics*, 55(2):217–243.

Gilchrist, S. and Williams, J. C. (2000). Putty-clay and investment: a business cycle analysis. *Journal of Political Economy*, 108(5):928–960.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Graff Zivin, J. and Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review*, 102(7):3652–73.

Greenwood, J. and Jovanovic, B. (2001). Accounting for growth. In *New developments in productivity analysis*, pages 179–224. University of Chicago Press.

Jovanovic, B. (1998). Vintage capital and inequality. *NBER working paper*.

Krusell, P. (1998). Investment-specific r and d and the decline in the relative price of capital. *Journal of Economic Growth*, 3(2):131–141.

Lennox, J. A. and Witajewski-Baltvilks, J. (2017). Directed technical change with capital-embodied technologies: Implications for climate policy. *Energy Economics*, 67:400–409.

Li, X., Narajabad, B., and Temzelides, T. (2016). Robust dynamic energy use and climate change. *Quantitative Economics*, 7(3):821–857.

Mattauch, L., Creutzig, F., and Edenhofer, O. (2015). Avoiding carbon lock-in: policy options for advancing structural change. *Economic Modelling*, 50:49–63.

Nordhaus, W. (2014a). Estimates of the social cost of carbon: concepts and results from the dice-2013r model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, 1(1/2):273–312.

Nordhaus, W. D. (2014b). *A question of balance: Weighing the options on global warming policies*. Yale University Press.

Nordhaus, W. D. and Boyer, J. (2000). *Warming the world: economic models of global warming*. MIT press.

Papageorgiou, C., Saam, M., and Schulte, P. (2017). Substitution between clean and dirty energy inputs: A macroeconomic perspective. *Review of Economics and Statistics*, 99(2):281–290.

Parente, S. L. (1994). Technology adoption, learning-by-doing, and economic growth. *Journal of economic theory*, 63(2):346–369.

Pindyck, R. S. (2017). The use and misuse of models for climate policy. *Review of Environmental Economics and Policy*, 11(1):100–114.

Solow, R. M. (1957). Technical change and the aggregate production function. *The review of Economics and Statistics*, pages 312–320.

Solow, R. M. et al. (1960). Investment and technical progress. *Mathematical methods in the social sciences*, 1:48–93.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy policy*, 28(12):817–830.

van den Bijgaart, I., Gerlagh, R., and Liski, M. (2016). A simple formula for the social cost of carbon. *Journal of Environmental Economics and Management*, 77:75–94.

Van Der Ploeg, F. and Withagen, C. (2014). Growth, renewables, and the optimal carbon tax. *International Economic Review*, 55(1):283–311.