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Abstract:
The major claim in Acemoglu, Aghion, Bursztyn & Hemous (2012) (AABH) is that subsidies for research and development of clean technologies are more important than carbon taxes when dealing with climate change. However, they – unconventionally – assume that a patent only lasts for one period. In this note we introduce long-lived patents into the AABH model. This makes the role of a research subsidy for clean technologies in AABH far less crucial and reestablishes the role of the carbon tax. This is good news as it is far easier to tax emissions than to pick the right technologies to subsidize.

Keywords: Environment, directed technological change, innovation policy

JEL classification: O30, O31, O33

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Sammendrag

Miljøet og forskning på rene teknologier

Artikkelen "The Environment and Directed Technical Change" av D. Acemoglu, , P. Aghion, L. Bursztyn, and D. Hemous som ble publisert i American Economic Review i år har fått mye oppmerksomhet. Utgangspunktet for artikkelen er at energiteknologier kan inndeles i to familier; rene teknologier og skitne teknologier. Forfatterne forklarer ikke dette nærmer, men vi tenker oss at skitne teknologier består av teknologier for olje-, kull- og gassutvinning, forbrenningsmotorer, kull- og gasskraft etc. Videre at rene teknologier er fornybar energi, hydrogen eller elektriske biler samt nye måter å organisere elektrisitetsmarkedet på som gjør det lettere med fornybar kraft.

Hensikten med å dele teknologier inn i familier er å få frem at teknologiutviklingen er styrt av historien, og at forskningen i dag har en tendens til å fokusere på skitne teknologier bare fordi man tidligere har forsket mye på det. På den annen side vil fortsatt fokus på skitne teknologier medføre høyere og høyere utslipp av klimagasser noe som i artikkelen "The Environment and Directed Technical Change" vil føre til katastrofe.

For å unngå katastrofe må man flytte all forskning fra den skitne teknologifamilien til den rene teknologifamilien. Dette er det vanskelig å oppnå ved hjelp av et kvotemarked eller en utslippsskatt alene. I følge Acemoglu og hans medforfattere må prisen på utslipp allerede i dag settes svært høyt noe som innebærer store kostnader på kort sikt. Forfatterne anbefaler derfor heller at man fokuserer på forskningssubsidier dvs. man innfører så store subsidier til forskning på ren teknologi at all forskning på skitten teknologi opphører. Økonomien vil da over tid kunne dreie seg bort fra bruk av skitne teknologier selv om skatten på utslipp er lav.

Vi synes tilnærmingen i "The Environment and Directed Technical Change" er meget interessant. I denne artikkelen studerer vi modellen i artikkelen nærmere. Spesielt er vi interessert i hvor avgjørende en av forutsetningene i den økonomiske modellen er. I modellen er det slik at forskere velger om de vil forske på rene eller skitne teknologier. Avgjørende for deres valg er hvor mye de kan forvente å tjene dersom de får en ny patent. Imidlertid varer patenter i modellen bare i 5 år. Dette avviker fra hvordan det er i andre modeller med patenter. Vi erstatter derfor forutsetningen om femårige patenter med en forutsetning om at forskerne beholder inntektene fra patentet så lenge ingen klarer å utvikle et bedre patent.

Dette endrer hovedresultatet i artikkelen. Når forskerne har forhåpninger om å kunne tjene på patentet lenger enn i fem år, så vil også fremtidige priser på utslipp spille en rolle. En moderat pris på utslipp i dag som stiger i fremtiden kan derfor være nok til å skifte all forskning til rene teknologier. Dette er gode nyheter. Det er grunn til å tro at å satse på forskningssubsidier alene for å løse klimaproblemet er mer komplisert enn i artikkelen til Acemoglu og hans medforfattere. For det første er det ingen kostnader ved å subsidiere forskning og utvikling. For det andre vet myndighetene hvilke rene teknologier de bør satse på. En utslippsskatt som er riktig satt løser langt på vei begge disse problemene; den gir incentiver til å forske på rene teknologier uten at staten må ut med store summer, og den favoriserer de beste rene teknologiene uten at staten trenger å velge.

1 Introduction

The major claim in Acemoglu, Aghion, Bursztyn & Hemous (2012) (AABH) is that subsidies for research and development of clean technologies are crucial for tackling climate change in a sensible way. Moreover, the carbon tax plays a minor role as directed technological change moves the economy away from dirty inputs.

It is well known that in an economy with several market failures the first-best policy is to have a policy targeting each of the market failures. Several papers have emphasized that, in the presence of environmental externalities and knowledge externalities in R&D, it is socially optimal to have a set of policy instruments, e.g. a tax on carbon emissions and a subsidy for R&D (Goulder & Schneider, 1999; Rosendahl, 2004; Gillingham, Newell & Pizer, 2008; Fischer & Newell, 2008). AABH follow this tradition by showing that the social optimum can be achieved with a carbon tax together with a subsidy for clean innovation. However, AABH argue that the two instruments are necessary because '*the subsidy deals with future environmental externalities by directing innovation towards the clean sector, whereas the carbon tax deals more directly with the current environmental externality by reducing production of the dirty input'*.

This statement is at odds with traditional economic thinking: The carbon tax should correct for both current and future environmental externalities, while a subsidy for R&D should correct for knowledge market failures (see, e.g. Popp, Newell & Jaffe, 2010). Furthermore, several studies point out that the most cost-efficient single policy to reduce emissions is a policy that directly targets emissions (Schneider & Goulder, 1997; Nordhaus, 2002; Popp, 2006). However, carbon taxes will not effectively induce clean innovation if the patent life is short, since future taxes matter little for today's investment decisions in this context. In a recent paper, Gerlagh, Kverndokk & Rosendahl (2011) show that optimal R&D policy is linked with carbon taxes when patent lifetime is finite since R&D is biased towards technologies that pay back within the patent lifetime.

In their analysis AABH make an unconventional assumption with regard to the patent lifetime, i.e. that a patent only lasts for one period.[1] We argue that patents should not expire after one period in a model that attempts to shed light on R&D subsidies and carbon taxes. Firstly, following the TRIPS agreement, patent protection is stronger than AABH assume in most economies, e.g. in the US the statutory

[1] A period is five years in AABH's simulations.

term is 20 years (Chu, 2011).[2] Second, in the literature on economic growth, patents typically have an infinite patent lifetime (see Barro & Sala-i-Martin, 2004; Jones, 2002).[3] In particular, this is the standard assumption in models of directed technological change (see Acemoglu, 2002; 2009). Lastly, future carbon taxes change the relative value of clean versus dirty technologies and may influence R&D decisions.

In this note we introduce long-lived patents into the AABH model. Our research question is to what extent this makes the role of a research subsidy for clean technologies in AABH less crucial. The answer is clearly to a great extent, as in the most likely of AABH scenarios, changing this assumption renders the R&D subsidy superfluous. With high elasticity of substitution between clean and dirty inputs – which, below, we argue is reasonable – the optimal carbon tax path gives a sufficient signal to move the economy away from dirty inputs.

The paper is organized as follows. Section 2 presents our change to AABH's model, while the simulation results are given in Section 3. Section 4 provides a conclusion.

2 Illustration of long-lived versus one-period patents

In this section we illustrate the difference between our model and AABH's model. The full AABH model is presented in the appendix. The per period profit π_{jit} of holding a patent on machine type i of quality A_{jit} in sector $j \in \{c, d\}$ is given by:

$$\pi_{jit} = \bar{\alpha}(p_{jt} - \tau_{jt})^{\frac{1}{1-\alpha}} L_{jt} A_{jit},$$

where $\bar{\alpha}$ is a parameter, p_{jt} is the price of intermediate inputs of type j at time t, τ_{jt} is the emission tax on intermediate inputs of type j at time t, L_{jt} is the labor effort going into producing intermediate inputs of type j at time t, and finally A_{jit} is the productivity of machine i of type j at time t.

When a new innovation is made in machine type i, A_{jit} bumps up to $(1 + \gamma)A_{jit}$, where $(1 + \gamma)$ is the quality step. A scientist cannot target a specific machine type; instead a scientist is randomly allocated to a machine type in the specific sector. A scientist engaged in innovation in

[2] The World Trade Organization's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) establishes that all member countries must provide a minimum level of intellectual property protection (patent protection must be available for inventions for at least 20 years).

[3] There are several recent papers that incorporate finite patent length and analyze patent policy in growth models (Futagami and Iwaisako, 2007; Mosel 2011; Acemoglu and Akcigit, 2012). However, a patent length of one period is not the usual choice in these models.

sector j then expects a quality $(1+\gamma)A_{jt-1}$ upon successful innovation, where A_{jt-1} is the average quality in j. The average machine quality is given by $A_{jt} \equiv \int_0^1 A_{jit} di$.

The probability of a successful innovation is η_j. Thus, in AABH the expected profit of an innovator entering sector j is:

$$E\left[\pi_{jt}\right] = \eta_j \bar{\alpha}(p_{jt} - \tau_{jt})^{\frac{1}{1-\alpha}} L_{jt}(1+\gamma)A_{jt-1}. \tag{1}$$

Note that only the current emission tax τ_{jf} enters in (1). Note also that the average machine quality A_{jt-1} plays a crucial role. Hence, if A_{dt} starts off much higher than A_{ct}, innovators will have tendency to choose sector d.

In AABH patents expire after one period. We assume that the patent lifetime is infinite. However, at each point in time there is a probability that someone successfully invents a better quality and replaces the current machine type. Denote this replacement rate z_{jt}. The expected discounted profits Π_{jt} for a scientist entering sector j at time t is then:

$$\Pi_{jt} = \eta_j \bar{\alpha}(1+\gamma)A_{jt-1} \sum_{k=0}^{\infty} \prod_{v=1}^{k} \left(\frac{1 - z_{j,t+v}}{1 + r_{t+v}} \right) \left((p_{j,t+k} - \tau_{j,t+k})^{\frac{1}{1-\alpha}} L_{j,t+k} \right), \tag{2}$$

where r_t is the discount rate. Note that in (2) the future tax rates $\tau_{j,t+k}$ are included in the expression for the expected profit of the innovator. This may have significant implications for policy. Let's say that the current per period profits are greater in the dirty sector and that the carbon tax rate rises over a number of future periods. The tax increases the value of clean machines relative to dirty machines over time. Scientists do not take into account the effect of future taxes if patents last for one period and they engage in dirty innovations. On the other hand, if patents are long-lived, scientists take into account that the value of clean machines improves over time. A switch to clean innovation may then be induced today without the need for innovation subsidies.

3 Numerical analysis

We use the same parameters as AABH: machine share $\alpha = 1/3$, probability of a successful innovation is equal to 0.02 (per annum) for both sectors, and quality step $\gamma = 1$ (for parameters that do not directly enter the R&D sector, see AABH Section V). As in AABH, the length of each period is five years. We have simulated 60 periods on all four of AABH's scenarios. In this note we only present results for the high elasticity - high discount rate case, i.e. $\varepsilon = 10$ and $\rho = 0.015$. We see dirty technologies as being coal power for electricity, gasoline for transport and oil for heating, while green technologies are hydro, solar and wind for electricity, electric cars for transport and energy storage and biofuels for heating. Clearly, the green technologies are more costly today; however they provide nearly identical services, thus warranting a high elasticity of substitution.[4]

The initial productivity A_{d0} and A_{c0} are calibrated as in AABH in each scenario. For a given allocation of scientists, the entire paths of the development of the productivities are then given. An optimal carbon tax path is calculated for any given allocation of scientists. By doing this repeatedly, different allocations of scientists can then be compared in order to find the optimal combination of the carbon tax path and the allocation of scientists.

The combination of an optimal carbon tax path and an optimal allocation of scientists is not necessarily an equilibrium of the model. That is, we do not have an equilibrium if, for any period, scientists could do better by switching sector. A subsidy to R&D is then necessary to implement the optimal combination of the carbon tax and the optimal allocation of scientists. Note that for the optimal allocation of scientists a subsidy for R&D can be added without affecting productivity levels, production or consumption of clean and dirty goods since the number of scientists is given.

The replacement rate z_{jt} is crucial with perpetual patents. In each period all scientist either work in the clean sector or in the dirty sector. Thus, for the sector in which all scientists work, the replacement rate must be equal to the probability of successful innovation. Moreover, for the other sector the risk must be zero since none of the scientists work in the sector.[5]

3.1 Results

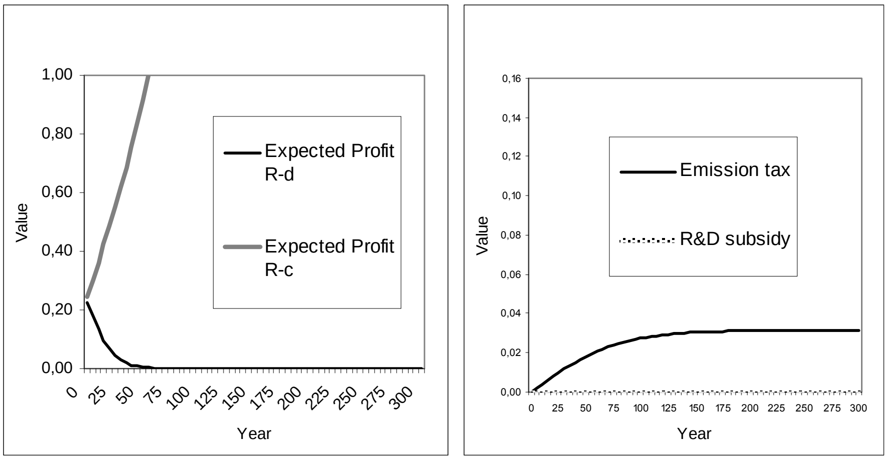
First, we find as did AABH, that without regulation all scientists stay in the dirty sector and a climate disaster happens. By implementing carbon tax, it is possible to avoid disaster – keeping all the scientists in the dirty sector; however, this is not an equilibrium. In all periods, scientists would like to switch to the clean sector. As in AABH, welfare is optimized with all scientists in the clean sector in all periods. This configuration is in fact an equilibrium without any R&D subsidy. This

[4]For instance, the electric car Tesla Model S can run more than 300 miles on one charge, carries 7 passengers and accelerates from 0-60 mph in 5 seconds.

[5]Let η be the probability of success over five periods. The per annum probability in AABH is 0.02. Thus, over five periods the probability of success is given by $\eta = P(X \geq 1) = 1 - P(X < 1) = 0.096$ (by using the binomial cdf). Implicitly we assume that innovators can only have one success in each period.

can be seen from the following figures:

Figure 1: Optimal policies with long-lived patents



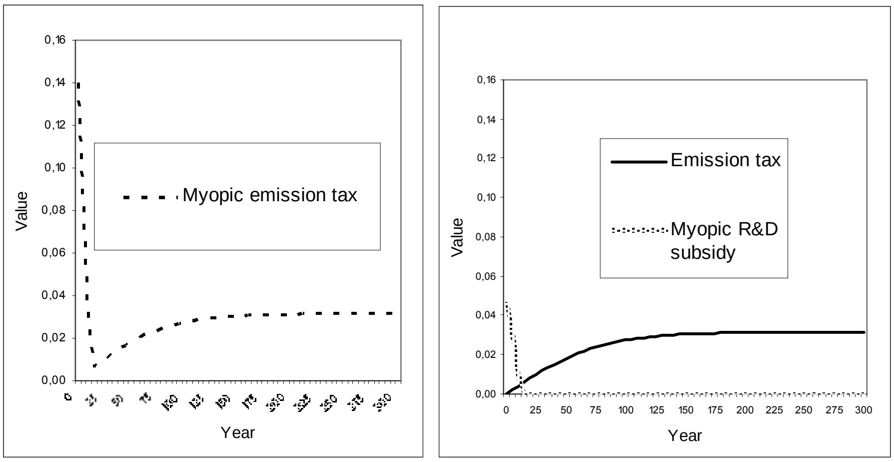
In the figure to the left we have drawn the expected profit of entering the two R&D sectors, given the optimal carbon tax.[6] As we can see it is always more profitable to enter the clean sector. Thus, there is no need for an R&D subsidy since having all scientists in the clean sector is desirable. Clearly, this result does not change with a lower discount rate ρ: It would only make future profits from an innovation more profitable.

In the figure to the right we can see that, in the beginning, the carbon tax is increasing before it flattens out after 150 years. With perpetual patents (that only are replaced with some probability), the future higher tax rates affect current profitability of innovations. It is this effect that renders the R&D subsidy superfluous. As we can see from the figure, the R&D subsidy is zero for all periods.

It is interesting to compare the above results with those of the original AABH model in which researchers are myopic, that is, they only consider the current period. We get the following results from our simulation model with one-period patents:

[6] R-d = Research dirty and R-c = Research clean

Figure 2: Optimal policies with one-period patents



In the figure to the left we have drawn the carbon tax for the case with one-period patents and no R&D subsidy. As in AABH, the carbon tax then has to be very high initially in order to move scientists to the clean sector. Finally, in the figure to the right we have drawn the carbon tax and the R&D subsidies for the case with one-period patents. As in AABH, there is a temporary subsidy for clean R&D. When the clean technologies are sufficiently advanced, the subsidy is no longer necessary. Furthermore, the carbon tax is as in Figure 1 since all scientists are in the clean R&D sector in both cases.

3.2 Discussion

The result that no R&D subsidy is necessary is not a general result. There are two market failures in the research sectors. One of them is knowledge spillovers, that is, current research makes future research more profitable. Remember that any innovation increases the average productivity with a given percentage. Thus, the higher the average productivity, the higher the absolute increase in productivity.

The other reason why patent owners do not get paid the social value of their innovation is due to the risk of losing the income from the patent. This would not have been a problem if the risk was equal between the sectors, since the number of scientists is given. However, there is only a risk of losing the income from a patent in the sector in which all scientists work. This tends to make the difference between the social value of an innovation and the private value of an innovation larger in the clean sector as long as it is desirable from a welfare point of view that all scientists work in the clean sector.

In the high elasticity of substitution scenario this effect was not strong enough to outweigh the profit opportunities in the clean sector created by the carbon tax. However, in the low elasticity of substitution scenario of AABH ($\varepsilon = 3$) the calibration procedure requires the initial A_{d0} to be much bigger than the initial A_{c0}. Thus, in the low elasticity of substitution scenario the clean technology starts with a greater disadvantage.

Our simulations then show that the government has to use a temporary R&D subsidy in order to implement the optimal combination of the carbon tax path and the optimal allocation of scientists. However, note that the subsidy deals with the market failure stemming from the risk of losing the patent. The future environmental externalities are dealt with by the future carbon tax which also contributes to redirecting scientists to the clean sector.

4 Conclusion

AABH find that it is always optimal to use an R&D subsidy to redirect R&D from dirty technologies towards clean technologies in order to tackle climate change in the most sensible way. Their clear cut result rests on an unconventional assumption: patents last for only one period. We relax this assumption and let R&D decisions depend on the present discounted value of the future income stream from an invention. This makes the role of a research subsidy for clean technologies in AABH far less crucial and reestablishes the role of the carbon tax. Removing the short-lived patent assumption renders the R&D subsidy in AABHs model superfluous in the most likely scenarios. This is good news, as it is far easier to tax emissions than to pick the right technologies to subsidize.

There are many more aspects of the AABH model that could be discussed and that will likely affect the desirability of R&D subsidies for the clean sector: There is no free entry to R&D, there is no stepping-on-toes effect which facilitates a corner solution for the R&D sector, and there are no spillovers between the two classes of technologies. In a model which includes these aspects we would be surprised if R&D subsidies had no role. Our main concern with AABH is not that they find that R&D subsidies are necessary, but that they downplay the role of a carbon tax. In our opinion, setting a correct price on carbon emissions now and in the future should still be an important priority of policy makers.

References

Acemoglu, D. 2002. Directed Technical Change. *Review of Economic Studies*, 69, 781-809.

Acemoglu, D. 2009. *Introduction to Modern Economic Growth.* Princeton University Press.

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous. 2012. The Environment and Directed Technical Change. *American Economic Review* 102, 131-166.

Acemoglu, D. and U. Akcigit. 2012. Intellectual Property Rights Policy, Competition and Innovation. *Journal of the European Economic Association* 10, 1–42.

Barro, R.J. and X. Sala-i-Martin. 2004. *Economic Growth.* MIT Press.

Chu, A.C. 2011. The welfare cost of one-size-fits-all patent protection. *Journal of Economic Dynamics & Control* 35, 876-890.

Futagami, K. and T. Iwaisako. 2007. Dynamic analysis of patent policy in an endogenous growth model. *Journal of Economic Theory* 132, 306-334.

Fischer, C. and R.G. Newell. 2008. Environmental and Technology Policies for Climate Mitigation. *Journal of Environmental Economics and Management* 55, 142-162.

Gerlagh, R, S. Kverndokk & K.E. Rosendahl. 2011. Timing of Environmental R&D Policy, *CREE Working Paper* 2/2011.

Gillingham, K., R.G. Newell, and W.A.Pizer. 2008. Modeling Endogenous technological Change for Climate Policy Analysis, *Energy Economics* 30, 2734-2753.

Goulder, L.H. and S.H. Schneider. 1999. Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics* 21, 211–253.

Jones, C.I. 2002. *Introduction to Economic Growth.* W.W. Norton.

Nordhaus, W.D. 2002. Modeling Induced Innovation in Climate Change Policy. In *Technological Change and the Environment.* Resources for the Future Press.

Mosel, M. 2011. Competition, imitation, and R&D productivity in a growth model with industry specific patent protection. *Review of Law and Economics* 7, 601–652.

Popp, D., R.G. Newell and A.B. Jaffe. 2010. Chapter 21 – Energy, the Environment, and Technological Change. In *Handbook of the Economics of Innovation* (eds B.H. Hall & N. Rosenberg).

Popp, D. 2006. R&D subsidies and climate policy: Is there a "free lunch"? *Climatic Change* 77, 311-341.

Rosendahl, K.E. 2004. Cost-effective environmental policy: implications of induced technological change. *Journal of Environmental Economics and Management*, 48, 1099–1121.

Schneider, S.H. and L.H. Goulder. 1997. Achieving low-cost emissions targets. *Nature* 389, 13–14.

Appendix

The model we use is presented in this appendix. We keep the presentation short as our model is identical to AABH except for the patent lifetime. The tax on carbon emission is paid by the producers of the dirty input to final goods production.

Consumers and the environment

A representative household solves

$$\begin{array}{c} \max \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \left(\frac{[C_t * \phi(S_t)]^{1-\sigma}}{1-\sigma} \right) \\ s.t \qquad C_t = W_t, \end{array} \tag{3}$$

where ρ is the subjective discount rate, σ is the intertemporal rate of substitution, C_t is consumption, S_t is the environmental quality, $\phi(S_t)$ is the costs of environmental degradation, and W_t is per-period income (from labor, profits, and net transfers). Households use all per-period income for consumption, i.e. there is no intertemporal trade-off in consumption.

The cost of degradation function is given by

$$\phi(S_t) = \frac{(\Delta_{distaster} - \Delta(S_t))^{\lambda} - \lambda \Delta_{distaster}^{\lambda-1}(\Delta_{distaster} - \Delta(S_t))}{(1-\lambda)\Delta_{distaster}^{\lambda}}, \tag{4}$$

where $\Delta(S_t)$ is the temperature increase relative to preindustrial levels, $\Delta_{disaster}$ is the critical temperature increase which leads to disaster, and λ is a calibration parameter.

The temperature increase given by CO_2 in the atmosphere

$$\Delta(C_{co_2}) = 3\log_2(C_{co_2}/280) \tag{5}$$

where C_{co_2} is the concentration in parts per million (ppm). Moreover, AABH defines the critical level of temperature increase as $\Delta_{distaster} = 6$. This amounts to $C_{CO_2,disaster} = 1120$ ppm. The environmental quality is related to CO_2 in the following way:

$$S_t = 1120 - \max\{C_{co_2}, 280\},$$

which given that $C_{co_2} \geq 280$ can be rearranged to $C_{co_2} = 1120 - S_t$. Then, we can rearrange the temperature increase:

$$\Delta(S_t) = 3\log_2((1120 - S_t)/280).$$

Finally, the law of motion for the quality of the environment is given by

$$S_{t+1} = -\xi Y_{dt} + (1+\delta) S_t, \tag{6}$$

whenever the right hand side of (6) is in the range $(0, 1120)$. Whenever the right hand side of (6) is negative, $S_{t+1} = 0$. The parameter ξ denotes the rate of degradation stemming from emissions from the dirty input Y_{dt}, while δ is the rate of regeneration.

Final goods

Production function of the unique final good (FG) :

$$Y_t = \left(Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{7}$$

where Y_{ct} and Y_{dt} is the input of clean and dirty inputs, respectively, and ε is the elasticity of substitution. The price of the FG is normalized to 1 so that

$$[p_{ct}^{1-\varepsilon} + p_{dt}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} = 1, \tag{8}$$

where p_{ct} and p_{dt} are the prices of the clean and dirty input, respectively.

Production of inputs to FG with carbon tax

Production function of clean and dirty inputs in sector $j \in \{c, d\}$:

$$Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di \tag{9}$$

where $\alpha \in (0,1)$, L_{jt} is labor use, A_{ijt} is the quality of machine type i, x_{jit} is the input of machine type i, and the number of machine types is 1.

The input firm's problem is:

$$\max_{L_{jt}, x_{jit}} \left\{ (p_{jt} - \tau_{jt}) L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di - w_t L_{jt} - \int_0^1 p_{jit} x_{jit} di \right\},$$

where τ_{dt} is the carbon tax ($\tau_{ct} = 0$) and p_{jit} is the price of machine type i in sector $j \in \{c, d\}$. The demand for machine type i is then

$$x_{jit} = \left(\frac{(p_{jt} - \tau_{jt})\alpha}{p_{jit}} \right)^{\frac{1}{1-\alpha}} L_{jt} A_{jit}. \tag{10}$$

Production of machines

The producers of machines are monopolists and solve

$$\max_{pijt} [(p_{ijt} - \psi(1-s)) x_{ijt}], \tag{11}$$

taking (10) as given, where ψ is the cost, and s is the subsidy rate to correct for the static monopoly distortion. Costs are normalized to $\psi = \alpha^2$ and the optimal subsidy rate that gives price equal to marginal cost is $s = 1 - \alpha$. Then, solving (11) gives the machine price $p_{ijt} = \alpha^2$. The demand for machine type i in sector j is then given by

$$x_{jit} = (\frac{p_{jt} - \tau_{jt}}{\alpha})^{\frac{1}{1-\alpha}} L_{jt} A_{jit}. \tag{12}$$

Innovation

The innovation sector is explained in the main text. The number of scientist is given and normalized to a measure of 1.

The per period profit of holding a patent on machine type i in sector j is given by

$$\pi_{jit} = (1-\alpha)\alpha^2 x_{jit} = (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} (p_{jt} - \tau_{jt})^{\frac{1}{1-\alpha}} L_{jt} A_{jit},$$

as long as there are no other machines of type i with higher quality. The expected discounted profit of a scientist engaged in research in sector j is then

$$\Pi_{jt} = \eta_j (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} (1+\gamma) A_{jt-1} \sum_{k=0}^{\infty} \prod_{v=1}^{k} \left(\frac{1 - z_{j,t+v}}{1 + r_{t+v}} \right) \left((p_{j,t+k} - \tau_{j,t+k})^{\frac{1}{1-\alpha}} L_{j,t+k} \right). \tag{13}$$

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