Società italiana di economia pubblica

XXI CONFERENZA

PUBLIC CHOICE E POLITICAL ECONOMY
I fondamenti positivi della teoria di finanza pubblica

Pavia. Università. 24-25 settembre 2009

TECHNOLOGICAL LOCK-IN AND THE SHAPING OF ENVIRONMENTAL POLICY

LAURA CASTELLUCCI, ALESSIO D'AMATO, ANNALISA CASTELLI

Provisional - Not for quotation

Technological lock-in and the shaping of environmental policy.

Laura Castellucci — Università di Roma "Tor Vergata"

Alessio D'Amato[1] — Università di Roma "Tor Vergata"

Annalisa Castelli — Università di Roma "Tor Vergata"

[1]Corresponding author. SEFEMEQ Department - Faculty of Economics - Via Columbia, 2 - 00133 Roma, Itally - Tel. +39 06 72595927 - Fax +39 06 2040219 - Email: damato@economia.uniroma2.it

Abstract

The aim of the paper is to outline the best environmental policy design when the prevention and/ or removal of the socially harmful technology lock-in effect is the target. Relying on Arthur [1] seminal paper, we point out that the well established result according to which incentive based instruments are to be preferred to the command and control ones, may be contradicted and even subverted when technology adoption is a concern. Command and control policies might be the only instrument ensuring the economy not to be locked-in on an unsustainable path. Our setting suggests a reason why environmental policy could be ill-designed when the "chance" for lock-in to take place is overlooked and draws attention on the importance (indeed crucial relevance) of knowing the "true" ranking among technologies for avoiding the dominance of an inferior one.

1 Introduction

Increasing returns to adopting a particular technology or system can be crucial in determining technology "lock-in" phenomena. Lock-in implies that, once led down a particular technological path, the barriers to switching to another one, even if more efficient, may be prohibitive.

The chance for lock-in to take place generates a two ways linkage between technical progress and the environment. Indeed, on one side technical change strongly affects the way economic activities impact natural resources quantity and quality. On the other hand, as Kneese and Schulze [8] underline, in the long run environmental policy is crucial in determining the state of pollution reducing technology and, therefore, is one of the most important sources of success or failure in environmental protection. The complexity of technology/environment relationships has been increasingly debated as industrial economies have become locked-into fossil fuel-based energy production through path dependent processes driven by technological and institutional increasing returns to scale.

The aim of this paper is to move a first step towards a full investigation of how environmental policy have to be designed when the need to avoid socially harmful lock in effects and to boost sustainable technical progress in the presence of increasing returns in technology adoption, is the main concern.

Our work builds on two strands of literature, one concerning the modeling of technological lock-in and the other addressing environmental policy effects, namely towards Research and Development and technology adoption (Jaffe et al. [5]). Our starting point is borrowed from papers in which technological lock-in is seen as determined by network externalities, learning by using and more generally, by increasing returns from the adoption of technologies. The bulk of these papers concludes that when competing technologies operate under dynamic increasing returns, an inferior technology will end up dominating the market. As Unruh ([12] and [11]) and Cowan [3] suggest, this analysis can be used to understand the case of fossil fuels energy systems as well as the history of nuclear power technology. The underlying driving forces are extremely clear and fully accepted in the literature: as a complex technology is increasingly adopted, the net benefits by adopting it increase, due to experience, improvements etc.... When two or more increasing-return technologies compete for a market of potential adopters, apparently insignificant events may by chance determine an initial advantage in adoption for one of them. Such technology will then improve more than the others so that a wider proportion of potential users will actually adopt it. It may therefore become further adopted and further improved. Thus a technology that gains an early lead in adoption may eventually "corner the market" of potential adopters with the other technologies becoming locked out. The events that determine the initial lead might also have institutional relevance. For example, a particularly powerful lobbying group might use resources in pushing the authorities to subsidize a desired technology, even if that technology is not the most efficient, just to gain short run rents. Even a static rent seeking behaviour might, therefore, be the starting point of lock-in, when increasing returns to adoption prevail[1].

The full investigation of lock-in phenomena implies the need to examine how historical events cumulate to drive the process towards a given market share outcome. Under this respect, we build on the model developed in the seminal paper by Arthur [1]. The author shows that the presence of increasing returns might lead to multiple equilibria and to the non predictability of the outcome: the knowledge that the economy will end up locked into a given technological path is not enough to fully characterize such path and, therefore, to assess the related potential efficiency gains or losses. In other words, increasing returns might act to magnify "small" events as adoptions take place, so that ex ante knowledge of adopters' preferences and the technologies' possibilities may not

[1] We would like to thank our colleague Stefano Gorini for suggesting this powerful idea. We are actually working with him in the attempt of modeling it.

suffice to predict the market outcome. Further, increasing returns might drive the adoption process into developing a technology that has inferior long run performance.

The need to restore efficiency in the presence of environmental externalities has been the main focus of environmental policy since its very beginning (see, for example, Baumol and Oates [2] and Roberts and Spence [10]). Since then, the available environmental policy instruments have been thoroughly evaluated in terms of cost effectiveness, efficiency in the presence of uncertainty and asymmetric information, incentive to technical progress. To the best of our knowledge a less amount of analysis has instead focused on the problem of technology lock-in

In fact, Kline [7] underlines how standard environmental policy, by adopting an *ex post* approach, ignores the chance for technological lock-in to take place, but more specifically, the chance to move "sideways" from one technological path to another, is neglected and only incremental adoptions are allowed for. On the other hand, no one can deny that lock-in phenomena are in place with respect to many environmental problems (the energy related ones being the most striking) and that such problems are getting more complex given the considerable uncertainty regarding their scale and duration (not to mention the possibility of irreversible effects).

Difficulties of standard environmental policy design in the presence of (potential) lock in phenomena are very well underlined in [7] in terms of "environmental policy shifts" and the existence of multiple equilibria. Under the first respect, a technology might be preferable before the related environmental damages are assessed, but could not be such when the assessment is made. Indeed, once we conclude that a technology is bad for the environment, we could be locked-in on a path where such technology is essential for production. At that stage, there is no feasible effluent tax rate that can take us to a different, more sustainable, path. Environmental policy is, in such circumstances, not effective in driving technology choices on the correct path. Furthermore, as Arthur [1] implicitly suggests, in the presence of increasing returns or positive feedbacks and/or network externalities, it is very likely that an apparently optimal environmental policy could not be optimal at all, as moving the economy slightly away from the unsustainable path where it is locked in does not favour a shift to a better existing technology. Both examples show how the "received" environmental policy design could not be able to move an unsustainable economy from an equilibrium that "looks" optimal to one that is indeed optimal in the long run.

In brief, the desirability and opportunity of standard environmental policy instruments in terms of technological development might change when lock-in phenomena are accounted for explicitly. In what follows, and as outlined in the introduction, we will focus on the incentives to technology adoption, which are (and have been) clearly crucial in determining lock in.

Both theory and empirical evidence unquestionably show that technology diffusion rates depend on the strength of economic incentives (see [5]). Environmental technology diffusion does not escape this “rule”. The literature focused on the incentives towards progresses in pollution reducing techniques have been analysed theoretically in a setting which could be called the "discrete technology choice" model. Firms have the choice to use a certain technology which reduces marginal costs of pollution abatement according to the related fixed cost of adoption. A conclusion which is agreed upon is that incentives for the adoption of new technologies are greater under market-based instruments than under direct regulation (Downing and White [4], Milliman and Prince [9], Jung, Krutilla and Boyd [6]). As we suggest in what follows, this result can be questioned if the need to avoid unsustainable technology lock-in is explicitly included as an objective for environmental policy instruments.

The paper is organized as follows. Next section recalls and synthesizes Arthur analytical framework, section 3 explains how lock-in effects take place, while section 4, focused on the implication in terms of the relative desirability of command and control and incentive based instruments, elaborates on two extreme scenarios. Section 5, as usual, contains concluding remarks.

2 A technological lock-in model

Using Arthur [1] model, we aim now at investigating how different environmental policy instruments might be (in)effective in influencing the chance for the economy to be locked in on an unsustainable path.

Consider two technologies S and U (details concerning the technologies will be provided below) and assume there are two types of agents, G and Q, that have to choose which technology has to adopt.

Agent i comes to the market in time t_i , chooses to adopt one of the two technologies and uses the adopted technology thereafter. In other words, at each point in time one agent gets to the market and chooses, once and for all, the technology he wants to adopt and use. We assume that the chance for each agent type to get to the market in each point in time is one half; roughly speaking, the number of agents of each type is the same. Agents differ in terms of the benefits they get from adopting the two technologies. The payoff function for agent G by adopting technology S is as follows:

$$s_G + gn_S$$

while the corresponding payoff from technology U is

$$u_G + gn_U$$

implying that the adoption of technology j ($j = S, U$) depends on positive values s_G and u_G as well as on how many agents have already adopted the technology, according to the positive parameter g. This is the most simplified way of modeling network externalities and/or increasing returns. The corresponding benefit functions for type Q agents are:

$$s_Q + qn_S$$

if they adopt technology S and

$$u_Q + qn_U$$

if they adopt technology U. As previously, q is a positive parameter playing the same role as g for G-type agents. Making the assumption, without loss of generality, that agents G have a "natural preference" for technology S while agents Q prefer technology U, it implies assuming that $s_G > u_G$ and that $s_Q < u_Q$.

The indeterminacy in the adoption process is introduced by the assumption that there is a social planner or an environmental regulator that can observe the sequence of agents choosing their preferred technology, but has no knowledge about the "historical events" (political and rent seeking behaviour, experience of adopters etc...) responsible for the sequence by which the agents make their choice. Everything about demand (i.e. agents' preferences) and supply (one unit of each technology is inelastically supplied at each point in time) is instead common knowledge.

3 How does lock-in take place?

Given the assumptions so far, we can still follow [1] and define the difference in adoption as the difference in the number of agents that adopted the new technology once n agents have made their own choice, that is:

$$d_n = n_S(n) - n_U(n)$$

Under the assumption of increasing returns, we can distinguish two circumstances concerning adoption incentives by the two agents types.

1. when the number of adopters is relatively low, then it is likely that G agents will choose technology S and Q agents will choose technology U. In other words, when increasing returns are not significant, the "natural ordering" of preference is maintained;

2. when a considerable number of agents has adopted a certain technology, then lock-in might occur. Consider the case in which the number of adopters of technology U is so high that also agents G, though having a "natural" preference for technology S, turn their choice to technology U. This happens when:

$$d_n = n_S - n_U < \Delta_U = \frac{u_G - s_G}{g}. \tag{1}$$

   When the above condition is satisfied, then all agents will choose technology U, so that the economy will be locked in. Following the same reasoning, it can be shown that the economy would be locked into technology S when the following condition holds:

$$d_n = n_S - n_U > \Delta_S = \frac{u_Q - s_Q}{q}. \tag{2}$$

   Roughly speaking, when increasing returns are present, if the number of adopters of one technology is so high to make it worthwhile for **all** agents to choose that technology, then the economy will be locked in.

The two threshold levels are represented in figure 1 (from [1]).

4 Lock in and environmental policy: a framework

We now investigate how an environmental regulator can avoid the lock-in effect within the above framework. We proceed by comparing the working of an incentive based instrument, such as a green tax/subsidy, with a command and

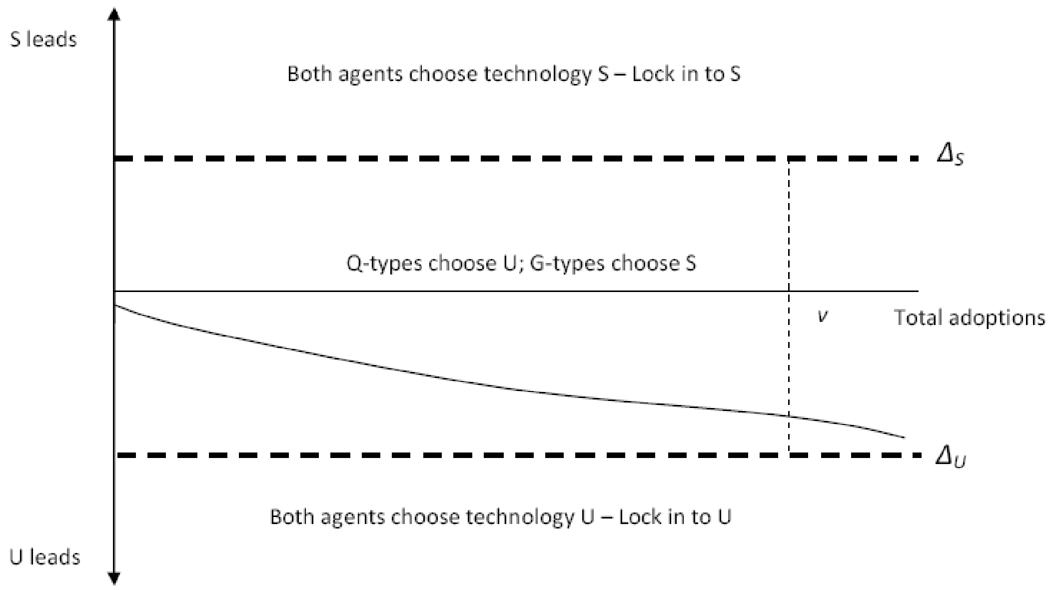

Figure 1

control instrument, such as a technology ban[2]. At the start, we assume that the lock in has not taken place yet and that the environmental regulator has a given budget (so that it cannot provide unlimited subsidies) and a finite taxing power (so that it cannot impose unreasonably high taxes).

The problem of the environmental regulator is therefore to choose the proper instrument to avoid that the economy is locked into the unsustainable technique.

We model the consequences of a command and control policy (i.e. a technology ban) on net benefits from technology adoption in the simplest way, by assuming that some of the benefits are lost by the two agents due to compliance costs. Under a technology ban the net benefits are as follows:

$$\alpha s_G + g n_S$$

[2] In the rest fo the paper we will call the incentive based instrument as "green tax". A negative value for such tax will indeed represent a subsidy.

$$\alpha u_G + g n_U$$

for type G, and

$$\alpha s_Q + q n_S$$

$$\alpha u_Q + q n_U$$

for type Q, where $\alpha < 1$ implies that net benefits are "scaled down" due to the ban.

Under a green tax the net benefits from technology adoption are:

$$\beta s_G + g n_S - t_S$$

$$\beta u_G + g n_U - t_U$$

for type G, and

$$\beta s_Q + q n_S - t_S$$

$$\beta u_Q + q n_U - t_U$$

for type Q, where $\beta < 1$, again, represents lost benefits due to compliance costs while t_U and t_S are the amount of levy on each technology. Notice that we allow for "green" taxation on both technologies because we want to account for the case where the regulator does not know which technology is the sustainable one.

The consequences of a technology ban are straightforward: it locks the economy in the unbanned technology[3].

Under a green tax, conditions (1) and (2) become:

$$d_n < \Delta_U^t = \beta \frac{u_G - s_G}{g} - \frac{t_U - t_S}{g} \tag{3}$$

$$d_n > \Delta_S^t = \beta \frac{u_Q - s_Q}{q} - \frac{t_U - t_S}{q} \tag{4}$$

As a consequence, given that $\beta < 1$ and that we assumed $s_G > u_G$ and $s_Q < u_Q$, then:

[3] Of course, we assume that once the ban has been introduced it cannot be easily removed. In other words, the ban is assumed to be in place for enough time to generate lock in.

- when $t_U > t_S$ then $\Delta_S^t < \Delta_S$, while $\Delta_U^t - \Delta_U$ is determined by the relative relevance of β and the tax differential.

- when $t_U < t_S$ then $\Delta_U^t < \Delta_U$, while $\Delta_S^t - \Delta_S$ is determined by the relative relevance of β and the tax differential.

In general, the effect of the green tax on the above thresholds will be determined by the complex interaction among:

1. the degree of increasing returns of the two technologies;

2. the difference in the two tax levies

3. the compliance cost parameter (i.e. β).

The height of the "no lock-in" band is given by

$$\Delta_S^t - \Delta_U^t = \beta \left(\frac{u_Q - s_Q}{q} - \frac{u_G - s_G}{g} \right) - (t_U - t_S) \frac{g - q}{gq}$$

We can, therefore, have two cases:

1. when increasing returns are greater for technology S $(g > q)$, then the no lock-in band will be narrower if $t_U > t_S$ while it can be wider only if $t_U - t_S < 0$ and sufficiently large in absolute value.

2. when increasing returns are smaller for technology S $(g < q)$, then the no lock-in band will be narrower if $t_U < t_S$ while it can be wider only if $t_U - t_S > 0$ and sufficiently large in absolute value.

4.1 Scenario 1: sustainable technology is known

Assume that at some point in time the environmental regulator has acquired perfect knowledge about the socially optimal technology. Suppose that technology U is the "bad" (Unsustainable) technology, while S is the "good" (Sustainable) technology. The model by [1] explained so far, implies that as the number of adopters (n) increases, then the probability that lock in takes place grows to one[4]. As a consequence, in an increasing returns setting, we know that the economy will be, sooner or later, locked-in.

As already discussed, an incentive based policy, such as a green tax, would have the effect of shifting the lock in threshold as well as changing the no-lock in ban height. This would, however, just change the timing and potential kind of lock-in, but it would not guarantee that the danger of being locked in the use of technology U is avoided. This conclusion is even stronger if the tax introduced is not a permanent one but only temporary.

The tax suffers, under this respect, from another shortcoming. Suppose that technology S is not taxed, as it is reasonable. The tax (amount) needed to avoid lock-in would have to be, in this case, such that:

$$t_U > \beta\,(u_G - s_G) - g d_n;$$

for a negative value of d_n, a weak preference for sustainable technology and significant increasing returns to the sustainable technology, the levy could be so high to exceed government taxing power. In such a case, the required incentive based instrument would become unfeasible.

Turning to the command and control policy example, a ban on technology U at a certain time would simply imply that onward all agents would be forced to choose the other technology. Of course, such a ban could encounter strong resistance from the most affected agents ($Q-type$ agents) so that not all the feasibility problems would be solved. On the other hand, a permanent technology ban[5] would be the only instrument capable of guaranteeing that the economy is not locked-in along a path where the "bad " technology is chosen by all agents.

[4] For the proof we refer to Arthur's paper [1].

[5] We could think, for example, in the case of two technologies, of a BAT - best available technology - standard.

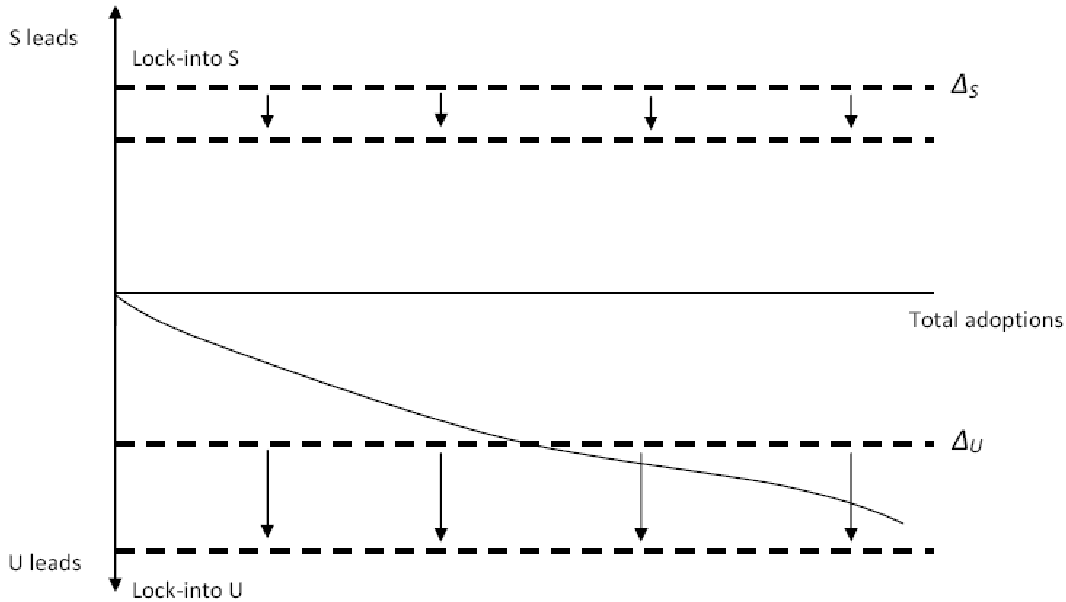

Figure 2

4.2 Scenario 2: sustainable technology is unknown

When the regulator does not have any knowledge concerning which technology is sustainable and which is not, a green tax can be an appealing instrument choice, as it allows to forward the lock-in effect and in so doing government has more time to learn which technology is the sustainable one. In this case, a technology ban would have the strong disadvantage of locking the economy in the unsustainable technology with probability one half.

To give a flavour of the working of our setting, suppose that technology S is indeed the sustainable one, but government does not know. Assume, further, that increasing returns are greater for the unsustainable technology, so that $q > g$. This means, in terms of figure 2 that, assuming $t_U > t_S$ and sufficiently large the no lock-in band becomes wider. As a consequence, the event of being locked in is somehow postponed.

Our analysis so far suggests that a tax could indeed be preferable to a standard when the environmental regulator does not have sufficient information to choose which technology must be favoured. A clear policy implication stems from our sketched results, namely, the need for a timely "combination" of instruments. Since in general government does not know which one is the sustainable technology, by introducing a tax in the early stages of technology adoption, government would avoid lock-in and gain time for learning; afterwards, when the sustainability implications of the competing technologies become clearer, government could switch to command and control in terms of a ban on the "bad" technology.

Although the desirability of a green tax and the switching time among instruments are only qualitative conclusions, as they depend on factors which are not explicitly modeled in our simplified setting, namely the government learning process and the *a priori* probability distribution among technologies, they may be an important signal for the government. When the main concern is to avoid technological lock-in, to which future increasing welfare losses are associated, and there is uncertainty about the sustainable technology, then to resort to a temporary green tax may be the best solution.

5 Concluding remarks

This paper is a first attempt towards a true inclusion of lock-in considerations into the choice of environmental policy instruments. Building on the seminal paper by Arthur [1] and on the received theory of environmental policy instruments, our paper is nothing more than a tentative analytical sketch of such problems. Non the less we provide additional considerations concerning the relative desirability of command and control and incentive based instruments. Based on the theory of lock-in under increasing returns, our paper provides promising insights in support of the conclusion that standard environmental policy approach is not enough when long run properties of policy instruments are the main concern. Indeed, including lock-in considerations into the analysis can subvert "traditional" conclusions, suggesting that command and control policies can be the only available instrument ensuring the economy not to be locked into an unsustainable technology. The crucial importance of knowing the “true” ranking among technologies is instead confirmed.

References

[1] Arthur, W.B. (1989), "Competing technologies, increasing returns, and lock-in by historical events", *Economic Journal,* 99, 116-131.

[2] Baumol, W. J. and W. E. Oates (1971). "The use of standards and prices for the protection of the environment", *Swedish Journal of Economics,* 73, 1

[3] Cowan, R. (1990) – “Nuclear power reactors: a study in technological lock in”, *The Journal of Economic History*, 50, 541-567.

[4] Downing, EB., and L.J. White (1986), "Innovation in pollution control", *Journal of Environmental Economics and Management* 13, 18-29.

[5] Jaffe, A.B., Newell, R.G., Stavins, R.N. (2003), “Technological change and the environment” in K.-G. Maler and J.R. Vincent (eds.), *Handbook of Environmental Economics*, Vol. I, Ch. XI.

[6] Jung, C.H., K. Krutilla and R. Boyd (1996), "Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives", *Journal of Environmental Economics and Management,* 30, 95-111.

[7] Kline, D. (2001), “Positive feedback, lock-in, and environmental policy”, *Policy Sciences,* 34, 95– 107.

[8] Kneese, A., and C. Schultze (1975), *Pollution, Prices, and Public Policy*, Brookings Institution, Washington, DC

[9] Milliman, S.R., and R. Prince (1989), "Firm incentives to promote technological change in pollution control", *Journal of Environmental Economics and Management,* 17, 247-265.

[10] Roberts, M. J. and M. Spence (1976). "Effuent charges and licenses under uncertainty", *Journal of Public Economics,* 5.

[11] Unruh, G.C. (2002) – "Escaping carbon lock in", *Energy Policy*, 30, 317 – 325.

[12] Unruh, G.C. (2000) – "Understanding carbon lock in", *Energy Policy*, 28, 817 – 830.