# Option values of low carbon technologies policies: how to combine irreversibility effect and learning-by-doing in decisions?

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**Abstract**

In this paper we analyze development and deployment of large-scale low carbon technologies. We first review several issues at stake for the development of a technology still in infancy and characterized by major learning effects. Then we develop an analytical model to analyze the interrelation between irreversible investment and learning effects in a context of uncertainty. Whereas the irreversibility effect usually justifies to limit irreversible investment in a context of uncertainty, we show that this result can be reversed in presence of learning effects. Learning effects can justify an early development of a technology in order to have the technology ready to face situations it will appear essential to reach CO2 emissions reductions targets.

*Key words:* investment, option value, learning by doing

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## 1. Introduction

Low carbon generation technologies (LCT) are seen as a major option to reduce emissions from the electricity industry which is the main emitting industrial sector. Some of these technologies such as capture and carbon sequestration (CCS), large scale solar plants, advanced nuclear plants are still in infancy; adoption costs will be high because equipments will be capital intensive and with long lead time for building. In the same time the development of such new technologies will be characterized by important learning effects which might justify the implementation of public policy in addition to the CO2 emissions cap and trade policy. Subsidies can be used to make producers internalize the learning spillovers, such a subsidy directly improving competitiveness of the new equipment by compensating its cost difference with conventional generation technologies (Arrow, 1962; Bardhan, 1971).

Learning investments are necessary after the demonstration stage if large scale renewables, CCS or new nuclear technology should have to be ready and competitive at the time private investors should invest in (Philibert, 2005; Reiner and Gibbins, 2008). It could be socially efficient to force their learning process in next decades after the demonstration stage in order that private producers could adapt their choices to possible stringent carbon policies which will definitively disqualify standard fossil fuel generation.

We first analyze elements of option value of a technology pull policy on large-scale LCTs before developing an analytical model. Then with this model, we analyze an agent's sequential choice of LCT power plants in a context of uncertainty on the cost of a carbon technology. We analyze the effect of uncertainty and option value by comparing investment with and without information acquisition.[1] Uncertainty to be considered will be on the cost/price of CO2 emissions which alters the economic position of conventional fossil fuel power plants.

After concluding on this case, we transpose the results to the case of each large scale and low carbon technology confronted to the competition of the other technologies. Assuming that the deployment of one or several of the LTCs is a historical necessity because the climatic urgency, and that one of the LCTs is more or less on the shelves but is exposed to a large regulatory an political risk, uncertainty is added to decision to develop and deploy other LCTs (for instance nuclear development could take the lead on large scale solar plants and CCS

[1] In the linear framework we develop it is equivalent to consider that there is no uncertainty or no information acquisition in the second period. The second interpretation suits more to the initial development of option value by Henry (1974) and Arrow and Fisher (1974).

which are at a much less advanced stage of their technological development). But for the specific policies to pull these last ones, there would be a rationale to value them by an option value because the uncertainty surrounding the “availability” of their substitute technologies.

*1.1. Option value to pull low carbon technologies deployment*

*Rationale to complement carbon price signal*

Capture and carbon sequestration, nuclear technology and renewable energy technologies will be the most straightforward options to be considered to reduce the CO2 emissions in the future in the most emitting sector, the electricity industry. Carbon pricing policies are unlikely to encourage sufficient technology deployment in the near term, and additional policies on top of carbon taxation or cap and trade systems are necessary to advance the introduction of large-scale LTCs.

Two issues arise for a LCT deployment by market pull based on carbon price signal: first uncertainty in competition with existing fossil fuel generation technologies the competitiveness of which depending upon future carbon price, and second immaturity of the technology which is reflected in classical market barriers to which new technologies confront such as learning costs and technological risks.

First the uncertainty on the long term carbon price magnifies risks for candidates to invest in large scale LCT technologies. It is mainly a regulatory uncertainty on cap and trade systems in the long-term because of uncertainties in the governments’ international commitment in the USA, Europe, Asia, etc. and their effects on designs of regional or international cap and trade mechanisms.

Second the transition from the demonstration stage to the stage of technology market-pull by only carbon price signal is not automatic when the chain of innovations is long, complex and diverse as in the cases of new nuclear and CCS. New large scale technological systems have to go through a long and risky transition stage before they become commercially available. This is the socalled “death valley” to go through in this innovation chain because incentives by revenue anticipation are too weak and uncertainty quite large (Grubb and Newbery, 2007). Policy development must help to install equipments in premature technologies to reduce costs, in particular the cost differential between LCT generation and conventional fossil fuel generation, even with high carbon price. Many advances in cost will result from learning by doing. So there is a need to pull the technology in learning investments by demand pull instruments.

We do not address the issue of social efficiency of the different regulatory approaches but we simply analyze the determination of the optimal capacity of LCT equipments chosen by an agent that internalizes learning-by-doing spillovers in a context of uncertainty.

*A focus on LCT development as an option*

Low carbon technologies are considered as alternative to coal and gas generation for the satisfaction of electricity needs. A LCT policy can help to accelerate the deployment of these technological systems for benefiting from learning effect; they could reach competitiveness threshold with carbon emitting technologies in case of definitive high carbon price situation resulting from a severe international commitment. We consider the choice of an optimal quantity of LCT when there is an uncertainty in the future cost of a carbon technology. We have in mind an uncertainty on the cost/price of CO2 emissions which alter the economic position of conventional coal power plants.

We consider two periods. In the first period a quantity of LCT plants is chosen, LCT being more costly today than the carbon technology there is an opportunity cost to invest in a LCT plant, but this plant reduces future cost of LCT thanks to learning-by-doing. In the second period, additional plants should be built to satisfy demand growth and these can be either of LCT or of the conventional carbon technology. In one case, without information acquisition, the agent considers the expected cost of the carbon technology when choosing to invest in LCT and ignores that he will acquire information. In the second case, with information acquisition, the agent anticipates that he will learn the true cost of the carbon technology. We compare the quantity of LCT chosen at the first period in both cases.

These two scenarios are typical problems of sequential decision under uncertainty. The option value literature has analyzed how irreversible decisions are influenced by uncertainty or information acquisition. Initiated in the literature on environmental preservation, the standard irreversibility effect (Henry, 1974; Arrow and Fisher, 1974) explains that the perspective to obtain information in the future should limit today irreversible action compare to a naïve cost benefit analysis that ignores this perspective. One should limit today irreversible actions in presence of uncertainty and wait for information arrival.

The notion of option value has been also used to analyze firms' investment decision under uncertainty. This approach decomposes the profit of a firm into a deterministic component–the naive net present value–and a random one that represents the option to invest later; this emphasizes that investing today kills the option to invest later and explains that uncertainty reduces investment.[2] However, it is now well known that the sign of the effect of uncertainty and information acquisition on investment is ambiguous even in a simple model.[3] Concerning the mitigation of CO2 emissions, Ulph and Ulph (1997) analyze the effect of information acquisition on the choice of today emissions. They show that this effect is ambiguous so it is difficult to conclude whether the perspec-

[2] This notion was first used to analyze the decision to invest in a single project (Bernanke, 1983; McDonald and Siegel, 1986), and then extended to consider the choice of a quantity of productive capacity (Pindyck, 1988); Dixit et al. (1994) provide an extensive survey of this literature. Abel et al. (1996) unify this approach with previous analysis of investment under uncertainty and show that besides the call-option related to the possibility to invest later, there is a put-option related to the possibility to disinvest, this second component implies that the effect of uncertainty is ambiguous.

[3] Two distinct strands of the literature analyze (i) the effect of an increase of uncertainty (Rothshild and Stiglitz, 1970, 1971; Gollier, 1995) and (ii) the effect of an increase of information precision (Epstein, 1980; Freixas and Laffont, 1984; Salanié and Treich, 2006) on ex-ante decision. In both cases, quite restrictive conditions are required on the objective function or the distribution of states to get a monotonicity result.

tive to obtain information should increase or decrease today emissions. Kolstad (1996) considers the tension between two irreversibilities: the irreversibility of today emissions and the irreversibility of clean capital investment and concludes that the former is more likely to be binding; thus, information acquisition implies that less investment should be done in clean capital but this neglects the existence of learning-by-doing that is at the root of the current policies toward LCTs.

Close to ours is the approach of Schimmelpfenning (1995). He develops a simple model with one non carbon technology on which R&D effort have to be done or not, and an uncertainty on carbon policy (having or not an international binding climate treaty in the future). He shows the relevance of a sequential approach. In the classical approach, as used by Kolstad (1996), it could be that not developing LCT until the uncertainty is resolved could create the option value. But it is not the case for R&D funding because of the interest to benefit from R&D investment in case of bad news: "Information is revealed through time and the flexibility to respond in different ways can be preserved (...). Option value is the value of flexibility created and it is only by allocating R&D funding to the development of renewable and alternative technologies that the option to use or ignore them in the future is created".

Schimmelpfenning only considers a binary decision: whether to launch or not R&D effort on LCTs, and get an unambiguous result: the presence of uncertainty increases the value of the project. We develop here a more complete framework but still relatively simple (two periods, two technologies), in order to clearly identify the potential tensions between irreversibility and learning-by-doing. The basic idea is that it appears difficult, indeed impossible, to renounce to pull LCT deployment after demonstration stage when technologies have been proved, as soon as we consider possible in the next decades a strong commitment of governments in an international regime to stabilize the CO2 emissions, which means a high carbon price. We first analyze a myopic scenario, where the agent ignores that information will be obtained, and determine under which conditions LCT should be developed. It is so if the future cost of the alternative technology is sufficiently large. Next we consider the influence of information acquisition on the development of LCT. We show that, if the average cost of the alternative technology (the carbon one) is large, the standard irreversibility effect holds: less LCT should be developed when information arrival is anticipated than in the myopic scenario. However, if the average cost of the alternative technology is small and uncertainty sufficiently important, more LCT should be developed with information than without. More precisely, no LCT are developed in the myopic scenario whereas a strictly positive quantity is in the informed one.

## 2. Model

### *2.1. Framework*

We consider a simple model with two time periods $t = 1; 2$ and two technologies. The first technology represents LCT plants whereas the second technology is the carbon technology. The aggregate quantity of plants that should be build is fixed: $D_1$ plants at the first period and $D_2$ additional ones at the second period. Thus, $D_2$ is the demand growth from period 1 to period 2. We consider a price inelastic demand for the output of power producing plants in order to simplify.

The cost of LCT plants is subject to learning by doing effects while uncertainty is on the cost of the alternative technology.

In the first period a quantity $x$ of LCT plants is chosen and the remaining $D_1 - x$ plants belong to the alternative technology. At the second period, the $D_2$ additive plants are either LCT or alternative depending on their marginal costs.

In the first period the marginal cost of plants of both types is constant, the marginal cost of LCT is $c_1$ and the marginal cost of the alternative is $\gamma_1$. Both are positive and we assume that the alternative technology is cheaper than LCT in the first period: $\gamma_1 < c_1$. The second period marginal cost of LCT depends on $x$; it is denoted $c_2(x)$. Learning by doing is represented by the assumptions:

$$c_2(0) = \bar{c}, \frac{\partial c_2}{\partial x} \leq 0, \frac{\partial^2 c_2}{\partial x^2} \geq 0. \tag{1}$$

The second period LCT marginal cost is decreasing with the quantity of first period LCT plants and this effect decreases too with the quantity of LCT plants: learning-by-doing is more important for the first plants developed. Furthermore, learning effects tend to vanish:

$$\lim_{x \to +\infty} c_2(x) = \underline{c}, \text{ and } , \lim_{x \to +\infty} \frac{\partial c_2}{\partial x} = 0. \tag{2}$$

Uncertainty on the alternative technology costs is assumed additive. The second period cost of an alternative plant is $\gamma_2 + \theta$ where $\theta$ is a random variable that represents either $CO_2$ emissions prices or nuclear political cost; $\theta$ is either low at the level $\theta_l$ with probability $\pi$ or high at the level $\theta_h$ with probability $1-\pi$. The average value of $\theta$ is 0 and $\gamma_2$ is the expected value of the alternative technology[4] which is assumed lower than the cost of LCT if none LCT plants are built in the first period: $\gamma_2 < \bar{c}$.

It is important to note that the cost of LCT plants is decreasing with respect to preceding investments and not with respect to current investment. This assumption is used to cast the temporal dimension of learning by doing. If we invest today we make LCT plants more competitive tomorrow. Learning gains cannot be immediately obtained by investing in LCT plants (a standard assumption in model on learning by doing or knowledge diffusion). This temporal aspect of learning by doing is at the root of the option value of today investment in LCT that we analyze.

### *2.2. Timing and option value.*

The objective is to minimize the cost of $D_1$ and $D_2$ plants. The aggregate cost in a state $\theta$ is:

$$C(x, \theta) = c_1 x + \gamma_1 (D_1 - x) + D_2 \min \{c_2(x), \gamma_2 + \theta\} \tag{3}$$

In order to understand the influence of information discovery we use the usual methodology of the option value literature. We compare two situations whether

[4] The first period cost of the alternative technology could also be random so $\gamma_1$ would be the expected first period cost of an alternative plant.

$\theta$ is known or not when second period plants are built. In the reference case—without information—$\theta$ is unknown when the second period technology is chosen; the choice is based on the expected cost $\gamma_2$. With our framework[5], the objective is:

$$\min_x C(x, 0). \tag{4}$$

The solution to this problem is denoted $x^0$.[6] It corresponds to the choice made when no information is obtained between the first and second period, or by an agent that ignores that he will acquire information. With our particular setting it is equivalent to consider that there is no uncertainty. For instance, if uncertainty is about the $CO2$ price, it means that the agent (a firm or the regulator) uses an expected $CO2$ price to assess whether LCT will be further developed in the future.

The influence of information is analyzed by comparing the scenario above with a second scenario where the agent anticipates that he will obtain information in the future. Formally, in this second scenario, the second period technology is chosen once $\theta$ is known. The timing is:

1. $x$ is chosen with prior belief on $\theta$;
2. $\theta$ is learned and either LCT or the alternative technology is used for the $D_2$ remaining plants.

In that case the problem is:

$$\min_x E\left[C\left(x, \theta\right)\right], \tag{5}$$

and its solution is denoted $x^L$.[7] The value of information acquisition for any $x$, formally represented by the concavity of $\min\left\{c_2(x), \gamma_2 + \theta\right\}$ with respect to $\theta$,

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[5] To better suit to the option value literature we could have made explicit the choice of the technology; for instance with a variable $z \in \{LCT, alt\}$ and a cost function $\Gamma(x, z, \theta)$, so the reference minimization problem would have been $\min_{x,z} E[\Gamma(x, z, \theta)]$ while with information discovery $\min_x E\left[\min_z \Gamma(x, z, \theta)\right]$. Thanks to the linearity of our framework the former is equivalent to equation (4) and the latter to (5), which simplify notations and exposition.

[6] There can be two solutions to the problem, if so, $x^0$ is the smallest solution. This multiplicity of solutions is a particular case that does not deserve great attention.

[7] As for $x^0$, there might be several solution that minimized expected cost (at most three),

is the difference:

$$C(x,0) - E\left[C(x,\theta)\right] > 0. \tag{6}$$

Finally, we denote $x^*(D)$ the quantity that minimizes of $(c_1 - \gamma_1)x + D_2 c_2(x)$ for $x \geq 0$. This quantity is either 0 or the solution of the equation:

$$c_1 - \gamma_1 = -D\frac{\partial c_2}{\partial x}(x)\,. \tag{7}$$

We want to avoid situations where all first period plants are LCT, because it seems unrealistic and can make the exposition rather fastidious. To ensure that this is true, the number of first period plants should be sufficiently large. Thus, in the rest of the paper we assume that the quantities of plants $D_1$ and $D_2$ satisfies:

$$-\frac{\partial c_2}{\partial x}(D_1) < \frac{c_1 - \gamma_1}{D_2}. \tag{8}$$

This assumption means that if all first-period plants were LCT plants the learning benefit (left hand side) would be less than the cost (right hand side). It ensures that the optimal quantities of LCT $x^0$ and $x^L$ plants are strictly less than $D_1$.

In the following sections we first analyze the optimal first period choice without information (section 3) before considering the effect of information and the option value of LCT (section 4). We finally discuss the policy implications.

## 3. Learning-by-doing

In this section, we analyze the optimal policy in a myopic scenario where information arrival is not anticipated. Learning-by-doing introduces a particular form of spillovers in the production process: plants that are developed initially reduce the cost of following projects. Learning-by-doing can be formally seen by deriving cost with respect to first period LCT plants:

$$\frac{\partial C}{\partial x} = (c_1 - \gamma_1) + \begin{cases} 0 & \text{if } c_2(x) > \gamma_2 \\ \frac{\partial c_2}{\partial x_1}(x) D_2 & \text{otherwise} \end{cases} \tag{9}$$

in that case $x^L$ is the smallest one.

The first term is the relative cost of an LCT plant compared to the alternative carbon technology. As LCT plants crowd out alternative plants this is the direct–first period–cost of LCT. The second term is the effect of LCT plants on the second period cost, it is null if LCT plants are not used in the long-term and strictly negative otherwise, thanks to learning-by-doing.

Figure 1 represents the aggregate expected cost with respect to the quantity of LCT built in the first period; it illustrates the non-convexity due to learning by doing. At first, with few LCT plants built, total cost increases with the quantity of LCT plants because they are not competitive in the long-term. At a point total cost possibly decreases thanks to learning-by-doing.

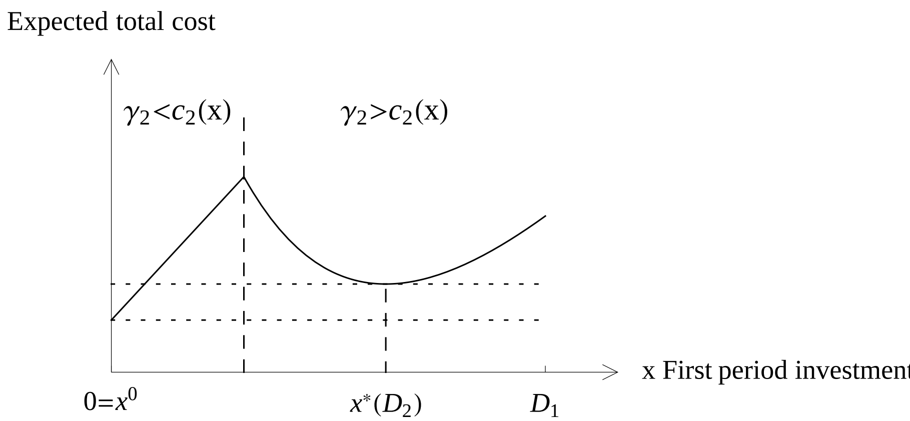


Figure 1: Expected cost with respect to first period LCT plants.

Figure 1 illustrates that to determine if some LCT plants should be developed in the first period cannot be done by marginal reasoning but requires the comparison of aggregate cost with and without LCT development.

**Lemma 1.** *A strictly positive quantity of LCT should be developed in the first period, i.e.* $x^0 > 0$*, if and only if the alternative technology cost* ($\gamma_2$) *is strictly larger than* $\tilde{\gamma_2}$ *where*

$$\tilde{\gamma_2} = c_2\left(x^*(D_2)\right) + \frac{c_1 - \gamma_1}{D_2} x^*(D_2) \tag{10}$$

**Proof.** First, the application $\psi : x \to (c_1 - \gamma_1)x + c_2(x)D_2$ is strictly convex; so $C(x, 0)$,which is not convex, is minimized either at 0 or $x^*(D_2)$ (possibly at both) and in the former case $c_2(x^*) < \gamma_2$.

If $x^0 > 0$ then $x^* = x^0 > 0$; hence, $C(x^*, 0) > C(0, 0)$ and as $\gamma_2 < \bar{c}$ (by assumption) $C(0, 0) = \gamma_1 D_1 + \gamma_2 D_2$ and $C(x^*, 0) > C(0, 0)$ is equivalent to $\gamma_2 > \tilde{\gamma}_2$.

If $\gamma_2 > \tilde{\gamma}_2$ then $\gamma_2 > c_2(x^*)$ so $C(x^*, 0) = \gamma_1 D_1 + \psi(x^*)$. As $\gamma_2 < \bar{c}$ the inequality $\gamma_2 > \tilde{\gamma}_2$ is equivalent to $C(x^*, 0) > C(0, 0)$. ■

A strictly positive quantity of LCT should be developed if learning effects are sufficiently important to compensate for the loss due to the relatively higher cost of LCT in the first period. The condition $\gamma_2 > \tilde{\gamma}_2$ stands for a global and not a marginal comparison of costs. It should be noticed that the second period LCT cost should be sufficiently lower than the alternative one to justify the development of LCT, and the difference $\tilde{\gamma}_2 - c_2(x^*)$ is decreasing with the number of plants developed in the second period. Quite naturally, learning by doing is all the more valued that the quantity of second period plants is important.

The influence of the second period quantity $D_2$ can be used to eventually consider the influence of the discount rate. The discount rate has not been introduced but it could be so by replacing $D_2$ by $D_2/(1+r)$ so that an increase of the discount rate has a similar effect than a decrease of the quantity of second period plants. If the discount rate increases the learning effects are less valued because the future is more discounted. An increase of the discount rate can also be interpreted as an increase of the time required for learning effect to take place and an increase of this delay naturally decreases the appeal of LCT.

The effect of the learning rate is also worth mentioning. Formally, a direct mean to represent the learning rate is to consider that $c_2(x) = \phi(lx)$ where $l$ is the learning rate and $\phi$ is decreasing and convex; a higher learning rate increases the influence of first period plants on second period marginal cost. The influence of the learning rate on the development of LCT has two components. First, the higher the learning rate the more likely LCT are used and, second, the quantity of LCT plants is not monotonous with respect to the learning rate. With a higher learning rate the effect of first period plants on second period costs is higher for first plants but smaller for following ones: lower second-period costs are reach with smaller number of first-period plants. Thus, in one hand first LCT plants are more valued but in the other hand less plants are needed to ensure the same reduction of cost.

Figure (2) depicted the optimal number of LCT plants with respect to the learning rate with an exponential cost i.e. $c_2(x) = \underline{c} + (\bar{c} - \underline{c})e^{-lx}$. The threshold cost $\tilde{\gamma}_2$ is decreasing with respect to the learning rate, for small learning rate LCT are not developed, then for sufficiently large one they are but the optimal quantity of LCT is not monotonic with respect to the learning rate.

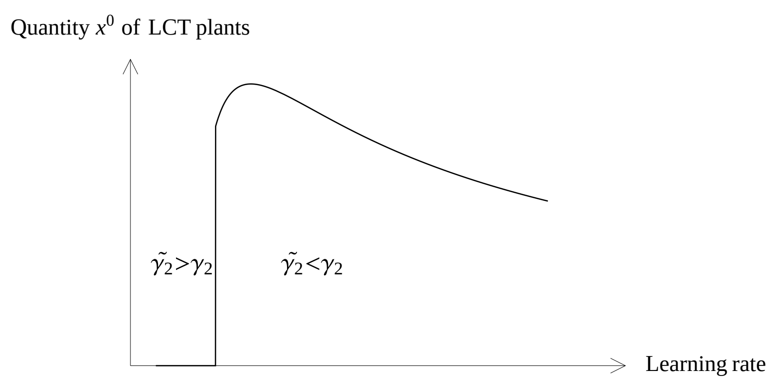


Figure 2: Optimal quantity of LCT plants and learning rate.

## 4. Learning-by-doing and information.

The introduction of information acquisition modifies the marginal benefit from first period LCT plants because the choice of the second-period technology is now contingent to the true cost of the alternative technology. If this technology appears cheap ($\theta = \theta_l$) LCT might be useless and the learning-by-doing spillovers are wasted, but, if the alternative technology is actually more expensive than expected ($\theta = \theta_h$) learning-by-doing effects are valuable. The former effect, the possibility to learn that LCT is not worth, is at the root of the standard irreversibility effect while the latter can justify an early development of LCT that would not have been done in a myopic scenario–without information anticipation. First period LCT plants might be more valuable with information because they increases flexibility by decreasing the cost of following plants.

Formally the marginal effect of first period LCT on the aggregate cost is:

$$\frac{\partial E\left[C(x,\theta)\right]}{\partial x} = c_1 - \gamma_1 \begin{cases} 0 & \text{if } \gamma_2 + \theta_h < c_2(x) \\ \pi D_2 \frac{\partial c_2}{\partial x} & \text{if } \gamma_2 + \theta_l < c_2(x) < \gamma_2 + \theta_h \\ D_2 \frac{\partial c_2}{\partial x} & \text{otherwise} \end{cases} \tag{11}$$

The interesting situation is the intermediary one where LCT plants are used in high cost scenarios but are not in low cost ones. In the two other cases expected costs with information are equal to costs without information. Figure (3) depicts the two costs in a situation where there is no development of LCT without information but there is with information. The area between the two curves is the value of information.

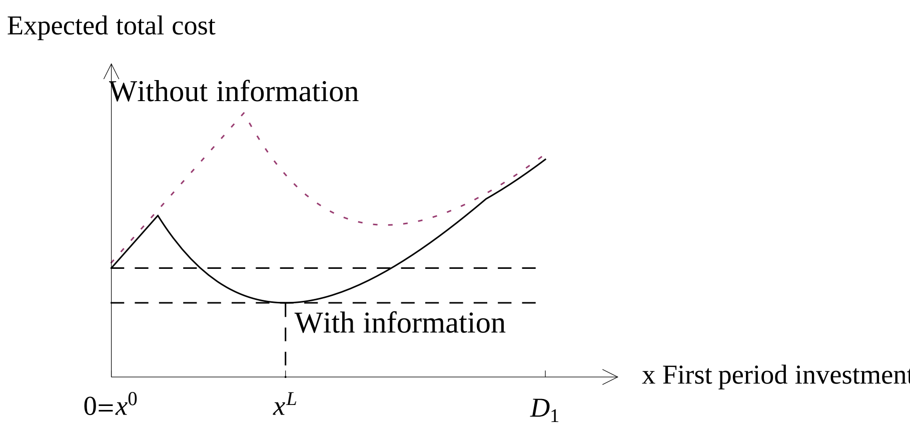


Figure 3: Quantity of LCT plants and expected cost without information (dotted curve) and with information (plain curve)

**Proposition 1.** *If $\gamma_2 > \tilde{\gamma_2}$, there is less investment with information than without:*

$$x^L \leq x^0.$$

*If $\gamma_2 \leq \tilde{\gamma_2}$, LCT is not developed without information, i.e. $x^0 = 0$, and if*

$$c_1 - \gamma_1 < \pi D_2 \frac{\partial c_2(0)}{\partial x} \tag{12}$$

$$\gamma_2 + \theta_l < c_2 \left( x^*(\pi D_2) \right), \tag{13}$$

$$\gamma_2 + \theta_h > c_2 \left( x^*(\pi D_2) \right) + \frac{c_1 - \gamma_1}{\pi D_2} x^*(\pi D_2) \tag{14}$$

*there is a strictly positive quantity of LCT plants build with information:*

$$x^L > 0 = x^0.$$

**Proof.** If $\gamma_2 > \tilde{\gamma_2}$, the LCT is developed without information and $x^0 = x^*(D_2) > 0$. With information, the expected cost $E\left[C(x, \theta)\right]$ is minimized either at $0$,$x^*\left(\pi D_2\right)$ or $x^*\left(D_2\right)$ all of which are smaller than $x^*\left(D_2\right)$ so $x^L \leq x^0$.

Otherwise, if $\gamma_2 < \tilde{\gamma_2}$, the LCT is not developed without information: $x^0 = 0$.

Condition (12) implies that $x^*\left(\pi D_2\right) > 0$.

Inequalities (13) and (14) ensure that $x^*\left(\pi D_2\right)$ locally minimizes $E\left[C(x, \theta)\right]$ because

$$\gamma_2 + \theta_l < c_2 \left( x^*(\pi D_2) \right) < \gamma_2 + \theta_h,$$

and, as $x^*(\pi D_2) > 0$:

$$\frac{\partial E\left[C(x^*(\pi D_2), \theta)\right]}{\partial x} = c_1 - \gamma_1 + \pi D_2 \frac{\partial c_2}{\partial x} (x^*(\pi D_2) = 0. \tag{15}$$

And finally $x^0 = 0$ and (14) imply that

$$E\left[C(x^*(D_2), \theta)\right] \leq E\left[C(0, \theta)\right] > E\left[C(0, \theta)\right] > E\left[C(x^*(\pi D_2))\right].$$

■

The proposition sets conditions under which the 'irreversibility effects' holds or not. For some range of parameters the irreversibility effect is reversed and uncertainty can justify an early development of LCT. If the LCT is developed without information, the anticipation of information arrival reduces the benefits from first period LCT plants because LCT could be unused if the alternative technology is cheaper; it is worth waiting and postponing some investment. However, if $\gamma_2$ is large, the anticipation of information arrival and the perspective to discover that LCT are necessary increases the value of first period plants and can consequently justify investment. To learn that the LCT should be used whereas it was not expected, can only arise if LCT are not developed in the myopic scenario. Thus, the 'irreversibility effect' is only reversed in the case where there is no investment in LCT in the myopic scenario.

For this last situation to hold, the range of uncertainty should be sufficiently important. Note that if

$$\gamma_2 + \theta_l \leq \underline{c} \leq \bar{c} \leq \gamma_2 + \theta_h,$$

the two conditions (13) and (14) are superfluous, and (12) is sufficient to ensure that $x^L > 0$.

The effect of the learning rate is of particular significance as it is at the roots of the option value created by LCT development. The comparison of the two situations is done on Figure 4 for an exponential cost:

$$c_2(x) = \underline{c} + (\bar{c} - \underline{c})\, e^{lx},$$

where $l$ represents the learning rate. For small learning rates there is no LCT developed in the first period in both cases, for intermediary values there are some plants developed with uncertainty and no plant developed without uncertainty, for larger learning rates there are plants developed with and without uncertainty and both quantities eventually coincide. Thus, the irreversibility effect holds for important learning rate because in that case it is worth developing LCT in any cases. It is for intermediary learning rates that uncertainty can justify an early development of LCT, because in that case, the cost reduction is sufficient to justify LCT further deployment in case of a stringent CO2 policy, but not sufficient in case of a lax one.

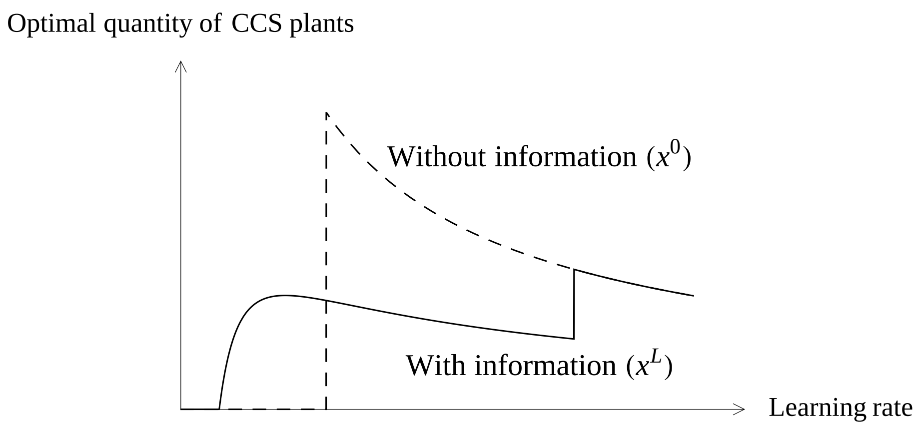


Figure 4: Optimal quantity of LCT plants with respect to the learning rate without information (dotted curve) and with information (plain curve).

A similar analysis can be done regarding demand growth. If demand growth is important, uncertainty is irrelevant because LCT are used whatever the stringency of the environmental policy. This stresses that learning-by-doing introduces a kind of scale economy that is all the more exploited that production is large. The irreversibility effect is reversed for medium demand growth. In such a case, learning effect are poorly valued because few plants are concerned, and it explains that LCT are only use if the environmental policy is stringent.

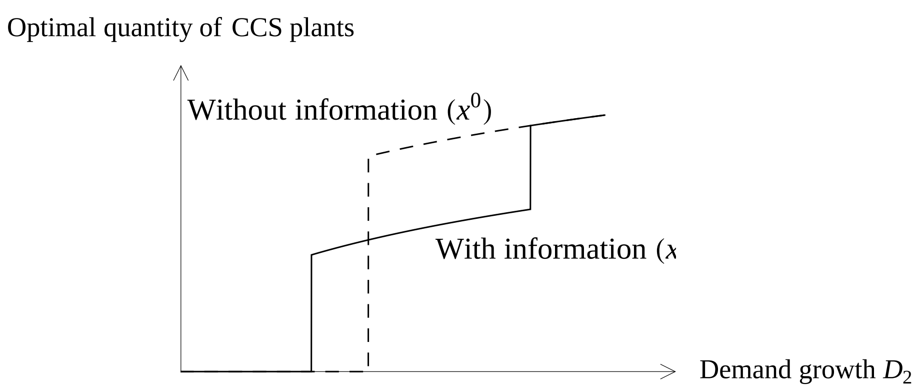


Figure 5: Optimal quantity of LCT plants with respect to demand growth

## 5. Discussion

The simple model used to analyze the potential option value created by an early development of an immature technology was very simple. We discuss here two of the simplifying assumptions: demand elasticity and state distribution. Within our framework, the non-convexity introduced by learning-by-doing was clear and easily handled. With an elastic demand, there are more variables to be chosen: not only the quantity of LCT plants but also the aggregate quantities of plants. The non-convexity can be exacerbated by an elastic demand because of the relationship between the aggregate quantity developed in the first period and the total quantity added in the second period. Particularly, LCT developed in the first period have two opposite effects on the second period quantity of plants: in one hand, by decreasing the marginal cost they increase the total quantity of plants, but on the other hand they also crowd out second period plants. Whether the quantity of second period plants is increasing or decreasing with the first period quantity is ambiguous and depend on the comparison of demand elasticity and learning rate.

Concerning the distribution of the carbon technology cost. The situation is similar in the sense that a continuum of demand states does not solve the issue of non convexity, and in any case marginal reasoning is limited. We think that the cost of analytical complexity is not worth the gain of realism. The effect at stake would have been similar but more painfully exposed.

## 6. A Transposition: the decisions on specific low carbon technology in uncertain competition

We can transpose the results concerning policy on the low carbon technologies cluster to the case of each large scale LCT (CCS, large renewables, new nuclear) confronted to the competition of other low carbon technologies. Assuming that the deployment of LCTs is an historical necessity because of the climatic urgency, and that one of the LCTs (the new nuclear for instance) is more or less on the shelves but is exposed to a large regulatory and political risk, uncertainty is added to the decision to pull the deployment of other LCTs. It is the case for a climate policy which would mainly rely on new nuclear development, with the risk of a failure in commercial nuclear redeployment for acceptability reasons, after the failures occurred in the seventies and eighties in some major OECD countries. It could be in countries which reopen the nuclear option as a priority mean to respect their carbon reduction commitment, but they make this choice under the risk of coming up against new political restrictions. In this case promotion of large renewables as well as CCS would open options in case of a failure of the nuclear technology.

With this interpretation, our result seems opposite to a recent paper of Löschel and Otto (2009) on technology policy related to climatic change which conclude to social inefficiency of a CCS policy. With an endogenous-growth model, they shows that information on a backstop technology, i.e. a situation where this backstop technology is anticipated related to a situation where it is not anticipated, can have a negative value by limiting technology externalities related to the deployment of substitutable technologies. The negative value of information they found is due to the existence of an externality–knowledge spillovers–that is not internalized. They consider that CCS is the backstop technology and renewable are alternative, so they conclude that CCS can be problematic because polluters would "become complacent by postponing some of their emission reduction efforts awaiting the silver bullet technology on the horizon"(Löschel and Otto, 2009)[abstract]. But this definition of the long term technological policy dilemma is disputable because they do not consider at all learning investments and their technological spillovers for making CCS competitive, while they do it for renewables.

We choose an opposite perspective than Loschel and Otto's one when we consider competing low carbon technologies in the transposition of our general case of the low carbon technology cluster. We take the case of two technologies (CCS and renewables) that could be deployed in the learning stage at different paces (determined, cautious) besides the case of one technology which should have to be developed because this technology is almost ready, but is exposed to uncertainty. Transposition of the results gives the following original story: if two non-carbon power generation technologies which are not commercially mature (CCS and large scale renewables) could be deployed in parallel or alternatively with a technology already on shelves (nuclear), promotion policies in a first period for the two non mature technologies will be socially efficient because the near mature technology could politically and economically failed in the second period. The risk of coming up against new political restrictions makes valuable to develop technological learning on CCS or large scale renewables plants by pulling their initial deployment. Indeed nuclear technology could not meet the societies' confidence and consequently the market test because of regulatory and political overcosts and risks.

## 7. Conclusion and policy implications

Several policy implications can be deduced from our analysis. The first message is related to the option value related to large scale low carbon technology characterized by learning-by-doing. Contrary to the usual irreversibility effect there might be an incentive to develop early such technology in order to have the option open to invest in this technology at a low cost in the future. This option is related to the uncertainty surrounding the cost of climatic change or the stringency of an international agreement in carbon emissions reduction. Because of a possibility that CO2 emissions are more costly than expected it is efficient to prepare to react to this occurrence and be ready with the set of LCT technologies by economically improving them thanks to learning-by-doing. In another word, rather than having an option value for not developing technologies until the uncertainty is resolved, in the case of technology deployment, it could be efficient to not wait because of the interest to benefit from learning-by-doing and opening technological option. A determined policy of support on CCS, large scale renewables and new nuclear creates flexibility to respond in different ways to eventual climate policy reinforcement. And this flexibility to use or to ignore in the second phase the LCT technologies economically improved in the first period has an option value.

A second implication is an invitation to open reflection about the social efficiency of different designs of specific policy for each technology (CCS, large scale renewables, new nuclear). The externality related to learning effect invites to define a policy for pulling each technology deployment in case of occurring deployment restrictions on the other ones. The policy issue would be henceforth on the social efficiency of instruments to be developed to promote alternative low carbon technologies. To take the particular CCS case, a technological policy can be based on a CCS mandate on new equipments or as more usually on a subsidization of CCS plants to investment or to production (like feed in tariffs for renewables. A CCS mandate to invest in coal power plants is a second-rank policy which will be a priori less efficient than a more market-oriented policy). On its side subsidy is apparently efficient but it has has to be calibrated in relation to decreasing costs of successive CCS investments in situation of information asymmetry with regulator. Policy instruments have to be designed in relation to the characters of large scale and high upfront cost of low carbon technologies in a context of large uncertainties. But it is a completely different issue.

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