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Option values of low carbon technology policies: how to combine irreversibility effects and learning-by-doing in decisions

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Dominique Finon and Guy Meunier

Abstract

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Keywords investment, option value, learning-by-doing

JEL Classification D83, O33, Q55

Contact finon@centre-cired.fr
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EPRG WORKING PAPER

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

Guy MEUNIER[1]

Ecole Polytechnique and INRA—UR1303 ALISS

Dominique FINON

CNRS—CIRED

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In this paper, the political dilemma of the deployment of a large-size low carbon technology (LCT) is analyzed. A simple dynamic model is developped to analyze the interrelation between irreversible investments and learning-by-doing within a context of exogeneous uncertainty on carbon price. Contrasting results are obtained. In some cases, the usual irreversibility effects hold, fewer plants of the LCT should be developed when information is anticipated. In other cases, this result is reversed and information arrival can justify an early deployment of the LCT. More precisely, it is shown that marginal reasoning is limited when learning-by-doing, and more generally endogenous technical change, is considered. When information arrival is anticipated the optimal policy can move from a corner optimum with no LCT deployment to an interior optimum with a strictly positive development.

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[1] Corresponding Author – guy.meunier@polytechnique.edu, (33)+149596971

1 Introduction

Low carbon technologies (LCTs) are considered to be a major option for reducing emissions from the electricity industry, which is the main emitting industrial sector. The most promising options are: carbon capture and storage (CCS), the new nuclear, solar thermal plants, and offshore windpower farms. These technologies require high upfront capital investments and long construction lead-times. Such new large-size technologies must undergo a long and risky transition stage before they become commercially available (Grubb and Newbery, 2007). In the chain of innovations, these technologies are still at the stage of demonstration or early commercialization, and important ``learning-by-doing'' should be expected from first investments. These investments must be performed in a context of uncertainty surrounding the carbon price, which itself is related to the uncertainty of future climate policies, the cost of adaptation or scientific knowledge. Such uncertainty must be considered by a firm when deciding how much to invest in LCT equipment. Similarly, governments must consider uncertainty surrounding any future international climate regime when creating policies to support the deployment of LCTs. The public support to an LCT is justified by learning-by-doing and more generally by endogenous technical change, if there are spill overs from one firm to another (Arrow, 1962).

In the present article, an analytical model of a regulator's sequential choice of LCT plants in the context of uncertainty of the carbon price is developped. There are two periods and two technologies a LCT and a carbon technology. In the first period, the regulator chooses a particular number of LCT plants. In this period, because the LCT is more costly than the carbon technology, there is an opportunity cost to invest in the LCT; however, due to learning-by-doing, these first period investments reduce the costs of future LCT plants. The uncertainty of the carbon price translates into an uncertainty regarding the cost of the carbon technology. The influence of learning, which is in fact a process of acquiring information in the second period on the development of the LCT in the first period, is investigated. Two optimal investments in the LCT capacity are compared. These two investments minimize the aggregate expected costs in two scenarios, with and without learning of the true CO2 price in the second period. In both scenarios, in the first period, the regulator has an a priori uncertainty regarding the carbon price. In the "uninformed" scenario, the regulator has still no information in the second period; in the "informed" scenario, the regulator learns the true carbon price in the second period. The change from the first to the second scenario is interpreted as an increase in information. The objective function, the aggregated expected cost, is not convex because of learning-by-doing: the initial investment in a LCT constitutes a pure loss until the technology becomes competitive, it is only once this competitivity threshold is reached that a marginal (first-period) investment could reduce aggregate expected costs. This non-convexity plays a key role in the result.

It is shown that, if the expected price of CO_2 is high, the standard irreversibility effect holds: there should be less investment in LCT plants when information will be available than in an uninformed scenario. However, if the expected price of CO_2 is low and uncertainty is sufficiently high, larger investment in the LCT occurs when information will be available. More precisely, the LCT is not developed in the uninformed scenario, whereas in the informed scenario, a strictly positive quantity of plants is developed. This stresses the distinction of the two decisions: whether or not to launch an LCT policy, and its size. It is established that, with information acquisition, LCT policy should be launched earlier and, if launched, it should be smaller.

The present approach is in the tradition of the option value literature that analyzes how irreversible decisions are influenced by uncertainty and information acquisition. Initiated in the literature on environmental preservation, the standard irreversibility effect (Henry, 1974; Arrow and Fisher, 1974) explains that the prospect of obtaining information in the future should limit today's irreversible actions. Applied to analyzing firms' investment decision, the notion of option value emphasizes the idea that investing today eliminates the option to invest later and explains that investments are reduced by the prospect to obtain information (Bernanke, 1983; Pyndick, 1988; Dixit et Pyndick, 1994). However, it is now well-known that the sign of the effect of uncertainty (Rothshild and Stiglitz, 1971) and information acquisition (Epstein, 1980) on investments is ambiguous even in a simple model (Salanié and Treich, 2009).

Concerning the mitigation of CO2 emissions, there is a vast litterature that analyzes whether uncertainty and learning can justify an increase or a reduction of today's abatment. It has been shown that not only emissions irreversibility but also their accumulation determines the sign of the effect of learning on today's emission; and Ulph and Ulph (1997) show that the effect of emissions accumulation counteracts the effect of emissions irreversibility. They establish in a quadratic framework, that learning reduces today's effort if the emissions constraint is never binding (see also Karp and Zhang, 2006). Gollier et al. (2000) provide an analytical analysis of the interactions between accumulation and irreversibility of pollutant emissions (see also Lange and Treich, 2008). Kolstad (1996) considers the tension between two irreversibility constraints: the irreversibility of today's emissions and the irreversibility of clean capital investment. Kolstad (1996) concludes that the latter is more likely to be binding; thus, information acquisition implies that less investment should be committed in clean capital, but this neglects the existence of learning-by-doing, which is often mentioned as the main rationale of current policies toward LCTs. The effect of learning on abatement policy has also been investigated with numerical simulations, the results of which are contrasted (Keller et al., 2004). In particular the work of Ha Duong et al. (1997) emphasizes the role of socioeconomic inertia on the optimal path under uncertainty. They show that, with inertia, uncertainty justifies to increase effort in 2020. The time required for the process of learning-by-doing is a form of inertia.

In the present article, accumulation and irreversibility of emissions are not considered in order to focus on the specific role of learning-by-doing. Investments in a new technology motivated by the learning-by-doing benefit are quite similar to investments in R&D intended to reduce the cost of an LCT. The influence of uncertainty surrounding the carbon price on R&D spending has been previously analyzed by Larson and Frisvold (1996) and Baker and Shittu (2006), and the effect of information acquisition on the binary decision to launch or not launch an R&D effort on LCTs has been analyzed by Schimmelpfenning (1995). These authors obtained contrasting results. On one hand, the application of the result of Baker and Shittu (2006, proposition 3 pp 170) to our issue of learning investments leads to the conclusion that information acquisition should result in decreased investments. On the other hand, Schimmelpfenning (1995) concludes that the presence of uncertainty on the carbon price increases the value of an R&D project. The present analysis creates a bridge between these two approaches. Considering the two aforementioned studies, contrasting results in the present article are obtained for two reasons: first while Baker and Shittu (2006) focus on interior equilibria and use marginal reasoning, the present analysis highlights that marginal reasoning is not sufficient because of the non convexity specific to R&D and learning-by-doing investments, it is necessary to consider global conditions; second, Schimmelpfenning (1995) only considers a binary choice and does not analyze how the size of the project is affected by uncertainty when the project is launched.

Both R&D and learning-by-doing are examples of endogenous technical change. In the debate on climate policy, endogenous technical change is recognized as a key element to assess the optimal abatement strategy, and it has been incorporated in numerical models devoted to the analysis of climate policy (see Wing et al., 2006, for a review). The introduction of learning-by-doing into such models increases model complexity and problematic non-convexities. Manne and Barreto (2004) discuss the difficulties associated with these non-convexities; they emphasize that with standard algorithms there is no guarantee that a local optimum will also be a global optimum. This issue is also outlined in the recent work of Keller et al. (2004), and Lorenz et al. (2012) on the role of uncertainty on climate threshold damages.

In the simple model developped in the present article the non-convexity is easily handled, and the analysis shows how it interacts with the uncertainty of climate policy. Furthermore, the results of numerical models are highly dependent of their calibration. Even though a thorough numerical simulation is not done here, it is worth mentioning the difficulties to estimate learning rates and some associated issues that are relevant to interpret the results. For instance, McDonald and Schrattenholzer (2001) survey estimations of learning rates in the energy sector and show, for photovoltaics, how the same data sets can generate a large range of estimations. The difficulty to get a persuasive estimation of a learning curve is related to the reduced form nature of learning curves, particularly when they are used at a sectoral level, and not, as initially, at the plant or firm level (Nemet, 2006). The empirical observation of the decrease of an output price with cumulative production could be explained by several mechanisms. It could be difficult to disentangle the specific role played by learning-by-doing from the role of R&D, economies of scale and spillovers or even producers' pricing strategies (Sagar and Van der Zwaan, 2006; Jamasb, 2007). In the present work, it is simply assumed that the cost of an LCT plant decreases with cumulative investment. The precise mechanisms underlying this effect are not detailed; these mechanisms are important to accurately assess public policies toward LCTs, because they determine the need for such policies and their optimal design (Jaffe et al., 2005).

The rest of the paper is organized as follows. In Section 2, the model is introduced. In Section 3, the choices of LCT investment when information arrival is not anticipated (the uninformed scenario) when information is anticipated (the informed scenario) are compared. In Section 4, the assumptions of the model are discussed, and a numerical illustration is provided. Section 5 concludes.

2 Model

2.1 Framework

There are two time periods $t = 1;2$ and two technologies are available to produce a homogenous good. The first technology represents an LCT whereas the second technology is conventional carbon technology. The aggregate quantity of plants that should be built is fixed. For the sake of simplification, existing and new equipment are supposed to produce at full capacity to satisfy the demand during the two periods. The demand to supply in the first period is D_1 and the demand in the second period is $D_1 + D_2$. The production capacity that should be installed in the first period is D_1 and the production capacity that should be built in the second period is D_2. The demand is assumed inelastic in order to simplify the analytical model, this assumption is relaxed in the numerical application provided in Section 4. The cost of LCT plants is subject to learning-by-doing effects while there is uncertainty regarding the cost of the conventional carbon technology.

In the first period, a quantity x of LCT plants is chosen and the remaining $D_1 - x$ plants belong to the conventional carbon technology. In the second period, the D_2 additional plants are either LCT or conventional, depending on their marginal costs. The cheaper technology is used to produce all plants.
In the first period, the marginal cost of plants of both types is constant; the marginal cost of the LCT is c_1, and the marginal cost of the conventional is γ_1. Both are positive, and the conventional technology is cheaper than the LCT in the first period: $\gamma_1 < c_1$. The second period marginal cost of the LCT depends on x; it is denoted $c_2(x)$. Learning-by-doing is represented by the assumptions:

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

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

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

The second period cost of a conventional plant is $\gamma_2 + \theta$ where θ is a random variable that represents the uncertainty surrounding CO_2 emissions prices. The expected value of θ is 0, and γ_2 is the expected cost of the conventional technology, which is assumed to be lower than the cost of LCT if no LCT plants are built in the first period: $\gamma_2 < \bar{c}$. The random parameter θ is either negative at the level θ_l with probability π or positive at the level θ_h with probability $1-\pi$. The parameter θ represents the state of the world, it is identified with the difference between the actual cost of the conventional technology and the expected one.

It is important to note that the cost of LCT plants decreases with respect to preceding investments and not with respect to current investments. This assumption is used to cast the temporal dimension of learning-by-doing. If firms invest today, it makes LCT plants more competitive tomorrow. Learning gains cannot be immediately obtained by investing in LCT plants (a standard assumption in most models of learning-by-doing or knowledge diffusion). This temporal aspect of learning-by-doing is at the root of the option value of first period investments in the LCTs.

The costs functions should be addressed given the three following simplifications: the differences in cost structures (ratio of variable to sunk costs) are not considered, the cost of a conventional plant in the first period is not random, and the discount rate is only implicit. First, all costs are complete costs that encompass both investment costs and the sum of annual operation and maintenance fixed and variable costs, which are implicitly discounted. The variables costs are accounted for in the technology cost of the decision period. Second, the first period cost of the conventional technology is modeled as certain while its variable component is related to the CO_2 price. Thus, γ_1 should be considered as the long run expected marginal cost of conventional plants in the first period. By not introducing the uncertainty in the first period conventional costs, it is implicitly assumed that all conventional plants built in the first period are used in the second period. This means that the CO_2 price is not sufficiently large to justify stopping the use of a conventional plant to replace it with an LCT plant. Third, no discount rate is explicitly introduced , and its influence will not be investigated in this article; however, some remarks can be made. An increase in the discount rate would decrease all expected costs and, presumably, have a greater effect on LCT costs than on conventional costs because LCTs are generally more capital intensive than conventional technologies. In addition, an increase in the discount rate would also modify the random component and decrease its variance.

The distribution of θ is exogenous, the first period quantity of LCT plants does not influence the distribution and the value of the CO_2 prices. The implicit assumption is that the environmental damage is linear, so the second period optimal price of emissions is neither influenced by the first period emissions or the development of the LCT..This assumption is justified for a sector based analyzis if the sector under consideration is relatively small compared to the rest of the economy. Furthermore, uncertainty is resolved through time and the cost to acquire information, i.e. the cost of scientific research, is not modeled.

2.2 Timing and option value

The objective of the regulator is to minimize the cost of D_1 and D_2 plants. The aggregate cost in a state θ is:

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

To understand the influence of information discovery, the usual methodology of the option value literature is used. Two situations are compared in which θ is known or not known when the second period plants are built. In the the *uninformed* scenario θ is unknown when the second period technology is selected; the choice is based on the expected cost γ_2. This corresponds to the choice made when no information is obtained between the first and second period, or to the choice made by a regulator that does not anticipate that he will acquire that information (see Lorenz et al., 2012, for a discussion). It means that the regulator uses the expected CO_2 price to assess whether the LCT will be further developed in the future. Given that the expected value of θ is zero, the objective is:[2]

$$\min C(x,0) \quad (4)$$

The solution to this problem is denoted x^0.

The influence of information is analyzed by comparing the scenario above with an *informed* scenario in which the regulator anticipates obtaining information in the future. Formally, in the informed scenario, the second period technology is chosen once θ is known. The timing is:

1. x is chosen with prior belief on θ;
2. θ is learned and either LCT or conventional technology is used for the D_2 remaining plants.

In this case, the problem is:

$$\min \mathrm{E}[C(x,\theta)] \quad (5)$$

and its solution is denoted as x^L.

The value of information acquisition for any x is the difference:

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

$$C(x,0) - E[C(x,\theta)] \geq 0. \quad (6)$$

In the next section the optimal first period choice in the uninformed scenario is analyzed before considering the effect of information and the option value of LCT.

3 Optimal investments

3.1 Uninformed scenario

In this section, the optimal policy in the uninformed scenario, when information arrival is not anticipated, is analyzed. Learning-by-doing introduces a particular form of spillovers across periods in the production process: plants that are developed initially reduce the cost of following projects. The effect of first period LCT plants on the aggregated expected cost (eq. 3) with $\theta = 0$ is:

$$\frac{\partial C}{\partial x} = (c_1 - \gamma_1) + \begin{cases} 0 & \text{if } c_2(x) > \gamma_2 \\ \frac{\partial c_2}{\partial x}(x) D_2 & \text{otherwise} \end{cases} \quad (7)$$

The first term is the relative cost of an LCT plant as compared to the conventional carbon technology. As LCT plants replace conventional plants, this is the direct--first period--cost of an LCT plant. 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 as a result of learning-by-doing.

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

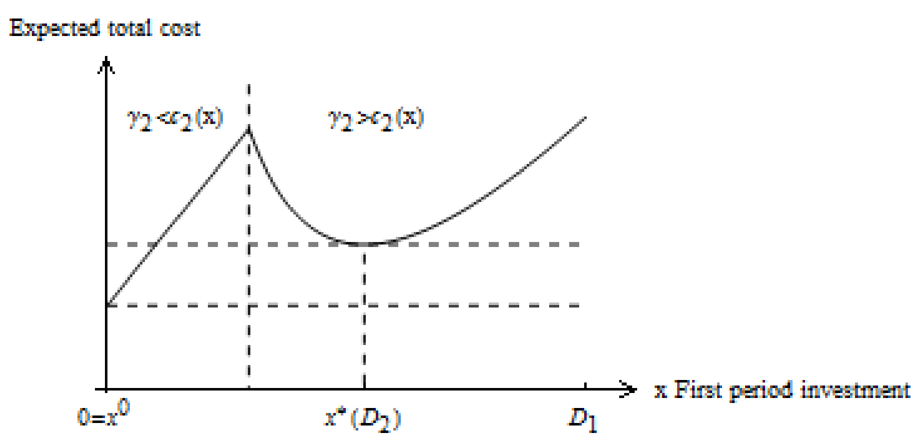


Figure 1: Expected cost with respect to first period LCT plants in the uninformed scenario with $c_2(x) = k_2 x^{-1}$

Figure 1 illustrates that a determination of whether LCT plants should be developed in the first period cannot be made by marginal reasoning but requires the comparison of aggregate costs with and without LCT development.
The solution of marginal reasoning would be $x^*(D_2)$ in which $x^*(D)$ is the quantity that minimizes the cost $(c_1 - \gamma_1)x + D c_2(x)$:

$$x^*(D) = \operatorname{argmin}\ (c_1 - \gamma_1)x + Dc_2(x) \text{ s.t. } x \geq 0, \tag{8}$$

$x^*(D)$ is the optimal quantity of first period LCT plants when a quantity D of LCT plants are built in the second period. This quantity is either 0 or the solution of the equation:

$$c_1 - \gamma_1 = -D_2 \frac{\partial c_2}{\partial x}(x). \tag{9}$$

In order to avoid situations in which all first period plants are of the LCT type, because it seems unrealistic and can make the exposition rather cumbersome, a further assumption is necessary; the number of first period plants should be sufficiently large. Thus, in the rest of the paper, it is assume that the quantities of plants D_1 and D_2 satisfy:

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

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). This ensures that the optimal quantities of LCT x^0 and x^L plants (eq. 4 and eq. 5) are strictly less than D_1.

Lemma 1 *A strictly positive quantity of LCT is developed in the first period, i.e.* $x^0 > 0$, *if and only if the conventional technology cost (*γ_2*) is strictly larger than* $\tilde{\gamma}_2$ *where:*

$$\tilde{\gamma}_2 = c_2(x^*(D_2)) + \frac{c_1 - \gamma_1}{D_2} x^*(D_2) \tag{10}$$

A strictly positive quantity of LCT plants is developed if learning effects are sufficiently important to compensate for the loss due to the relatively higher cost of the LCT in the first period. The condition $\gamma_2 > \tilde{\gamma}_2$ stands for a global and not a marginal comparison of costs. Two situations in which marginal reasoning would be misleading can arise because there are two local minimums one at 0 and the other one at $x^*(D_2)$, in both cases the necessary marginal conditions to be a minimum are satisfied but these are not sufficient given that the expected cost function is not convex.

3.2 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 on the true cost of the conventional technology. If this technology turns out to be cheap ($\theta = \theta_l$), the LCT might be useless and the learning-by-doing effects are wasted. However, if the conventional technology turns out to be expensive ($\theta = \theta_h$), the learning-by-doing effects are valuable. The former effect, the possibility of finding that the LCT is worthless, is at the root of the standard irreversibility effect, while the latter can justify an early development of LCT plants that would not have been completed without information anticipation. First period LCT plants might be more valuable with information because they increase flexibility by decreasing the costs of following plants.

Formally, the expected cost with information is:

$$E[C(x,\theta)] = \gamma_1 D_1 + (c_1 - \gamma_1)x \quad (12)$$
$$+\begin{cases} \gamma_2 D_2 & \text{if } c_2(x) \geq \gamma_2 + \theta_h \\ [(1-\pi)(\gamma_2+\theta_l)+\pi c_2]D_2 & \text{if } \gamma_2+\theta_h > c_2(x) \geq \gamma_2+\theta_l \\ c_2 D_2 & \text{otherwise.} \end{cases}$$

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

$$\frac{\partial E[C(x,\theta)]}{\partial x} = c_1 - \gamma_1 + \begin{cases} 0 & \text{if } c_2(x) \geq \gamma_2 + \theta_h \\ \pi D_2 \dfrac{\partial c_2}{\partial x} & \text{if } \gamma_2+\theta_h > c_2(x) \geq \gamma_2+\theta_l \\ D_2 \dfrac{\partial c_2}{\partial x} & \text{otherwise} \end{cases} \quad (13)$$

The interesting situation is the intermediary one in which LCT plants are used in the high carbon cost state but are not included in the low carbon cost state. In the two other cases expected costs with information are equal to costs without information. Figure (2) depicts the two costs in a situation where there is no development of the LCT without information but there is with information. The distance between the two curves is the value of information.

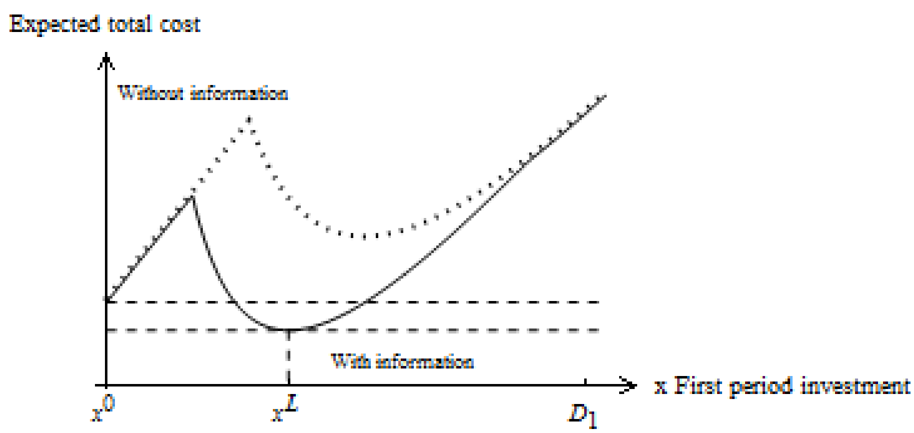


Figure 2: Expected cost as a function of the quantity of first period LCT plants in the informed (dotted curve) and uninformed (solid curve) scenario, with the specification $c_2(x) = k_2 x^{-1}$.

Proposition 1 *If $\gamma_2 > \tilde{\gamma}_2$ (cf. eq. 10)there is less LCT developped 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

$$c_1 - \gamma_1 < \pi D_2 \frac{\partial c_2(0)}{\partial x} \quad (14)$$

$$\gamma_2 + \theta_l < c_2\left(x^*(\pi D_2)\right), \quad (15)$$

$$\gamma_2 + \theta_h > c_2\left(x^*(\pi D_2)\right) + \frac{c_1 - \gamma_1}{\pi D_2} x^*(\pi D_2) \qquad (16)$$

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

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

The proposition sets conditions under which the classical irreversibility effect does or does not hold. For some range of parameters, the irreversibility effect holds. If the LCT is developed without information, the anticipation of information arrival reduces the benefits from first period LCT plants because the LCT may go unused if the conventional technology is cheaper than expected. In this case, it is worth waiting and postponing investment in the LCT. However, Proposition 1 proves that for other ranges of parameters, the irreversibility effect is reversed, information acquisition can justify an early development of LCT. If γ_2 is large, the anticipation of information arrival and the possibility of discovering that the LCT is necessary increase the value of first period plants and can, consequently, justify investments. In that case, consequent cost reduction is sufficient to trigger further deployment of the LCT only in the case of a stringent CO_2 policy ($\theta = \theta_h$); it is not sufficient in the case of a lax policy ($\theta = \theta_l$) A situation in which it is found (against the classicla ireeversibility effect) that the should be used can only occur if the LCT is not developped in the uninformed scenario. Thus, the irreversibility effect is only reversed in the case in which there is no investment in LCT plants in the uniformed scenario. For this last situation to hold, the difference between the two possible cost $\theta_h - \theta_l$ should be sufficiently important. Note that if:

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

the two conditions (15) and (16) are superfluous, and (14) is sufficient to ensure that $x^L > 0$.

The misleading nature of marginal reasoning is illustrated by Figure (2); in the case depicted, the expected cost without information (the dashed curve in the figure) decreases at x^L; thus, if the optimal policy x^0 were an interior solution of the optimization problem, it would be larger than x^L. The expected cost without information is decreasing at x^L because LCT is more likely to be used with information than without it. It is therefore true that if x^L has been already built it would be rational to further develop the LCT technology in the first period to $x^*(D_2)$.

3.3 Discussion

The simplicity of the model could naturally be criticized for lack of realism. Three simplifying assumptions are discussed: (i) the number of periods used, (ii) the state distribution and (iii) demand elasticity.

First, the use of a two-periods framework is common in option value literature. In our case, one limit of this simplification is that the learning-by-doing associated with the second period plants is not considered. If we do not invest in LCT today, learning-by-doing benefits could still be obtained from later investment after information acquisition. The assumption that investment in the first period reduce the cost, thanks to the learning effect, only in a second period could be justified by the large time-span of construction and return on experience. This timespan is particularly important for complex technologies. Nevertheless to model an analysis with more periods that would take into account the successive learning-by-doing effects and scale economies in the equipment industries, it would require to specify the timing of information revelation and demand growth (see Karp and Zhang, 2006). This would raise the following questions: When and in which information set should the LCT policy be launched? Which scale the LCT deployment should have ideally ? A priori, the same kind of effect that has exhibited in the present analyzis would be at work in any information set. The present framework could describe the particular situation where, in the second period, all information is obtained and demand stops increasing. It is relevant for addressing the current situation of the European electricity sector because it is at an intersection between the need for new investments and high uncertainty concerning future CO_2 regulation, even if all uncertainties would not be resolved in the ten next years. If a third period is simply added while all uncertainties are resolved at the second period but demand still grows in the third one, the second-period LCT investments would be more valuable because of learning-by-doing. In such case, the results would still hold but the threshold cost $\tilde{\gamma}_2$ would be smaller and the optimality of the early development situation less likely.

Second, concerning the distribution of the carbon price, a continuum of states of the world does not solve the issue of non-convexity and marginal reasoning would still be limited in that case. With a more general distribution of demand state our results would not be significantly modified, and, the effect at stake would be similar, however, more painfully exposed. A related matter is that two extreme cases are compared here: without and with information and it would be possible to analyze more general changes in the distribution of demand states, as an increase in risk (Rothshild and Stiglitz, 1970), on the optimal quantity of LCT plants. Such an analysis would lead to ambiguous results that are similar to those obtained in the seminal work of Rothshild and Stioglitz (1971) as well as in the more recent, and more closely related, work of Baker and Shittu (2006). These ambiguities would be obtained by comparing interior equilibriums. The insight of the present work is not the mere possibility that in some situations an increase in risk can imply an increase of an irreversible investment, a result that is well-known since the work of Rothshild and Stiglitz (1971), but the fact that an increase in risk can move the global optimum from a corner (in which the LCT is not developped) to an interior equilibrium and that marginal reasoning could be misleading.

Third, in the framework, the quantity of plants developed in each period was considered to be exogenous i.e., demands were assumed to be price inelastic. With this assumption, the non-convexity introduced by learning-by-doing was clear and easily handled. With elastic demands, there are more variables to be chosen in the first period: not only the quantity of LCT plants but also the total quantity of plants. More precisely, if the social surplus created by plants in period $t = 1{,}2$ is denoted by S_t, the social welfare in a state θ would be

$$W(D_1, D_2, x, \theta) = \quad S_1(D_1) - \gamma_1 D_1 - (c_1 - \gamma_1)x + \left[S_2(D_1 + D_2) - \min\{c_2(x), \gamma_2 + \theta\} D_2\right] \quad (17)$$

and D_2 would be chosen with or without information. In a state θ it would solve the first order condition $S_2'(D_1 + D_2) = \min\{c_2(x), \gamma_2 + \theta\}$. The non convexity that was exposed in the simple model is also present in such a model; it is related to the need to invest sufficiently in LCT plants to make them competitive. The effect stressed with the simpler version would still hold and explain the possibility of situations in which the LCT is not developed without uncertainty but is developed with uncertainty. However, in the other case, where the LCT is developed without uncertainty, the comparison is less straightforward because of a cross effect. With information, the total quantity of first period plants D_1 should be smaller (as the irreversibility effect suggests), and this reduction induces more plants to be built in the second period and this increase has a positive effect on the marginal value of LCT plants. The substitution between first and second periods plants would increase the incentive to invest in LCT today. Because of this cross effect the model is hardly solvable and the comparison between the local optima difficult. However, even though a full analytical analyzis is not provided this issue is partly adressed in the numerical illustration that follows.

4. A numerical illustration

To complete the formal analyzis a numerical illustration is performed. This illustration is used to partly adress one of the limitations mentionned, the inelasticity of demand, and to consider the effect of some key parameters: the learning rate, the expected CO_2 price and volatility. The illustration is based on the case of coal power plants and Carbon Capture and Storage (CCS).

The two periods are 2015-2030 for t=1, and 2030 and beyond for t=2. Two yearly demand functions are calibrated and two surplus $S_1(D_1)$ and $S_2(D_1 + D_2)$ are obtained from these demands with a proper discounting. The welfare function in a state θ is $W(D_1, x, D_2, \theta)$ given by eq. (17). In the uninformed scenario the objective is

$$\max_{D_1, x, D_2} E[W(D, x, D, \theta)] = \max_{D_1, x, D_2} W(D, x, D, 0)$$

And in the informed one

$$\max_{D_1,x} E[\max_{D_2} W(D,x,D,\theta)].$$

4.1. Parameters choice

The conventional technology is pulverized coal conbustion power generation without CO_2 capture and the LCT is the same technology with a post-conbustion capture equipment. The calibration of costs is presnted in Table 1. These assumptions are from MIT (2007). Each cost is composed of an investment part, that represents the cost to build the capacity and a variable part that is composed of three terms: operation and maintenance costs, fuel costs and CO_2 cost. All costs are normalized and expressed in $/kW. Concerning the first-period conventional cost $\gamma_1 = \gamma_{1k} + \gamma_{1w}$ the variable part is it self decomposed into two parts because it is modified by the CO_2 price in the second period.

The expected CO_2 price in 2030 is 40$/t CO_2. The distribution is assumed to be symmetric, the CO_2 price is either 50$/t (in θ_h) or 30$/t (in θ_l) with probability 0.5 ($\pi = 1 - \pi = 0.5$). The probability of being in either states is kept constant at 0.5. Therefore, the distribution of the prices of CO_2 is characterized by its mean and the difference between the two CO_2 prices. This difference is denoted Δp_{CO2}, it is 20$/t in the central set of assumptions.

	Conventional	LCT
Investment ($/kW)	1300	3000
O&M ($/kW)	400	1150
Fuel ($/kW)	800	850
CO2@40$/t	1700	0

CO_2	
$E[p_{CO2}]$ ($/t)	40$/t
$p_{CO2}(\theta_h)$ ($/t)	50$/t
$p_{CO2}(\theta_l)$ ($/t)	30$/t
π	0.5

Table 1: assumptions about costs.

Concerning the second period LCT cost, it is modeled by

$$c_2(x) = \underline{c} + (\bar{c} - \underline{c})(x/x_0)^{-l}.$$

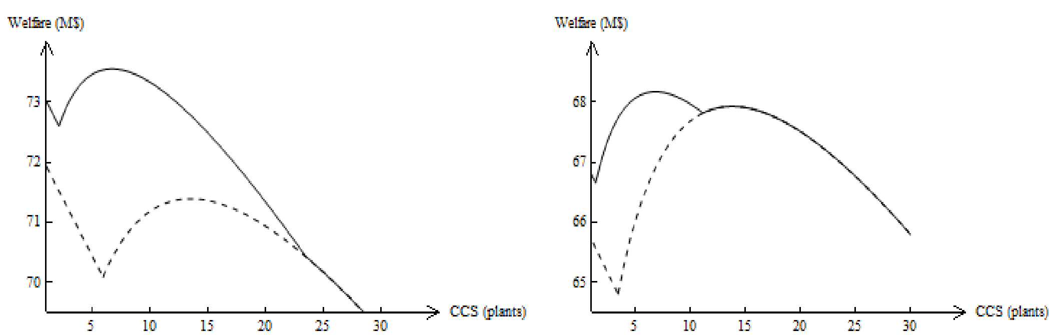
The secondt term represents the part of the cost that is subject to learning-by-doing effects. The parameter $-l$ is the elasticity of this term with respect to cumulative investment. The learning rate is $1-2^{-l}$, that is, the relative cost reduction for each doubling of capacity. According to MacDonald and Schrattenholzer (2001) the average learning rate is 15% for the energy sector. This estimated is used together with the assumption that the floor cost $\underline{c}$ is slightly larger than the cost of a conventional coal plant (without emissions cost), it is set at 2600 $/kW. is .

Finally, concerning the demand, in each period t=1,2 the yearly demand is represented by a linear price function $p_t(D) = a_t - b_t D$, the corresponding yearly consumer surplus is $(a_t - 0.5b_t D)D$. These surplus are discounted to get S_1 and S_2 by $(1-\delta^{15})/(1-\delta)$ and $\delta^{15}/(1-\delta)$ respectively. The inverse price function is calibrated so as to have a market of 300GW initially for an electricity price of 50$/MWh and an elasticity of -0.7 (see the survey of Espey and Espey, 2004). In the second period the market is twice larger than in the first period. This growth of the market can be originated either from an increase of demand or a reduction of avalaible capacity. A doubling of the demand in fifteen years correspond to a yearly growth rate of 5%, which is an intermediary situation between OECD countries and the BRICs. The coefficients are

$$a_1 = a_2 = 115.3\$/kWh \text{ and } b_1 = 2b_2 = 2.3.10^{-8}\$/(kWh)^2.$$

4.2. Results

First, the comparison of welfare is done in Figure 3. As could be seen in Figure 3a, with the central set of assumptions, no CCS plants should be built in the uninformed scenario whereas approximately 6 plants should be built in the informed scenario. However, with an expected CO_2 price of 45$/t as in Figure 3b, the picture is different and a positive amount of CCS should be invested in both scenarios and more in the uninformed than in the informed one. The optimal policies and the comparison of these policies seems to be highly sensitive in a neighborhood of the central set of assumptions.



3a Ep_{CO2}=40$/t   3b Ep_{CO2}=45$/t

Figure 3: Expected Welfare in the informed (plain line) and the uninformed scenario (dashed Line) as a function of the number of CCS plants.

The effect of the learning rate is of particular significance as it is at the root of the option value created by LCT develoment. The comparison of the two scenarios is completed in Figure 4. In Figure 4, for small learning rates (region A) there is no LCT plants developed in the first period in both scenarios; for slightly larger values (region B), there are some plants developed with information and no plants developed without information; for large learning rates (region C) there are plants developed with and without information and both quantities eventually coincide (region D). Thus, for large learning rates (regions C and D) it is worth developing LCT in any cases and the possibility of learning that the LCT is not necessary calls for a prudential development of the technology in the informed scenario. It is for intermediary learning rates (region B) that future information can justify an early development of LCT. In that case, the cost reduction is sufficient to trigger further deployment of the LCT only in the case of a stringent CO_2 policy ($\theta = \theta_h$); it is not sufficient in the case of a lax policy ($\theta = \theta_l$).

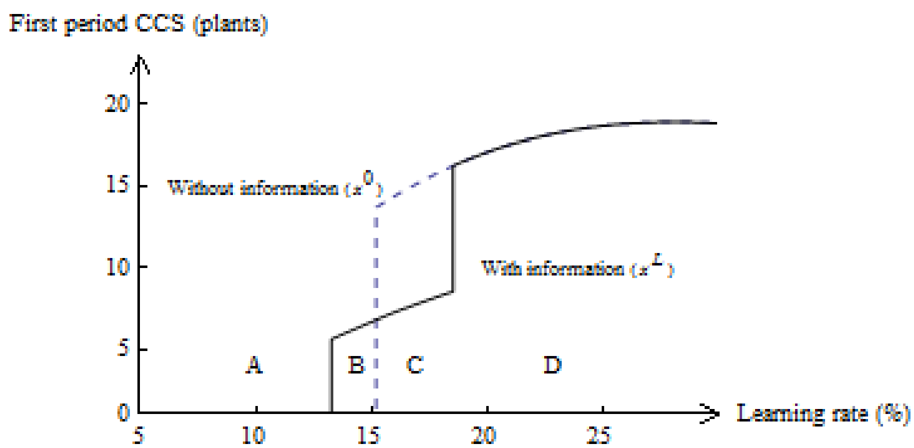


Figure 4: Optimal quantity of LCT plants and learning rate, in the informed scenario (plain line) and the uninformed scenario (dashed line).

On Figure 4 the sets B and C in which the two optimal policies differ are relatively small, even though they concern relevant values of learning rates. In Figure 5, the optimal policies with the two scenarios are depicted with a wider distribution of CO_2 prices. In Figure 5, the price of CO_2 is either 60$/t or 20$/t. The distinction between the two scenarios is amplified and the sets in which the two scenarios differ are enlarged by an increase of the variance of the distribution of the CO_2 price.

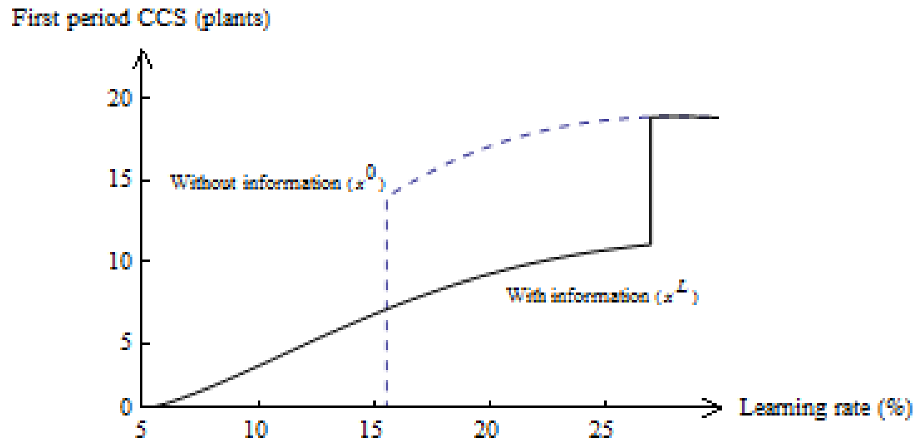


Figure 5: Optimal quantity of LCT plants and learning rate, in the informed scenario (plain line) and the uninformed scenario (dashed line), with $E[p_{CO2}] = 40\$/t$ and $\Delta p_{CO2} = 40\$/t$

A similar analysis can be performed regarding the expected CO_2 price. In Figure (6), the two optimal policies are depicted with two different variances of the CO_2 prices distribution. In Figure 6a, the central assumption $\Delta p_{CO2} = 20\$/t$ is used and in Figure 6b the distribution is wider with $\Delta p_{CO2} = 40\$/t$. The same patern as previously is observed. In both cases, as the CO_2 price increases four situations successively occurs. For small price (region A) the LCT is not developped in neither scenarios. For intermediary value it is only developped in the informed scenario (region B) then in both with a larger development in the uninformed one (region C). Eventually, both policies coincide for large CO_2 prices (region D). The intermediary regions B and C, in which the two policies differ, are enlarged when the distribution of the CO_2 price is increased.

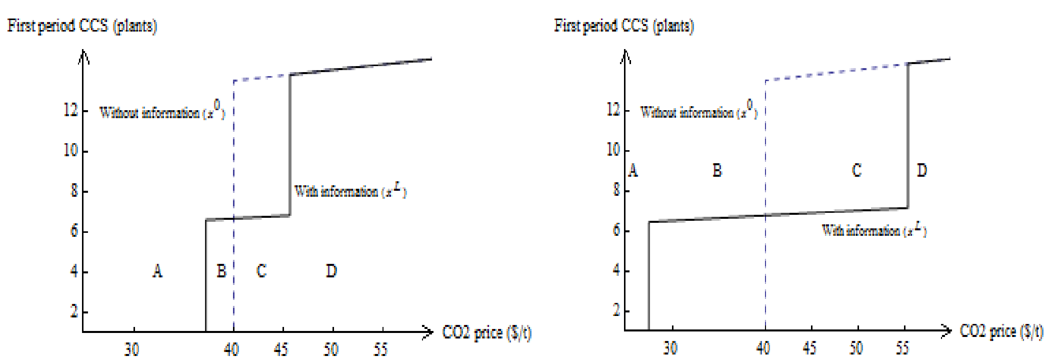


Figure6a $\Delta p_{CO2} = 20\$/t$ Figure 6b $\Delta p_{CO2} = 40\$/t$

Figure 6: Optimal quantities of LCT plants with respect to the expected CO_2 price in the informed (plain line) and uninformed (dashed line) scenarios. With two amplitude of variations.

▪ 5 Conclusion

The aim of the present work was to solve an apparent contradiction in the literature and in intuitive thinking on investments in LCTs in situations of uncertainty on the future carbon price: on the one hand, these policies open options, and on the other hand, uncertainty usually calls for careful investment policies. A simple analytical model was used to resolve this contradiction. The analysis showed how the anticipation of information acquisition influences the two decisions: the choice to launch an LCT policy and the choice of its size. The perspective to acquire information increases the incentive to launch a LCT policy, but it also calls for a reduction of its size. Therefore, if the decision maker does not invest when he ignores future information discovery, he could be incited to do so when anticipating the future revelation of information; but, if he does implement an LCT policy when ignoring information discovery he should have to reduce it when anticipating information arrival. The key to this result is the possible move from a corner equilibrium to an interior equilibrium when information arrival is anticipated.

An essential feature of the model is the existence of multiple local optima. This multiplicity is related to learning-by-doing, and more generally to endogeneous technical change. The initial investment in a technology constitutes a pure loss until the technology becomes competitive. It is only once this competitivity threshold is reached that a marginal investment could increase welfare. A numerical illustration was done to extend the analyzis to a framework with a welfare function and to consider the effect of the learning rate and the distribution of the CO_2 price.

The model does not, in itself, identify a justification for policy intervention toward LCTs. Such a policy is justified if there are spillovers effects from one firm to another. If this is the case, two important lessons could be deduced.

A first lesson is related to the non monotonicity of marginal welfare with respect to the investment in LCT. Governements witnessing the financial costs of the support to renewable energies are contemplating this `non-convexity'', a support policy should be sufficiently important in order to ensure that LCTs are competitive. These policies constitute a bet; whether the cost to subsidize LCTs today is worth will depend on their relative cost tomorrow. Many uncertainties surround these relative costs among which the uncertainty of the future price of greenhouse gas emissions. The terms of this bet should be acknowledged. A support to LCT opens an option to face high carbon price and the size of this support should integrate the possibility that the carbon price be lower than expected.

The second lesson is with respect to LCT policies that are decided by ignoring uncertainty and considering an expected carbon price. It is important to stress that the anticipation of information arrival does not constitute an argument to stop these policies but only to downsize them. The move from a corner optimum with no support to LCT to an interior optimum with a strictly positive support arise when information is anticipated and not the other way around.

Several limits of the model have also important consequences in terms of policy, two of them are worth further investigations. First, the uncertainty surrounding the carbon price was considered exogeneous. It is important to recognize that this uncertainty could be reduced by investing in research and international cooperation. It would be interesting to analyze whether investment in scientific research on climatic change is a substitue or a complement to investment in technological options. Second, the analyzis considers only one general LCT whereas an important issue is the choice of a portfolio of LCTs. To analyze this issue would require to consider the uncertainties surrounding learning curves which was ignored in the present article.

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- **Appendix**

Proof of Lemma 1

The application $\psi : x \to (c_1 - \gamma_1)x + c_2(x)D_2$ is strictly convex and minimized at $x^*(D_2)$.
The cost $C(x,0)$ is:

$$C(x,0) = \gamma_1 D_1 + \begin{cases} (c_1 - \gamma_1)x + \gamma_2 D_2 & \text{if} c_2(x) > \gamma_2 \\ \psi(x) & \text{otherwise} \end{cases} \quad \text{(A1)}$$

As $\gamma_2 < \bar{c}$ (by assumption) $C(0,0) = \gamma_1 D_1 + \gamma_2 D_2$. $C(x,0)$ is minimized either at 0 or $x^*(D_2)$ (possibly at both); in the latter case, if $x^*(D_2) > 0$ then $c_2(x^*(D_2)) < \gamma_2$ and $C(x^*,0) = (c_1 - \gamma_1)D_1 + \psi(x^*)$. With these preliminaries we can prove the equivalence stated.
($\Rightarrow$) If $x^0 > 0$, then $x^0 = x^*(D_2)$ and $x^*(D_2) > 0$, so $C(x^*,0) = \gamma_1 D_1 + \psi(x^*)$. Replacing both members of the inequality $C(x^*,0) < C(0,0)$ by their expressions (from (A1) and above preliminaries) implies $\gamma_2 D_2 > \psi(x^*)$ and dividing both sides by D_2 gives $\gamma_2 > \tilde{\gamma}_2$.
($\Leftarrow$) If $\gamma_2 > \tilde{\gamma}_2$, then $\gamma_2 > c_2(x^*)$ and $x^*(D_2) > 0$ (because $\gamma_2 < \bar{c}$); therefore, $C(x^*,0) = \gamma_1 D_1 + \psi(x^*)$ and the inequality $\gamma_2 > \tilde{\gamma}_2$ implies $C(x^*,0) < C(0,0)$ (by multiplying both sides by D_2 and adding $\gamma_1 D_1$).

Proof of proposition 1

Few preliminaries are necessary.

First, the function $x^*(D)$ is strictly increasing, this can be shown by derivating equation (9) with respect to D and using the fact that c_2 is convex (cf eq. 1).

Second, x^L is either 0, $x^*(\pi D_2)$ or $x^*(D_2)$. x^L is defined as the smallest argmin of the expected cost given by (12). The expected cost is twice differentiable by parts; if it is differentiable at x^L its derivative is null and x^L is either $x^*(\pi D_2)$ or $x^*(D_2)$. There are three points where the expected cost is not differentiable : 0, $c_2^{-1}(\gamma_2 + \theta_l)$ and $c_2^{-1}(\gamma_2 + \theta_h)$. Let us show that if x^L is one of these points then it is 0:

- x^L cannot be $c_2^{-1}(\gamma_2 + \theta_l)$ because expected cost are larger at this point than at 0;

- if $x^L = c_2^{-1}(\gamma_2 + \theta_h)$ then $x^*(\pi D) \geq x^L$ (because $E[C(x,0)]$ is decreasing to the left of x_L) and $x^L \geq x^*(D_2)$ (because $E[C(x,\theta)]$ is increasing to the right of x_L), so $x^*(D_2) \leq x^*(\pi D_2)$, a contradiction (because x^* is increasing in D and $0 < \pi < 1$)

The proposition can now be prooved

- If $\gamma_2 > \tilde{\gamma}_2$, the LCT is developed without information and $x^0 = x^*(D_2) > 0$. With information, the expected cost $E[C(x,\theta)]$ is minimized either at 0, $x^*(\pi D_2)$ or $x^*(D_2)$ all of which are smaller or equal than $x^*(D_2)$ so $x^L \leq x^0$.
- Otherwise, if $\gamma_2 < \tilde{\gamma}_2$, the LCT is not developed without information: $x^0 = 0$. Condition (14) implies that $x^*(\pi D_2) > 0$. Inequalities (15) and (16) ensure that $x^*(\pi D_2)$ locally minimizes $E[C(x,\theta)]$ because $\gamma_2 + \theta_l < c_2(x^*(\pi D_2)) < \gamma_2 + \theta_h$, and $x^*(\pi D_2) > 0$ so $\partial E[C(x^*(\pi D_2),\theta)]/\partial x = 0$. And finally (16) implies that $E[C(x^*(\pi D_2),\theta)] < E[C(0,\theta)]$