Extending the limits of the abatement cost

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Abstract

Public authorities have to decide whether to support projects to mitigate GHG emissions. In the context of the transition toward Net Zero Emissions, all polluting activities need be decarbonised one day or the other, and the two questions are when and how. The paper proposes the relevant dynamic cost benefit framework to evaluate decarbonization projects. We derive two metrics of abatement cost, the first one to determine when to implement a given project, and the second one to compare alternative projects. Our methodology is not a simple extension of current abatement metrics which ordinarily would provide spurious answers. We generalize our metrics to situations with exogenous technical change, a random arrival of a backstop, and different growth rates of the social cost of carbon. We show how to incorporate endogenous technical change and spillovers between sub-components of a project. Two applied studies are revisited to highlight the interest of our approach.

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1 Introduction

Many studies analyze the transition paths of technologies to a Net Zero Emission (NZE) target through complex multisectoral models.[1] In practice, public authorities, whether local or national, often must decide whether to fund finite-life "projects" based on simpler studies in which the incremental costs and the environmental benefits relative to Business As Usual (BAU) are the only key elements. To decide whether a project should be eligible to public support, a common practice consists in calculating an abatement cost: the cost per tCO_2 avoided and compare it with the Social Cost of Carbon (SCC). However, in the context of NZE the relevant question is not *whether* an activity should be decarbonized (any emitting activity should be) but *when* and *how*. Therefore, the proper evaluation of a project requires to determine when it should be implemented and compare it with competing projects (able to decarbonize the same source). To do so, we propose a relevant dynamic Cost Benefit Analysis (CBA) framework and derive two metrics to answer the questions of when and how. The methodology proves to be a simple and versatile tool to take into account relevant aspects of decarbonization trajectories and overcome shortcomings of traditional abatement cost metrics such as their inability to take into account inertia and endogenous technical change (Gillingham and Stock, 2018).

To start with we consider that for achieving the NZE target, the projects under consideration should be *extended* to ensure the perpetual decarbonization of the polluting activity. The extended project would then typically include a transitory phase (possibly the finite-life project as such) followed by a steady state phase in which full decarbonization is maintained through some future incremental costs. Along the transitory phase abatements progressively increase until emissions are null.

To illustrate the need for a reformulation of current metrics, consider a finite-life project, extending over several years, intended to decarbonize a pre-existing polluting activity. There are two standard approaches to compute the abatement cost of such project, they both consider the discounted cost of the project but differ with respect to the discounting of abatements over the life of the project. The common approach, inspired by the levelized cost of energy, discount abatements with the social discount rate. For instance, Friedmann et al. (2020) label this metric the Levelized Cost of Carbon Abatement (LCCA) and apply it to compare various projects. Such metric is grounded in cost-effectiveness analysis and is valid, to compare projects, if they abate the exact same profile of abatement, which is not the case for large scale projects with a progressive ramping of abatement over years. Another metric was proposed by Baker and Khatami (2019) who argue that the dynamic of the SCC should be taken into account. From a static cost benefit analysis they derive the Levelized Cost of Carbon (LCC) in which abatement are discounted with the difference between the social discount rate and the growth rate of the SCC. If the Hotelling's rule hold, which is consistent with a carbon budget, abatement are not discounted and simply summed over the life time of the project. However, if one considers an extension of the project with perpetual renewal the LCC drops to zero, which indicates that it is not a relevant tool to evaluate and compare long-term decarbonization trajectories consistent with the NZE.

[1] see for instance https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze, and https://europeanclimate.org/net-zero-2050/

Our approach is a non trivial extension of these two approaches, we also start from a CBA for answering the question of when to launch an extended project and introduce time considerations for ranking competing extended projects. More precisely, under the Hotelling's rule, we prove that the extended project should be launched when the Social Cost of Carbon (SCC) equalizes the Dynamic Abatement Cost (DAC); the DAC being defined as the annualized overall cost of the extended project divided by the long term annual abatement (Proposition 1). It is remarkable that intermediary abatements, abatements occurring during the ramping up to the steady state phase, play no role in this new metric. The question of comparing competing projects (to decarbonize the same pre-existing activity) requires to first determine the optimal launch time of each project and then select the one which minimizes total emissions until full decarbonization (Proposition 2). Interestingly, this procedure amounts to defining a second metric, it is related to the DAC but adjusted to take into account intermediary abatements (Proposition 3). Our analysis shows that the notion of abatement costs hides surprises, since the two issues for which abatement costs are typically used (when and how) require two different metrics if there are intermediary abatements. Only in the special case in which there are no intermediary abatements the DAC coincides with the LCCA and can be used to both determine the launch time and compare projects. We generalize these results to several relevant situations: exogenous technical progress (Proposition 4); random arrival of a backstop technology (Proposition 5); and a SCC trajectory that departs from the Hotelling's rule (Proposition 6). We show how learning-by-doing and spillovers can be integrated into our approach and derive some interesting results (Propositions 7 and 9).

Our contribution bridges a gap between climate policy practices, the computation of abatement costs, and the theory of cost benefit analysis. CBA is ordinarily considered in a static environment (e.g. Sartori et al., 2014; Atkinson and Mourato, 2015), and how well suited the current CBA methodology copes with the dynamic aspect of the energy transition is worth revisiting. For the energy transition a key feature is that the SCC is growing over time which induces new issues to be addressed.[2]

To the best of our knowledge, only two previous articles provide interesting conceptual steps in that direction: Vogt-Schilb et al. (2018) and Creti et al. (2018). Vogt-Schilb et al. (2018) introduce adjustment costs, that is, convex investment costs in clean capital, in a model of the energy transition. They show that standard metrics of abatement costs can be misleading and should be corrected to account for the time needed to decarbonize an activity.[3] Some options that are apparently more expensive than others should be deployed earlier because of their larger potential. Creti et al. (2018) analyze the replacement of a given fleet of polluting vehicles by clean ones subject to learning-by-doing, and propose to overcome the difficulty associated with the computation of the abatement costs of each

[2]Indeed, there is large theoretical literature on investment in capital that substitutes an exhaustible resource, the price of which follows Hotelling's rule, or some generalization of it (e.g. Dasgupta and Heal, 1974; Stiglitz, 1974; Dasgupta and Heal, 1979, for seminal contributions). Among these, numerous contributions have considered endogenous technical change, from Kamien and Schwartz (1978) to Grimaud and Rouge (2008).

[3]Indeed along the optimal trajectory marginal abatement costs are equal to the SCC, they should encompass the evolution of clean marginal investment cost whereas standard myopic calculations are based on current costs. This point relates to the notion of user cost of capital (Jorgenson, 1967).

vehicle by taking a "deployment perspective": a given trajectory is considered and the optimal launch date is determined through a relevant dynamic metric. Creti et al. (2018) introduce the idea of the DAC in that specific context. We generalize this idea along several lines, notably for the comparison of competing projects.

From an applied perspective, our approach greatly facilitates the incorporation of learning-by-doing and spillovers into the evaluation of decarbonization options as recommended in a number of papers (e.g. Kesicki and Ekins, 2012; Popp et al., 2010; Gillingham and Stock, 2018). More precisely Gillingham and Stock (2018) stresses that myopic abatement costs do not integrate relevant dynamic features. They distinguish four such features: learning-by-doing, R&D spillovers, indirect network effects, investment irreversibility and inertia. Indeed, each of these elements has been analyzed in the literature on climate policy (e.g. Manne and Richels, 2004; Goulder and Mathai, 2000; Meunier and Ponssard, 2020; Vogt-Schilb et al., 2018). However, there is no attempt to provide a practical procedure to integrate these aspects into a relevant metric of abatement cost. Our general formulation of an extended project fills this gap. As a matter of fact, part of our motivation comes from challenges we faced in our own applied studies.[4] In each of these evaluations a key aspect was left open: what is supposed to happen at the end of the finite-life project? This is a crucial question since the project is only one element in a much longer trajectory of actions that aims to ultimately decarbonize the activity. Because the project is expected to generate future benefits for the overall decarbonization process these longer-term benefits should ideally be integrated in the evaluation.

The paper is organized as follows. In section 2 we revisit the limits of the current metrics in the context of the NZE. In Section 3, we formally define our new metric and show how it can be used to obtain the optimal launch time of a project and to compare competing projects. This is done under the assumption that the social cost of carbon grows at the same rate as the social discount rate and that the characterisitcs of the extended project do not depend on calendar time. In section 4, we show how the results should be modified when this assumption does not hold. In section 5 we consider the cases of learning-by-doing and spillovers. In section 6, two empirical projects are reformulated and analyzed as extended projects. Section 7 presents our conclusions. Appendix A provides the proofs. Appendix B explicits the differences between our metric and traditional ones through an illustrative example.

2 The limits of current metrics in the context of a project consistent with the NZE

In this section, we revisit two common metrics of abatement costs and explain their main limitations, which will allow us to motivate our approach and precise for which type of projects it is particularly relevant.

The notion of project, while the term is commonly used in practice, is not clearly de-

[4]These evaluations comprise: EAS-Hymob (Brunet and Ponssard, 2017), Zero Emission Valley (Teyssier d'Orfeuil, 2020) in France, H-Vision in the Netherlands and HyNet NW in the UK (Athias, 2020), and fuel cell electric buses for European metropolitan areas (Meunier et al., 2019).

fined in the economic literature. What we have in mind are large investments, over several years, aiming at decarbonizing an identified source of pollution with a progressive ramping of abatements. One could think of decarbonizing a fleet of vehicles requiring a codeployment of vehicles and charging infrastructure (Teyssier d'Orfeuil, 2020), a port area involving several interacting polluting activities (Athias, 2020), or potential green technologies for clean industrial production (Friedmann et al., 2020). Such projects consist of numerous inter-dependent actions that cannot be evaluated independently, a global approach is needed.

These projects should be distinguished from "flexible" abatement options that have a short life-time and no ramping, and no interdependency. Flexibility is implicitly assumed behind abatement curves as used in most IAMs (Vogt-Schilb et al., 2018). Absent learning-by-doing, and charging infrastructure need, a battery electric vehicle could be considered a flexible option to be compared with, for instance, a hydrogen electric vehicle, or a hybrid one, though the latter raises the question of remaining emissions. A flexible option k is fully described by an annual cost c^k and an annual abatement a^k. Its abatement cost is c^k/a^k. Between two such alternatives one should favor the one with the lowest abatement cost, and the better alternative should be deployed when the SCC is greater than its abatement cost.

For the projects we consider, two issues need be addressed: the time dimension and the ramping of abatement until full decarbonization. Let us introduce some notations: BAU emissions are E and a project k is described by a life-time T^k, a flow of annual costs (relative to BAU) c_t^k and abatements a_t^k for each $t \in [0, T^k]$. The (social) discount rate is denoted i and the SCC at time $t \geq 0$ is P_t, growing at rate γ, so that $P_t = P_0 e^{\gamma t}$. The discounted cost of the project is $C^k = \int_0^{T_k} e^{-it} c_t^k dt$.

First, with a constant annual abatement $a_t^k = a^k$, ignoring time to build for now, the numerator of the abatement cost could be simply replaced by an annualized cost comprising both capital and operating costs. The ratio between the annualized cost, that is $iC^k/(1 - e^{-iT^k})$, and the annual abatement is called the *levelized cost of carbon abatement* (LCCA) to emphasize the similarity with the levelized cost of energy (LCOE), it is:

$$LCCA^k = \frac{iC^k}{a^k(1 - e^{-iT^k})} \tag{1}$$

Second, the LCCA, as defined above, can also been described as the ratio between the discounted cost C^k and the discounted abatement over the life-time of the project, that is $\int_0^{T_k} e^{-it} a^k dt$. This opens the way to the introduction of intermediary abatements, with non constant a_t^k the LCCA writes:[5]

$$LCCA^k = \frac{C^k}{\int_0^{T_k} e^{-it} a_t^k dt} \tag{2}$$

It is similar to the general formula of the LCOE.[6] It is grounded in a cost-effectiveness analysis with the implicit assumption that alternatives to be compared have similar time profiles. LCOE has received criticisms, notably on its limited relevance for intermittent energy

[5]For an example of an empirical project using this formulation see the H-Vision project to decarbonize oil refineries and power generations in the area of Rotterdam by substituting hydrogen to fossil fuels as inputs as detailed in Lak (2019).

[6]see for instance https://corporatefinanceinstitute.com/resources/valuation/levelized-cost-of-energy-lcoe/

sources (Joskow, 2011). In many applications intermediary abatements are not considered and formula (1) is applied (e.g. Friedmann et al., 2020). Without intermediary abatements, as would be the case with flexible technologies, the best alternative is the one with the lowest LCCA and it should be launched at the time its LCCA equals the SCC. The question is: can formula (2) be used when there are intermediary abatements. We will show that the answer is no.

Indeed Baker and Khatami (2019) have questioned the rationale of the LCCA to evaluate a project. They propose to set the evaluation into a cost benefit analysis in which the discounted cost C^k is compared with the discounted environmental benefit. The corresponding metric is called the *levelized cost of carbon* (LCC). Recall that $P_t = P_0 e^{\gamma t}$. Denoting $\beta = i - \gamma$, the environmental benefit B writes

$$B^k(P_0) = \int_0^{T^k} P_0 e^{\gamma t} e^{-it} a_t^k dt = P_0 \int_0^{T^k} e^{-\beta t} a_t^k dt \tag{3}$$

The difference between benefit and cost is positive if the today SCC P_0 is greater than the LCC which is then defined as

$$LCC^k(\beta) = \frac{C^k}{\int_0^{T^k} e^{-\beta t} a_t^k dt}. \tag{4}$$

According to Baker and Khatami (2019) the alternative k is socially valuable if and only if $LCC^k(\beta) \leq P_0$. With a carbon budget, the Hotelling's rule applies and $\beta = 0$ during the transition,[7] and the LCC simply writes:

$$LCC^k = \frac{C^k}{\int_0^{T^k} a_t^k dt}. \tag{5}$$

Intermediary abatements are not discounted, which shows that $LCCA^k$ is not consistent with this CBA. However, the use of LCC^k leads to a troubling result. If we let T^k going to infinity assuming that after some point of time T^*, $a_t^k = E$ for $t \geq T^*$ while adding the corresponding annual cost that totally decarbonize E, the LCC converges to zero! This means that any alternative which leads to full decarbonization would be worth launching immediately. In the context of the NZE, the evaluation of only one alternative is clear, it should be launched and the relevant question is how to compare alternatives. The question is: can this cost benefit analysis be used to determine when to launch a project and compare projects? We will show that the answer is no because BAU is not explicitly modeled and one is left wondering what happens with emissions if the project is not implemented.

Our objective is to provide the relevant cost benefit analysis to rank extended projects in the context of the NZE that is, projects which leads to a full permanent decarbonization at the horizon. Our methodology consists in the following three stages: (1) insert the finite-life project into a decarbonization trajectory that provides an alternative to BAU, (2) in the special case in which trajectories only differ in their timing, they consist in the same project

[7] Surprisingly, Baker and Khatami (2019) consider that $\gamma = 0$ when applying their metric to transportation projects. A stable SCC would only hold over the very long-run when the transition is completed, but we are interested precisely by the evaluation of projects to be deployed along the transition.

launched at different dates, we want to determine the optimal launch time of the project based on an appropriate metric, (3) if trajectories differ both in their timing and other characteristics (there are competing projects) we want to use that metric to rank projects. In appendix B we use a simple illustration which makes clear the differences between our CBA framework and the one used by Baker and Khatami (2019), and the difference it implies in terms of metrics.

3 The dynamic cost of abatement

3.1 The general framework

We consider a benevolent social planner who has to select the best alternative among a set of *extended projects* which enable the complete decarbonization of a polluting activity (BAU). For each alternatives, the social planner decides when to implement the project by choosing the *launch time* to be denoted s.

Time is continuous and denoted $t \in \mathbb{R}^+$. We assume that BAU emits E tCO_2 per unit of time. The social cost of carbon (SCC) at time t is noted P_t. For all $t \geq 0$ let $a_{s,t}$ and $c_{s,t}$ denote respectively the abatement and the incremental cost of an extended project relative to BAU. It alleviates notations to normalize the BAU cost at zero, an implicit assumption is that the annual cost of BAU, net of the social cost of emissions, is constant over the relevant horizon. Abatements and costs depend both on the launch time and the calendar time. Abatements and costs are null before the project is implemented, $a_{s,t} = c_{s,t} = 0$ for all $t \leq s$. Further on, an extended project involves two phases : a *transitory* phase, in which $0 \leq a_{s,t} < E$ for all $s \leq t < s + T(s)$ with $T(s)$ standing for the *completion time* of this phase, followed by a *steady state* phase, in which $a_{s,t} = E$ for all $t \geq s + T(s)$. Once the transitory phase is completed, the activity is fully decarbonized until the end of time. The total discounted cost $\int_0^{+\infty} e^{-it} c_{s,t} dt$ may be conveniently be written as $e^{-is} I(s)$ in which $I(s)$ stands for the total discounted cost evaluated at the launch time s. It is:

$$I(s) = \int_s^{+\infty} e^{-i(t-s)} c_{s,t} dt = \int_0^{+\infty} e^{-i\tau} c_{s,\tau-s} d\tau \tag{6}$$

The extended project is a full decarbonization trajectory, and embeds what is traditionally evaluated as a project plus a continuation. Traditional project evaluation focuses on the transitory phase and the lifetime of the project considered, ignoring possible continuation. The date T, as introduced in the preceding section, would refer to the lifetime of the capital invested while in our analysis T refers to the date at which the activity is fully decarbonized. We shall introduce the lifespan if needed.

The total discounted cost, including the environmental damage, of an extended project launched at time s may be written as:

$$\Gamma(s) = \int_0^s e^{-it} P_t E dt + \int_s^{s+T} e^{-it} P_t (E - a_{s,t}) dt + e^{-is} I(s) \tag{7}$$

The first two terms stand for the environmental damage until completion, and the last one standing for the total discounted cost.[8] This expression will be used for answering two questions: at what date a project should be launched, and to compare extended projects (take the one with the lowest total discounting cost). A new metric denoted as the *dynamic abatement cost* (DAC) will be instrumental in this process. To highlight the novelty of our approach it will be developed under the simplifying assumptions that the characteristics of the project do not depend on the calendar time. We shall relax this assumption in section 4.

3.2 The base case: the characteristics of the extended project are independent of the calendar time

We distinguish between the calendar time t, and the project time τ, which is the time since the extended project is launched. In this section we suppose that the incremental costs and abatements only depend on the extended project time τ, they are denoted $a_\tau = a_{t-s}$ and $c_\tau = c_{t-s}$. T is also supposed independent of s. The discounted cost $I(s)$ is then independent of s ($I'(s) = 0$). Furthermore, we assume that the SCC at time 0 is P_0 and that it grows at the rate γ, $P_t = e^{\gamma t} P_0$, and that $\gamma = i$ (Hotelling's rule). Equation (7) may be rewritten as:

$$\Gamma(s) = (s+T)P_0 E - P_0 \int_0^T a_\tau d\tau + e^{-is} I(s) \tag{8}$$

For this base case we can readily obtain the optimal launch time by using the following metric:

Definition 1 *For the base case, the dynamic abatement cost (DAC) is defined as*

$$DAC = \frac{iI(s)}{E}$$

And we get:

Proposition 1 *The social cost of carbon at the optimal launch date s^* is such that:*

$$P_0 e^{is^*} = DAC \tag{9}$$

Proof. Setting the derivative of equation (8) with respect to s equal to zero we get

$$\Gamma'(s) = P_0 E - ie^{-is} I(s) = 0 \tag{10}$$

which gives equation (9). Note that the second order conditions is indeed satiffied ($\Gamma'' > 0$). ■

There is something remarkable in this result. The optimal launch time does not depend on the intermediary abatements. This comes from the fact that these abatements will take place anyway and, since the growth in the SCC exactly compensates the discounting, it does

[8] Observe that BAU may be seen as postponing the launch time s to infinity. In all our applications the optimal s is finite and BAU is not selected. Note that with an SCC growing at least as fast as the social discount rate BAU would be undefined because of infinite environmental damage.

not matter when they occur. The DAC is a marginal abatement cost (in €$/tCO_2$): it is the cost per tCO_2, at the launch time, to wait an additional year. At the optimal launch time, it is equal to the SCC, which generalizes the standard result for the MAC of a flexible project.

While the DAC is independent of the intermediary abatements in the transitory phase, they do matter when comparing extended projects. Consider a situation in which the social planner has the choice among two competing extended projects. Index by $k = 1, 2$ the characteristics of each one: T_k, a_τ^k, I_k. Denote s_k^* the optimal launch time for extended project k. Let $A_k = \int_0^{T_k} a_\tau^k d\tau$ and $E_k^* = (s_k^* + T_k)E - A_k$. A_k is the sum of the intermediary abatements during the transitory phase. E_k^* is the sum of emissions up to the steady state phase. Comparing these emissions is enough to make the selection.

Proposition 2 *Between two competing extended projects* 1 *and* 2 *to decarbonize an activity which emits* E *per unit of time, extended project* 1 *should be selected over extended project* 2 *if and only if it is associated with fewer total emissions up to their steady state phases, that is* $E_1^* < E_2^*$.

Proof. For s_k^* to be optimal, it must be that $P_0 = e^{-is_k^*} DAC_k$. It follows that the total discounted cost for the optimized extended project $\Gamma(s_k^*)$ becomes

$$\Gamma(s_k^*) = P_0 \underbrace{E(s_k^* + T_k) - P_0 A_k}_{=E_k^*} + \underbrace{e^{-is_k^*} DAC_k}_{=P_0} E/i$$

Comparing the $\Gamma(s_k^*)$ amounts to comparing the emissions from time 0 to time $s_k^* + T_k$, that is E_k^*. ■

For the base case, the question of ranking extended projects can be solved in a two steps: First, compute the DAC of each extended project and derive its optimal launch time s_k^*. Second, compute the total emissions associated with each extended project. The best project is the one with the lowest total emissions.

The total discounted cost $\Gamma(s_k^*)$ has two components: the social cost of emissions $P_0 E_k^*$, and the discounted cash cost $e^{-is_k^*} DAC_k E$. Proposition 2 states that when comparing two extended projects, only the first component matters since, at the optimal launch time, the discounted cash costs of the two extended projects taken at time $t = 0$ are identical.

In terms of metric, the DAC should be adjusted to compare competing projects.

Proposition 3 *Project 1 should be selected over project 2 if and only if*

$$DAC_1 e^{iT_1} e^{-i\frac{A_1}{E}} < DAC_2 e^{iT_2} e^{-i\frac{A_2}{E}}.$$

See Appendix A.1 for the proof. One way to interpret this result is to see that for the extended project $k \in \{1, 2\}$, A_k/E is the number of years $\tilde{T}_s$ such that total emissions $\tilde{T}_s E$ equals the sum of intermediary abatements A_k. A_k saves A_k/E years of emissions, it is as if extended project k stops decarbonizing the emission flow $T_s - A_k/E$ years after it starts, instead of T_s years. The DAC stands for the annual discounted cost per unit of emissions. The proper assessment consists then in comparing the annualized cost for the extended project discounted at year $T_k - A_k/E$.

It is worth stressing, that, absent intermediary abatements the DAC and the LCCA coincide to a discount factor: $DAC = e^{-iT}LCCA$. The discount factor accounts for completion time, with the LCCA the abatement cost is computed at the time abatement take place $(s+T)$ and with the DAC at the time the project starts (more on this in Appendix B). Without intermediary abatements the LCCA (of the extended project) can be used to both determine the launch date and compare projects. Indeed, it is not the case with intermediary abatements, and two different metrics are required, and neither the LCCA nor the LCC is one of them.

4 Some generalizations

In this section we show how our three stages approach to rank extended projects could be generalized to integrate relevant issues. The three stages approach consists in: firstly properly frame the cost benefit analysis, secondly use of a revisited DAC to determine the optimal launch time, thirdly use this metric to compare extended projects. We first consider a special case in which the costs of the project vary over time, then the possibility that a backstop appears, and finally, situations in which the SCC does not grow at the interest rate.

4.1 Exogenous technical progress

If the cost of the project varies with the launch time, $I'(s) \neq 0$, the DAC should be modified to integrate the evolution of cost and the value of waiting. Indeed, exogenous technical progress is key driver of the evolution of cost and we propose a simple way to integrate it in the analysis of extended projects.

The exogenous technical progress is modeled by a factor $e^{-\nu t}$ in which $\nu \geq 0$ is a constant parameter. We keep the same notations as for the base case except that for the incremental cost which is now $c_{s,t} = c_\tau e^{-\nu t}$, with t standing for the calendar time and $\tau = t - s$ for the project time. The discounted cost of the project depends on the launch time s and the rate of technical progress ν as follow:

$$I(s,\nu) = e^{-\nu s} \int_0^{+\infty} e^{-(i+\nu)\tau} c_\tau d\tau \tag{11}$$

The total discounted cost becomes:

$$\Gamma(s) = (s+T)P_0E - P_0 \int_0^T a_\tau d\tau + e^{-is} I(s,\nu) \tag{12}$$

Propositions 1, 2 and 3 can then be generalized. Canceling the derivative of the total discounted cost with respect to s gives the following Proposition 7:

Proposition 4 *With an exogenous technological progress characterized by a constant rate ν the relevant DAC is*

$$DAC(\nu) = \frac{(i+\nu)I(s,\nu)}{E} = e^{-\nu s}\frac{(i+\nu)I(0,\nu)}{E}$$

and optimal launch date s is such that

$$P_0 e^{is} = DAC(\nu) \tag{13}$$

Proof. In general with a total cost that depends on the launch time $I(s)$, the optimal launch time is such that $P_0 E = iI(s) - I'(s)$. With our specification of technical progress $I' = -\nu I$. ■

Technical progress has two contrasting effects on the DAC: it reduces the total cost ($I(s,\nu) < I(0,\nu) < I(0,0)$) which suggests an earlier launch, but it also calls to wait future reduction (factor $i+\nu > i$). For the case with only investment cost, so that $I(0,\nu) = I(0,0)$, the optimal launch time exhibits a bell-shaped variation with respect to the rate of technical progress, it is first increasing as long as $s \leq 1/(i+\nu)$ and then decreasing.[9]

If the technical progress identically affects all projects, after some manipulation, we can rewrite the total discounted cost as

$$\Gamma(s) = P_0[(s+T)E - \int_0^T a_\tau d\tau] + \frac{P_0 E}{i+\nu} \tag{14}$$

and Proposition 2 readily applies since the last term is independent of the project. In terms of metric, Proposition 3 should be adjusted and the metric to be compared among several competing projects k is

$$I_k(0,\nu)e^{(i+\nu)(T_k - A_k/E)}.$$

4.2 What if a backstop technology may appear

If a backstop technology may appear in the future to decarbonize the pre-existing polluting activity at no cost, the extended project should then be interrupted and the backstop implemented. We suppose that the backstop appears according to a Poisson process with rate μ, then at date t the backstop did not materialize with probability $e^{-\mu t}$. Costs and emissions should then be discounted by a factor $e^{-\mu t}$. And the total discounted cost given by equation (7) becomes:

$$\Gamma(s) = \int_0^{s+T} e^{-\mu t} P_0 E dt - e^{-\mu s}\int_0^T e^{-\mu\tau} P_0 a_\tau d\tau + e^{-(i+\mu)s} I(0,\mu) \tag{15}$$

The choice of the optimal launch date gives the following Proposition 5 which generalises Proposition 1.

Proposition 5 *With a backstop technology characterized by a Poisson process with rate μ the optimal launch date s is such that*

$$P_0 e^{is} = \frac{(i+\mu)I(0,\mu)}{\mu\int_0^T e^{-\mu\tau} a_\tau d\tau + e^{-\mu T}E} \tag{16}$$

[9] Differentiating equation (13) with respect to ν shows that $\partial s/\partial\nu$ has the same sign as $I/EP_0 - se^{(i+\nu)s} = e^{(i+\nu)s}(1/(i+\nu) - s)$ which is positive if and only if $s < 1/(i+\nu)$.

Intermediary abatements intervene in the launch date, because the probability that they materialize decrease along the project deployment. The denominator in equation (16) can be interpreted as the annualized expected abatement of the project.

The impact of the probability μ on the launch date depends on the allocation of costs through time. An increase of the probability μ decreases the denominator and has an ambiguous impact on the annualized cost. If costs are decreasing (e.g. the project consists mainly in costly capital expenditures before cheaper operating expenditures) the numerator is increasing with respect to μ and an increase of the probability of a backstop should delay the implementation of the project: A familiar result in the theory of option. To compare projects it is again sufficient to compare total expected emissions. For a project k, expected emissions are

$$E_k^*(\mu) = \int_0^{s_k^*+T_k} e^{-\mu t} E dt - \int_{s_k^*}^{s_k^*+T_k} e^{-\mu t} a_t^k dt \tag{17}$$

$$= \frac{E}{\mu} - e^{-\mu s_k^*} \left[\int_0^{T_k} e^{-\mu\tau} a_\tau^k d\tau + e^{-\mu T_k} \frac{E}{\mu} \right] \tag{18}$$

In the second line, total expected emissions are written as the difference of total emissions without the project and total expected abatement with the project. Indeed, with the probability that a backstop appears total expected abatement are no longer infinite and can be expressed. Proposition 2 and 3 could be generalized as follow:

Proposition 6 *With a backstop technology characterized by a Poisson process with rate μ, Project 1 should be selected over Project 2 if and only if expected total emissions are lower with Project 1 than with Project 2, $E_1^*(\mu) < E_2^*(\mu)$, which is the case if and only if*

$$I_1(\mu)\Big[e^{-\mu T_1} E + \mu A_1(\mu)\Big]^{-\frac{i+\mu}{\mu}} < I_2(\mu)\Big[e^{-\mu T_1} E + \mu A_2(\mu)\Big]^{-\frac{i+\mu}{\mu}}$$

in which $A_k(\mu) = \int_0^T e^{-\mu\tau} a_\tau d\tau$ and $I_k(\mu) = \int_0^{+\infty} e^{-\mu\tau} c_\tau d\tau$.

Proof in Appendix A.2

4.3 The social cost of carbon does not grow at the social discount rate

Denote $\beta = i - \gamma$ the difference between the interest rate and the growth rate of the SCC. The optimal launch date of the extended project is obtained by minimizing the overall social discounted cost $\Gamma(s)$ given by equation (7).

Proposition 7 *The optimal launch date is such that*

$$P_s = \frac{iI}{\beta \int_0^T e^{-\beta t} a_t dt + E e^{-\beta T}} \tag{19}$$

See Appendix A.3 for the proof. The right-hand side generalizes the DAC obtained for $\beta = 0$. With a carbon price not growing at the interest rate postponing intermediary abatements has an impact on the total discounted cost, namely:

Corollary 1 *If the carbon price grows more quickly than the interest rate ($\beta < 0$), the optimal launch time occurs earlier and vice versa.*

Proof. The denominator of the right-hand side is positive and decreasing with respect to β if the abatements a_τ are increasing,[10] an increase in the growth rate of the carbon price advances the optimal launch time since it increases the value of subsequent abatements.[11] ■

Another way to obtain this result is to consider the carbon price at the end of the transitory phase:

$$P_{s+T} = \frac{ie^{iT}I}{\beta \int_0^T e^{\beta(T-t)} a_t dt + E}.$$

The numerator of the right-hand side is the discounted cost at T of the extended project, and the denominator is increasing with respect to β (if a_τ is increasing), so that an increase in the growth rate of the carbon price decreases the carbon price at the end of the transitory phase.

There are a number of situations in which the Hotelling's rule would not striclty apply, for instance with a carbon neutrality target coupled with a carbon budget, the rate of growth of the carbon price should be larger than the discount rate until reaching a steady state. For instance, in France Quinet et al. (2019), the official reference price of CO_2, the so-called "valeur tutélaire du carbone", is growing at a non constant, decreasing, rate that is initially larger than the discount rate ($\beta < 0$) but decreasing to zero over time ($\beta = i$). The initial value in 2020 was not determined as a welfare maximization under a carbon budget constraint, which would have resulted in a Hotelling's rule, but rather as a carbon price that would ensure carbon neutrality in 2050, together with a carbon budget consistent with the Paris Agreement and political constraints. As a consequence, according to Corollary 1, cost benefit analysis based on this social cost of carbon has advanced green investments. However one may also argue that, for political acceptance, the Quinet social cost of carbon in 2020 is lower than what it should be according to economic reasoning. This has delayed green investments.

The question of ranking projects can be solved through the comparison of total emissions discounted at a rate β. The comparison with the case of a backstop helps build intuition. The two situations being formally similar, Proposition 6 can be applied (replacing $i + \mu$ with i and μ with β), and the project to be selected is the one with the lowest $E_k^*(\beta)$ or equivalently (taking due care of the case $\beta < 0$) the lowest

$$I_k \left[e^{-\beta T_k} E + \beta A_k(\beta) \right]^{-|\frac{i}{\beta}|}$$

[10] The derivative of the denominator with respect to β is $\int_0^T e^{-\beta t}(1 - \beta t) a_t dt - Te^{-\beta T}$ which is, after an integration by part of the first term: $-\int_0^T te^{-\beta t} \dot{a}_t dt$.

[11] Indeed, in theory the extended project costs and abatements should be optimized according to the growth rate of the carbon price.

5 Introducing learning-by-doing or spillovers into an extended project

While many authors emphasize that learning-by-doing or spillovers are important factors to be introduced in applied studies (see for instance Gillingham and Stock (2018)), no practical procedure has been provided to do so. Our approach based on the notion of extended projects greatly facilitates taking such phenomenons into account, and generates interesting results.

It will be shown that the higher the rate of learning-by-doing the earlier the project should be launched. It will also be shown that in the presence of spillovers between two projects, it may be optimal to introduce a delay between two projects and advance the launch time of the first one.

All through this section we assume that the assumptions of the base case hold, we open the box of the project, to be subdivided into several subprojects, and we integrate externalities into the associated cost.

5.1 Learning-by-doing and the consistency between the unit and the fleet scale

Many studies of the deployment of clean technologies in the transportation sector emphasize the likely decline over time of the total cost of ownership of low-carbon vehicles (e.g. Neuhausen et al., 2020; Ballard and Deloitte-China, 2020). Implicit in the decline is the assumption of increased cumulated production over time and learning-by-doing. Let us show how this sequence can be related to the DAC of the deployment of the clean fleet, which is the extended project to be considered.

Our "trajectory" approach should be contrasted with the standard 'cross-sectional" approach, in which abatement costs are computed at each point of time. In the following we show how to reconcile the two approaches. Learning-by-doing could be integrated in the standard approach if learning benefits are taken into account in the computation of the instantaneous abatement cost. These learning benefits constitute the glue between instantaneous snapchots of abatement costs to turn them into an abatement trajectory. Indeed, a difficulty with the cross-sectional approach is that each unit generates a long-term learning benefit that depends on the future production path. Our approach simply solves that difficulty by taking a broad perspective.

We consider the decarbonization of an activity consisting of N units (vehicles, plants...). Each unit may be operated either by a dirty or a green technology. The life time of a unit is one unit of time in both cases. Assume that the cost of a dirty unit is constant and normalized to zero. Its rate of emissions is also constant and normalized to 1.

The analysis is made using as the cost of a green unit the following specification:

$$C(X_t, x_t) = [\underline{c} + (\bar{c} - \underline{c})e^{-\lambda X_t}]x_t$$

in which, the variables X_t and x_t respectively stand for the cumulative production and the production at time t; the parameters $\underline{c}$ and $\bar{c}$ respectively stands for the long and short term marginal costs; and λ represents learning-by-doing.

This cost function is a special case of the one considered in Creti et al. (2018) in two respects. Firstly it is linear with respect to x so that Lemma 2 in that paper applies: the transition to the green technology take place instantaneously at a date s to be determined.[12] The total social discounted cost $\Gamma(s)$ is reduced to:

$$\Gamma(s) = P_0 s N + e^{-is} I,$$

with I given by[13]

$$I = \frac{1}{i}\underline{c}N + (\bar{c} - \underline{c})e^{-\lambda X_0}\frac{N}{i+\lambda N} \tag{20}$$

and the DAC writes

Lemma 1 *The DAC of an activity consisting of N units, the cost of which benefits from a rate of learning-by-doing λ, is such that*

$$DAC(\lambda) = \frac{iI}{N} = \left[\bar{c}\frac{i}{i+\lambda N} + \underline{c}\frac{\lambda N}{i+\lambda N}\right] = \left[\underline{c} + (\bar{c} - \underline{c})\frac{i}{i+\lambda N}\right]$$

The DAC may be seen as a weighted average between two terms: one with the short term marginal cost $\bar{c}$, and the other with the long term marginal cost. The weighting depends on the learning rate which determines the speed at which cost reductions occurs. This simple formula encapsulates several key aspects of learning-by-doing: The higher the rate of learning-by-doing, the lower the DAC and the earlier the optimal launch time, a result with important empirical significance (see for instance Creti et al. (2018)). A larger fleet also calls for an earlier launch, and the more so the higher the learning rate, which illustrates the scale effects associated with learning-by-doing. Learning-by-doing also interacts with the discount rate in a non trivial manner, its influence on the DAC being maximized for intermediary value of the discount rate.[14] Indeed, for low (large) values of the discount rates only the long-term (short-term) cost matters.

For each unit, one may distinguish a 'myopic abatement cost' (denoted $\tilde{ac}(t)$) that ignores the long-term learning benefit generated by this unit and the relevant abatement cost (denoted $ac(t)$) that includes this benefit. The myopic abatement cost corresponds to the LCCA of that unit, as defined by formula (2), while the DAC, given the absence of intermediary abatements in that special case, correspond to the LCCA of the whole clean fleet. At each date t, the myopic abatement cost is $[\underline{c} + (\bar{c} - \underline{c})e^{-\lambda X_t}]$. It goes from $\bar{c}$ to $\underline{c}$ as t goes from 0 to ∞. However, a unit produced at t contributes to the stock and reduces the cost of all units produced afterwards. The learning benefit is the discounted sum of all these cost reductions:

$$-\int_t^{+\infty} e^{-i\tau}\frac{\partial C}{\partial X}(X_\tau, x_\tau)d\tau = \int_t^{+\infty} e^{-i\tau}\lambda(\bar{c} - \underline{c})e^{-\lambda X_\tau}x_\tau d\tau.$$

[12] In a number of applications this assumption cannot be taken as granted: the deployment cannot be instantaneous. A simple and relevant way to proceed is to assume that the transition takes place over some time T and that its speed is constrained by exogenous factors (availability of materials and man power, infrastructure, transaction costs...) which are outside the scope of the model.

[13] With instantaneous deployment the cost I is $\int_0^{+\infty} e^{-it}[\underline{c} + (\bar{c} - \underline{c})e^{-\lambda t N}]xNdt$, the expression follows.

[14] The cross derivative of the DAC with respect to i and λ is $\frac{N(i-N\lambda)}{(i+N\lambda)^3}$, the size of the effect of λ on the DAC is maximimized for $i = 1/(N\lambda)$.

With a production path such that full decarbonization occurs at a date s ($x_\tau = 0$ for $\tau < s$ and $x_\tau = N$ otherwise), this benefit can be explicitly written as :

$$\lambda(\bar{c} - \underline{c})\frac{N}{i + \lambda N} \begin{cases} e^{-i(s-t)} & \text{if } t < s \\ e^{-\lambda N(t-s)} & \text{if } t \geq s \end{cases}$$

The learning benefit is first increasing as the launch date is getting closer, and then it is decreasing after launching. The relevant abatement cost of a unit produced at date t is the difference between the myopic abatement cost and the learning benefit, it can then be written as a function of the distance $t - s$:

$$\begin{aligned} ac(t-s) &= \bar{c} - \lambda(\bar{c} - \underline{c})\frac{N}{i + \lambda N} e^{-i(s-t)} && \text{if } t < s \\ &= \left[\underline{c} + (\bar{c} - \underline{c})e^{-\lambda N(t-s)}\right] - \lambda(\bar{c} - \underline{c})\frac{N}{i + \lambda N} e^{-\lambda N(t-s)} && \text{if } t \geq s. \end{aligned}$$

The abatement cost goes from some value below $\bar{c}$ to $\underline{c}$ as t goes from 0 to ∞. At the optimal launch date s^* it must be such that $P_t < ac(t - s^*)$ for $t < s^*$, $P_{s^*} = ac(0)$ and $P_t > ac(t - s^*)$ for $t \geq s^*$. The consistency between the two approaches is reflected in a result stated as the following proposition:

Proposition 8 *The optimal launch time s^* for decarbonizing an activity consisting of N units, the cost of which benefits from learning-by-doing, can be alternatively determined by the DAC of the whole trajectory or by the relevant abatement cost at the unit level $ac(t-s^*)$. It is such that:*

$$P_0 e^{is^*} = DAC = ac(0) \tag{21}$$

It is illustrated in Figure 1 in which the SCC and the various cost metrics are depicted. Firstly, the launch date s^* is determined as the date at which the SCC and DAC are equal. Secondly, the myopic and relevant abatement costs can be depicted given the launch date s^*. They both decreases, the relevant abatement cost is below the myopic one thanks to the learning benefit which first increases and then decreases. The relevant abatement cost is first above the SCC and then below, which is consistent with the production pattern. The abatement cost is precisely equal to the SCC and the DAC at the optimal launch date.

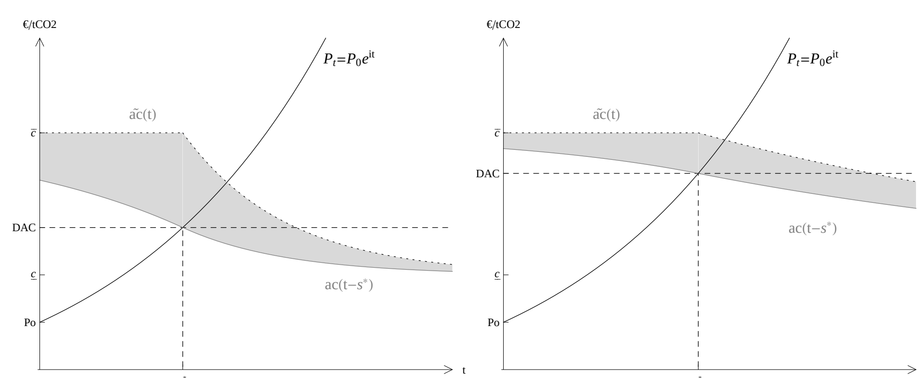

Figure 1: Optimal launch date of the decarbonization of an activity consisting of N units. The area between the myopic abatement cost $\tilde{ac}$ and the relevant abatement cost ac of each unit is the learning benefit. The learning rate is fifth time lower on the right panel.

5.2 Spillovers accross projects induce to enlarge the intervals between launch times and advance the first launch

In some applications an extended project may involve several interdependent components. For instance a sector may consist of several plants to be decarbonized. As with the previous application there might be externalities (i.e. spillovers) between plants, and taking a broad perspective helps integrate spillovers into the evaluation of options to decarbonize the whole set of plants. Indeed, the first plant not only reduces emissions but may also constitute a proof of concept with large spillovers for the following plants. However, learning takes time and it might be worth waiting between the pilot and the following plants despite the increased emissions. We propose a simple model to analyze that trade-off and its consequence on the optimal sequence of investments.

Consider the case of two polluting plants to be replaced by clean ones. The extended project consists of the building of the two clean plants, the pilot is build first, then the follower. The completion time of the extended project T corresponds to the time between the construction of the first plant and the second one. Thanks to spillovers the cost of the second plant progressively decreases at rate θ once the first plant is built. Plants are infinitely lived, the first plant costs $C/2$, and the second one costs $e^{-\theta T}C/2$. Each plant abates $E/2$ emissions.

The question of the optimal launch involves the selection of two dates, when to launch the pilot plant and with what delay to launch the follower thereafter.

For a given T, the discounted cost of the extended project is $I = C(1 + e^{-(i+\theta)T})/2$ and intermediary abatement $A = TE/2$. The optimal launch date of the extended project is (Proposition 1):

$$P_0 e^{-is} = DAC(T) = \frac{iC}{E}\frac{1 + e^{-(i+\theta)T}}{2}$$

Then the choice of the optimal T is made by selecting the best extended project, that is, the one with the lowest $DAC(T)e^{iT}e^{-iA/E}$ (Proposition 3). The optimal T then minimizes $(1 + e^{-(i+\theta)T})e^{iT/2}$, it solves:

$$e^{(i+\theta)T} = \frac{i + 2\theta}{i}$$

At the plant level the SCC at the date of construction of each plant are

$$P_0 e^{is} = \frac{iC}{E}\left[1 - \frac{\theta}{i + 2\theta}\right] \text{ and } P_0 e^{i(s+T)} = \frac{(i+\theta)Ce^{-\theta T}}{E} \tag{22}$$

These two dates can alternatively be obtained by directly minimizing the total cost with respect to the launch dates of the two plants. Each plant would then constitute a local extended project the DAC of which could be computed. The choice of the optimal launch date of the second plant is similar to the case with an external technical progress (Proposition 4) and the DAC of the follower determined accordingly. The DAC of the leader should include the benefits of the spillover:

$$DAC(leader, T) = \frac{iC}{E}(1 - \frac{\theta}{i}e^{-(i+\theta)T}) \text{ and } DAC(follower, T) = \frac{(i+\theta)Ce^{-\theta T}}{E}$$

Indeed, at the optimal launch dates, the DAC of the leader coincide with the DAC of the global extended project and the time between the two launches correspond to the optimal completion time of the global extended project.

The higher the spillovers, the earlier the optimal launch time for the pilot, in this example, a correcting term equal to $-\theta/(i + 2\theta)$ should be introduced into the evaluation of the pilot plant to take the spillovers into consideration. These DAC can also be used to contrast the industry abatment curve for an industry consisting of these two plants from the one obtained in which spillovers are neglected. This extension opens the way to explicit the relationship between a local cost benefit analysis at the plant level and more aggregated abatement cost curve at the industry level (e.g. https://www.mckinsey.com/capabilities/sustainability/our-insights/greenhouse-gas-abatement-cost-curves).

6 Revisiting some empirical applications

6.1 A case study: the H-vision project in Rotterdam

Here, we provide an example of a project representative of the type of projects and associated questions we faced in our own applied studies. Our approach through the notion of extended project answers those questions and clarifies the importance for expliciting the perimeter under consideration to make a relevant cost benefit analysis.

The H-Vision project in the area of Rotterdam, reported in Lak (2019), intends to decarbonize an industrial cluster. The scope of analysis is illustrated in Figure 1. The project is expected to be operational in 2026, decarbonizing an estimated 1 to 2 million tons of CO_2 per year, then ramping up to 4 million tons per year in 2030, and achieving a steady state from 2030 until 2045 (which corresponds to the life-time of the invested capital). The proposed project is based on the development of "blue" hydrogen as a substitute to coal and natural gas in two local industries (oil refineries and power generations), and a limited amount in mobility uses. Hydrogen is produced through the ATR (auto-thermal reforming) process, the CO_2 emissions being captured and stored in the North Sea. Lak (2019) estimates the cost of the project and the private benefits coming from avoided EU-ETS emissions permits and the sales of green electricity.[15]

The proposed project is evaluated with respect to a business as usual reference defined up to 2045. We reproduce a summary of the financial analysis. Several components are detailed: capital expenditures, operating expenses, and revenues over the life time of the project for the period 2023-2045. The net cash flows for each component, assuming a 3 % weighted average cost of capital (wacc), are summarized in Table 1.

[15] For a review of some similar port projects see Athias (2020); note that professional conferences are regularly devoted to this subject: https://meet4hydrogen.com/en/program.php#hyports-conferences. These port projects are at the heart of co-located carbon intensive industrial activities (e.g., gas turbine electricity generation, oil refineries, steel, aluminum, chemicals) and close to major metropolitan areas (e.g., Rotterdam, Hamburg, Liverpool, Dunkirk, Marseille Fos) affected by air pollution. As such decarbonizing these areas is a national objective in several European countries.

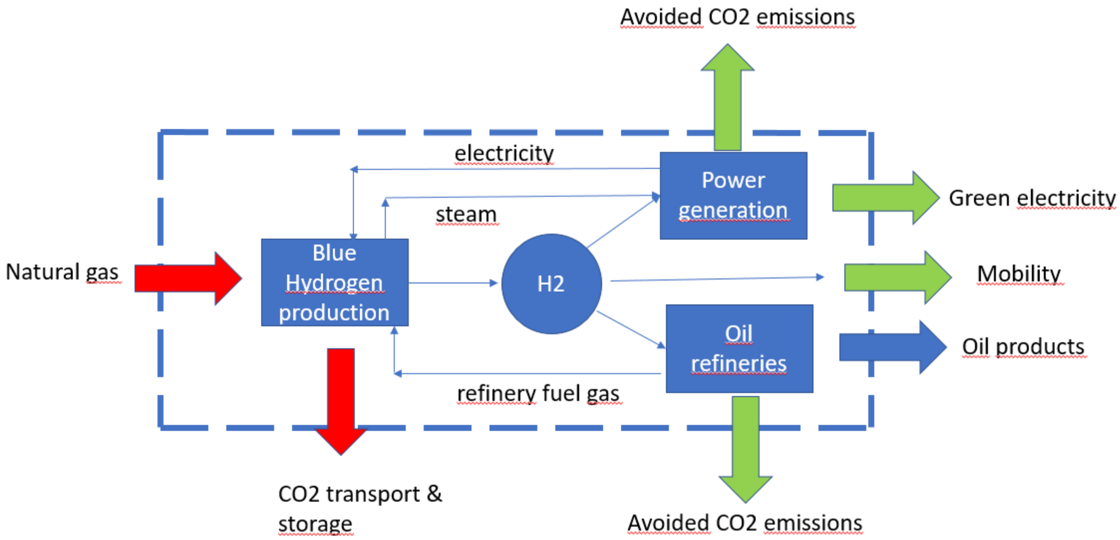

Figure 2: Overview of the energy and cash flows considered in the H-vision project (from Lak, 2019, Figure 6B)

Component	Value in billion €
H_2 **production capex**	-2.1
H_2 **production opex**	-5.8
H_2 **transport and storage**	-3.2
Refineries retrofitting	-0.3
Power plants retrofitting	-0.5
Power plants revenues	7.7
Refineries avoided ETS certificates	3.4
Rounding errors	0.1
Net present value	-0.7

Table 1: Components of the economic model (Lak, 2019, Project economics, section 9)

The abatement cost is derived to be 146 €per tCO_2. It is defined as the ratio between the discounted cashflows and the CO_2 emission reductions discounted with the wacc, which corresponds to the LCCA of a project with intermediary abatements (see eq. (2))). This evaluation does not introduce what will happen after 2045, nor the fact that this project is part of a larger national plan in which it is expected to be interconnected with other projects developed in industrial areas in the Netherlands, as well as in Belgium and Germany. Furthermore, decarbonization through blue hydrogen is introduced as a progressive path to full decarbonization through a future national green hydrogen plan, taking advantage of large deployments of offshore wind farms, or through imports. Our approach would require explicitly addressing these limitations while avoiding getting into an inextricable complex model.

6.2 How to generate an extended project from a LCCA analysis to derive the DAC

Corberand et al. (2021) provide an analysis using the LCCA to compare various portfolios for the French electricity mix for a given level of consumption for the year 2050. It will be used as an illustration, and to show how to extend the analysis through our approach. The main assumptions are the following: The demand level is given and fluctuates by hour and day within the year. A portfolio is characterized by a mix of technologies. An optimization model is used to define the required capacities to meet the fluctuating demand. The investment and operating costs of the corresponding capacities are defined, given their respective life time and assuming that they are greenfield. All costs are based on what is expected to be the state of the art of the technologies in the year 2050.

BAU is 30% nuclear, 50% renewables, 10% hydropower, and 10% natural gas whereas alternative portfolios would show reductions in natural gas (and related emissions). We focus on the portfolio Proxy AMS which consists of 34% nuclear, 50% renewables, 10% hydropower, complemented by methanation and methanisation. The capacities in the two scenarios are different because the fluctuations in demand are matched with a different mix of technologies. Electrolysers, batteries and gas turbines are used in Proxy AMS to cope with fluctuations. For a consumption level at 532 TWh, the yearly equivalent cost for BAU is estimated to be € 45 815 million, while the excess yearly equivalent cost for Proxy AMS is estimated to be € 6 900 million, which gives respective LCOEs at 86 € /MWh versus 99€ /MWh (Table 18, page 66). The calculation of the avoided emissions amounts to 18.7 Mt CO_2, that is .035 tCO_2/MWh. This gives a LCCA of 370 € /tCO_2 (Table 21, page 75).

A simple way to illustrate our approach would be to embed the steady state into a trajectory. Suppose that a smooth transition from BAU to Proxy AMS starts at some predefined year and be completed over ten years, $T = 10$. Assume that the excess yearly cost would linearly converge from some multiple of € 6 900 million to € 6 900 million. Say that the multiple is 2. The actual excess cost at year τ is computed as this excess cost multiplied by the percentage of substitution at that year; for instance at year $\tau = 1$, the percentage of implementation is 10% and $c_1 = 6900 * (1 + .9) * .1 = 1311$, at year $\tau = 2$ the percentage is 20% and $c_2 = 6900 * (1 + .8) * .2 = 2884$, and so on until year $\tau = 10$, when the percentage of implementation is 100% and $c_{10} = 6900 * (1 + 0) * 1 = 6900$). For years after T, we assume that they remain constant (no learning-by-doing, no backstop technology).[16]

The question is at what time should one launch the Proxy AMS portfolio? The answer suggested in this paper is to use the DAC. With our set of parameters using a discount rate of 3%, recalling that intermediary abatements are irrelevant, we get DAC=322 € $/tCO_2$. If the social cost of carbon in 2050 is 500 € tCO_2 in line with Quinet et al. (2019), the optimal launch time for Proxy AMS would be year 2035. Similar calculations could be done for the other portfolios that completely decarbonize the French electricity mix so as to select the best one using Proposition 2. Eventually the benefit of a partial decarbonization phase could be introduced.

[16]More realistic assumptions should be introduced such as having the set of costs for a portfolio depend on the calendar date accounting for exogenous technological change and a specific learning-by-doing for the future portfolio.

7 Conclusions

The paper is intended to provide to public authorities with a relevant CBA framework and the corresponding metrics for ranking projects to decarbonize a pre-existing activity through the deployment of new technologies. While traditional projects have finite life-time, we propose to insert them in a decarbonization trajectory consistent with the Net Zero Emission Target. We consider *extended* projects which include a transitory phase followed by a full decarbonized steady state phase thanks to some future incremental costs. In many empirical studies the steady state phase is not considered, which may invalidate the ranking obtained through current metrics. We propose a new metric based on a relevant cost benefit analysis over then extended project.

The new metric, denominated as the dynamic abatement cost (DAC), is a non trivial extension of either the levelized cost of carbon (LCC) or the levelized cost of carbon abatement (LCCA) as operationalized in (Baker and Khatami, 2019) and (Friedmann et al., 2020) respectively. The approach is fully displayed for a case in which the characteristics of an extended project only depend on the timing of deployment and not on calendar time. The DAC is calculated as the annual discounted cost divided by the long term abatement, intermediary abatements play no role in the calculation as long as the social cost of carbon grows at the same rate as the social discount rate (following Hotelling's rule). This metric is instrumental to rank extended projects through a two step process: Firstly determining the optimal launch time of each extended project, i.e. the calendar date at which the social cost of carbon equals the DAC; Secondly, comparing the total emissions until full decarbonization of the extended projects launched at their optimal launch times. The best extended project is the one with the lowest total emissions. We generalize our results to situations in which the cost of the project declines thanks to exogenous technical progress, a backstop technology may appear in the future, or a social cost of carbon which does not grow at the social discount rate. Furthermore, we also show how learning-by-doing and spillovers effects can be integrated into the analysis.

The emphasis here is on methodology. Some theoretical extensions may be interesting going beyond the simple cases of a constant exogenous technical progress, or an uncertain clean backstop technology following a Poisson process making the characteristics of an extended project calendar dependent in more realistic terms. Indeed in terms of applications, in any specific field study, a number of idiosyncratic features should be looked in details. In some circumstances, the evaluation of the BAU requires introducing stranded assets and additional maintenance expenditures. A life cycle analysis may also be introduced to correctly address the NZE target. More generally, the question of the energy transition through interdependent upstream and downstream activities should be addressed.

We do provide a starting point to formalize the articulation between a cost benefit analysis done at the project level and a cost analysis done at the industry level. Our metric may be used to generate an *industry* abatement curve opening the black box of global large multisector studies which are often criticized for their lack of transparency (Kesicki and Ekins, 2012). Enlarging a local project study to encompass time dimensions and externalities as suggested here may be a more operational route than resorting to a complex numerical model. We think that pursuing the enrichment of the project methodology is a relevant exercise to generate empirical studies fully addressing these issues in specific settings.

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A Proofs

A.1 Proof of Proposition 3

With a given project $k = 1, 2$ the optimal launch date s_k^* is such that $P_0 e^{is_k^*} = DAC_k$ so

$$s_k^* = \frac{1}{i}[\ln(DAC_k) - \ln(P_0)]$$

Recall that $A_k = \int_0^{T_k} a_{\tau,k} d\tau$ stands for the total intermediary abatements of the project for $k = 1, 2$. Project 1 has fewer emissions $\bar{E}_1$ than project 2 if and only if

$$\begin{aligned}
\bar{E}_1 < \bar{E}_2 &\Leftrightarrow (s_1^* + T_1)E - A_1 < (s_2^* + T_2)E - A_2 \\
&\Leftrightarrow (\frac{1}{i}\ln(DAC_1) + T_1)E - A_1 < (\frac{1}{i}\ln(DAC_2) + T_2)E - A_2 && \text{replacing } s_k^* \\
&\Leftrightarrow \ln(DAC_1) + iT_1 - i\frac{A_1}{E} < \ln(DAC_2) + iT_2 - i\frac{A_2}{E} && \text{multiplying by } i/E \\
&\Leftrightarrow DAC_1 e^{iT_1} e^{-i\frac{A_1}{E}} < DAC_2 e^{iT_2} e^{-i\frac{A_2}{E}}
\end{aligned}$$

A.2 Proof of Proposition 5 and 6

We use the notation, introduced in Proposition 5:

$$A(\mu) = \int_0^T e^{-\mu t} a_t dt,$$

and the presentation is further alleviated with the notation for the "annualized" abatement

$$\bar{a}(\mu) = \Big[\mu A(\mu) + e^{-\mu T} E\Big]$$

The launch time maximizes the cost

$$\Gamma(s) = P_0 \frac{E}{\mu}(1 - e^{-\mu(s+T)}) - P_0 e^{-\mu s} A(\mu) + e^{-(i+\mu)s} I(\mu) \tag{23}$$

$$= P_0 \frac{E}{\mu} - P_0 \frac{e^{-\mu s}}{\mu} \bar{a} + e^{-(i+\mu)s} I(\mu) \tag{24}$$

canceling the derivative gives:

$$(i + \mu) e^{-\mu s} I(\mu) = P_0 \bar{a}$$

Proposition 5 follows.

The total discounted cost with project k, with the optimal launch time is

$$\begin{aligned}
\Gamma_k &= P_0 \frac{E}{\mu} - P_0 \Big[\frac{1}{\mu} - \frac{1}{i+\mu}\Big] \bar{a}_k e^{-\mu s_k^*} && \text{replacing } I_k \text{ with eq. (16)} \\
&= P_0 \frac{E}{\mu} - P_0 \Big[\frac{1}{\mu} - \frac{1}{i+\mu}\Big] \bar{a}_k \left[\frac{1}{i+\mu} \frac{\bar{a}_k P_0}{I_k}\right]^{\frac{\mu}{i}} && \text{replacing } e^{-s} \text{ with eq. (16)}
\end{aligned}$$

From the first equation above, when comparing two projects one should compare the $e^{-\mu s_k^*}\bar{a}_k$ which is equivalent to comparing their total expected emissions.

Then, from the second equation, getting rid of commons terms and factors, the project associated with the lowest cost among two projects is the one with the lowest:

$$\bar{a}_k^{-(1+\frac{\mu}{i})} I_k^{\frac{\mu}{i}}$$

Proposition 6 follows.

A.3 Proof of Proposition 7

With $P_t = P_0 e^{\gamma t}$ the project abatements are worth (from today point of view):

$$\int_s^{s+T} e^{-it} P_t a_{t-s} dt = \int_s^{s+T} e^{-\beta t} P_0 a_{t-s} dt = P_0 e^{-\beta s} \int_0^T e^{-\beta t} a_t dt = P_0 e^{-\beta s} A(\beta)$$

The total discounted cost (7) is then

$$\begin{aligned} \Gamma(s) &= \int_0^{s+T} e^{-\beta t} P_0 E dt - P_0 e^{-\beta s} A(\beta) + e^{-is} I \\ &= P_0 \frac{E}{\beta} - P_0 \frac{e^{-\beta s}}{\beta} \bar{a}(\beta) + e^{-is} I \end{aligned}$$

Then canceling the derivative with respect to the starting date s gives equation (19). The second order condition is satisfied since the second order derivative with respect to s is $(i-\beta)P_0 e^{-\beta s}\bar{a} > 0$ at s^*.

For comparing competing projects, similar calculations as before gives

$$\Gamma(s^*) = P_0 \frac{E}{\beta} - P_0 \Big[\frac{1}{\beta} - \frac{1}{i}\Big] \bar{a}(\beta) \Big[\frac{P_0 \bar{a}}{iI}\Big]^{\frac{\beta}{\gamma}}$$

The best project is the one with the largest second term, and so is the one with the lowest (beware that β might be negative):

$$I_k \bar{a}_k^{-|\frac{i}{\beta}|}$$

If β is negative ($\gamma > i$) then $1/\beta - 1/i$ is negative and the best project is the one with the lowest $\bar{a}^{1+\beta/gamma} I^{-\beta/\gamma} = \bar{a}^{i/\gamma} I^{-\beta/\gamma} =$, raised to the power $-\gamma/\beta$ gives the above expression.

B Comparison of the metrics: a simple illustration

In order to clarify the relationship with traditional metrics, we will consider a simple illustrative example, in which a polluting plant is replaced by a clean one. BAU emissions are denoted E. Hotelling's rule holds.

B.1 Metrics with no intermediary abatements

Let us start by considering a clean plant and no ramping of abatement to replace a dirty plant. Launching the clean plant involves an incremental set up cost C, it will take b years to be built, and it will last d years during which emissions are null.

For such a simple project the traditional metrics are:

$$LCC = \frac{C}{dE} \text{ and } LCCA = \frac{C}{\int_b^{b+d} e^{-it} E dt} = \frac{1}{E} \frac{iCe^{ib}}{1 - e^{-id}} = \frac{c}{E}.$$

in which c corresponds to the annualized cost of the plant:

$$c = \frac{iCe^{ib}}{1 - e^{-id}}.$$

From this finite life project we define the extended project which consists in perpetually renewing the plant every d years. In that case $T = b$, the activity is fully decarbonized once the plant is built.

It is a simple matter to derive the LCC and the LCCA of the extended project. The total discounted cost of the extended project is[17]

$$I = \frac{C}{1 - e^{-id}}$$

The sum of abatements goes to infinity. The LCC of the extended project is zero. The LCCA of the extended project is equal to the LCCA of the simple project.[18]

Using the DAC, the optimal launch time (Proposition 1) is such that

$$P_0 e^{is} = DAC = \frac{iI}{E} = LCCAe^{-ib}$$

In this special case we find a relationship between the DAC and the LCCA. The SCC is equal to the DAC at the beginning of the construction of the plant (s) and to the LCCA at the end of the construction ($s + b = s + T$).

$$P_0 e^{i(s+T)} = \frac{1}{E} \frac{iCe^{ib}}{1 - e^{-id}} = LCCA.$$

Note that the LCC of the finite life time plant is lower than the DAC and would induce a too early launch time.

From Proposition 3, the comparison of two such technologies k requires to compare their $DAC_k e^{iT_k}$. Since $A_k = 0$, this is similar to comparing their LCCA (remember $T_k = b_k$). In such a case, the LCCA is a good metric to compare competing projects. In the following section we prove that this is no longer true in case of intermediary abatements. We also prove that LCCA can no longer be used to determine the optimal launch time even if building time is taken into account.

[17] It is $\sum_{n=0}^{+\infty} e^{-ind} C$.

[18] The LCCA can be computed for any number of renewals of the plant, and the same expression holds. Consider n renewals every d years, the discounted cost is $C(1 - e^{-ind})/(1 - e^{id})$ and discounted abatement $e^{-ib}E(1 - e^{-ind})$, the ratio between the two is independant of n and equal to $c = iCe^{ib}/E(1 - e^{-id})$.

B.2 Metrics with intermediary abatements

Suppose the activity consists in two colocated plants, to be replaced by clean ones each decarbonizing $E/2$ and for an incremental setup cost $C/2$. We introduce a simple deployment scenario with ramping due to exogenous constraints: only one clean plant can be built at a time. The first plant is built and renewed every d years (in years $s + n.d$ with $n \in \mathbb{N}$), the second plant is built once the first is completed, after b years, and then renewed every d years (in years $s + b + nd$ with $n \in \mathbb{N}$). The completion time for this extended project is $T = 2b$, and intermediary abatements are $a_\tau = 0$ for $0 \leq \tau \leq b$ and $a_\tau = E/2$ for $b \leq \tau \leq 2b$. Total intermediary abatements are $A = Eb/2$, the emissions of the second polluting plant replaced b years after the first.

The total discounted cost with ramping is

$$I_r = \frac{C}{1 - e^{-id}} \frac{1 + e^{-ib}}{2} < I$$

The DAC being iI_r/E it is lower with ramping than without ramping, which means that the launch time is earlier with ramping than without. The first plant is built earlier with ramping than without but final completion of both plants occurs latter.[19] The LCCA is:

$$LCCA = \frac{I_r}{E/2 \times (e^{-ib} + e^{-i2b})/i} = \frac{1}{E} \frac{iCe^{ib}}{1 - e^{-id}} = \frac{c}{E}$$

which corresponds to the LCCA of a single plant, or of the couple of plants without ramping. And we have the following comparison of the LCCA with optimal dates of completion of the first and second plants

$$DAC_r e^{ib} < LCCA < DAC_r e^{2ib}.$$

It shows that with ramping the LCCA does not deliver the relevant information to determine the optimal launch time even if building time is taken into account.

For the comparison of competing projects the relevant metric (Proposition 3) is $DACe^{iT}e^{-i\frac{A}{E}}$, which is higher than the LCCA:

$$DACe^{iT}e^{-i\frac{A}{E}} = \frac{1}{E} \frac{iCe^{ib}}{1 - e^{-id}} \frac{e^{i\frac{b}{2}} + e^{-i\frac{b}{2}}}{2} = LCCA \frac{e^{i\frac{b}{2}} + e^{-i\frac{b}{2}}}{2} > LCCA$$

The LCCA cannot be used because it ignores the inertia of sequential deployment and the associated ramping of abatement. For instance, for $i = 5\%$ and $b = 10$ the corrective factor is approximately 1.13.

B.3 With learning by doing or spillovers

The model of two plants with spillovers developped in Section 5.2 illustrates that intermediary abatements and spillovers can be associated. Waiting to learn from a pilot plant creates

[19] Without ramping the SCC at completion is $c/E = e^{ib} \times (iF/(1 - e^{-id}))/E$, and with ramping it is $(1 + e^{ib})/2 \times c/E$ at completion of both plants which is larger.

intermediary abatements. The LCCA is then an inadequate metric even if applied to the whole trajectory.

In Section 5.2 plants are infinitely lived so $d = +\infty$ and time to build is ignored $b = 0$ (or equivalently already embedded in C) so $c = iC$. The DAC is

$$DAC = \frac{iI}{E} = \frac{c}{E}\frac{1 + e^{-(i+\theta)T}}{2}$$

Applied at the plant level the LCCA of the Pilot plant is c/E, it neglects learning benefits, and therefore advocates for a too late investment. Taking our trajectory perspective, the LCCA could also be computed for the extended project consisting of both plants :

$$LCCA(extended) = \frac{I}{\int_0^T e^{-it}E/2dt + \int_T^{+\infty} e^{-it}Edt} = \frac{iI}{E(1 + e^{-iT})/2} = \frac{c}{E}\frac{1 + e^{-(i+\theta)T}}{1 + e^{-iT}}$$

It is lower than the LCCA of the first plant in isolation but still larger than the DAC because annualized abatement are lower than the annual abatement E.