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Thierry Bréchet, Henry Tulkens

January 2009

ENVIRONMENTAL
ECONOMICS & MANAGEMENT
MEMORANDUM

UCL
Université
catholique
de Louvain

Chair Lhoist Berghmans
in Environmental Economics
and Management

Center for Operations Research
and Econometrics (CORE)

Journal of Environmental Management 90 (2009) 1790–1801

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Beyond BAT: Selecting optimal combinations of available techniques, with an example from the limestone industry

Thierry Bréchet[a,*], Henry Tulkens[b]

[a] CORE and Louvain School of Management, Chair Lhoist Berghmans in Environmental Economics and Management, Université catholique de Louvain, Voie du Roman Pays, 34, B-1348 Louvain-la-Neuve, Belgium
[b] CORE, Université catholique de Louvain, Belgium

A R T I C L E I N F O

Article history:
Received 29 July 2007
Received in revised form
21 August 2008
Accepted 23 November 2008
Available online 23 December 2008

JEL classification:
D20
Q50

Keywords:
Best available techniques
Eco-efficiency
IPPC
Linear programming
Combination of techniques

A B S T R A C T

Technological choices are multi-dimensional and thus one needs a multi-dimensional methodology to identify best available techniques. Moreover, in the presence of environmental externalities generated by productive activities, 'best' available techniques should be best from Society's point of view, not only in terms of private interests. In this paper we present a modeling framework based on methodologies appropriate to serve these two purposes, namely linear programming and internalization of external costs. We develop it as an operational decision tool, of interest for both firms and regulators, and we apply it to a plant in the lime industry. We show why, in this context, there is in general not a single best available technique (BAT), but well a best combination of available techniques to be used (BCAT).

1. Introduction

One of the cornerstones of the European Commission's environmental protection policy today is the implementation of some *best available techniques* (BAT) in industrial activities. Leaving aside the issue of whether technological choices are to be made by industry or by public administrations, this paper focuses on the preliminary question of the identification of a *best technique*. The Integrated Pollution Prevention and Control (IPPC, hereafter) Directive defines BATs as technologies and organizational measures expected to minimize overall environmental pressures at acceptable private costs. The purpose of the Directive (European Commission, 1996) is *to achieve integrated prevention and control of pollution arising from industrial activities*. The Directive includes operating permits for industrial installations based on BAT. Quoting the Directive, a BAT is defined as follows:

1. 'techniques' shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned,
2. 'available' techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and the advantages,
3. 'best' shall mean most effective in achieving a high level of protection of the environment as a whole.

The IPPC Directive is a major piece of environmental regulation, covering around 55,000 installations in the EU.

Further examination of the Directive and of its application leads one to observe that, in spite of the plural used in the just quoted definition, the regulatory effort focuses on identifying a *single* technique in each sector, declared to be *best* on the criterion consisting in maximizing environmental protection, subject to economic and technical viability. This flows from the fact that the

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[*] Corresponding author. Tel.: +32 10 478186; fax: +32 10 474301.
E-mail addresses: thierry.brechet@uclouvain.be (T. Bréchet), henry.tulkens@uclouvain.be (H. Tulkens).

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doi:10.1016/j.jenvman.2008.11.012

emission standards assigned in the BREFs[1] on multi-pollutants are such that only one single technique can satisfy them. An illustrative example may be the lime industry where only a specific kiln (named PFR) and a specific fuel (natural gas) can match the standards, thus implicitly defining the very *best* available technique. The observation of industrial practice, however, leads one to conclude that it is not only impractical but also inefficient, both environmentally and economically, to formulate the desirable course of action of industry in terms of a single technique in each sector. When various techniques exist in industrial life, each one of them has historical or technical justifications, due to characteristics that may – or may not anymore – contribute validly to the realization of the desired output. The relevant question then is how to *combine* these techniques in the best way without *a priori* restricting this combination to only one of them.

In the meantime, during the 90s, the European Commission has developed the ExternE methodology to evaluate social and environmental damages due to polluting activities in monetary terms. Yet, this methodology is not used when determining the BAT. Recently, the IPPC Bureau issued a specific Reference Document to assist in the determination of best available techniques (EC, 2006). And one avenue discussed in that document is the use of monetarized external costs. Data concerning costs of available techniques are provided in the IPPC reference documents called BREFs, but only given as a rough indicator of the magnitude of the costs involved.

Our aim in this paper is twofold. First, given the multiplicity just mentioned of available techniques, we wish to show that a multi-dimensional methodology is appropriate to identify best combinations of these available techniques. Secondly, we want to integrate the economically well-grounded monetary valuations of environmental costs provided by the ExternE methodology in our optimization procedure of selecting best techniques at the plant level. Our contribution thus consists in developing an economically consistent optimization tool for choosing among available techniques. To prove it to be operational, we take as an example the particular case of a plant in the lime industry.

The article proceeds as follows. After a literature survey, Section 3 presents and discusses the economic conceptual foundations of the methodology we advocate. In Section 4 we briefly describe the industrial activity of our case-study; we also present the overall structure of the optimization model and give the numerical values of some key parameters. Section 5 exhibits the BCATs that are so obtained, while Section 6 presents, by means of a diagrammatic decision tool, how BCATs are a function of the parameters reflecting both private and environmental costs. Section 7 concludes on the implications of this approach for the design of both market and environmentally friendly technology regulation. The full (linear programming) optimization model is given in Appendix 1 while Appendix 2 presents an overview of the ExternE methodology.

2. Literature on BATs

Despite the issues at stake the economic literature on BAT and the IPPC process remains sparse. Early papers provide an overview of the directive. In particular, Backes and Betlem (1999) propose a multi-disciplinary and comprehensive analysis of the directive and Faure and Lefevere (1999) a general economic appraisal. A few case studies of the implementation of the directive have been published, *e.g.* for the fruit and vegetable processing industry (Derden et al., 2002), for the pig industry (Pellini and Morris, 2001), for the dairy industry (Honkasalo et al., 2004) or for the whole Finnish industry (Silvo et al., 2002). A few papers investigate the relationship between IPPC-type regulation and other policy issues, such as voluntary agreement (Cunningham, 2000) or cleaner technologies adoption (Bansal and Gangopadhyay, 2005). The economic literature devoted to methodological issues related to the selection of BAT is even more sparse.

Under the pressure of the IPPC directive two main methodologies have been put forward and used to select BATs[2], namely the reference installation approach (Geldermann and Rentz, 2004) and the VITO[3] methodology (Dijkmans, 2000; Vercaemst, 2002). Actually these two methodologies are quite similar. Their objective is to face the issue of technique selection through a pragmatic procedure. The first one played a role in the way in which the information is presented in the BREFs. The BREFs' documents are designed to help national policy-makers determine BATs and BAT-based emission limits.

Geldermann and Rentz (2004) propose an integrated approach which illustrates the decision process under the IPPC directive. The basic procedure corresponds with the structure set by the ISO14040 and with the Life-Cycle Assessment and is called the reference installation approach. It is stressed out that, in no case, certain techniques or a specific technology is prescribed, because local environmental conditions must be taken into account. However it assumes that, for all installations of a category the same abatement options apply. The authors recognize that, for such an approach to be efficient, a profound knowledge of the production process and the technical parameters on the installation/process level is required. In our setting we challenge this by arguing that only few information are required to set the best technique at the plant level, but this requires adequate tools, such as the one we propose in this paper.

The VITO has developed its own methodology to select the BAT at the industry level with a stepwise procedure. The first step is the identification of the key environmental issues and the collection of a list of candidate-BAT techniques. The second step analyzes the technical feasibility of the techniques. If the technique is not feasible, it cannot be a candidate-BAT; otherwise, it can. The third step evaluates the overall environmental benefits related to the implementation of the candidate-BAT under analysis. If there are no clear environmental benefits the technique is rejected. The fourth step consists in analyzing the economic feasibility of the selected technique. A candidate-BAT is considered as economically acceptable if (*i*) it is feasible for an average, well managed company of the sector and (*ii*) if the ratio between costs and environmental benefits is not unreasonable. Economic feasibility is calculated by VITO with a non-optimization tool called the MIOW+ model (see Dijkmans, 2000). See Derden et al. (2002) for an application of this methodology to the fruit and vegetable processing industry.

When implementing this methodology, it turns out that most of the remaining BAT-options are not mutually exclusive. In other words, the implementation of a specific candidate-BAT does not exclude the use of another one (although some candidate-BATs are mutually exclusive at the process level). Indeed, several techniques often have close environmental benefits, and are all rated '+' in the BAT evaluation table, so that no choice can be recommended at the sectorial level.

From a theoretical perspective it is well-established that command-and-control regulation is inefficient under imperfect information, that is, when industrial plants are numerous and

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[1] BREFs stands for Bat REFerence documents, which are sector-specific in the IPPC directive.

[2] The early concept of BATNEEC (Best Available Technique Not Entailing Excessive Costs) may also be met in the literature, see e.g. Pearce (1993) and Pearce and Brisson (1993).

[3] Vlaamse Instelling voor Technologisch Onderzoek, the Flemish Institute for Technological Research.

heterogenous. For a directive such as IPPC covering multi-pollutants over 55,000 industrial plants, the issue of imperfect information is particularly relevant. However, the literature on the selection of BATs widely disregards this point and tries to gather the full information to identify the BAT at the plant level. We thus depart from this literature by acknowledging the inefficiency of command-and-control approaches under imperfect information. This leads us to promote comprehensive cost-benefit analyses at the plant level, and the contribution of the paper is to propose an adequate methodology.

3. The methodology for optimal selection of techniques

In this section we present the concepts behind the idea of best combination of available techniques.

While maximizing environmental protection (as implied by item 3 in the BAT definition) is a respectable objective, we consider in this paper that the constraint of *technical and economic viability* (as implied by item 2) is an ill specified one, at least in its economic component. Indeed, what are the limits of economic feasibility? Zero profit? Bankruptcy threshold? In a market economy, no industrial firm can be seriously considered being run on such a basis.

Classical microeconomic reasoning has been suggesting instead, for decades, the profit maximization criterion. And no less classical theorems in welfare economics have established the extent to which this criterion is compatible with the public interest in market economies. The recent emergence of environmental economics, also concerned with the public interest, has changed this basic behavioral criterion of firms, not in its nature (profit), but well in its choice of the cost component of profit. It recommends that environmental concerns be taken into consideration by introducing them as *external* costs *added up* to the usual private (internal) cost of any firm, the two components thus forming what is called the *social* cost. In the same spirit, environmental economics recommends that when a firm's behavior is modeled in terms of total cost minimization subject to satisfying a given demand[4], total cost be understood as including, besides usual accounting (thus private) costs, the *external* cost of all forms of environmental damages entailed by the productive activity.

This leads one to describe in two distinct ways the profit maximizing behavior of firms in the choice of their techniques: on the one hand the *Privately Best Combination of Available Techniques* (*P-BCAT*), that is, the choice that minimizes private cost, and on the other hand the *Socially Best Combination of Available Techniques* (*S-BCAT*) that minimizes the social cost just defined, *i.e.* private and environmental. These two alternative choices of techniques will emerge and be exhibited numerically for a lime production plant from the model presented below. As far as the optimization method is concerned, we propose to identify such best combination of technologies as the solution of a linear programming model. Linear programming is a classical mathematical model of production activities that has a long history, both theoretical and applied. It recognizes from the start the variety of alternatives – and it even allows for changes in that variety. This methodology is of general nature and, *per se*, independent of both BAT and environmental issues. It has been applied in many sectors [5].

The properties of the model do not exclude that its solution might recognize a single technique as the optimal one. But this will generally not be the case, due to the nature of the inherently varied components of the industrial problem under study.

4. An application to the lime industry

4.1. Description of the plant

We consider a single plant comprising a quarry with a stone crushing station and several kilns of given capacity, producing given quantities of final products of various qualities and emitting various kinds of pollutants. The lime production process is represented in Fig. 1.

The raw material for lime production is limestone. Only high purity limestone is quarried. The unused stone goes directly to the landfill. Limestone is crushed to the appropriate size range, from 2 to 150 mm depending on the kiln(s) to be used. The burning of the limestone is necessary to liberate carbon dioxide and to obtain the derived oxide ($CaCO_3 \rightarrow CaO + CO_2$). The temperature required is between 1000 and 1200 °C. Energy can be provided by many fuels (gas, liquid or solid). Most kilns can operate with more than one fuel, but some fuels cannot be used in some kilns. A large variety of kilns is also potentially available. We assume that the producer can choose between six types of kilns. The differences between these kilns are twofold: they vary in energy efficiency and they do not accept all sizes of limestone.

The environmental impact of such a plant is manifold. Fuels combustion yields emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and carbon monoxide (CO). In particular, carbon dioxide emissions depend on the carbon content of each fuel. The other pollutants, in particular CO_2 and dust, are related to the activity level of each kiln with a technological relationship. Dust appears during the process, some of which is recovered and sold while the rest goes to the landfill, as well as the unused limestone.

In the context of our case-study the *technique* is given by the type of kilns under operation and the way they are used, *i.e.* the choice of fuels, granulars and kilns feeding.

4.2. The optimization model

As explained in Section 3, the *BCAT* can be seen as the solution of a linear programming problem in which the objective function includes both private and environmental costs. The objective consists in minimizing the firm's total operational cost with respect to the variables that determine this cost, subject to *(i)* meeting a given level of demand, *(ii)* not exceeding given capacities of the quarry and of the plant, and *(iii)*, operating according to available given technologies.

Let us denote by the scalar n the quantity of usable limestone extracted from the quarry before crushing is taking place, and let the components of the vector u denote the quantities of alternative granularometric sizes obtained after crushing. Consider a vector y whose components denote the quantities of crushed limestone flowing into the various types of kilns, a vector $\bar{y}$ specifying the kilns' capacities, and a vector x whose components denote the quantities of alternative fuels used in these kilns. Let the components of a vector z denote the quantities of the resulting output of the various categories of limestone destined to meet the demand, which is in turn represented by the components of a vector D. Next, let the components of a vector w measure the quantities of the various pollutants emitted by the activities of the plant. Finally, C, a scalar, will stand for total operational cost. All these magnitudes are per unit of time (say, a year).

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[4] Environmental protection may require also reducing a polluting output – thus, reducing the demand taken here as given. However, this is a decision variable to be considered by the firm in the wider context of its overall profit maximization policy (*e.g.* if a tax is levied on its output). Now, whatever the level of this tax and of the resulting demand, cost minimization in the sense mentioned above remains an implication of profit maximization.

[5] e.g. electricity, transportation, postal services, telecommunications, oil refining,… See Cooper et al. (1996) for a survey of mathematical programming models in air pollution management.

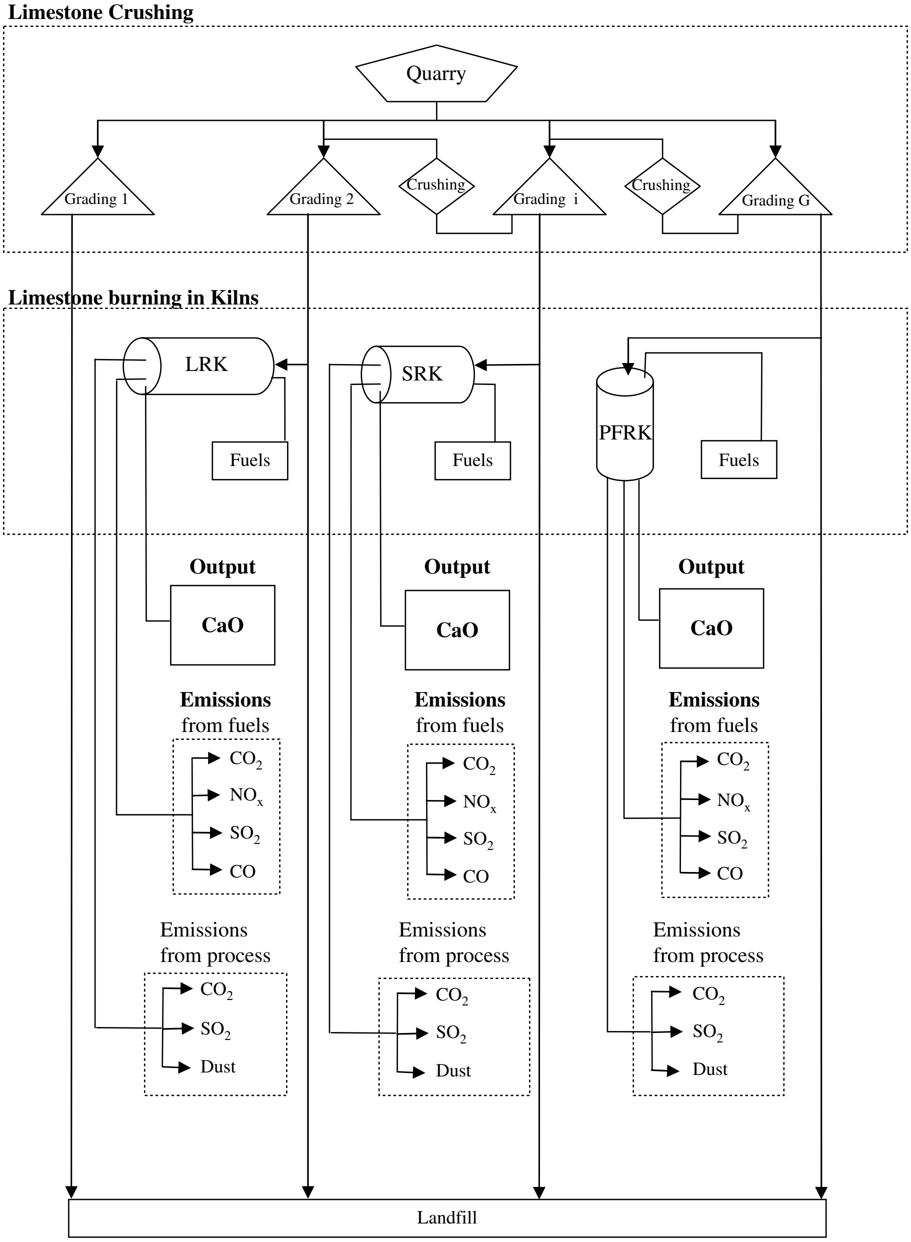

Fig. 1. Lime production flow chart.

With this notation, the optimization problem takes on the following general form:

$$\min_{\{n,u,w,x,y,z\}} C(n,u,w,x;D,\overline{y}) \tag{1}$$

$$\text{s.t.}\begin{cases} u\in\Gamma(n;n^{\max}) \\ (v,y)\in\Theta(u) \\ z\in\Phi(y;\overline{y}) \\ x\in\Lambda(z) \\ z\geq D \\ w=\Pi(v,x,z) \end{cases} \tag{2}$$

where the variables are the scalars and vector components just defined, namely stone extraction (n), crushing (u), dust sent to landfill (v), kiln loading (y), fuel use (x), lime production (z) and pollutant emissions (w). Only n, u, y and x are decision variables, though, because once their numerical value is specified, z and w are uniquely determined.

The variables are subject to various categories of constraints which account for the successive stages taking place in the physical production process of lime:

- the vector u must belong to a set $\Gamma(n;n^{\max})$ that describes crushing possibilities of the gross flow n in various grades, $n^{\max}$ being the maximal possible stone extraction from the quarry;
- the vectors y and v must satisfy material conservation in assignments of stone flows between alternative kilns (y) and landfill (v), a condition formalized by the requirement of belonging to the set $\Theta(u)$;
- the output vector z must meet the feasible production possibilities of the kilns, given the amounts y that flow into them as well as their capacity limits $\overline{y}$. These possibilities are described by the set $\Phi(y;\overline{y})$ to which z is required to belong;
- the fuel uses vector x must satisfy the kilns energy efficiency requirements and ability to accept or not each kind of fuel, conditions which are represented by belonging to the set $\Lambda(z)$;

- the output vector z must meet demand D;
- the vector of environmental pressures w results, as a function, from what is sent to the landfill, v, from effluents related to fuel uses, x and to kiln operations as measured by their output z.

The alternative technologies that this paper is about are essentially those represented by the third and fourth constraints, that is, those that imply, respectively, alternative choices of kiln operation and alternative fuel uses.

Depending upon the perspective adopted, private or social, the total cost of the objective function (C) takes on one of two forms: either that of a private cost function (PC), or that of a social cost function (SC) in which environmental costs are added up to the private costs. Formally,

$$C = \begin{cases} PC \equiv P(n, u, x) \\ \text{or} \\ SC \equiv P(n, u, x) + E(w) \end{cases} \tag{3}$$

where $E(w)$ represents the environmental costs function. When the former formulation is chosen by the analyst, the resulting *BCAT* selection yields what we have defined above as the private optimum. With the latter formulation, each pollutant variable in the term $E(w)$ of the objective function is multiplied by a positive cost coefficient, reflecting the pollutant's unit cost to society, essentially a marginal damage cost. The solution to the program thus selects a *BCAT* that achieves the social optimum. Depending upon the weight of these pollutant cost coefficients, the socially optimal *BCAT* differs from the privately optimal one.

4.3. Numerical values of the parameters

The values of the parameters are gathered in Appendix 1 and briefly discussed in this section. Some of these values are specific to the plant or the technologies considered. Some others do not, but they may differ from one application to another for exogenous reasons (for example, fuel prices change every day). As a result, these values must be considered as illustrative.

We consider a quarry with a maximum gross flow of 3000 kt of limestone per year. The proportion of usable stone is 90%. Five kilns are available on the plant: one LRK, two SRKs and two PFRKs. The firm faces an exogenous demand of 1150 ktCaO/year. Only one quality category of lime is considered. Each kiln is characterized by its technological features (input acceptability, fuel acceptability, energy efficiency, etc.): the values of the parameters for all these characteristics are standard and come from reference document under the IPPC directive, called the BREF, as well as from discussions with specialists. We consider that all the dust is sold and without lost of generality, that the price for dust sold is 1.

Environmental costs are tricky to evaluate. To date, the main project devoted to these evaluations is the ExternE project undergone on behalf of the European Commission (see European Commission, 2005). An overview of this methodology is given in Appendix 2. As the European Commission itself recognizes, *the derivation of these values is a complex process and involves a detailed analysis of the predicted impacts of the release of these pollutants. Methods for calculating the values follow the impact pathway approach, which involves tracing emissions through dispersion and environmental chemistry, to their impact on sensitive receptors (calculated using exposure-response functions)* (European Commission, 2006, page 60). It must be clear that large uncertainty prevails. The fact that external costs depend on local conditions is of major interest for our purpose, by the way. If such a method allows to better reflect local environmental conditions in an objective and neutral way, then it is fine.

Although our methodology fits for multi-environmental pressures analysis, in this paper we will focus on two pressures having very distinct impacts. The first one, carbon dioxide, is a *global pollutant* related to fuel combustion and process. The second one, the landfill, is a *local burden* related to the extraction activity and kiln feeding options. What is of particular interest here is to analyse how global and local pollutants may conflict at the plant level. As to carbon dioxide, the benchmark value given by ExternE for environmental cost will be considered, which is 19 Euros/tCO_2. The external cost of landfill will heavily depend on the location of the plant. As a preliminary value we shall retain 5 Euros/t.[6]

5. Selecting the best combination of available techniques

5.1. BCAT that minimizes private costs (P-BCAT)

Table 1 displays the complete results for the private optimum. All figures are in tons per year, except for the costs at the bottom of the table which are in Euros/year.

Starting from the top of the Table, one may observe that the gross flow of limestone needed to face the demand is 2649 kt/year. The quantity of usable limestone is 2384 kt/year (90%, by assumption). The amount of limestone of each granularity is given on line 10. Only limestone of granular 6 (60–80 mm) is partially crushed (330,606 t/year among the 357,602 t/year available). No kiln can accept granular 1. As a result, granular 1 goes to the landfill (line 12). The loading of each kiln is given in lines 16–24: we can see the amount of limestone entering each kiln (for example 238,402 tons of granular 2 limestone and 70,412 tons of granular 4 limestone are burnt in the LRK kiln). The kilns SRK and PFRK are used at full capacity (respectively 1214 kt/year and 623 kt/year) and, not surprisingly, the finest limestone goes in LRK kiln (the utilization rate of the kiln is 82%). Finally we see that petcoke, the cheapest fuel available, is used in all kilns (line 36).

Pollutants are reported in full detail. We distinguish CO_2 emissions from process (line 47) and from fossil fuels combustion (line 48). The usual average emission rates prevail here: 1.6 tCO_2/tCaO with the LRK, 1.4 tCO_2/tCaO with the SRK and 1.2 t with the PFRK kiln. Most of these emissions occur inside the kiln during the process (55%, 60% and 67% respectively). For information, the emissions of NO_x, SO_2 and CO are given in line 50–52. Dust emissions are completely captured into the filters and recovered (line 53).

The last section of the Table displays the total emissions of each pollutant and the related total external costs. It appears that CO_2 emissions constitute the major external cost: it amounts to 96% of the overall external cost of this plant[7]. With these two pollutants being considered, the total environmental cost reaches 31 million per year for this plant, which implies an average external cost of lime production of 26 Euros/tCaO.

To summarize, the privately best combination of available techniques (*P-BCAT*) for the plant to produce 1150 kt of lime per year consists in extracting 2649 kt of limestone, using an appropriate crushing, using a LRK kiln at 82% capacity, using SRK and PFRK kilns at full capacity and using a single fuel, petcoke (5985 TJ).

This result shows that, even in the private optimal solution it is required to make use of the vertical kiln (PFRK), supposed to be *the* BAT (see the introduction), in combination with other kilns. The question is now whether this combination will change in the socially optimal solution, and whether only vertical kilns should be used.

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[6] This value is purely indicative. It roughly represents the restoration cost of a landfill.

[7] Let us recall that, to date, the external cost of the landfill is only indicative.

Table 1
Private optimum.

Line	Quarry									
1	*n*	2,648,910 (gross_material_flow)								
2	*q*	2,384,020 (net_material_of_limestone)								
3	Demand	1,150,000	0	0	0					
4										
5	Grading	1	2	3	4	5	6	7	8	9
6	[mm]	0–2,	2–10,	10–20,	20–40,	40–60,	60–80,	80–100,	100–120,	120–150
7	Alpha	10%	10%	10%	15%	15%	15%	15%	10%	0%
8										
9	Crushing									
10	*u*	238,402	238,402	238,402	357,602	357,602	357,602	357,602	238,402	0
11	*uc*	–	0	0	0	0	330,606	0	0	0
12	*v*	238,402	0	0	0	0	0	0	0	0
13										
14	Kiln	LRK	SRK	FLMK	PFRK	NSK	ASK			
15	Loading									
16	*y*(1,*k*)	0	0	0	0	0	0			
17	*y*(2,*k*)	238,402	0	0	0	0	0			
18	*y*(3,*k*)	0	238,402	0	0	0	0			
19	*y*(4,*k*)	70,412	287,190	0	0	0	0			
20	*y*(5,*k*)	0	688,208	0	0	0	0			
21	*y*(6,*k*)	0	0	0	26,996	0	0			
22	*y*(7,*k*)	0	0	0	357,602	0	0			
23	*y*(8,*k*)	0	0	0	238,402	0	0			
24	*y*(9,*k*)	0	0	0	0	0	0			
25										
26	yagg	308,814	1,213,800	0	623,000	0	0			
27	Ybar	374,000	1,213,800	0	623,000	0	0 (capacity_max)			
28	Ybar/kiln	374,000	606,900	227,500	311,500	63,000	126,000 (capacity_max/kiln)			
29	numb_kilns_avail	1	2	0	2	0	0			
30										
31	Energy_consumption									
32	xagg_fuel[TJ/year]	1099	3557	0	1329	0	0			
33	xagg_Gas[TJ/year]	0	0	0	0	0	0			
34	xagg_Liquid[TJ/year]	0	0	0	0	0	0			
35	xagg_Lignite[TJ/year]	0	0	0	0	0	0			
36	xagg_Petcoke[TJ/year]	1099	3557	0	1329	0	0			
37	xagg_Coal[TJ/year]	0	0	0	0	0	0			
38										
39	Final_products									
40	zagg	157,214	647,360	0	345,426	0	0			
41	*z*(*k*,1)	157,214	647,360	0	345,426	0	0			
42	*z*(*k*,2)	0	0	0	0	0	0			
43	*z*(*k*,3)	0	0	0	0	0	0			
44	*z*(*k*,4)	0	0	0	0	0	0			
45										
46	Pollutants									
47	wCDp	135,878	534,072	0	274,120	0	0 (from_CO_2_process)			
48	wCDfk	115,437	373,477	0	139,499	0	0 (from_CO_2_fuel)			
49	CO_2_total	251,315	907,549	0	413,619	0	0			
50	wNO_x	503	1295	0	121	0	0			
51	wSO_2	377	155	0	24	0	0			
52	wCO	126	388	0	121	0	0			
53	Dust_recovered	15,721	32,368	0	3,454	0	0			
54	Dust_to_landfill	0	0	0	0	0	0			
55										
56	Pollution_costs									
57		Total_emissions		Unit_external_cost		Total_external_cost				
58	CO_2	1,572,480		19		29,877,200				
59	SO_2	557		0		0				
60	NO_x	1,919		0		0				
61	CO	635		0		0				
62	Landfill	238,402		5		1,192,010				
63										
64	Environmental_cost: 31,069,200									
65										
66										

5.2. BCAT that minimizes social costs (S-BCAT)

The question addressed now is the following: when internalising external costs in a social cost function, what combination of techniques emerges and what social benefit may be expected?

Prior to answering, let us consider what are the options for pollution abatement in the model. Basically, we can distinguish between emissions from fuels and emissions from the processes. The former can be reduced through fuel switch (for a given kiln). The latter cannot be reduced by kiln shift (for a given fuel) because, in our case, given the demand level, all the kilns available have to be used.

Given these options, our model provides numerical answers to the two questions for the industrial plant under study. Table 2 displays the complete results for the social optimum.

Like with the *P-BCAT* the least-cost solution consists of using the kilns SRK and PFRK at full capacity. Fuel switch depends on the relative price of fuels. Under private optimization the cheapest fuel (petcoke) was used in all kilns. However, this fuel is also the dirtiest in terms of CO_2 emissions. As soon as its environmental cost is

Table 2
Social optimum.

Line	Quarry									
1	*n*	2,648,910 (gross_material_flow)								
2	*q*	2,384,020 (net_material_of_limestone)								
3	Demand	1,150,000	0	0	0					
4										
5	Grading	1	2	3	4	5	6	7	8	9
6	[mm]	0–2,	2–10,	10–20,	20–40,	40–60,	60–80,	80–100,	100–120,	120–150
7	Alpha	10%	10%	10%	15%	15%	15%	15%	10%	0%
8										
9	Crushing									
10	*u*	238,402	238,402	238,402	357,602	357,602	357,602	357,602	238,402	0
11	*uc*	–	0	0	0	0	330,606	0	0	0
12	*v*	238,402	0	0	0	0	0	0	0	0
13										
14	Kiln	LRK	SRK	FLMK	PFRK	NSK	ASK			
15	Loading									
16	$y(1,k)$	0	0	0	0	0	0			
17	$y(2,k)$	238,402	0	0	0	0	0			
18	$y(3,k)$	0	238,402	0	0	0	0			
19	$y(4,k)$	70,412	287,190	0	0	0	0			
20	$y(5,k)$	0	688,208	0	0	0	0			
21	$y(6,k)$	0	0	0	26,996	0	0			
22	$y(7,k)$	0	0	0	357,602	0	0			
23	$y(8,k)$	0	0	0	238,402	0	0			
24	$y(9,k)$	0	0	0	0	0	0			
25										
26	yagg	308,814	1,213,800	0	623,000	0	0			
27	Ybar	374,000	1,213,800	0	623,000	0	0 (capacity_max)			
28	Ybar/kiln	374,000	606,900	227,500	311,500	63,000	126,000 (capacity_max/kiln)			
29	numb_kilns_avail	1	2	0	2	0	0			
30										
31	Energy_consumption									
32	xagg_fuel[TJ/year]	1099	3557	0	1329	0	0			
33	xagg_Gas[TJ/year]	0	0	0	0	0	0			
34	xagg_Liquid[TJ/year]	0	0	0	0	0	0			
35	xagg_Lignite[TJ/year]	1099	3557	0	1,329	0	0			
36	xagg_Petcoke[TJ/year]	0	0	0	0	0	0			
37	xagg_Coal[TJ/year]	0	0	0	0	0	0			
38										
39	Final_products									
40	zagg	157,214	647,360	0	345,426	0	0			
41	$z(k,1)$	157,214	647,360	0	345,426	0	0			
42	$z(k,2)$	0	0	0	0	0	0			
43	$z(k,3)$	0	0	0	0	0	0			
44	$z(k,4)$	0	0	0	0	0	0			
45										
46	Pollutants									
47	wCDp	135,878	534,072	0	274,120	0	0 (from_CO_2_process)			
48	wCDfk	109,940	355,692	0	132,856	0	0 (from_CO_2_fuel)			
49	CO_2_total	245,818	889,764	0	406,976	0	0			
50	wNO_x	503	1295	0	121	0	0			
51	wSO_2	377	155	0	24	0	0			
52	wCO	126	388	0	121	0	0			
53	Dust_recovered	15,721	32,368	0	3454	0	0			
54	Dust_to_landfill	0	0	0	0	0	0			
55										
56	Pollution_costs									
57		Total_emissions		Unit_external_cost		Total_external_cost				
58	CO_2	1,542,560		19		29,308,600				
59	SO_2	557		0		0				
60	NO_x	1919		0		0				
61	CO	635		0		0				
62	Landfill	238,402		5		1,192,010				
63										
64	Costs w.r.t. private optimum									
65										
66	Private_cost $\Delta + 1.2\%$		Environmental_cost $\Delta - 1.8\%$			Total_cost $\Delta - 0.5\%$				
67										

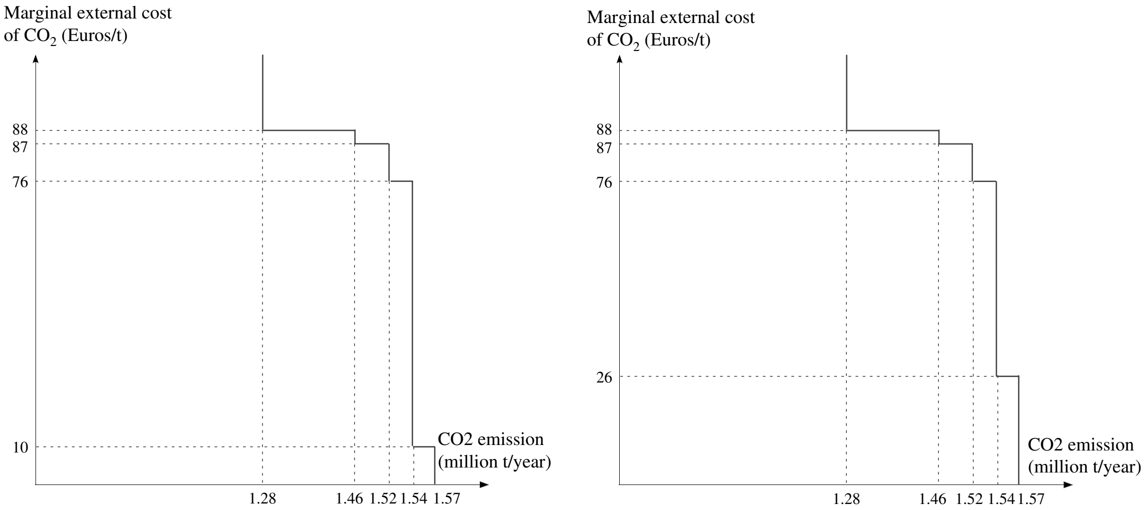

Fig. 2. Left: marginal abatement cost curve for carbon dioxide; Right: influence of a 3%-fall of the price of petcoke.

included and a social optimum is sought, the model chooses to burn a cleaner fuel, namely lignite in all kilns.

The socially best combination of available techniques (*S-BCAT*) for the plant considered to produce 1150 kt of lime per year is obtained in this example as an extraction of 2649 kt, a crushing set, a kiln use of LRK (82% capacity), SRK and PFRK (full capacity), and a fuel use of lignite (9985 TJ). Total CO_2 emissions decrease by 2% in comparison with the *P-BCAT*. Interestingly, the optimal solution does not suggest to make use only of the vertical kiln (PFRK) and to get rid of the others. It thus shows that the BAT cannot be reduced to a single kiln.

Comparing private and social optima, it appears that the total private cost increases by 1.2% in the *S-BCAT* with respect to *P-BCAT*, whereas total external costs are reduced by 1.8%. Overall, the social benefit resulting from the adoption of this combination of techniques is a decrease of the social cost by 0.5%.

5.3. Sensitivity analyses

The social optimum just computed is in part determined by the unit external cost, H^{CO_2}, of carbon dioxide emissions. A sensitivity analysis bearing on this parameter shows that fuel switches occur as a result of increased values of H^{CO_2}. We have indeed the following fuel mixes at the successive social optima[8]:

- if $0 < H^{CO_2} < 10$, petcoke in all kilns;
- if $10 \leq H^{CO_2} < 76$, lignite in all kilns;
- if $76 \leq H^{CO_2} < 87$, coal in LRK and SRK, lignite in PFRK;
- if $87 \leq H^{CO_2} < 88$, coal in LRK and SRK, gas in PFRK;
- if $H^{CO_2} \geq 88$, gas in all kilns.

The carbon dioxide emissions occurring at the optimum for each level of H^{CO_2} is depicted on Fig. 2 (Left). We see that the optimal emissions decrease with increases of H^{CO_2}. The resulting staircase shaped curve is to be interpreted as a marginal abatement cost curve of carbon dioxide for the plant.

The successive simulations also show that, as H^{CO_2} is increasing, after each threshold, total private costs increase but total external costs decrease.

Moreover, the shape of the marginal abatement cost curve is sensitive to the relative price of fuels. As an example, Fig. 2 (Right) displays the same marginal abatement cost curve with a 3%-lower petcoke price, all other things being equal. This shows that such a curve, while revealing technological constraints, is also dependent upon relative input prices.

Lastly, it is interesting to notice that imposing a tax above 88 € would not further reduce CO_2 emissions from that plant.

6. A decision tool for policy support

The sensitivity analysis just presented only shows how the best choice of techniques varies with one of the external costs. It is a fairly straightforward computational exercise to extend this parametrization to any number of such external costs. We wish to illustrate it diagrammatically for the case of two of them because of its pedagogical interest: it allows one to present results in a way that vividly highlights the respective roles of these two costs in the choice of techniques induced by optimization.

At this stage, the generality of the approach will be enhanced if we ignore the capacity limits $\bar{y}$: they are indeed unnecessary in an argument whose purpose is to identify optimal techniques rather than actual activity and production flows.

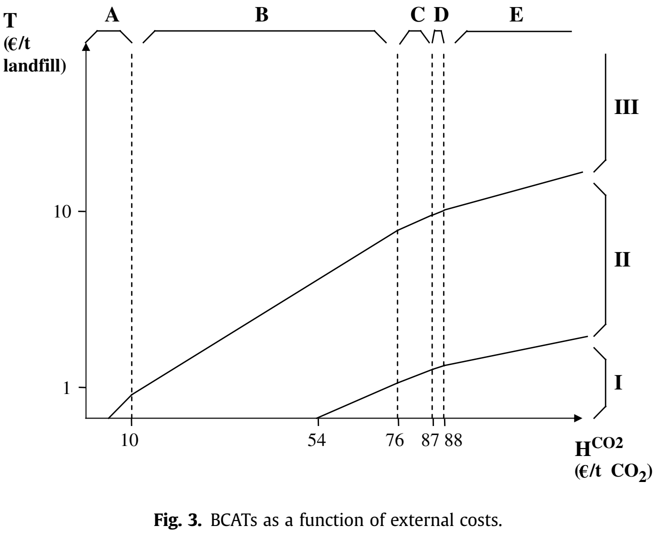

Fig. 3. BCATs as a function of external costs.

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[8] These critical values are approximate in the sense that decimals are not given.

Table 3
Legend to Fig. 3.

Alternative **kiln** combinations	Alternative **fuel use** combinations				
	A	B	C	D	E
III	PFRK, SRK & LRK kilns petcoke in all n = 2,630,000 tons	PFRK, SRK & LRK kilns lignite in all n = 2,630,000 tons	PFRK, SRK & LRK kilns lignite in PFRK coal in SRK & LRK kilns n = 2,630,000 tons	PFRK, SRK & LRK kilns gas in PFRK coal in SRK & LRK kilns n = 2,630,000 tons	PFRK, SRK & LRK kilns gas in all n = 2,630,000 tons
II	PFRK & SRK kilns petcoke in all n = 2,930,000 tons	PFRK & SRK kilns lignite in all n = 2,930,000 tons	PFRK & SRK kilns lignite in PFRK coal in SRK kiln n = 2,930,000 tons	PFRK & SRK kilns gas in PFRK coal in SRK kiln n = 2,930,000 tons	PFRK & SRK kilns gas in all n = 2,930,000 tons
I		PFRK kiln lignite in PFRK n = 5,760,000 tons		PFRK kiln gas in PFRK n = 5,760,000 tons	

Consider again a given quarry and its geological features (gross flow, granular…), also with a given amount of demand to be met. The two pollutants we retain are contrasting ones: dust sent to the landfill (whose unit external cost is denoted T) – a local one, and a global one: carbon dioxide (whose unit external cost is denoted H^{CO_2}). For each configuration of the two unit external costs, taken over a range reasonably likely to be met in practice, we compute the optimal solution of the model (1) and (2) stated above with the objective function (3.2), after deletion of $\bar{y}$ in the third set of constraints.[9] The outcome of the successive computations is conveniently presented in Fig. 3 where the x-axis measures H^{CO_2} and the y-axis measures T. To each point of the space so defined there corresponds a numerical solution of the model, which is also a well identified *S-BCAT* choice expressed in terms of a combination of kilns and a specific profile of fuel uses.

The space is partitioned by continuous lines into three zones labeled I, II and III, with the respective optimal kiln combinations indicated in the accompanying table (ignore momentarily the vertical dotted lines). The continuous lines that separate the zones reflect indifference (that is, equal total optimal operating cost) between the combinations induced by the points on either side. For the configurations of external costs that determine zone I, which is characterized by zero or very low level of the landfill unit external cost T and a high level of H^{CO_2}(≥ 54 €/t), the best combination of techniques is in fact a single technique: the PFRK kiln.

For higher levels of the landfill unit cost T, the best combination is the mixed one of PFRK and SRK kilns. And for rather high values of T, LRK kilns also enter the optimal combination. In the table, one can see the values of n (extraction of gross stone from the quarry) resulting from each kiln combination. Note that the extraction required in zone I exceeds the assumed extraction capacity in our example (3000 kt).

The above only describes alternative optimal kiln choices. However, the use of fuels with these kilns is also optimized within the model. This is illustrated by the dotted lines in Fig. 3. As the fuels do not generate landfill environmental effects, the level of the associated external cost is nil. Only CO_2 emissions matter. As the external unit cost H^{CO_2} raises from zero to 88 €/t, optimal fuel uses with the appropriate kilns switch from petcoke to lignite, to coal and then to gaseous fuel.

It is only in very specific cases that the *S-BCAT* requires the use of one single kiln, the vertical PFRK: it is when the external cost of the local environmental pressure is very small and the external cost of CO_2 very high. In all other cases the *S-BCAT* consists in a combination of kilns.

Taken together, the two partitions just described of the $T - H^{CO_2}$ space induces 12 zones, within each of which any point corresponds to an optimal choice of kilns, of the fuels to be used in them and of extraction and crushing activity. Thus for example, if the external cost of carbon dioxide is 80 €/t and the external cost of the landfill is 10 €/t, then Fig. 3 reveals that the *S-BCAT* plant is composed of the combination of three kinds of kilns (LRK, SRK and PFRK) operated jointly with a mix of fuels (lignite and coal).

Such a diagram is to be seen as a tool for guiding optimal decisions in this multi-dimensional context. The full legend to Fig. 3 is provided in Table 3.

7. Conclusion

To cope appropriately with both the multi-dimensionality of technological choices and with the detrimental externalities that production can generate, we have developed a methodology to identify best available techniques from society's point of view. It consists of a comprehensive decision tool based on linear programming modeling of the productive operations and on internalization of the external costs generated by these operations. We conclude that in this context there is in general not a single best available technique (BAT), but well a best combination of available techniques to be used (BCAT).

From our example in the lime industry, let us underscore that when comparing the two scenarios (*private* and *social*) with fixed capacities there essentially appeared a drop of 2% in carbon dioxide emissions. Private total operating cost increased by 1.2% whereas external costs were reduced by 1.8%. Overall, the social benefit resulting from the adoption of the best combination of techniques is a decrease of the social cost by 0.5%.

This example illustrates the extent to which the internalization of the external costs can influence the choice of the techniques, that is, the very definition a BAT.[10] It further shows that the relation between the choice of kilns and the way to use them in terms of fuel choice does matter: good use of an existing technology can be as important as replacing it. Thus, the example identified that for certain structures of the external cost, switching to gas is preferable to kiln change. The example also showed that local conditions, as illustrated by the landfill external cost, do play a role no less important in socially best combination of techniques than global pollutants.

Finally, a graphical tool that summarizes the results yielded by our methodology may prove convenient for illustrating the managerial decisions involved.

Acknowledgments

We are grateful to Gérard Flament and Thomas Schlegel for fruitful discussions, as well as to the editor and four anonymous reviewers for their suggestions. We also thank Marion Courtois, Johan Lepers and Fabienne Henry for computational and editing

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[9] More precisely, we solve model (4)–(17) in Appendix 1, with the *SC* objective function.

[10] The selection of a BAT may also depend on market equilibrium, as shown by Bréchet and Michel (2007).

support. The earlier version (November 2006) was circulated under the title 'From BAT (best available technique) to BCAT (best combination of available techniques)'.

Appendix 1 : the optimization model

Indexes

The following indexes are defined.

$k \in \{1, \ldots K\}$: kiln types (LRK, SRK, FLMK, PFRK, NSK, ASK)
$g \in \{1, \ldots G\}$: granular categories (1–9)
$l \in \{1, \ldots L\}$: quality categories of final output
$f \in \{1, \ldots F\}$: fuel types (Gaseous, Liquid, Lignite, Petcoke, Coal, others)
$p \in \{1, \ldots P\}$: pollutants (NO_x, SO_2, CO and CO_2)

Variables and vectors

All variables are flow variables expressed in tons per year, except for $x_{f,\,k}$, which is expressed in terajoules per year.

We consider the following endogenous variables:
n: gross material flow from the quarry after explosion
q: flow of limestone from the quarry
u_g: limestone flow of granular g; $u = \{u_1, \ldots u_G\}$
v_g: amount of thin stone useless for lime production, going to the landfill
$u_{g+1,\,g}$: amount of crushed stone (from granular $g+1$ to granular g)
$y_{g,\,k}$: amount of limestone of granular g entering kiln k; $y = \{y_{11}, \ldots y_{GK}\}$
$x_{f,\,k}$: energy input of fuel f in kiln k (in TJ/year); $x = \{x_{11}, \ldots x_{FK}\}$
$z_{k,\,l}$: amount of quicklime of quality l exiting kiln k; $z = \{z_{11}, \ldots z_{KL}\}$
w_k^p: amount of pollutant of type p emitted by kiln k; $w = \{w_{11}, \ldots w_{KP}\}$
w_k^d: amount of dust leaking from kiln k

Parameters

The parameters and exogenous variables are the following:

- Demand to be satisfied:
  D_l: quicklime demand of quality l (tons of CaO/year); $D = \{D_1, \ldots D_L\}$
- Quarry and material flows characteristics:
  $N^{\max}$: maximum gross material flow from the quarry
  λ: proportion of gross flow from the quarry available for lime production
  α_g: granular distribution of quarry's gross flow ($0 \le \alpha_g \le 1$, $\forall g$, with $\sum \alpha_g = 1$)
- Technologies:
  $\bar{y}_k$: limestone input capacity of kiln k; $\bar{y} = \{\bar{y}_1, \ldots \bar{y}_K\}$
  $\Omega_{g,\,k}$: acceptability of limestone of grading g in kiln k (1 = yes, 0 = no)
  $\Psi_{f,\,k}$: acceptability of fuel f in kiln k (1 = yes, 0 = no)
  $\Phi_{k,\,l}$: capacity of kiln k to produce quality l (1 = yes, 0 = no)
- Environmental parameters:
  ϵ_k: energy efficiency of kiln k ($tCaO/TJ$)
  ρ_f^p: emission rate for pollutant p from fuel f (t/TJ)
  ρ_k^p: emission rate for pollutant p from kiln k (t/t limestone)
  η_k: dust emission rate of kiln k
  ξ: proportion of dust recovered and sold
- Economic parameters:
  M: unit cost of gross stone extraction ($Euro/t$)[11]
  $C_{g+1,\,g}$: unit cost of crushing ($Euro/t$)
  K_f: unit cost of fuel f ($Euro/TJ$)
  T: unit external cost of landfill ($Euro/t$)
  H^p: unit external cost of pollutant p ($Euro/t$)
  P: market price of dust sold ($Euro/t$)

The model

As stated in Section 4.2, we define $C(n, u, w, x; D, \bar{y})$ as the total operating cost (expressed in Euros/year) of delivering a given demand level D, from a plant of capacity $\bar{y}$. With the presently more detailed notation the alternative objectives read as follows:

$$\left\{ \begin{array}{l} \underset{f\in\{1,\ldots F\};\, g\in\{1,\ldots G\};\, k\in\{1,\ldots K\}}{\overset{\text{Min}}{\{u_1; u_{g+1,g}; x_{f,k}; y_{g,k}\}}} \quad PC \equiv \left[\sum_{g=1}^{G} C_{g+1,g} u_{g+1,g} + \sum_{k=1}^{K} \right. \\ \left. \times \sum_{f=1}^{F} K_f x_{f,k} + Mn \right] \quad \text{or} \quad \underset{f\in\{1,\ldots F\};g\in\{1,\ldots G\};k\in\{1,\ldots K\}}{\overset{\text{Min}}{\{u_1; u_{g+1,g}; x_{f,k}; y_{g,k}\}}} \\ SC \equiv \left[\sum_{g=1}^{G} C_{g+1,g} u_{g+1,g} + \sum_{k=1}^{K} \sum_{f=1}^{F} K_f x_{f,k} + Mn \right] \\ + T \left[\sum_{g=1}^{G} v_g + (1-\xi) \sum_{k=1}^{K} w_k^d \right] + \sum_{k=1}^{K} \sum_{p=1}^{P} H^p w_k^p - \left[P\xi \sum_{k=1}^{K} w_k^d \right] \end{array} \right. \tag{4}$$

In either case, the variable are subject to the following constraints:

$$n \le N^{\max} \tag{5}$$

$$q = \lambda n \tag{6}$$

$$u_g = \alpha_g q, \forall g \tag{7}$$

$$u_g + u_{g+1,g} = \sum_{k=1}^{K} \Omega_{g,k} y_{g,k} + v_g, \quad \text{for } g = 1 \tag{8}$$

$$u_g + u_{g+1,g} - u_{g,g-1} = \sum_{k=1}^{K} \Omega_{g,k} y_{g,k} + v_g, \quad \forall g \in [2, \ldots G-1] \tag{9}$$

$$u_g - u_{g,g-1} = \sum_{k=1}^{K} \Omega_{g,k} y_{g,k} + v_g, \quad \text{for } g = G \tag{10}$$

$$\sum_{g=1}^{G} \Omega_{g,k} y_{g,k} \le \bar{y}_k, \quad \forall k \tag{11}$$

$$\sum_{g=1}^{G} z_{g,k} = \epsilon_k \sum_{f=1}^{F} \Psi_{f,k} x_{f,k}, \quad \forall k \tag{12}$$

$$z_{k,l}(1+\eta_k) = \left(1 - \rho_k^{CO_2}\right) \Phi_{k,l} \sum_{g=1}^{G} y_{g,k}, \quad \forall k, l \tag{13}$$

$$w_k^p = \sum_{f=1}^{F} \rho_f^p x_{f,k}, \quad \forall k, \quad \text{for } p = CO_2^f, SO_2^f, NO_x, CO \tag{14}$$

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[11] M also includes the opportunity cost expressing the fact that the producer wants to avoid the waste of his quarry.

Table 4
Parameter values.

				Kilns k									
				LRK	SRK	FLMK	PFRK	NSK	ASK				
Grading g	1	<2 mm	Acceptability matrix δkg	0	0	0	0	0	0	Granular distribution vector αg	10%	Extraction cost M(€/t)	3
	2	10		1	0	0	0	0	0		10%		
	3	20		1	1	0	0	0	0		10%	Crushing cost $Cg+1$,g (€/t)	5
	4	40		1	1	1	0	0	0		15%		
	5	60		0	1	1	0	1	1		15%		
	6	80		0	0	1	1	1	1		15%		
	7	100		0	0	0	1	1	1		15%	usable limestone λ	90%
	8	120		0	0	0	1	1	1		10%		
	9	>150		0	0	0	0	1	0		0%		
Fuels f	Gas		FuelPanel FPfk	1	1	1	1	0	1	CO_2 emission rate vector ρk (t/TJ)	56	Price Kf (€/TJ)	6500
	Liquid			1	1	1	1	0	1		78		6500
	Lignite			1	1	1	1	0	1		100		2700
	Petcoke			1	1	1	1	0	0		105		2650
	Coal			1	1	0	0	1	0		96		3000
	Fuel 1			0	0	0	0	0	0		0		0
	Fuel 2			0	0	0	0	0	0		0		0
	Fuel 3			0	0	0	0	0	0		0		0
	Fuel 4			0	0	0	0	0	0		0		0
Quality l of output	1		Quality matrice βkl	1	1	1	1	1	1	Demand vector D	1,150,000		
	2			0	0	0	0	0	0		0		
	3			0	0	0	0	0	0		0		
	4			0	0	0	0	0	0		0		
Process pollutants p	CO_2		t/t limestone ρpk	0.44	0.44	0.44	0.44	0.44	0.44	Environmental unit cost (€/t)	Hp	19	
	NO_x		mg/NM3	800	500	100	100	100	200			0	
	SO_2		mg/NM3	600	60	20	20	50	50			0	
	CO		mg/NM3	200	150	100	100	60,000	400			0	
	Dust		ηk	10%	5%	1%	1%	1%	1%		T (landfill)	*5*	
	Dust recovered		ξ	100%	100%	100%	100%	100%	100%	Price of dust sold (€/t)	P	1	
	Gas volume		NM3/t of limestone	4000	4000	3500	3500	3500	3500				
Plant	Number of kilns available			1	2	0	2	0	0				
	Capacity per day		t/day	1100	1785	650	890	180	360				
	Running days		per year	340	340	350	350	350	350				
	Energy efficiency		ϵpk t limestone/TJ	143	182	236	260	250	238				

$$w_k^p = \rho_k^p \sum_{g=1}^{G} y_{g,k}, \quad \forall k, \quad \text{for } p = CO_2^p, SO_2^p \tag{15}$$

$$w_k^d = \eta_k \sum_{l=1}^{L} z_{k,l}, \quad \forall k \tag{16}$$

$$\sum_{k=1}^{K} z_{k,l} \geq D_l, \quad \forall l \in \{1, \dots L\} \tag{17}$$

The objective functions expresses the aggregate private and social cost, respectively, that we advocate as a substitute to exclusively environmental considerations. The first bracketed terms are the private operational costs (costs of fuels, crushing and extraction)[12] whereas the remaining three bracketed terms are the external costs due to dust and gaseous emissions. The decision variables are those mentioned within braces under the Min operator. The next thirteen equations describe the array of available techniques to produce D_l. Thus, Equation (7) expresses the fact that a quarry is characterized by its usable limestone (q) being distributed into G categories of granulars, according to fractions α_g. The quarry is characterized by a maximal gross flow capacity, denoted $N^{\max}$. Equation (9) is essentially a material conservation relation applying to the type g of granular obtained after an initial explosion. On the left hand side we have the stone u_g coming directly from the quarry, plus $u_{g+1,\ g}$, the stone crushed from granular $g+1$ into granular g, minus $u_{g,\ g-1}$, the stone of granular g crushed into the smaller category $g-1$. This flow is equal to the total amount of limestone put in kilns, $\sum_{k=1}^{K} \Omega_{g,k} y_{g,k}$, plus the residual v_g, not used for production and which goes to the landfill. This constraint does not hold for $g=1$ and $g=G$ since the variables $g(0)$ and $g(G+1)$ do not exist. In these two cases, the specific constraints (8) and (10) are relevant. The capacity constraint of the plant, and so the one of each kiln, is assumed to be given. It is imposed by Equation (11). Equation (12) specifies the fuel inputs $x_{f,\ k}$ needed to process the amount $\sum_{g=1}^{G} y_{g,k}$ loaded in each kiln k. Equation (13) specifies the total output ($z_{k,\ l}$) of limestone of each quality l obtained in kiln k, as determined by the technical coefficients $\Phi_{k,\ l}$. The three following equations are devoted to discharges. The emissions of carbon dioxide resulting from fossil fuels combustion are given by Equation (14) considering the carbon content of each fuel (ρ_f^p). The other pollutants are related to the activity level of each kiln with the parameter ρ_k^p, as given in Equation (15). The quantity of dust emitted by each kiln (w_k^d) is calculated using the output level of each kiln. Finally, Equation (17) ensures that, for each quality l, total output of lime meets at least the demand D_l.

Parameter values

All parameter values are gathered in Table 4.

Appendix 2 : an overview of the ExternE Project

External costs of emissions come from the ExternE (Externalities of Energy) project. For almost 15 years the European Commission

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[12] We thus implicitly assume that all the other costs (*e.g.* manpower, transportation and taxes) do not depend on the kiln use.

has supported the development and application of a framework for assessing external costs of energy use. Researchers from all EU Members States have taken part. The main scope at this time has been the airborne pollutants from power plants and the development of the impact pathway approach. In fact, the ExternE project began in 1991 as the European part of a collaboration with the US Department of Energy in the *EC/US fuel Cycles Study*. The term *fuel cycle* refers to the chain of processes linked to the generation of electricity from a given fuel. For example, the assessment of the coal fuel cycle includes evaluation of the impacts associated with construction of new plant, coal mining, limestone quarrying (for flue gas desulphurisation, where used), transport of coal, wastes, other materials, power generation, waste disposal and electricity transmission. Damage assessments are carried out in the following areas: human health, building materials, crops, forests, freshwater fisheries and biodiversity.

The methodology may be applied at any industry level, but this is far from being straightforward. As soon as local pollutants are considered for a given industrial plant, local conditions under which this plant is running ought to be considered. Consequently, using the results from the ExternE study as such would be misleading. An extension of the methodology has been made and many results (as well as many others useful materials) are available on the web site of the Environment DG Bookshop[13] and on the ExternE website [14]. In particular, the last methodology update published[15] includes assessment of the external costs for SO_2 (sulphur dioxide), NO_x (oxides of nitrogen) and PM (particulate matter). Externalities are calculated to give marginal figures. Health effects dominate.

A comprehensive description of these data is beyond the scope of this paper and is available on the web site given above. However, it is clear that, on the one hand, all the drawbacks of these figures must be kept in mind. The usefulness, inherent limitations and methodological shortcomings of these figures are discussed by Krewitt (2001), Eyre (1997) and Stirling (1997).

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[13] See http://europa.eu.int/comm/environment/enveco/studies2.htm.

[14] See http://www.externe.info/.

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Chair Lhoist Berghmans in Environmental Economics and Management
Center for Operations Research & Econometrics (CORE)
Université catholique de Louvain (UCL)
Voie du Roman Pays 34
B-1348 Louvain-la-Neuve, Belgium