Internalisation of externalities into energy decision-making: A model for the social optimisation of the operation of electrical power systems

Pedro Linares, Lucía Muñoz, Andrés Ramos, Julio Montes

Instituto de Investigación Tecnológica. Univ. Pontificia Comillas. Sta. Cruz de Marcenado 26,. 28015
Madrid, Spain. Tel. +34 91 5422800 Fax. +34 915423176 pedro.linares@iit.upcomillas.es

Abstract. This paper assesses the consequences of the internalisation of the environmental externalities of the Spanish power system. Based on results from the ExternE project, a model has been developed which is able to incorporate environmental externalities and thus allows for a socially efficient electricity system operation. Results show how when externalities are internalised, the electricity system operation may be altered significatively, even when only part of the externalities are taken into account. They also show that in some cases, the efficient allocation of resources seeked by this internalisation of externalities is prevented by the existence of political constraints, which may be justified on a social basis.

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1. Introduction

Energy, and in particular, electricity, are essential for economic activity and social development. However, its continued growth raises concerns abouth the ability of the environment to sustain this development. Electricity generation is usually associated to air pollutant emissions, in the case of fossil fuelled generating units; to radioactive risks, in the case of nuclear; and to ecological impacts, in the case of hydro. These impacts in turn originate what are known as external costs, or externalities, that is, effects caused by the electricity generation activity on other economic agents or activities, and which are not duly compensated, or even accounted for.

The existence of these externalities is a market failure, since it prevents the market from assigning resources efficiently from a social point of view. Given that the market is the most widely accepted tool for the allocation of resources, and the growing awareness that the market should reflect all (not only economic) costs, many efforts have been directed at the correction of this market failure. This is even more important now that electricity markets are being restructured around the world. As mentioned in IEA (1996), externalities do not disappear with electricity markets restructuring, but rather they appear more frequently.

The first step taken to correct this market failure has been to try to determine it quantitatively. To that end, several studies have been undertaken, starting with the pioneer work by Hohmeyer (1988) and Ottinger et al (1991), and encompassing a really large number of scientists across the globe, such as in the ExternE study, which put together research centres from both Europe and the United States to develop a transparent, comprehensive and consistent methodology for the assessment of the externalities of energy (European Commission, 1999a-d; Rowe et al, 1995). This work on the quantification of externalities is still ongoing, since there are several aspects yet to be resolved. Issues such as risk perception, valuation or discounting of damages, or impacts such as global warming still make up large sources of uncertainty to the estimation of externalities of electricity generation, and therefore require further research (Krewitt, 2002; Sundqvist, 2004).

However, it should be noted that, although it sometimes may seem so, the quantification of the externalities of electricity generation is not a goal in itself, but rather an intermediate step prior to the internalisation of these externalities into energy operation and planning decisions. The development of ways for this internalisation may be even more complex than the quantification of externalities itself. In fact, this quantification may not even be required, since methods exist for the internalisation of externalities which do not need this quantification, such as multiple-criteria techniques (see e.g. Linares and Romero, 2000), and which may constitute equally attractive alternatives.

Therefore, the real issue now is, as expressed in several political documents (e.g., the EU White Paper on Energy, 1995, or the EU Green Paper on Energy Efficiency, 2005), to take a step ahead from the assessment of externalities, and to develop methods and tools to internalise them efficiently into energy decision-making, in order to correct the market failure, and thus to achieve a socially efficient allocation of resources. Some exercises have already been attempted in this direction. For example, Kypreos and Krakowski (2004) have analysed the internalisation of externalities into the Chinese power generation system,

Here an overview is presented of the different methods proposed for the internalisation of externalities into energy decision-making processes, focusing on electricity systems operation and planning, and discussing their advantages and disadvantages. A model developed at the Instituto de Investigación Tecnológica is presented for the operation of electricity systems which incorporates environmental externalities and thus allows for a socially efficient electricity system operation. The major results for its application to the Spanish electricity system are shown and discussed.

2. Methods for the internalisation of externalities into electricity systems operation and planning

Society requires energy to satisfy its needs. However, energy resources are limited, and thus it is necessary to decide which use is more efficient for them. This has promoted the development of several decision models for the electricity sector, which try to provide low-cost, high-reliability combinations. These models use simulation or optimisation in order to determine the most appropriate strategies, and vary according to the objectives pursued, and to the time horizon considered (Hobbs, 1995). However, these models may no longer be valid, due to the conflict created by the environmental impact of electricity production.

Some time ago, this conflict did not exist, since the only criteria considered in electricity operation and planning were cost and reliability. Recently, however, due to the social concern for the environmental impact of electricity generation, and the understanding that this impact must be internalised, environmental criteria have been added to decision-making processes (Petrovic and Kralj, 1993). The conflict arises because of the impossibility of optimising simultaneously these economic, technical, and environmental criteria. In fact, it is already difficult to make different social groups agree on the relative importance of each of these criteria (Diakoulaki et al, 1996). So the usual situation is one in which no optimal decision exists.

Due to this conflict, energy resources are not allocated efficiently with traditional decision models. New models are required, which allow to handle conflicting objectives, which allow to integrate externalities into the decision-making process, in order to achieve a socially efficient allocation of resources. All this taking into account the numerous alternatives existing, and the complexity of electricity systems.

This very complicated task has been approached with different methods, some simpler, some more complex, and with different social efficiency implications, as described below.

Firstly, it should be said that, according to some authors, mainly Coase (1960) and its followers, the only condition required for the internalisation of the externalities would be the assignment of property rights over all goods (for example, clean air, or ecosystems). Under a set of assumptions (mainly the absence of transaction costs), social optimum would be achieved by bargaining between the economic agents affected. This theory, which has been applied sometimes to solve local pollution problems - for example, Coll (1993) used it to determine the optimal pollution level for a thermal power plant in Spain, given its effects on nearby orchards -, is difficult to apply for regional or global environmental problems, in which the identification of the affected agents is very difficult, and transaction costs very large. This is generally the case for electricity generation, so other mechanisms for the internalisation of externalities have been developed.

2.1 Setting of environmental constraints

The first approach to internalise externalities into electricity systems operation and planning models was to set environmental objectives, for the whole system, or for parts of it (e.g., for specific generating plants), as constraints to the optimisation or simulation problem. These environmental objectives could be set directly, as environmental quality standards, or indirectly, as fuel, technology, or emission standards. Generally, the indirect approach has been the one chosen, since the direct one requires the decision models to be coupled to pollutant dispersion modules, in order to relate emissions with their effect on the environment.

The major advantage of setting environmental constraints is that decision models do not need substantial modifications for including them, so their implementation is quite easy. However, this approach has two large drawbacks, which are that it cannot provide an efficient assignment of resources by itself, and that it is not flexible, since it does not account for changes in technology or fuel characteristics.

In order to solve the second problem, other more efficient methods have been proposed to achieve environmental objectives, and which are termed market instruments. All of them are based on the provision of economic incentives to market agents, so that they may attain a previously determined environmental objective. The most used market instruments are pollution taxes, and tradable emission permits.

Pollution taxes are those imposed as a consequence of a polluting activity. Developed early in this century (Pigou, 1920), they are used to limit the realisation of a polluting activity, by incorporating the tax into the cost function of the polluter, and thus disincentivating its activity.

Later, an even more flexible instrument to achieve an environmental objective was proposed by Dales (1968), tradable emission permits. These permits introduce a larger degree of competition into environmental regulation, and therefore are considered more efficient.

The introduction of these market instruments into traditional decision making models for the electricity sector is not excessively complicated, since either taxes or permits are expressed in monetary terms, so they can be entered directly into the cost functions to be minimised.

However, in spite of the higher economic efficiency of these market instruments, they still cannot solve the major drawback of the setting of environmental constraints, which is the determination of the constraint by itself, that is, they cannot by themselves alone achieve the social optimum.

Therefore, all methods based on the setting of environmental objectives by the regulator are only valid as long as this objective is the social optimum. And this is not the usual situation, since objectives are usually set as a result of political negotiation. Although some authors (e.g., Bernow and Marron, 1990) argue that this is the real social optimum, as in theory it incorporates the social will expressed by the election of society’s representatives, this statement seems quite doubtful in the real world.

The theoretically correct way to determine the social optimum for the allocation of economic and environmental resources would be to compare the costs and benefits of an improvement or degradation of the environment. This is complicated, mainly because of the problems in the quantification of environmental costs and benefits. If the environmental objective set by the regulators, and incorporated as a constraint to the decision model, were determined this way, the instruments mentioned above would achieve a socially efficient allocation of resources. The problem is that this method, in which the regulator first determines the optimum, and then sets the instruments required to achieve it, is very rigid, and cannot answer effectively and quickly to technology, fuel, or demand changes, what in turn generates inefficiencies.

2.2 Integration of externalities as decision criteria

Hence, we find that the better way to achieve an efficient allocation of economic and social resources is then not to consider social aspects as constraints for the decision model, but rather as criteria in the same decision level as traditional criteria such as cost or reliability. When social aspects are introduced in operation or planning models, these are termed full-cost dispatch, or integrated resource planning, respectively.

Full-cost, or minimum-social-cost dispatch is the one in which, besides from economic or reliability criteria, other social or environmental criteria are incorporated, thus minimising the social cost of the operation of an electricity system.

The advantages of full-cost dispatch are that first, it is a very quick way to internalise externalities, since it affects to the existing generating units, and thus do not need to wait for the modification of the system. Second, its implementation is not difficult even in competitive markets, in which dispatch is usually centralised, and so it would only be necessary to modify the dispatch algorithm used by the system operator.

Its major disadvantage is that because of being so quick in promoting changes, it may be traumatic for some electric utilities, which might not recover their investments if some generating units are stopped due to environmental reasons. This kind of "stranded cost" should be compensated in some way, being thus an extra cost to the system. And this extra cost is difficult to justify nowadays given the uncertainties and difficulties still existing for the quantification of externalities.

On the other hand, Integrated Resource Planning is not so traumatic, since it only affects future modifications of the system. But it also has disadvantages, the major one being the difficulty to implement it in competitive markets, with no centralised planning processes.

In spite of their evident attractive, both methods for the internalisation of externalities have been rejected by some sectors, mainly due to the following reasons (Almeida, 1994):

- sometimes, they may increase the cost of electricity, by promoting cleaner but more expensive equipment,

- equity problems may appear, since the increase in costs may not affect homogeneously different income groups,

- results may not be optimal, due to the uncertainties still lied to the assessment of externalities,

- and there may be regional or sectoral distortions, when the internalisation is only required for specific areas or sectors.

The first drawback cited is not really so, but rather an advantage, since the efficient allocation of resources by the market is only achieved when prices incorporate the full costs, and thus make the quantity consumed to be optimal. As for the equity concerns, it is true that there may be distributional problems, but modern states have already available a panoply of measures for income redistribution.

Regarding the two latter points, it must be noted that they are not associated to the internalisation of externalities, but rather to an incorrect implementation of it. Regional or sectoral distortions may be corrected with an adequate definition of policy. And the uncertainties in the assessment of externalities are something that will be reduced with further research.

So we find that, although there are yet problems to be solved, the most efficient way to internalise externalities is to integrate them as additional criteria into the planning and operation models. And, given the liberalisation of electricity markets, we find that the development of dispatch algorithms which minimise the social cost of electricity production is a rather straightforward option, provided that measures are taken to avoid traumatic transitions, and its associated stranded costs.

This integration of externalities into electricity systems operation models presents some difficulties, which will be discussed in depth in the following section.

3. Integration of externalities into electricity systems operation models

Two major difficulties may be identified when integrating externalities into electricity systems operation models:

The first one is how to quantify the externalities to be introduced into the decision model. This question has been addressed by several research projects, as already mentioned. But, before getting into the details of all the methodologies proposed, we should ask ourselves what type of information on externalities we need in order to incorporate it into our operation model. To put it in other words, which are the units in which the externalities should be expressed.

In order to answer this question, we should analyse the characteristics of the electricity system operation model studied. Typically, an operation model tries to minimise the cost (economic or social) of the production of electricity from a given set of power plants, in monetary units per kWh. So the first idea would be to introduce externalities also in monetary units per kWh.

That would be right if externalities were correlated to the kWh produced. However, that is not usually so. Changes in fuel, technology, operating conditions, etc., will alter the damage caused by each kWh generated. So this is a very rigid approach. If we express externalities in monetary units per kWh, we will not be able to account for changes in the fuel used, or in the conversion technology of a given power plant, and thus we will obtain higher economic and environmental costs than the real ones, since we will have less options to minimise costs.

Therefore, we should look for another unit which allows for greater flexibility. That will depend on the type of impact considered. For example, the visual intrusion caused by wind generators will only depend on the amount of them placed in the wind farm. As for the risk perception from a nuclear plant, it is usually independent of the amount of electricity or nuclear waste produced, it rather depends on the feelings of the population of the country in which the plant is sited. So for these examples the best unit would be monetary units per power plant.

As for fossil power plants, for which the major impact is caused by its atmospheric pollutant emissions, the unit which allows most flexibility is monetary units per unit of pollutant emitted. This unit is not subject to possible modifications in the emission rates, so it also allows for considering possible changes in technology, once we know its pollutant emission rates.

Now, how to estimate the damages caused by each unit of pollutant emitted by the different power plants? As we said before, several methodologies have been proposed for this estimation: top-down, bottom-up, control costs, etc. Their pros and cons have been extensively reviewed by several authors, so we will not attempt to do that here. But we may say that we find that the best one developed till now, both from a theoretical and practical point of view, is the ExternE methodology (European Commission, op.cit), which allows for the assessment of damages specifically for each technology and site, in a transparent, consistent, and comprehensive way.

But it has to be remarked that the ExternE methodology has been developed with a focus on the assessment of the externalities due to increments in electricity production, that is, of marginal values. This may be perfect for assessing the addition of individual power plants to a system, but not for evaluating the performance of the whole system.

So here comes the second difficulty of the integration of externalities into electricity systems operation models, the aggregation of the marginal values provided by the ExternE methodology to average system externalities.

This issue was addressed by the ExternE Project, but it was only solved in part. The approach proposed was to use the EcoSense model (European Commission, 1999a), developed by IER (Univ. Stuttgart) to simulate the atmospheric dispersion of the pollutants emitted by the fossil power plants of a given electricity system, and to quantify the externalities produced by them. However, since the EcoSense model is not linked to a dispatch model, it is only capable of producing ex-post results, but not to optimise the social cost of electricity production.

The best approach would be to couple this model, or a similar one for the valuation of externalities on a site- and technology-specific approach, to an electricity systems optimisation model, so that the optimisation process would take into account the environmental impacts of each power plant, according to its pollutant emission rates, the meteorological and topographic conditions, the receptors affected, etc. Unfortunately, this development would be enormously complicated, so alternative approaches have to be designed.

The one chosen here has been the following: first, to assess the externalities of each individual power plant, and then introduce these values into an electricity systems operation model. Of course, this approach also presents several drawbacks, which are described below.

3.1 Damage transferability

The first one is the large effort required to assess the externalities of each individual power plant in the system. While this may be feasible for small power systems, the assessment of more than 100 power plants such as in the Spanish power system is far above the budget of any reasonable research project. So some method must be used to assess only a limited number of power plants, and then transfer the damages assessed to the rest of the system.

As mentioned before, this may be really difficult for wind farms, in which the externalities generated are largely dependent on the site evaluated (due to its ecological and aesthetic values, the population affected, etc.), and quite straightforward for nuclear plants, for which the damages are not really dependent of their site and size.

For fossil power plants, choosing the right unit for the quantification of externalities makes things easier. As mentioned before, the right unit is monetary units per unit of pollutant emitted. This unit is independent of the fuel and technology chosen for the power plant, and therefore is only affected by the location in which the pollutant is emitted. Therefore, for fossil power plants the damage transferability problem is mostly a spatial one.

For global damages, spatial transferability is not really an issue, given that it is reasonable to assume that the damages caused by greenhouse gases are not dependent on where their emissions take place. For regional or local scale damages, however, the location of the emissions may affect damages to a large extent, based on different factors.

The first one may be the emission stack height. Most electricity sector emissions come from high stacks, and therefore could be assumed to be relatively well mixed into the boundary layer. This may not be true, however, for those power plants sited in regions with complex orography. In addition, some emissions may be from sources closer to the ground, for example those from small power plants. These will typically produce larger local impacts, particularly where the emissions are in an urban area.

Emissions may also have different impacts depending on the time of the emission. Ozone formation from nitrous oxides, for example, is conditioned by sunlight and temperature, so there will be strong daily and seasonal variations. The impacts of peak load power plants in winter will therefore be lower than those of base load plants. However, since the ExternE methodology uses average concentrations, these differences may be smoothed.

Local meteorological and topographic conditions may also affect the dispersion of the emissions, and their mixing in the atmosphere. While in some sites prevailing winds may drive pollutants to the sea, in others they may place them over populated regions, thus causing very large differences on the damages produced. Of course, these large variations may also happen with homogeneous pollutant dispersion, due only to the differences in receptors (population, crops, forests) distribution.

Another factor which might be important is the spatial differences in dose-response functions, which relate pollutant levels with impacts, and in valuation estimates, which relate impacts with monetary values of the damages.

In general, dose-response functions which relate to human beings may be transferred without too much problem, as well as impacts on crops or buildings. Natural ecosystems are more problematic, as impacts are very dependent on climate, soil, or other variables which may vary largely across one country.

As for the transferability of valuation estimates, the message is very similar: those related to human health are quite valid to transfer across one country, as well as crop or building damage estimates, or noise valuation, since all of them are based mostly on societal or cultural assumptions which remain more or less stable across one country. Transferability of monetary values for natural ecosystems is much more difficult, and should not be attempted lightly.

In spite of all these factors affecting regional and local damages, the ExternE Project considered that damages in monetary units per unit of pollutant emitted might be transferred within one country, without large differences. Again, we should say that this will depend on the country studied. For Spain, we found differences of 20% for power plants sited only 100 km away, and differences of a 100% across the whole country. And this without considering ozone damages, what is even more problematic because of the difficult chemistry involved.

So we think that spatial transferability should be handled with care in large countries, or in those countries with complex topographies or uneven receptor distribution.

3.2 Aggregation of impacts

The second major difficulty of the approach proposed is to aggregate the marginal damages estimated with the ExternE methodology to the total damages produced by the operation of the whole electricity system. Although it might be thought that all that it is necessary is to multiply the incremental impact by the total pollution, this approach only holds if, and only if, all processes in the impact pathway are linear. Again, this issue has already been dealt with by the ExternE Project, so here only a summary of their conclusions is presented.

In general, the natural world and socio-economic systems are characterised by non-linearity. However, sometimes the linearity assumption may be considered valid: when the system is sufficiently close to it, or when the uncertainties about the nature of the process do not justify more complicated hypotheses. The existence of thresholds for impacts is also an issue to be discussed when aggregating damages for the whole system.

These two aspects have to be checked for pollutant dispersion, dose-response functions, and economic valuation.

Classic pollutant (such as SO_2 or particulates) dispersion is usually considered linear, for example in Gaussian plume type atmospheric dispersion models. However, the situation is more complex for chemically active species, such as aerosols, or ozone. Therefore, simple aggregation of pollutant concentrations would not be valid for these compounds.

Regarding dose-response functions, some may be considered linear (for example, for human health impacts or damages to building materials) and some not (effects on crops). In some cases, for example, for the impacts of SO_2 on crops, the dose-response functions are not only non-linear, but have a maximum in the range of concentrations of concern. At low pollution levels, there is a fertilisation effect, which is turned to yield reduction at a certain level. For forest, fisheries and natural ecosystems, there are not even dose-response functions, but just thresholds for certain pollutants, termed critical loads. Of course, simple addition of marginal exceedance of these critical loads is not an appropriate aggregation measure. So again, a simple addition of marginal damages is not allowed according to the dose-response functions characteristics.

As for the aggregation of monetary values, here what should be accounted for are the possible changes in market prices resulting from changes in production of crops, or timber, or materials damage. Another example would be the changes in the valuation of noise when two noise sources are aggregated. The most acute changes may be that caused by ozone in some crops with a small market, as has been demonstrated by some studies (Adams and McCarl, 1985).

The problems caused by the non-linearity of both pollutant dispersion models and some dose-response functions would be solved, as mentioned before, if they were linked to the electricity dispatching model. As for the aggregation of monetary values, market equilibrium models should be employed to account for the above mentioned changes in supply or demand. However, this is not usually the case because of the complexity of this task, so we will have to accept that there may be errors in our estimations which are quite difficult to eliminate, and which add to the uncertainties inherent to the externalities assessment process itself.

In spite of all the drawbacks and difficulties described of the approach proposed, an attempt has been made to incorporate the externalities of individual power plants to an operation model for the Spanish electricity system. This we hope will show the effect, although approximate, of the internalisation of externalities into electricity decision-making models. The large amount of uncertainties lied to it should prevent, for the moment being, for this exercise to be applied to real situations, but it may give an indication to electricity sector regulators of the possible impact that the internalisation of externalities may have in the system.

It has to be reminded that some externalities have not been included in the case study, given that the large uncertainty to which is subject their monetisation does not recommend their consideration. This might be solved multiple criteria techniques in parallel to the monetary valuation of externalities. As has been mentioned repeatedly (Fritsche, 1994; Lee, 1996), these methodologies are not self-exclusive. The monetisation of externalities will be preferred when the analyst wishes to eliminate all subjectivity, and when uncertainty is small, while multicriteria techniques are recommended when there is conflict among different groups of society (see e.g. Linares and Romero, 2002), when subjectivity has to be taken into account, and when uncertainty is large.

4. A model for the social optimisation of the operation of the Spanish electricity system

The electricity network model named GREEN has been developed by the Instituto de Investigación Tecnológica (IIT) of the Universidad Pontificia Comillas of Madrid (Muñoz, 1998). The model is of the operational type and not a planning tool. The aim of the model is to provide the minimum variable cost for the exploitation of the Spanish electricity system, subject to operating constraints such as generation and fuel consumption limits. It has been designed to represent yearly operation of the Spanish electric power system, and it could be used for medium term economic planning.

The Spanish electricity system is composed of hydroelectric, nuclear and fossil fuelled thermal units. These last units are mainly coal plants, which consume national and imported coal. Domestic coal may have a compulsory consumption quota set by the Government, which is one of the constraints of the system. Each one of these areas of electricity production has a different contribution to the domestic production. Their share may vary depending on the hydro inflows per year, fuel imports policy or other yearly constraints.

All the electricity production units of the country that exceed a certain capacity (50 MW) are included in the model. At the moment, only the internal costs of the system are taken into account to perform the economic central dispatch of the overall generation units of the Spanish electric power system. The integration of external costs in the model may vary in a significant way the decision process.

The results from this case study give a first approximation of the influence of external costs in the medium term economic planning of the electricity power system of an EU country.

4.1 Model description

Power plants have been traditionally dispatched by minimum fuel cost criteria, in what has been called economic dispatch optimal load flow. This process did not consider the environmental impact produced by energy generation, mainly by that generated with fossil fuels.

The tool described in this document allows for the evaluation of the pollution reduction mechanisms in large electric systems (more than 100 generators). It is a model of annual operation that reproduces the system considering in detail the generation activities. It also considers co-generation as well as energy exchanges with other systems. It models precisely the most relevant pollutants and apply the external costs that environmental impact implies. Some of its results are the gross and net monthly productions, fuel consumption, different pollutant emissions and variable and external costs of operation. All these can be obtained in different optimisation conditions as minimum emissions, minimum social costs, minimum operation costs under certain pollutants constraints, etc.

This model provides the minimum variable (or social) cost subject to operating constraints (generation, fuel and emissions constraints). Generation constraints include power reserve margin with respect to the system peak load, balance between generation and demand, hydro energy scheduling, maintenance scheduling, and generation limitations. Fuel constraints include minimum consumption quotas and fuel scheduling for domestic coal thermal plants. Emissions constraints apply to fossil fuel units. The relevant decision variables and the real operation of the power system are adequately represented, two types of decisions are addressed, intraperiod and interperiod decisions.

This operations planning problem is formulated as a large-scale mixed integer optimisation problem. The model has been implemented in GAMS, a mathematical specification language specially indicated for the solution of optimisation problems, and solved by using CPLEX, a well-known mixed integer programming (MIP) solver.

The medium term planning problem is stochastic by nature. Uncertainties arise in load, hydro inflows, thermal unit availability, etc. However, the model described is deterministic. Stochasticity in unit availability and load can be naturally implemented within this methodology via scenarios. Uncertainty in hydro inflows is modelled deterministically because medium term operation planning is performed under the assumption of average hydrology.

No model with this whole set of characteristics (i.e., fuel, maintenance and hydro scheduling on one hand and commitment decisions on the other hand) has been found in the literature. Models deciding seasonal hydro scheduling, usually based on stochastic dynamic programming or decomposition methods, represent in detail the spatial hydro dependencies but usually ignore the fuel and maintenance scheduling problems. Medium term fuel scheduling is decided using a large-scale linear programming approach in several works. Maintenance scheduling has been solved by many different techniques, decomposition techniques and integer programming among others. Combined seasonal and weekly/daily operation of pumped units has not been addressed so far. Emissions dispatch and social costs have been recently incorporated in production cost models and not in detail as in this tool.

4.1.1 System description

A production cost model determines the variables defining the system operation at minimum variable cost for the scope of the model. Let us define horizon as the point in time for which the system operation is to be modelled and scope as the duration of the time interval to be studied. In this medium term model, the horizon is two or three years ahead and the scope is usually one year. The scope is divided into periods, subperiods and load levels. Typically, periods will correspond to months, subperiods to weekdays and weekends of a month, and load levels to peak, plateau and off-peak hours.

The load for each period is modelled as a staircase load duration curve, where an step is a load level. Hence, generation will be constant for each load level.

Each thermal, hydroelectric, pumped-hydro and pumped-storage unit is modelled individually. Each thermal unit is divided into two blocks, being the minimum load block the first. Heat rate is specified by a straight line with independent and linear terms. Random outages are deterministically modelled by derating the unit's full capacity by its equivalent forced outage rate. Fuel constraints affect the fuel consumption of domestic coal thermal plants. The model also incorporates the mixing of up to three different fuels in the same boiler. This mixing may be done for economic, efficiency, energy policy, or environmental reasons.

Very small hydro units are aggregated. Spatial dependencies among hydro plants are considered irrelevant to the medium term thermal generation scheduling problem and ignored. Therefore, the variation in the hydro energy reserve of a reservoir due to the generation in a hydroelectric plant located upstream is not taken into account.

Nuclear plants are modelled as generating units with no minimum load, maximum power, a very small equivalent forced outage rate, and a linear fuel consumption function.

4.1.2 Emissions modelling

The emissions modelling of pollutants is quite recent in this type of tools and in the analysis of electric systems operation.

Each power group with fossil fuel is modelled as a point-source emitter of pollutants. For this purpose it is necessary to define the combustion conditions (humidity, temperature, % O_2, etc.), in the boiler and in the exit of the chimney. A detailed model needs as well the elementary analysis of the fuel or fuels used in the unit.

In this tool four pollutant emissions are considered: sulphur dioxide, nitrogen oxides, particulates and carbon dioxide.

The legal limits are introduced in the model as constraints. The form can vary: some times it is the concentration of pollutants in the exhaust gases from the chimney; in others it is the total amount of emissions in a group of generators or in a single one.

There are two options for emissions modelling. The first one is using historical rates for each power plant. This is the simplest option, but it does not allow for discrimination among the fuels used by a certain group. So the best one is the second option, which is to model emissions based on the elementary analysis of each fuel, and the boiler combusting conditions.

4.1.3 Model formulation

As mentioned previously this medium term production cost model performs hydro, maintenance and fuel scheduling, seasonal operation of pumped-hydro units, weekly/daily operation of pumped-storage units, and thermal unit commitment for a generation system. The model is formulated as a large-scale mixed integer optimisation problem. The objective function to be minimised is the total variable cost for the scope of the model subject to operating constraints. These can be classified into inter and intraperiod, according to the periods that are involved in. The interperiod constraints are associated to the co-ordination in the use of limited resources (minimum quotas of fuel consumption, hydro inflows, seasonal pumping, storage and generation). The intraperiod constraints deal with the system operation in each period (thermal unit commitment, weekly/daily pumping, storage and generation limits).

The detailed mathematical formulation of the objective function, the constraints and the variables involved in the problem are described elsewhere (Muñoz, 1998). Here, it is described their meaning.

A. Objective functions

- *Objective function #1.* The first objective function is the minimisation of the fuel costs (including independent and linear terms of the heat rate and O&M variable costs) plus start-up costs plus storage costs of fuel stocks plus some penalties (due to non served power, interruptibility, and reserve margin defect) for all the load levels, subperiods and periods of the time scope.

- *Objective function #2.* It is the minimisation of social costs, including operation variable costs set in objective function #1 and the environmental external costs associated to the power generation. Usually externalities are associated to a technology or to a particular facility. This last option is better since the environmental impact and its valuation depend on the location of the unit. The externalities can be defined in different ways: in monetary units per kWh produced or in monetary units per tonne of pollutant produced. In this model both ways are available.

- *Objective function #3*. It represents the minimisation of pollutants. The unit dispatch under economic and environmental criteria is to reduce the pollutants emissions caused in the fossil fuelled generation. The reduction can be reached through constraints or with penalties in the objective function in the system operation. When this is done in the objective function it is called emissions dispatch (the previous functions are considered economic dispatch).

B. System constraints

- Generation-Demand Balance

Balance between generation and demand for any load level including non served power and interruptibility.

- Hydro Scheduling

For each hydro unit, the hydro reserve level at the beginning of each period is a function of the previous level, the hydro inflow, pumping and generation on that period. The initial and final hydro reserves are specified by the user.

- Reserve Margin

A power reserve margin for the peak load level of each subperiod must be met. This constraint represents the condition imposed to provide some amount of power available to account for increments in demand or failures of committed generation units.

- Maintenance Scheduling

The units will be an integer number of periods in maintenance according to the specified requirement. Also limits on the maximum number of thermal units simultaneously on maintenance on the same plant and on the maximum thermal capacity simultaneously on maintenance in any period with respect to the total installed thermal capacity are imposed. Contiguity among the periods in maintenance is required too if more than one is specified.

- Fuel Scheduling

For each thermal plant, the stock level at the beginning of each period is a function of the previous stock and the purchase and consumption done in the period. The initial and final storage levels are prespecified by the user. It represents the must-buy fuel purchase mandated by socio-economic and political considerations for domestic coal plants, although their cost can be more expensive than other available fuels.

- Pumped-Storage Units

Balance between pumped and generated energy by pumped-storage units in a period and a reservoir limit imposed to the pumped energy.

- Thermal Generation Constraints

For each thermal unit the maximum generation is less than the maximum available capacity and the minimum generation is greater than the minimum load. Thermal unit commitment related constraints state that the unit's output during higher load levels must be larger than its generation in lower load levels and that the commitment decision in a higher load subperiod (weekdays) must be greater than the commitment decision in a lower load subperiod (weekends).

The above constraints enforce a minimum generation for each thermal unit committed at peak load level. Note that since the heat rate curves are represented as linear curves, during any load level all the committed units will be at their maximum or minimum output except one marginal unit.

C. Environmental constraints

The limitation of emissions in power generation in most countries can have different formulations. It can focus on the total amount of emissions, on the concentration in the exhaust gases or in the ambient concentration of the pollutant (inmissions). The scope can also be annual, monthly, hourly, etc. Finally it can refer to the units individually or to a group of them.

This model reproduces the Spanish power system through the following types of constraints:

- Maximum SO_2 emissions in the *old** and *new*** units
- Maximum NO_x emissions in the *old** and *new*** units
- Maximum particles emissions in new units
- Minimum rate of desulphurization
- etc.

(*: units licensed before 1st July 1987, **: units licensed after 1st July 1987)

D. Variables

All the variables involved in the previous formulation are: maintenance decisions, fuel stock levels, hydro productions, consumption of pumped-hydro units, hydro energy reserves, commitment decisions of thermal units, thermal generations, generation and consumption of weekly/daily pumped-storage units, non served power, interruptible power and reserve margin defect.

The initial and final fuel stocks levels for each thermal plant and the initial and final energy reserves for each hydro unit are predefined by the user.

The variables regarding operation of the pumped-hydro and pumped-storage units are defined only for the periods, subperiods and load levels where they are meaningful according to the system operation.

The variables commitment and maintenance decisions for thermal units cause the problem to be mixed integer with the associated difficulty to be solved.

5. Analysis of the operation of the Spanish power system

5.1 The Spanish electricity system

Since the objective of this paper is to present an example of how the internalisation of externalities might affect power operation, an “old” data set has been chosen in order to give realistic data without interfering with the current situation. Therefore, year 1998 has been chosen as reference. That year, the Spanish power system met a maximum peak load of 28000 MW and a yearly energy demand of 165 TWh. The installed generation capacity was 45551 MW (16532 MW hydro, 11224 MW coal, 8214 MW oil/gas and 7581 MW nuclear).

There were about 71 thermal generators (8 nuclear, 36 coal and the remaining oil/gas). Their production was about 80 % of the total generation.

There were 70 hydro units with capacity greater than 5 MW and annual energy production greater than 100 GWh, that can be grouped into about 10 basins. In the model have been used units smaller than these. The maximum capacity at the same location is 915 MW. They produced as an average about 20 % of the total generation, ranging in between 13 % and 28 %, depending on the hydrology.

There were 8 pumped storage units, but their impact on annual energy production was minimum (about 1%). Co-generation and other units represented a very small fraction of the total, so they are not considered.

5.2 Quantification of the externalities of the Spanish electricity system

The externalities of the Spanish electricity system have been estimated according to the ExternE methodology (CIEMAT, 1999), with different approaches for fossil, nuclear, and hydro power units. Other power plants, such as those fuelled by renewable energies, have not been considered because of their very small contribution to the system. Co-generation has not been analysed either, due to lack of information. For these cases, then, externalities are assumed to be zero.

It has to be remarked that global warming damages have not been included in the analysis, since the uncertainty lied to their assessment is still high.

5.2.1 Fossil fuelled power units

As mentioned before, the methodology requires that externalities are estimated for every power plant, and for the whole fuel cycle. However, due to the very large effort required to do this, and the already available results within the ExternE Project, the following simplifying assumptions have been made:

Only health damages caused by SO_2, NO_x and particulates have been assessed, given that current results show that they account for more than 90% of the damages estimated for the whole fuel cycle. These damages have only been calculated for ten power plants, then extrapolating the damages to the rest of the system. This assumption is justified by the fact that the atmospheric dispersion model used has a resolution of a 100 km, so emissions of power plants located nearer than this distance produce the same effects.

Therefore, the following power plants have been chosen as representative, based on their geographic location: Puentes de García Rodríguez, Teruel, Compostilla, Aboño, Pasajes, Litoral, Puertollano, Colón, and Foix. The extrapolation of results, in terms of damages per unit of pollutant emitted, is direct, since damages depend only on the emission location, not on the type of fuel or technology.

The atmospheric dispersion of the emissions, and the quantification of the damages, has been modelled for the whole Europe, with the EcoSense model.

The externalities obtained are shown in the next tables. There are two types of results: damage estimates in mEuro/t of pollutant emitted and in mEuro/kWh produced. The second is obtained using the specific emission rate of each unit and pollutant. The model uses the first type of estimation in order to choose one or other fuel considering its environmental, economic or technical characteristics in each unit.

Table 5.1 Externalities of the Spanish Power System. Coal units.

Unit	Damages mEuro/kWh	Damages Euro/t SO_2	Damages Euro/t NO_x	Damages Euro/t TSP
Aboño 1	76.02	6991	8170	6121
Aboño 2	75.90	6991	8170	6121
Lada 3	90.18	6991	8170	6121
Lada 4	84.44	6991	8170	6121
Soto Ribera 1	73.13	6991	8170	6121
Soto Ribera 2	90.18	6991	8170	6121
Soto Ribera 3	82.23	6991	8170	6121
Narcea 1	81.99	6991	8170	6121
Narcea 2	86.54	6991	8170	6121
Narcea 3	84.32	6991	8170	6121
Anllares	74.49	5813	6554	4876
Compostilla 1	73.25	5813	6554	4876
Compostilla 2	74.49	5813	6554	4876
Compostilla 3	74.49	5813	6554	4876
Compostilla 4	74.49	5813	6554	4876
Compostilla 5	74.49	5813	6554	4876
La Robla 1	73.25	5813	6554	4876
La Robla 2	73.83	5813	6554	4876
Guardo 1	69.20	5813	6554	4876
Guardo 2	69.20	5813	6554	4876
Puertollano	82.34	6361	7556	6483
Puentenuevo	83.73	6361	7556	6483
Pasajes	64.81	9583	12076	10780
Litoral	35.65	5657	6136	5083
Los Barrios	26.84	4219	4651	4418
Serchs	149.92	7450	4823	6847
Escatrón	47.16	7450	4823	6847
Teruel 1	180.20	7450	4823	6847
Teruel 2	180.94	7450	4823	6847
Teruel 3	181.42	7450	4823	6847
Escucha	221.39	7450	4823	6847
Puentes 1	99.74	5073	2918	5262
Puentes 2	102.41	5073	2918	5262
Puentes 3	99.74	5073	2918	5262
Puentes 4	99.44	5073	2918	5262

Unit	Damages mEuro/kWh	Damages Euro/t SO_2	Damages Euro/t NO_x	Damages Euro/t TSP
Meirama	128.42	5073	2918	5262

Table 5.2 Externalities of the Spanish Power System. Fuel-oil units

Unit	Damages mEuro/kWh	Damages Euro/t SO_2	Damages Euro/t NO_x	Damages Euro/t TSP
San Adrián 2	58.97	8427	8983	8107
Algeciras 1	29.84	4219	4651	4418
Algeciras 2	29.84	4219	4651	4418
Escombreras 1	39.68	5657	6136	5083
Escombreras 2	39.68	5657	6136	5083
Escombreras 3	39.68	5657	6136	5083
Escombreras 4	39.68	5657	6136	5083
Escombreras 5	39.68	5657	6136	5083
Aceca 1	45.83	6361	7556	6483
Aceca 2	45.83	6361	7556	6483
Sabón 1	31.59	5073	2918	5262
Sabón 2	31.59	5073	2918	5262
Castellón 1	58.97	8427	8983	8107
Castellón 2	58.97	8427	8983	8107
Badalona 1	34.87	8427	8983	8107
Badalona 2	34.87	8427	8983	8107
Colón 1	34.87	4820	5753	5426
Colón 2	34.87	4820	5753	5426
Colón 3	34.87	4820	5753	5426

Table 5.3 Externalities of the Spanish Power System. Natural gas units

Unit	Damages mEuro/kWh	Damages Euro/t SO_2	Damages Euro/t NO_x	Damages Euro/t TSP
Besós 1	14.37	8427	8983	8107
Besós 2	14.37	8427	8983	8107
Foix	14.37	8427	8983	8107
San Adrián 1	14.37	8427	8983	8107
San Adrián 3	14.37	8427	8983	8107
Elcogas	3.02	6361	7556	6483

An analysis was carried out in order to determine the amount of damages caused by these emissions within Spain. An average of a 30% of the damages was obtained.

5.2.2 Nuclear units

The assessment of the externalities of the nuclear power plants has been carried out based on the results obtained in other European countries within the ExternE Project, since no particular analysis has been carried out yet for any Spanish power plant. This study would be recommended in order to give more reliable results.

In general, the nuclear fuel cycle presents several difficulties for the assessment of its externalities. The major problems lie in the fact that most of its impacts are produced in the long-term, and so the determination of the time horizon for the study and the appropriate discount rate are very important issues. Another important fact is the risk perception issue, which also present problems for being included in the analysis.

This explains at least partly why results differ so much among different studies, from almost negligible to 7 mEuro/kWh, depending on the impacts included, and on the discount rate used. Therefore, the solution adopted here has been to use an intermediate value of 2 mEuro/kWh for PWR plants, and 8 mEuro/kWh for BWR plants.

These values are assigned to the Spanish power plants in the following table. It has to be reminded that these figures should be considered only approximations, probably lower than their real value, so they should be handled with caution.

Table 5.4 Externalities of Spanish Power System. Nuclear units

Unit	Technology	Damages mEuro/kWh
Asco 1	PWR	2.0
Asco 2	PWR	2.0
Almaraz 1	PWR	2.0
Almaraz 2	PWR	2.0
Cofrentes	BWR	8.0
Vandellós	PWR	2.0
Garoña	BWR	8.0
Trillo	PWR	2.0
J. Cabrera	PWR	2.0

5.2.3 Hydro units

As for nuclear, there are no studies on the externalities of hydro power plants for Spain. And in this case the extrapolation of results is even more complicated, due to the large dependency of results to the plant location.

Hydro presents external costs (mainly ecological and accident risks) but also external benefits (recreation, water regulation). And these costs and benefits are highly variable depending on the site and the type of power plant. In Europe, values obtained vary from damages of 7 mEuro/kWh to benefits of 2 mEuro/kWh.

Again, here an intermediate value has been used, a damage of 2 mEuro/kWh, as a reference, and with all the caveats applicable.

Table 5.5 Externalities of Spanish Power System. Hydro units

	Damages mEuro/kWh
All units	2.0

5.2.4 Other units

Wind and biomass generation technologies were in 1998 of very little importance in the Spanish system (now this situation has radically changed). Thus, they have not been incorporated. Co-generators produce a more significant amount of energy but they have not been considered in this study because its externalities have not been quantified for the moment.

In Figure 5.1. a summary of the externalities calculated depending on technology and fuel are presented. These figures are approximate averages for the different power plants, so large variations should be expected from these figures depending mainly on the location of the power plant.

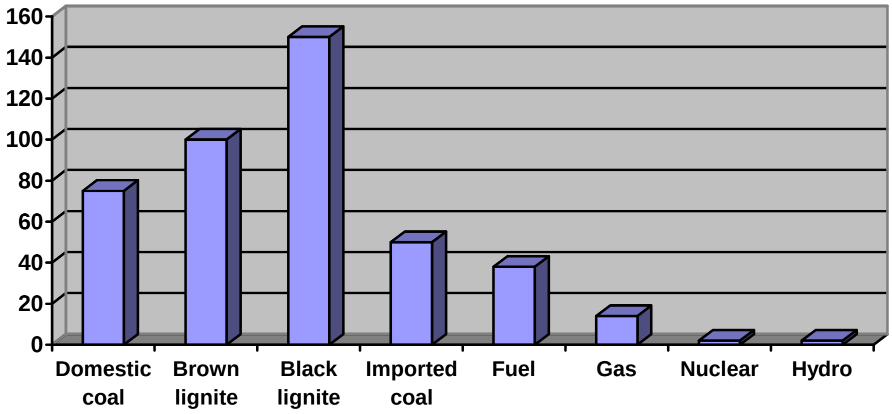

Figure 5.1. Average externalities for the Spanish electricity system (in mEuro/kWh)

5.3 Results

The model described and the externalities assessed were used to analyse the operation of the Spanish power system for a past period, year 1998, so that they might be compared to real results. It has to be noted that a different regulation framework existed then in the system compared to the current one: there was no competition in the market, prices were regulated, and there were quotas for national coal.

In 1998, a new competitive market was introduced, and national coal quotas disappeared. Therefore, the operation of the system would be expected to differ from the one provided by the model. However, studies carried out have shown that the operation does not differ much in spite of the new regulation framework, with national coal quotas being substituted by price incentives. So we think that the results provided by the model, and the indications it gives in terms of the impact of the internalisation of externalities in the system operation, remain valid.

In order to show the impact of the internalisation of externalities in the system operation, six dispatch strategies have been studied:

- Current centralised dispatch, with optimisation of the standard variable costs, with and without domestic coal constraints due to energy policies (A.1 and A.2)

- Minimisation of the standard variable costs, including the environmental externalities, with and without domestic coal constraints due to energy policies (B.1 and B.2).

- Minimisation of the standard variable costs, including the 30% of the environmental externalities, with and without domestic coal constraints due to energy policies (C.1 and C.2).

A.1 and A.2 strategies consist in operating the system being the objective function the minimisation of the standard variable costs of operation (objective function #1) with the operation, reliability and environmental constraints described before. Case A.1 is the reference case for the later comparison with the other strategies.

Strategies B.1 and B.2 have both the objective function (#2) of minimisation of the social costs of the system operation but B.1 includes the constraints of minimum consumption of domestic coal due to energy policies and B.2 does not.

In cases C.1 and C.2 the formulation is similar to cases B being the only difference that cases C only consider the 30% of the externalities calculated for the Spanish power system. The interest of these strategies is because this is the percentage estimate that can affect the Spanish population, being a first approximation for the external costs generated by the power system in Spain.

In all cases the values for the externalities are held in mEuros by ton of emitted pollutant, except in the nuclear and hydro technologies where the values are in mEuros per kWh generated.

The results obtained are shown in the following tables.

Table 5.1 Operation results in 1998 of the Spanish power system

	Case A.1	Case A.2	Case B.1	Case B.2	Case C.1	Case C.2
SOCIAL COSTS (million Euros)						
Total variable costs	2,016.3	1,898.9	2,192.8	2,201.1	2,116.8	2,133.5
Total external costs	7,901.6	4,829.6	7,034.5	1,242.5	2,155.9	414.0
TOTAL SOCIAL COSTS	9,917.8	6,722.5	9,227.3	3,443.6	4,272.7	2,553.6
NET GENERATION (GWh)						
hydro	30,352	30,135	29,451	31,293	29,253	29,253
nuclear	51,133	51,133	51,133	51,133	51,133	51,133
brown lignite*	8,957	7,332	8,588	0	10,283	0
black lignite*	8,780	966	8,760	0	8,772	0
anthracite*	33,575	39,837	27,677	3,083	27,694	6,957
imported coal	10,436	10,490	0	8,583	4,417	8,834
fuel-oil	0	2,805	14,334	38,988	9,254	34,721
natural gas	893	893	2,895	12,388	1,794	11,657
NET GENERATION (GWh)	142,196	142,196	142,196	142,196	142,196	142,196
Pumping consumption	1,930	1,619	643	3,274	360	359
POLLUTANT EMISSIONS						

	Case A.1	Case A.2	Case B.1	Case B.2	Case C.1	Case C.2
Emissions of SO_2 (kt)	1,105	678	1,058	166	1,079	175
Emissions of NO_x (kt)	219	214	164	59	177	70
Emissions of TSP (kt)	23.7	20	19.8	1.7	21	2.6
Emissions of CO_2 (kt)	77,016	77,616	73,359	48,178	74,557	49,623

* are referred to the total production of the units which main fuel is this one, although they may use another as complementary fuel.

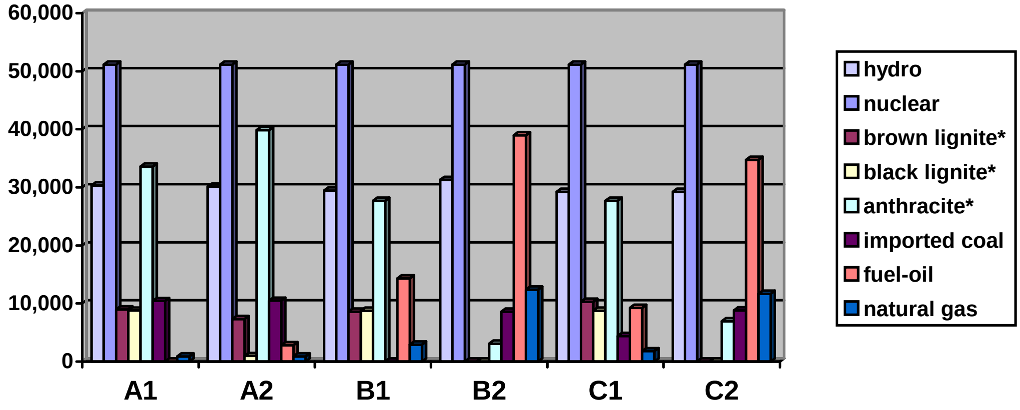

Figure 5.2. Power generation by the different technologies (GWh)

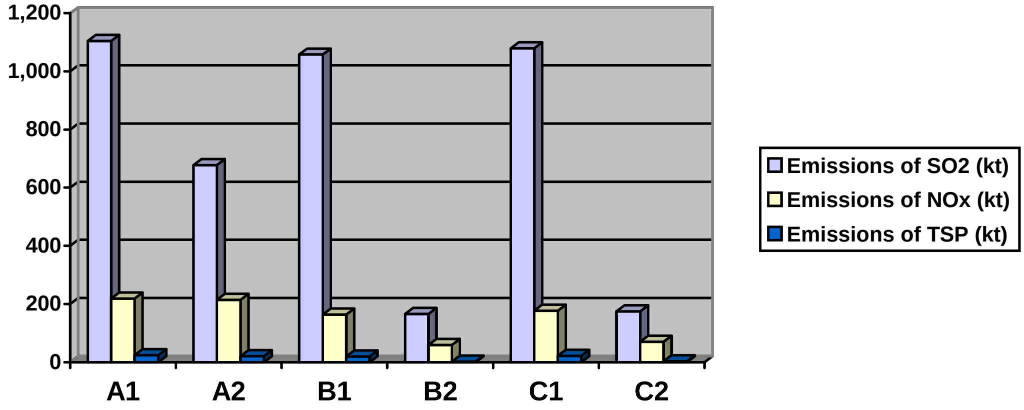

Figure 5.3. SO_2, NO_x and TSP emissions under the strategies considered

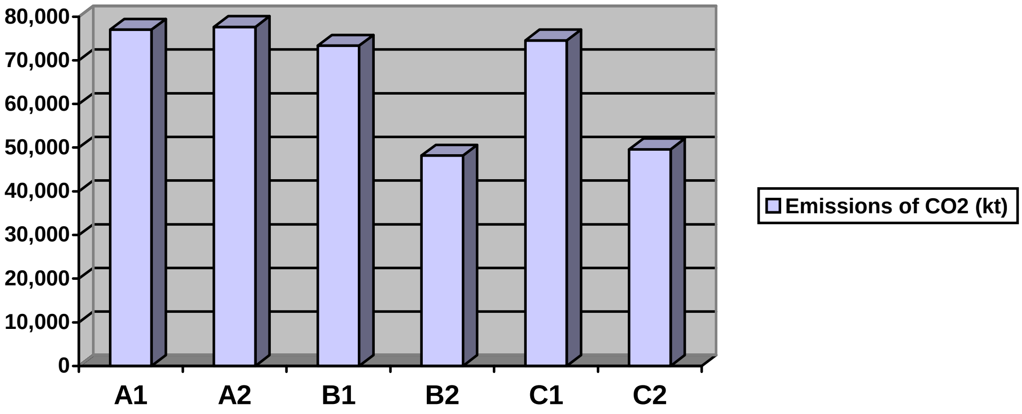

Figure 5.4. CO_2 emissions under the strategies considered

Table 5.2 Coal consumption among the different cases (kt)

	A.1	A.2	B.1	B.2	C.1	C.2
brown lignite	9,635	6,208	9,635	0	9,635	0
black lignite	4,092	0	4,092	0	4,092	0
anthracite	13,720	7,999	13,720	0	13,720	0
imported coal	9,566	16,373	3,338	4,038	5,826	5,523
total COAL	36,552	30,580	30,785	4,038	33,273	5,523

As a general conclusion from these results, it has to be remarked the significant change in the electricity dispatching system when externalities are introduced. Lignites, due to their high sulphur content, disappear from the system, and the contribution of national coal is greatly reduced. However, here it has to be noted that this result, that is, the minimisation of social costs, is only achieved if other constraints are removed from the dispatching model. Of these, the major one is the compulsory consumption of national coal. As may be seen, if this constraint is not removed, the change induced by the introduction of externalities into the system is the elimination of imported coal, which is indeed cleaner than national coal. This change is very small indeed, since the contribution of imported coal is quite small.

In fact, it may be said that, if the constraint is not removed, the introduction of externalities into the dispatching system produces hardly any change, as may be observed from cases A.1, B.1, and C.1. When it is eliminated, external costs are greatly reduced, even if their minimisation is not an objective. This may be seen in case A.2., where the constraint is removed but externalities are not included. In this case, external costs are reduced, simply by the change from national coal and lignites to imported coal. However, eliminating the constraint by itself does not minimise social costs, externalities have to be included, as shown in cases B.2 and C.2. In these cases, national coal is completely eliminated, being substituted by fuel-oil and gas.

Nevertheless, it has to be reminded that here only environmental externalities have been assessed. National coal and lignites have also several advantages, such as their contribution to energy security, and their support of local economies in mining regions. Therefore, in order to decide whether the constraint mentioned above is justified or not, a full analysis of these aspects should be carried out.

6. Conclusions

In order to achieve an efficient allocation of resources in electricity production, we must not only assess the externalities of individual power plants, but also develop tools to internalise them effectively into the decision-making processes.

The study presented here has shown the importance of the development of tools for the internalisation of externalities into energy decision-making processes, and the need to have good estimates for the externalities of the individual power plants of an electricity system if this internalisation is to be carried out effectively and efficiently.

The results obtained by the application of an electricity system operation model for Spain show how when externalities are internalised, the electricity system operation may be altered significatively, even when only part of the externalities are taken into account. They also show that in some cases, the efficient allocation of resources seeked by this internalisation of externalities is prevented by the existence of political constraints, which may be justified on a social basis. Similar results have been observed in other studies (e.g. Owen, 2004).

However, these results should only be considered as a first approximation towards the internalisation of externalities into electricity systems operation and planning, given the large uncertainties still existing in the quantification of externalities, and their aggregation into system damages.

Further research is needed in order to improve externalities assessment methodologies, so that they may provide reliable results which may be included in electricity systems operation and planning tools. This research should go in parallel to research in multi-criteria techniques which allow for the incorporation in these tools of those environmental and social impacts which are too difficult or uncertain to monetise.

It is expected that, when these improved tools are available, the objective many times expressed in all sorts of political documents, that of a cheap, reliable, and environmentally-benign electricity supply, will be achieved.

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