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# METHOD FOR EFFICIENT DISTRIBUTION OF MEANS TO REDUCE $CO_2$ EMISSIONS IN A SET OF POWER PLANTS

A method for the allocation of technologies of reduction of $CO_2$ emission to sources of emissions based on dynamic programming has been described. The purpose of the application of the method was to develop an efficient strategy of allocating financial means for reducing $CO_2$ emissions from a set of coal and lignite fired power plants (carbon dioxide sources) which enables reduction of the total emissions to the required level within a given time horizon, at the minimum cost. The application of the method is illustrated based on the set of the 20 largest Polish coal and lignite fired power plants.

Keywords*: $CO_2$ emissions, reduction, dynamic programming*

## 1. Introduction

In recent years, one can observe increasing activities in the developed countries, especially in the richest countries of the European Union, aimed at creating a so-called "emission-free economy" in the long-term horizon, not precluding the application of economic means of pressure on some countries. It can be considered that the present action is the next stage of the process started at the Kyoto conference in 1997. This first big international conference on global warming resulted in a protocol that by 2005 had been ratified by more than 140 countries, including Poland, accounting for over 60% of carbon emissions associated with human activity. After that, there were a number of lesser-known conferences and international agreements, as well as the internal arrangements which came into force in the European Union. As a result, Poland has committed to a large reduction in greenhouse gas emissions in the coming years and possibly much larger reductions in the future. This will entail the need to

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spend huge sums on investments in new equipment and technologies, especially in the power generation industry. It is worth noting that the entire European Union is responsible for approximately 11%, and Poland for approximately 1%, of all $CO_2$ emissions related to human activity.

Among EU countries, the Polish situation in the area of greenhouse gas emissions is relatively very difficult, being the result of long-term negligence in the implementation of modern energy technologies (including nuclear power plants), omissions in terms of reducing emissions, and the huge importance of heavy industry, particularly steel, cement and energy plants, based mainly on the use of coal and lignite.

In this situation, the reduction of total national $CO_2$ emissions by 20% by 2020, according to the rules adopted by Poland in 2008, has become one of the major economic problems to be faced in the near future. The problem is so new that neither scientific analyses nor studies exist concerning the effects of emissions reduction on Poland. Furthermore, there is currently no Polish research center, after the liquidation of the Government Centre for Strategic Studies (RCSS), preparing analyses on this issue. The Ministry of Industry has its Social Council of the National Program for the Reduction of Emissions but it is a body oriented towards exchange of views, in many cases very interesting, and publication of final documents rather than their own research [5]. Meanwhile, the assessments of some economists are alarming – they even talk of a possible 2% decline in Polish GDP associated with such a significant reduction in $CO_2$ emissions. The opinions of Professor Krzysztof Żmijewski of Warsaw University of Technology, the General Secretary of the Social Council of the National Program for the Reduction of Emissions, deserve special attention. Unfortunately, they are presented mainly in the daily newspapers [6], at conferences, on web sites. In this situation, it is worth mentioning the report published in February 2012 by the National Chamber of Commerce entitled *Assessment of the impact of the establishment of «Roadmap 2050» on the energy sector, economic development, industry and households in Poland by 2050. A synthesis* [1]. This report can be considered as the first attempt to quantitatively analyze the effects of reduction of $CO_2$ emissions on the Polish economy.

Due to the importance of this problem, there is urgent need to develop methods that enable efficient use of financial means, mainly state-owned, intended to reduce emissions. Even a slight reduction in spending, due to the huge scale of the problem, gives significant savings. The method described later is not designed to determine the optimal plan for reducing $CO_2$ emissions, but can be a tool to create and compare different scenarios. One of the main problems with the practical application of quantitative methods, such as the one described, is the lack of reliable data on the costs associated with the introduction of technologies of emission reduction and data concerning the costs and conditions for purchasing $CO_2$ emission rights, which in this case can be explained by the fact that these rights will be a subject of international trade, and the market price will be heavily dependent on supply and demand, as well as the world's economic activity. Also, the costs of installing and operating CCS are not yet known, because no such system has been implemented on an industrial scale – in Germany there exists only a pilot scale installation. CCS (Carbon Capture and Storage) is a new concept in $CO_2$ abatement, developed at the beginning of 2000, rather costly but of high efficiency. It consists of capturing carbon dioxide from the sources of emissions, and then transporting and depositing it underground.

## 2. Formulation of the problem

The task is to allocate technologies of emission reduction to all the considered sources in order to achieve the desired level of $CO_2$ emissions within a given time horizon at the lowest costs (primary task). In order to solve the primary task, an auxiliary task is solved. The auxiliary task is formulated as follows: determine the allocation of technologies of emission reduction to all the considered sources so that the total $CO_2$ emissions from all sources in a given time horizon $T$ are minimal, given a limit on the total investment and the operational costs of all the technologies.

### 2.1 Formulation of the auxiliary problem

Consider $N$ sources of $CO_2$ emissions. There are $M$ technologies of emission reduction, each technology characterized by its efficiency of emission reduction and costs of investment and operation. The following symbols are used:

$N$ – number of sources considered,
$M$ – number of available technologies,
$T$ – planning horizon divided into periods $t = 1, 2, ..., T$
$C_t$ – available means in period $t$, where $C_1 = C_2 = ... = C_T$,
$u = [u_1, u_2, ..., u_N]$ – vector of emission volumes from sources,
$e = [e_1, e_2, ..., e_M]$ – vector of reduction technology efficiencies.

Introduction of a new technology is associated with incurring the costs of investment (setup costs), consisting of both fixed costs and variable costs, as well as operational costs (costs for running a technology). These costs should be interpreted as the extra costs connected with the change of the currently used technology to a new one. Thus it is assumed that no change in technology is also a new technology where both the investment and operational costs equal 0. The following symbols for the unit costs (per unit of emissions) associated with the introduction of the $j$-th technology to source $i$ are used: $f^1_{ijfix}$ – fixed investment costs, $f^1_{ij\,\mathrm{var}}$ – variable investment costs, $f^2_{ij}$ – operational costs.

Fixed investment costs (e.g. purchase of equipment) are spread out over time and do not depend on the length of the investment process. Variable investment costs (e.g. staff salaries) are incurred in each period of the investment process. Operational costs are incurred in each period the technology is operated.

Total $CO_2$ emissions from all the sources over the time horizon $T$ can be written as the following function $F$:

$$F=\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=1}^{M} x_{ijt}\, u_i \left(1-e_j\right) \tag{1}$$

where $x_{ijt}$ is a binary variable, defined as follows: $x_{ijt}\in\{0,\ 1\}$, $x_{ijt}=1$, if technology $j$ is operated at source $i$ in period $t$, $x_{ijt}=0$, otherwise.

The investment costs related to the introduction of technology $j$ to source $i$ in period $t$ are given by the formula:

$$\sum_{j=1}^{M} y_{ijt} f_{ijt}^{1} u_i \tag{2}$$

where $y_{ijt}$ is a binary variable, defined as follows: $y_{ijt}\in\{0,1\}$, $y_{ijt}=1$, if the investment costs related to the introduction of technology $j$ to source $i$ are incurred in period $t$, $y_{ijt}=0$, otherwise.

The $x_{ijt}$ and $y_{ijt}$ variables are subject to the constraint

$$x_{ijt}+y_{ijt}\le 1 \text{ for } i=1, 2, ..., N, \quad j=1, 2, ..., M, \quad t=1, 2, ..., T \tag{3}$$

Investment costs for source $i$ over the time horizon $T$ are given by the formula:

$$\sum_{t=1}^{T}\ \sum_{j=1}^{M} y_{ijt} f_{ijt}^{1} u_i \tag{4}$$

where $f_{ijt}^{1}$ is the sum of variable investment costs and fixed investment costs being associated with the implementation of technology $j$ at source $i$ in period $t$

$$f_{ijt}^{1}=f_{ij\,\mathrm{var}}^{1}+\alpha_{ijt}\, f_{ijfix} \tag{5}$$

$$\sum_{i=1}^{T}\alpha_{ijt}=1, \qquad i=1, ..., N, \qquad j=1, ..., M \tag{5a}$$

where $a_{ijt}$ is the share of the fixed investment costs incurred in period *t* in the total fixed investment costs.

The total investment costs for all the sources in period *t* are given by the formula:

$$\sum_{i=1}^{N}\sum_{j=1}^{M} y_{ijt} f_{ijt}^{1} u_i \tag{6}$$

The operational costs of technology *j* at source *i* in period *t* are given by the formula:

$$\sum_{j=1}^{M} x_{ijt} f_{ijt}^{2} u_i \tag{7}$$

where

$$f_{ijt}^{2} = f_{ij}^{2}$$

The total operational costs for all the sources in period *t* are given by the formula:

$$\sum_{i=1}^{N}\sum_{j=1}^{M} x_{ijt} f_{ijt}^{2} u_i \tag{8}$$

The sum of both the investment costs and the operational costs for all the sources in period *t* must not be greater than the available means $C_t$. Hence,

$$\sum_{i=1}^{N}\sum_{j=1}^{M} \left( x_{ijt} f_{ijt}^{2} + y_{ijt} f_{ijt}^{1} \right) u_i \le C_t, \qquad t = 1, 2, ..., T \tag{9}$$

The auxiliary problem of allocating technologies of emission reduction to the sources can thus be defined as minimizing function (1) subject to constraint (9).

## 3. Application of dynamic programming to solve the auxiliary problem

Even for small numbers of sources and technologies, the problem described above is characterized by a large number of variables: $x_{ijt} \in \{0, 1\}$, $y_{ijt} \in \{0, 1\}$ and $f_{ijt}^{1} \in \Re$, $f_{ijt}^{1} \ge 0$. It is thus very difficult to find an analytical solution, if possible at all. There are both *NMT* $x_{ijt}$ and $y_{ijt}$ binary variables and *NMT* real variables $f_{ijt}$ as well. In the case of a practical example presented later, this means that there are 20×4×20 = 1600 of each of the $x_{ijt}$, $y_{ijt}$ and $f_{ijt}$ variables. Concerning the constraints there are $T = 20$ easy to formulate constraints (9) and a huge number of constraints difficult to formulate, reflecting the dependences between variables in neighboring periods. Since the goal function (1) and the constraints are linear, one can try to solve the problem using the Simplex method. The solution obtained($x_{ijt}$, $y_{ijt}$) would certainly not be binary and would have to be converted to binary with possibly a big loss in quality. Therefore, a heuristic method based on dynamic programming was developed according to the scheme described in [2].

For the purposes of applying dynamic programming, the resources available are discretized. Discretization of the resources over the time axis is natural, due to the definition of resources (financial means). The degree of the discretization of resources over the value axis depends on computational capabilities.

The method of solution is split into two levels, according to the algorithm described below. At level 1 (higher), dynamic programming is used to determine a sequence of best partial solutions by allocating resources between the sources already included in the partial solution and the newly examined source. At level 2 (lower) the best solution for a single source is determined through enumeration of the possible solutions. A detailed description of the algorithm is given in [3] and [4].

## Algorithm for solving the auxiliary problem

*Step 1.* Create a list of all the considered sources.

*Step 2.* Select the first source from the list.

*Step 3.* For all levels of available resources, determine the best solution for the selected source, through enumeration of all the possible solutions. Store the best solution for each level of resources.

*Step 4.* If there are no sources listed for consideration – exit. Otherwise, go to the next step.

*Step 5.* Select the next source from the list.

*Step 6.* For each level of available resources, proceed as follows. Divide the resources into 2 parts and:

– allocate the first part to the stored solution, taking into account the sources considered so far,

– allocate the second part to the newly examined source.

By enumerating all the possible solutions, determine the best solution for each division and for each level of resources. Store the best solution. Go to step 4.

Using the proposed method of solution, the resources available are defined to be made up of the unit value of means in the whole $T$ horizon, as indicated in Fig. 1.

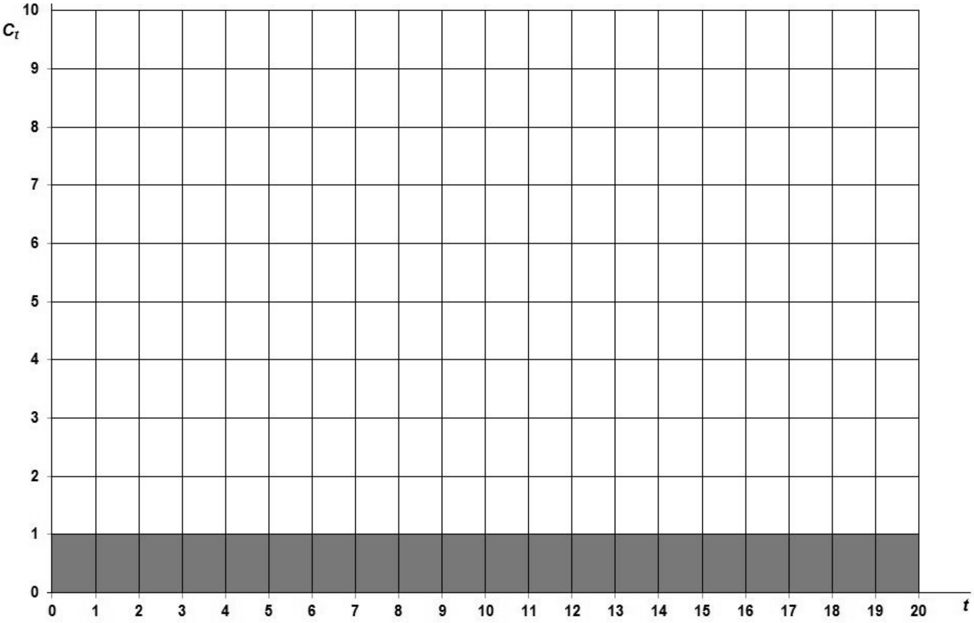

Fig. 1. One unit of resource (dark fields)

As a result of applying this method, the solution of the auxiliary problem is obtained – the allocation of reduction technologies to all the sources which reduces the total emissions in a given time horizon to the lowest possible level given the constraint on costs.

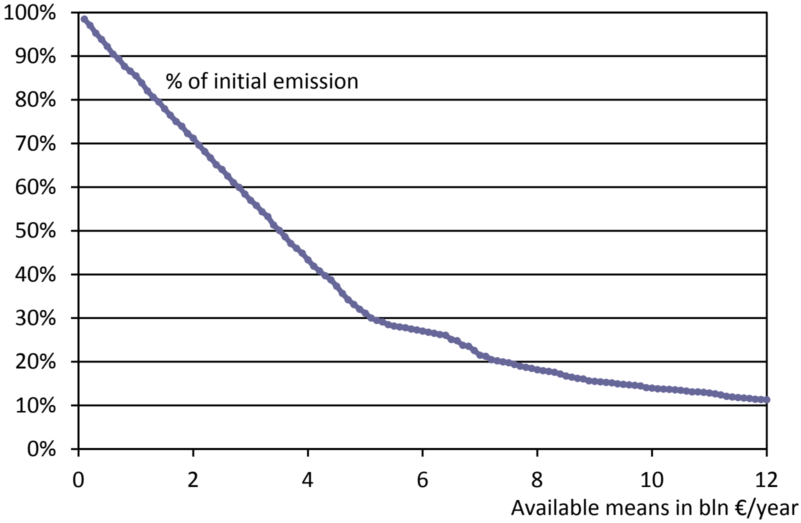

Fig. 2. $CO_2$ emissions reduction as a function of available means

The method described above is used to solve the primary problem – to calculate the minimum costs of reducing $CO_2$ emissions to achieve the given reduction level, e.g. 20%. This is done by repeating the calculations and solving the auxiliary problem for different constraints on resources and obtaining the curve, as shown in Fig. 2, which illustrates the dependence of the level of emissions reduction on the required means to reduce emissions.

## 4. Numerical example

The proposed method was examined using a practical example based on the set of the 20 largest power plants in Poland burning coal or lignite. The annual emissions of $CO_2$ are given in Table 1. Table 2 shows data on the efficiencies and costs of $CO_2$ technologies of emission reduction.

Table 1. Annual emissions of $CO_2$ for 20 major power plants in Poland

| Power plant | Fuel | Power [MW] | $CO_2$ emission [million tons/year] |
|---|---|---|---|
| Bełchatów | lignite | 4320 | 35.3 |
| Kozienice | coal | 2880 | 20.7 |
| Turów | lignite | 1900 | 15.6 |
| Połaniec | coal | 1800 | 13.0 |
| Rybnik | | 1775 | 12.8 |
| Dolna Odra | | 1740 | 12.6 |
| Jaworzno III | | 1635 | 11.8 |
| Opole | | 1530 | 11.0 |
| Pątnów | lignite | 1200 | 9.8 |
| Łaziska | coal | 1155 | 8.3 |
| Siersza | | 810 | 5.8 |
| Ostrołęka | | 720 | 5.2 |
| Łagisza | | 710 | 5.1 |
| Ostrołęka | | 650 | 4.7 |
| Siekierki | | 620 | 4.5 |
| Adamów | lignite | 600 | 4.9 |
| Skawina | coal | 490 | 3.5 |
| Konin | lignite | 490 | 4.0 |
| Stalowa Wola | coal | 350 | 2.5 |
| Żerań | | 350 | 2.5 |

Figure 2 shows the dependence of the degree of reduction in $CO_2$ emissions on the available means to reduce emissions. This curve was obtained by repeating the calculations using the auxiliary method for multiple levels of available means. The curve has two regions in which the shape is almost linear which may facilitate its approximation. The change in slope of the curve, seen around the centre of the figure, is due to the exhaustion of cheap technologies and the need to use expensive technologies. This change of technologies can be also seen in Fig. 3, where the price of reducing emissions by one ton of $CO_2$ is shown as a function of the means spent.

Table 2. The efficiencies and costs of $CO_2$ technologies of emission reduction

| Technology | Efficiency [%] | Investment costs [€/kW] | Operation costs |
|---|---|---|---|
| Biomass | 15 | 100 | 10 €/kW |
| Gas | 40 | 300 | 160 €//kW |
| CCS | 100 | 600 | 30 €//t of $CO_2$ emission |
| Purchase of $CO_2$ emission rights | 100 | – | 40 €/t of $CO_2$ emission |

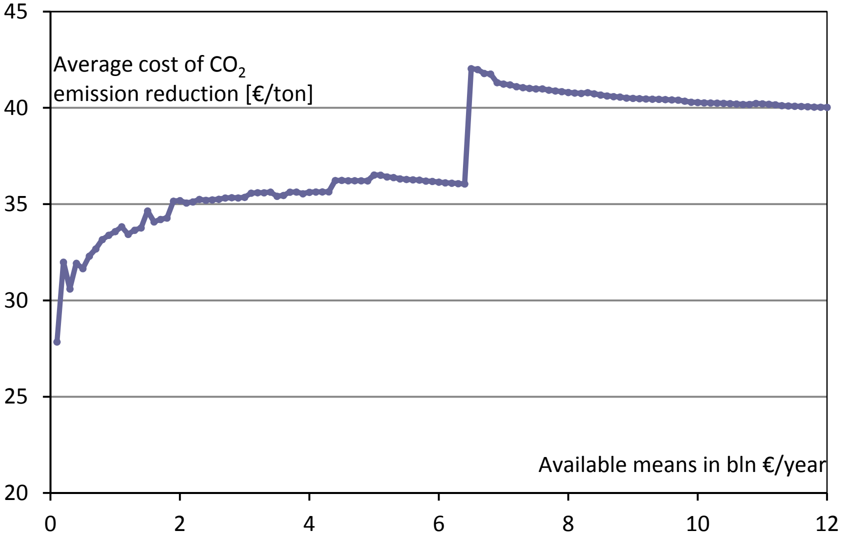

Fig. 3. Average cost of reducing emissions by one ton of $CO_2$ as a function of means spent

Figure 3 shows the average price of reducing emissions by one ton of $CO_2$, depending on the costs incurred to reduce emissions. The shape of the curve is affected by two phenomena:

- increase in the average price of reducing emissions by one ton of $CO_2$ at higher expenditures, due to the fact that at low levels of expenditure low-cost technologies are used, such as biomass burning, then subsequently more expensive technologies are used, such as CCS, after exhaustion of the cheaper ones,

- decrease in the average price of reducing emissions by one ton of $CO_2$ at higher expenditures, due to the relatively declining share of investment costs in the total costs of introducing a new technology.

Conclusions that can be drawn from the analysis of this numerical example are as follows:

- in the case of the possibility of purchasing $CO_2$ emission rights in the open market for less than 25 €/ton (the current price is around 7–8 €/ton), the application of any of the considered technologies is not cost-effective,
- in the case of an increase in the price of $CO_2$ emission rights to more than 40 €/ton (some forecasts predict the possibility of a price increase up to 50 €/ton), it makes sense to invest in the technologies considered here, and the method described above allows us to select the cheapest solution using the appropriate technologies, not taking into account the purchase of $CO_2$ emission rights,
- in the case of the price of $CO_2$ emission rights being in the interval 25–40 €/ton, the proposed method allows us to select the cheapest technologies, including the purchase of $CO_2$ emission rights

The results obtained confirm that huge funds are needed for reducing the $CO_2$ emissions of just the group of the 20 biggest power plants. This will affect the costs of energy generation and in turn the price of electrical energy for the entire economy and some industry sectors in particular. Thus the influence of an increase in the price of electrical energy on the Polish economy should be analyzed using macroeconomic models. Since the problem lies at the intersection of economic modeling and technological issues, it should be discussed and analyzed within an interdisciplinary team. Due to the importance of the problem, such a team should investigate legal, economic and technological changes concerning the conditions for emissions reduction: European Commission regulations on emissions, price of $CO_2$ emission rights, prices of coal and gas and new technologies of emission reduction.

## 5. Conclusions

Effective reduction of gaseous emissions requires a lengthy, costly investment policy in new technologies. With limited means, largely public for such investments, it becomes necessary to effectively manage funds so that their use is maximally effective.

The described method for the allocation of technologies of emission reduction can be helpful when deciding on a strategy to reduce $CO_2$ emissions. In the case of $CO_2$ emission reduction, the costs are huge and even a small reduction justifies searching for an optimal strategy to achieve it.

The method should also be tested using other practical examples. The algorithm is relatively easy to use and fast. The list of technologies taken into account should be extended to building new installations in coal based power plants. Such an operation is necessary for older plants, due to installations becoming out of date. It is very costly, but increases coal burning efficiency from 30–32% to 40–42%. This in turn reduces demand for coal, operational costs and $CO_2$ emissions. Since the lifetime of such an installation is about 40 years, the planning horizon used should be at least 40 years.

The next step in the research is to analyze the sensitivity of the solution to such factors as the price of $CO_2$ emission rights, coal, gas and $CO_2$ abatement via the CCS method.

The method developed and described in this paper can also be used to create scenarios for reducing emissions of gases other than $CO_2$, including sulfur oxides, emitted in large quantities by the Polish power plants based on coal and lignite. Poland is also committed to reducing emissions of these gases according to international agreements. In the case reducing sulfur oxides emissions, it is, however, necessary to reformulate the problem, as shown in [3] and [4].

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