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Economy and CO_2 emissions trade-off: A systematic approach for optimizing investments in process integration measures under uncertainty

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ABSTRACT

In this paper we present a systematic approach for taking into account the resulting CO_2 emissions reductions from investments in process integration measures in industry when optimizing those investments under economic uncertainty. The fact that many of the uncertainties affecting investment decisions are related to future CO_2 emissions targets and policies implies that a method for optimizing not only economic criteria, but also greenhouse gas reductions, will provide better information to base the decisions on, and possibly also result in a more robust solution. In the proposed approach we apply a model for optimization of decisions on energy efficiency investments under uncertainty and regard the decision problem as a multiobjective programming problem. The method is applied to a case of energy efficiency investments at a chemical pulp mill. The case study is used to illustrate that the proposed method provides a good framework for decision-making about energy efficiency measures when considerations regarding greenhouse gas reductions influence the decisions. We show that by setting up the problem as a multiobjective programming model and at the same time incorporating uncertainties, the trade-off between economic and environmental criteria is clearly illustrated.

1. Introduction

Investment decisions in industry are often based on a number of conflicting objectives, although economy is usually the main focus. The increased climate concern in society makes, however, the CO_2 emissions associated with industrial investments a more important issue. For strategic investments especially, economy and emissions reductions depend on the future energy market. Electricity and fuel prices, marginal electricity production and marginal wood fuel usage, and emissions charges and taxes are all examples of energy market parameters that are highly uncertain, but directly influence the profitability and the CO_2-reducing potential of the investments.

The aim of this paper is to present a systematic approach for analysis of the trade-off between economy and CO_2 emissions when investments are optimized under uncertainty. A methodology for identification of robust investments in energy efficiency under uncertainty [1–3] is here further developed to include multiple objectives and is then applied in a case study. The purpose is to illustrate how the previously published single-objective model can be extended to include both an economic and an environmental objective. Many uncertainties affecting investment decisions are related to future CO_2 emissions targets and policies, which implies that a method for optimization of both economic and environmental criteria will provide better information for decision-makers in industry to base the decisions on.

Most strategies for improvement of the energy efficiency of an industrial plant will lead to reductions of CO_2 emissions if a wide systems perspective is employed. By reducing the use of fossil fuels, emissions are decreased on-site. Biomass is generally assumed to be CO_2-neutral; nevertheless, the reduction of wood fuel use will also lead to CO_2 emissions reductions, but in this case off-site, since reduced usage enables substitution of fossil fuels elsewhere. Also decreased imports or increased exports of electricity will affect the net CO_2 emissions.

The pulp and paper industry, from which the case study of this project is taken, is the fourth largest industrial energy user in the world [4], which makes it important in the progress to mitigate climate change. Cost-effective energy savings and potential CO_2 reductions have been identified in the pulp and paper sector in several studies [5–7]. The cost of CO_2 reduction is, however, dependent on, for example, the electricity prices and the marginal electricity production, which are uncertain parameters. Furthermore, the trade-off between cost-effectiveness and CO_2 reductions is unclear. By applying the methodology proposed by Svensson et al. [1], the uncertainties are directly incorporated in the optimization, and the trade-off between CO_2 reductions and profitability can easily be analyzed.

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2. Related work

The benefits of applying multiobjective optimization in process integration studies have been illustrated in a number of papers (see e.g. [8]). Multiobjective optimization has been used in combination with pinch analysis for the thermo-economic optimization of wood gasification systems [9,10] and solid oxide fuel cell systems [11], and for the trade-off between energy and capital costs in site-wide applications [12]. An extension to the traditional pinch technology to include several targets, called the Multi Objective Pinch Analysis (MOPA), has also been proposed [13].

Multiobjective optimization has also been used in other process integration studies, for example, in a methodology for pollution prevention where economic and environmental performance were optimized [14]. It has been used to find the optimal integrated design of a natural gas combined cycle plant with CO_2 capture, minimizing CO_2 emissions and electricity cost [15], and to find the optimal retrofit of a methanol process, maximizing income and minimizing depreciation [16]. There are also examples of process integration studies where not only two, but several conflicting criteria such as investment costs, fuel consumption, safety, and water recovery are taken into account [17].

There are also other applications of multiobjective optimization which are not concerning process integration, but well energy and industry. One example is the optimization of operation strategies of cogeneration systems, minimizing costs and emissions [18]. A number of studies applying a multiobjective approach concern the efficient and sustainable use of energy in industry, but are aimed at the whole industrial sector in a specific region [19,20]. In addition to the mathematical programming methodologies using multiple objectives, there are also other methods for multi-criteria decision problems such as the Analytic Hierarchy Process (AHP) which, for example, has been used to evaluate power plant technologies with regard to seven criteria [21].

Heinrich et al. [22] combined multiobjective and stochastic optimization in a model for policy-making in the electricity supply industry under demand growth uncertainty. The multiobjective approach applied to a stochastic optimization problem is similar to what is done in our study. The applications and the sources of uncertainty are, however, rather different.

Finally, there are several recent studies that show the importance of incorporating uncertainties into the optimization of energy investments. Some examples are studies that investigate the influence of uncertainties and timing for investments in power generation [23,24], or the difference between market and policy uncertainty, also with application to the electricity sector [25]. Other studies concern investments in integrated gasification and combined cycle plants within an emissions trading scheme [26], or the choice between investment in combined heat and power or heat-only production for an industrial firm [27]. The reader is referred to a previous article by the authors of this paper for a more detailed survey of the related work in this area [1].

3. Methodology

This study has been conducted using a methodology for optimization of investments in energy efficiency under uncertainty [1]. The proposed methodology enables the optimization of investments with respect to their net present value and with respect to their corresponding CO_2 emissions reductions. Uncertainties regarding the future energy market, such as uncertain energy prices or marginal electricity production, are explicitly incorporated in a mixed-integer linear programming (MILP) model for optimization under uncertainty (a stochastic programming model).

The general assumptions, which apply to both the economic optimization and the emissions reductions, are that decisions are made ‘here-and-now’, before uncertainties are resolved and any price changes or energy market changes occur. Uncertain parameters, such as energy prices and policies, and CO_2 emissions from marginal use of biomass or electricity, are modelled using a scenario-based approach. For a more detailed description of the optimization model for the single-objective case, including all constraints, see [3]. For literature on multiobjective optimization in engineering problems, see e.g. [28,29].

The economic objective is to find the combination of investments resulting in the highest expected net present value (NPV). The objective is thus:

$$\max_{\mathbf{x}\in\Omega} f_{NPV}(\mathbf{x}) := -C_0(\mathbf{x}_0) + \sum_{s\in S} p_s \sum_{t=1}^{T} \frac{C_t(\mathbf{x}_0, \mathbf{x}_s, \omega_s)}{(1+r_C)^t}, \tag{1}$$

where S is the set of all scenarios s, p_s is the probability for scenario s to occur, and ω_s are the uncertain price parameters for scenario s, Ω is the solution space, i.e. the set of all feasible solutions $\mathbf{x}$, where $\mathbf{x} = (\mathbf{x}_0, \mathbf{x}_s)$ are all decision variables, representing e.g. investment and operating decisions, $\mathbf{x}_0$ are the decision variables associated with the initial investment (not dependent on s) and $\mathbf{x}_s$ are the decision variables corresponding to scenario s. Further, $C_0(\mathbf{x}_0)$ is the initial investment cost function, $C_t(\mathbf{x}_0, \mathbf{x}_s, \omega_s)$ is the function for the net cash flow (revenues minus costs) in year t, T is the economic lifetime of investments, and r_C is the discount rate used for cash flows.

The initial investment, C_0, is required to be the same for all scenarios since the first investment decision is taken before the outcome of the uncertain parameters is known. The net cash flow of the final year, C_T, is adjusted for the value remaining after the economic lifetime (the residual value).

The CO_2 objective is to maximize the expected net CO_2 emissions reductions. Using the same notation as for the economic objective, the CO_2 objective is expressed by:

$$\max_{\mathbf{x}\in\Omega} f_{CO2}(\mathbf{x}) := \sum_{s\in S} p_s \sum_{t=1}^{T} \frac{E_t(\mathbf{x}_0, \mathbf{x}_s, \boldsymbol{\pi}_s)}{(1+r_E)^t}, \tag{2}$$

where $\boldsymbol{\pi}_s$ is the uncertain CO_2 emissions parameters for scenario s, $E_t(\mathbf{x}_0, \mathbf{x}_s, \boldsymbol{\pi}_s)$ is the function for the net CO_2 emissions reductions in year t, and r_E is the discount rate used for CO_2 emissions.

Discounting of CO_2 emissions is not conventional; neither is it necessary in traditional CO_2 emissions calculations. Here, however, the multiobjective problem formulation, in combination with the assumption that investments can be made at different points in time, makes some kind of discounting essential. Because discounting of emissions is unconventional, both discounting and no discounting are possible model settings through the choice of the r_E value. Tests have shown, however, that by choosing no discounting ($r_E = 0$), the optimization will give meaningless results. To understand this, consider first that cash flows are always discounted. With no discounting for emissions, a cheap way of improving the CO_2 emissions objective is to make the investments in CO_2 reductions as late as possible. The cost will then be low in present value, but the reductions are valued the same as if they were made today. This would imply that it is always better to postpone the investments in CO_2 reductions – that it is better to earn money now, and save the climate later. This has, unfortunately, been the philosophy of industry, and is exactly the reason we have landed up in the difficult situation of global warming. These kinds of results, where emission abatements are constantly postponed, are not our intention, nor is it what is asked for by those decision-makers in industry who are willing to use this kind of sophisticated methodology.