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Bottom-up method for potential estimation of energy saving measures

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Abstract

Technology and energy saving potentials in the industrial sector are key data that policy makers rely on to drive decision making. A literature review reveals a distinct discrepancy between *general potential estimation* and *detailed design* studies. The former relies principally on top-down conceptual approaches based on temperature levels of the processes' thermal requirements, while the latter aims at mathematically optimized solutions for specific technologies in specific processes under specific economic conditions.
This work attempts to close this gap by proposing a bottom-up method for potential estimation of energy saving measures. To this end, a generalized optimization framework was developed which aims at generating a database of optimal solutions which are independent from most economic and environmental input data. By fixing these data, the optimal solution for the same process type in different countries and under various criteria can be identified in the database. The method also increases accessibility of optimization techniques by providing the solution database which then requires limited input parameters and background knowledge to provide expert guidance toward optimal utility integration.
The method was applied to the dairy industry, highlighting that energy saving potentials can be achieved through heat recovery and integration of heat pumps, mechanical vapor re-compression, and co-generation units economically favourable especially in Japan and Switzerland.

Keywords: dairy industry, heat pump, co-generation, MINLP, mathematical programming, generalized optimization

1. Introduction

Constant efforts are undertaken to estimate energy saving and technological potentials in the industrial sector. Such analyses are used to formulate policy recommendations, determine target markets, and advance technological development. A state-of-the-art analysis is introduced concerning both *general potential estimation* and *detailed design* studies, before highlighting the contribution of this work and the outline of the study.

General potential estimation: This section concerns studies which aim at estimating energy saving potentials in the industrial sector. Most such studies are based on top-down approaches relying mainly on the temperature levels of the thermal requirements in certain industries and with specific technologies. Concerning heat pump integration, Wolf et al. (2014) presented a study which focused on the German low temperature sectors, estimating the overall energetic potential of heat pumps used as hot utilities. Similarly, Brückner et al. (2015) performed such an analysis for the European industrial sector with compression and absorption heat pumps. For other technologies, analogous studies have been conducted by Lauterbach et al. (2012) (solar thermal) and Campana et al. (2013) (organic Rankine cycles), as representative examples.

Though top-down approaches offer a clear and simple approach to estimate general potentials, conclusions drawn from such analysis may be misleading. Firstly, they account only for hot utility requirements neglecting the double impact of certain utilities (especially heat pumps) according to the 'more in, more out' principle of pinch analysis. Secondly, they do not consider possible process improvements and efficiency measures such as internal heat recovery.

Bottom-up approaches have also been presented by Wilk et al. (2017) who analyzed different process types and the heat pump integration potential for a set of energy price ratios, and Müller et al. (2014) who suggested an approach for solar thermal integration to the liquid food industry based on the available land surface area and process temperature levels. These approaches are often limited in their scope (in terms of economic and environmental boundary conditions) and lack rigorous methods.

Detailed design: Various detailed design studies are present in academic literature and typically focused on few technologies and processes. Studies by Kamalinejad et al. (2015), Yang et al. (2017), and Becker (2012) presented optimal integration approaches of heat pumps in different industrial processes relying on mathematical programming and superstructure-based design. Most recently Wallerand et al. (2018) presented a comprehensive heat pump integration method based on mathematical programming and expert insight. For organic Rankine cycles, superstructure-based approaches are also common, such as presented by Yu et al. (2017) and Kermani et al. (2018).

Though such approaches offer rigorous solutions to complex problems, the scope of treated problems is usually limited to specific processes, technologies, and economic and environmental boundary conditions.

Synthesis: The state-of-the art analysis can be summarized in two points.

1. Potential studies are either conducted coarsely by top-down approaches, or in a non-rigorous and limited in scope with bottom-up analyses.
2. Detailed design studies provide rigorous methods, however limited to specific conditions.

This work attempts to bridge this gap by suggesting a bottom-up method for potential estimation of energy saving measures through heat recovery and technology integration. The methodology is presented in section 2, followed by the results in section 3 presenting the solutions for various perspectives (from policy-makers to plant managers). The work is summarized and critically reviewed in section 4.

2. Methodology

The methodology presented in this work aims at reducing computational time while producing a large set of feasible and potentially 'good' solutions. The expensive optimization problem is therefore solved once, independent from most input parameters and its solutions are stored in a database from which a large number of scenarios with varying input conditions can be derived. An overview of this approach can be seen in Figure 1. The approach is clarified below in more detail.

Comprehensive solution space generation: The goal of this part is to formulate an op-

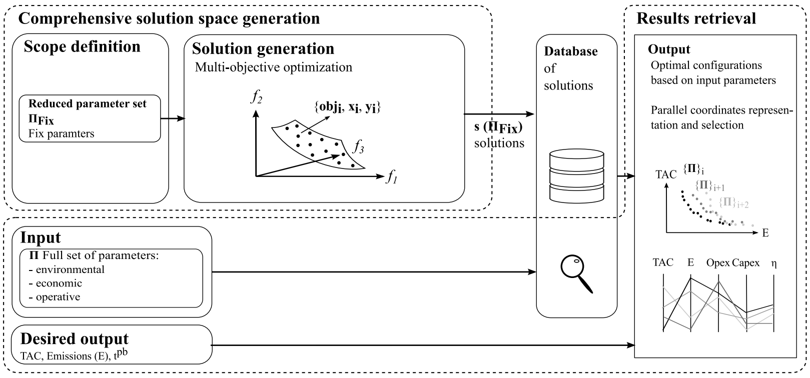

Figure 1: Bottom-up method for potential estimation.

timization problem independent of most typical input parameters. Usually the objectives of main interest for such analyses are the *total annual system cost (TAC)* and/or the *total emissions*. Both of these objectives require a wide range of input parameters ranging from economic (energy prices, investment cost parameters, interest rate, CO_2 tax, maintenance cost), operative (operating time), process specific (product mass flow rates, specific requirements), equipment specific (lifetime, efficiency, fuel consumption) to emissions associated with electricity and natural gas consumption (environmental parameters). Even though the final objectives are *total system cost* and/or the *total emissions*, a different set of objectives is selected at this stage, which requires fewer input parameters with the goal of generating a large set of potentially optimal solutions. The choice of objective depends on the exact goal of the study. In this case, the focus was placed on national differences, which have a drastic effect on energy prices, interest rates, and environmental parameters.

Therefore, the new set of objectives was defined as *consumption* of all resources and *investment cost (capex)*, which requires less input parameters to be fixed. The choice of the new set of objectives requires engineering common sense and needs to be carefully adapted to each problem. The new objectives are fed to a multi-objective optimization framework, similar to the one described by Wallerand et al. (2018) and Weber et al. (2007) to generate a set of solutions. The solution space generation needs to be carried out only once and requires a few days of computational effort.

Database: Depending on the number of objectives, the previous step generates a multi-dimensional surface of solutions. In this study, the resource consumption was distinguished between electricity and natural gas consumption, which led to a total of three objectives. Upon successful completion of the optimization, all solutions and the corresponding values of their decision variables (solution properties) can be stored in a database for later access and evaluation.

Results retrieval: The results retrieval procedure works in two steps: Initially, a solution together with its entire set of properties is retrieved. Subsequently, knowing the optimal values of each decision variable, a user can evaluate the original objective function as well as any other indicators given a new set of parameters (e.g. energy prices, operating time, CO_2 tax). This leads to a new set of objective values among which the user can identify their preferred choice. In this case, the lowest cost and lowest emission solutions were selected. This step is accessible without knowledge of optimization algorithms thus encouraging utilization of such methods by a variety of audiences which is briefly demonstrated in section 3.3. The results retrieval has been implemented in a tool, which can be found online.

3. Results

3.1. Case study

The underlying case study of this section is a dairy plant as presented by Kantor et al. (2018) with a two-stage refrigeration cycle, free cooling water (from a nearby river) and an existing boiler. The heat pump superstructure suggested by Wallerand et al. (2018) with various fluids and a co-generation engine (Becker (2012)) were studied as potential new technology options. Decision variables were the heat pump fluids, temperature levels, and number of stages, as well as the T_{min} of the heat recovery in the process. The heat exchanger network cost was graphically approximated as proposed by Townsend and Linnhoff (1984).

3.2. Comprehensive solution space generation

The three-dimensional surface of solutions resulting from the multi-objective optimization described in section 2 is shown in Figure 2. It can be seen that points closest to the reference case have lowest capital expenses (capex), while lower electricity and/or natural gas consumption necessitates an increase in capex.

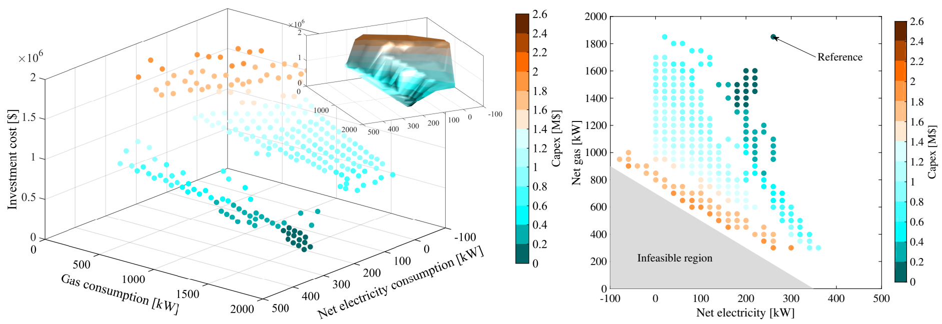

Figure 2: Solutions from multi-objective optimization considering consumption of natural gas and electricity with the corresponding investment required.

3.3. Results retrieval

The retrieval of results is illustrated in Figure 3 for the three exemplary countries, namely Switzerland (CH), Germany (DE), and the United States of America (US). The countries were selected due to their different economic and environmental conditions, as illustrated in the figure, ranging from a high natural gas price and low electricity/natural gas ratio in CH to a low natural gas price and high electricity/natural gas price ratio in the US. The total emissions and TAC are calculated for each solution in the database, but only the minimum cost solutions are selected (indicated with grey circles).

Plant operators: The minimum cost points from Figure 3 are depicted with more cost details in Figure 4, indicating the potential interest of a plant operator in reducing energy-related costs or emissions. CH is visibly the country with highest potential where up to 70% emission reductions could be achieved with heat recovery (firstly), with heat pumping providing options with payback times below 5y. This is in stark contrast to the US context where solutions are not economically attractive compared to the reference case. Here, and in DE, the highest emission reductions can only be achieved with heat pumps and co-generation units, due to the high emissions related to generation of electricity.

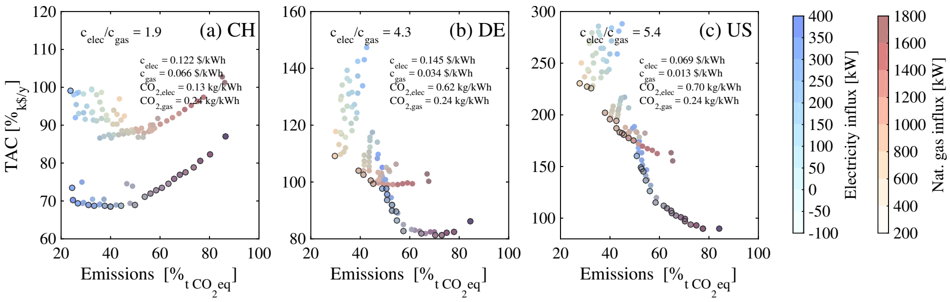

Figure 3: Results retrieval: minimum cost solutions, 8000 h/y operation, 0 \$/t CO_2.

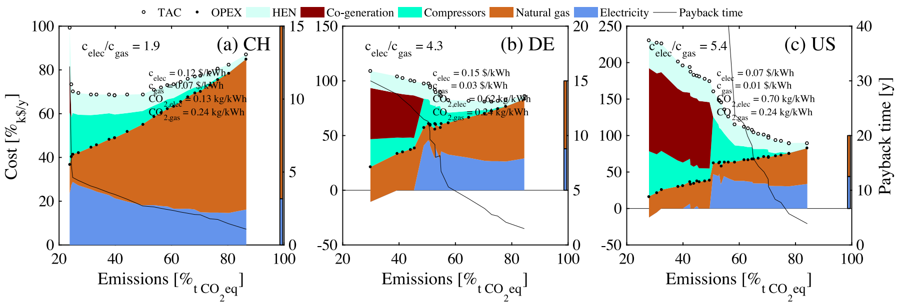

Figure 4: Minimum cost solutions for operating time 8000 h/y, 0 \$/t CO_2.

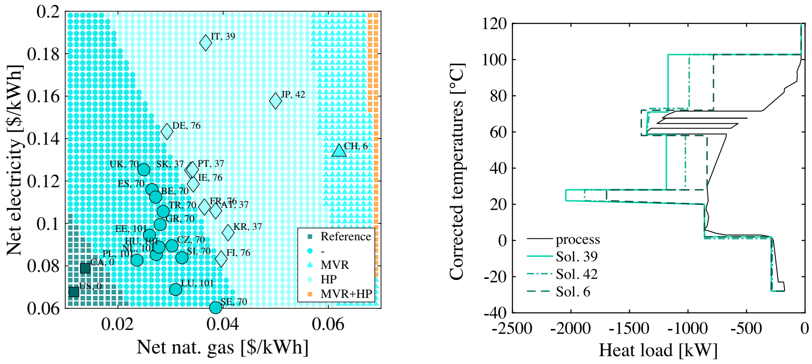

Figure 5: Utility map for operating time 2500 h/y (left), 0 \$/ton CO_2; composite curves of solutions for Italy, Japan and Switzerland (right).

Policy-makers: Another type of analysis can be conducted for policy-makers as shown in Figure 5. With this analysis, the lowest emitting solution for each country (resource price) is selected with a payback time below 3 years. The countries with highest resource prices (Italy (IT), Japan (JP) and Switzerland (CH)), have the highest heat pump potential. The other solutions are principally based on improving process heat recovery to achieve the potential reduction in consumption.

4. Conclusions

This work proposes a bottom-up method for potential estimation of energy saving measures. To this end, a generalized optimization framework was developed based on multi-objective optimization which aims at generating a database of optimal solutions which are independent from most economic and environmental input data. By fixing this data, the optimal solution for the same process type in different geographical, economic and environmental contexts are retrieved from the database to address various objective criteria.

The method was applied to the dairy industry investigating energy saving and technological potentials through heat recovery and utility integration with heat pumps, mechanical vapor re-compression, and co-generation units. A set of countries was determined in which industrial heat pumping is particularly beneficial from environmental and economic perspectives, namely: Switzerland, Japan, and Sweden. Use cases for plant operators and policy-makers were briefly demonstrated and a variety of additional analyses could be conducted using the solution database; one such example was briefly presented.

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