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Patrik Thollander, Nawzad Mardan and Magnus Karlsson

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Optimization as investment decision support in a Swedish medium-sized iron foundry – a move beyond traditional energy auditing

Patrik Thollander ^{a,*}, Nawzad Mardan ^a, Magnus Karlsson ^a

^a Department of Management and Engineering, Division of Energy Systems,
Linköping University,
SE-581 83 Linköping, Sweden

Abstract

Due to increased globalisation, industries are facing greater competition that is pressing companies into decreasing their expenses in order to increase their profits. As regards Swedish industry, it has been faced with substantial increases in energy prices in recent years. Barriers to energy efficiency such as imperfect information inhibit investments in energy efficiency measures, energy audits being one means of reducing barriers and overcoming imperfect information. However, an evaluation of such energy audits in Sweden reveals that it is chiefly low-cost measures that are undertaken as a result of an audit. Moreover, these audits often tend to focus on support processes such as ventilation, lighting, air compressors etc., while measures impacting production processes are often not as extensively covered, which underlines the need for further support in addition to energy audits. Decision support is practised in a variety of different disciplines such as optimization and simulation and the aim of this paper is to explore whether investment decision support practices may be used successfully towards small and medium-sized manufacturers in Sweden when complex production-related investment decisions are taken. The optimization results from the different cases, involving a foundry's investment in a new melting unit, indicate that with no electricity price fluctuations over the day, the investment seems sound as it lowers the overall energy costs. However, with fluctuating electricity prices, there are no large differences in energy costs between the option of retaining the existing five melting furnaces at the foundry and investing in a twin furnace and removing the holding furnaces – which was the initial investment plan for the foundry in the study. It would not have been possible to achieve this outcome without the use of investment decision support such as MIND. One of the main conclusions in this paper is that investment decision support, when strategic investment decisions are to be taken, may be a means of emphasising energy efficiency for energy-intensive SMEs beyond the level of traditional energy auditing.

Keywords: Energy efficiency; Foundry industry; Investment decision support; Optimization

* Corresponding author. Tel.: +46-13-28 17 88; fax: + 46-13-28 17 88.

E-mail addresses: patrik.thollander@liu.se (P. Thollander), nawzad.mardan@liu.se (N. Mardan), magnus.karlsson@liu.se (M. Karlsson).

1. Introduction

Reducing the use of energy is an essential task for the future as the world's greatest environmental impact originates from the use of energy [1]. Finding ways to decrease industrial energy use is thus of great importance. In Sweden, the total industrial energy use is 39% of the final energy demand or about 155 TWh, where the Swedish energy-intensive industry, represented for example by the pulp and paper and iron and steel industries, accounts for about 70% of the final industrial energy demand [2]. Due to increased globalisation, industries as a whole are facing greater competition that is forcing companies to decrease their expenses in order to increase their profits. Swedish industry has been faced with substantial increases in energy prices in recent years [3]. Swedish industry also uses more electricity than industries in other European countries. This is explained by historically low electricity prices, in turn explained by large proportions of hydropower and nuclear power [3-7]. For energy-intensive Swedish industry, rising energy prices, especially electricity prices, are considered to be one of the greatest threats to the long-term survival of the industries [8, 9]. Furthermore, not only have prices risen but electricity prices are also expected to fluctuate more as a consequence of market deregulation, i.e. higher prices during the day when the markets' aggregated demand is high and lower prices during the evening and the night when the market's aggregated demand is low. Fig 1 shows the hourly spot prices on the Nordic and German electricity markets. In the figure, it can be seen that the daily prices vary more on the German market, which is partly explained by the fact that the top load production units differ between the two markets.

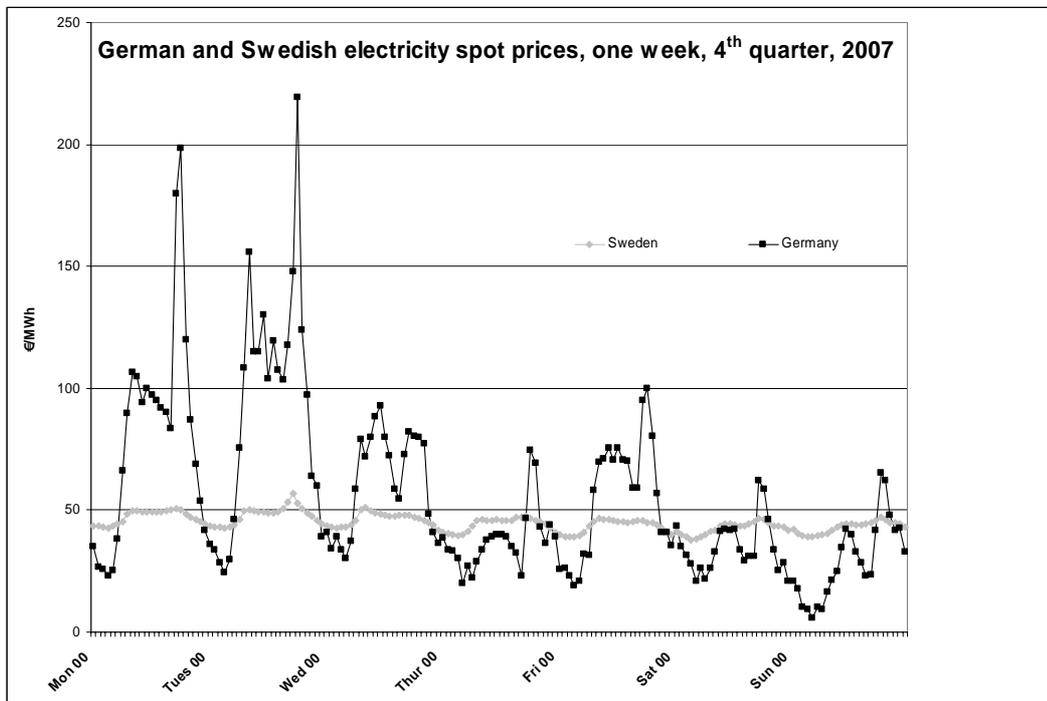


Fig. 1: German and Swedish electricity spot prices one representative week during the 4th quarter of 2007 [32-33].

These factors emphasise a need for greater management focus on means to overcome these challenges, i.e. reduce the cost of energy. To accomplish this, the two main means employed by company managements are: 1) focus on the

actual energy contract, and 2) emphasise ways to decrease the cost of energy, e.g. investments in energy efficiency, changed behaviour and load management (e.g. reduce peak loads to reduce power tariffs). The implementation of successful energy management practices demands both methods, i.e. not only an energy contract focus but also behavioural and technological approaches are needed [10]. As regards the implementation of cost-effective energy efficiency investments, there are a number of barriers related to this. According to mainstream economic theory, barriers related to market failures are considered to be significant as they may justify public policy intervention. One of the most frequently cited market failures is imperfect information, meaning that the purchaser of a product or service is not fully aware of all the information needed to take a “rational” decision, e.g. decision-making complexities that inhibit energy efficiency investments from being undertaken [11]. In order to overcome the imperfect information barrier in industry, information programmes such as industrial energy programmes that offer energy audits at no or minimal cost are used. An evaluation of such energy audits in Sweden reveals that it is chiefly low-cost measures that are undertaken as a result of an audit [12-13] and even though both production processes and support processes have been included in the energy audit report, the implemented measures mainly include support processes such as ventilation, lighting, air compressors etc. [12]. This indicates a need for further support in addition to an energy audit. What further supports this is the fact that research on barriers to energy efficiency in the Swedish foundry industry found that among the largest barriers were technical risks such as the risk of production disruptions, lack of access to capital and lack of budget funding [14]. Production-related measures may, however, be inhibited by these measures often being more capital-intensive and the risk of production disruptions when the measures are implemented. The company may thus need further support for such investments.

Decision support is practised in a variety of different disciplines such as optimization and simulation [15], originating from Operational Research (OR), and may be a means to offer such further support. In a study by [16], it was stated that the size and complexity of energy systems in the process industry make existing engineering and statistical tools alone insufficient to provide efficient solutions. Moreover, future energy price fluctuations and how an investment will affect other parts of the production line further complicate the issue. It was also shown that mixed-integer linear programming (MILP) provides a methodology for determining optimal strategies in order to minimise the overall energy costs in such industries [16]. Studies using such a methodology in a Swedish context include for example [17-24], where MIND (Method for analysis of INDustrial energy systems) was used. MIND is a method developed for optimization of dynamic industrial energy systems [17]. These studies comprise large energy-intensive sites such as Swedish pulp and paper mills and steelworks, e.g. [17-24]. The need to apply the method in other sectors, including small and medium-sized manufacturers such as the Swedish foundry industry, cannot be understated. Among such small and medium-sized manufacturers, most of the companies have only limited possibilities to apply such methods.

The aim of this paper is to explore whether investment decision support practices may be used successfully towards small and medium-sized

manufacturers in Sweden when complex production-related investment decisions are taken. The research question in this paper is: How can the use of optimising methods, such as MIND, provide energy-intensive small and medium-sized enterprises (SMEs) with additional information when strategic investments are to be made? The research question was examined using the MIND-method, applied at a Swedish medium-sized foundry to analyse a potential investment in a new melting unit.

2. Method

This study emphasises systems analysis using the reMIND software as investment decision support. reMIND is based on the MIND method and was developed at the division of Energy Systems at Linköping University. The method was developed to optimise dynamic industrial energy systems [17] and is based on MILP. This enables an entire industrial energy system to be modelled. The analysis basically includes four steps [21]. In the first step, the real system should be delimited. Processes must be identified and reasonable boundaries and simplifications introduced, in order to describe the system mathematically. In the second step, the model is formed from a set of equations based on the simplified, delimited problem identified in the initial step and verification that the description of the problem is satisfactory [21]. A MILP problem can be described as [25].

$$\begin{array}{ll} \min & Z = f(x, y) \\ \text{subject to} & g(x, y) = 0 \\ & h(x, y) \leq 0 \\ & x \geq 0, y \in \{0/1\} \end{array}$$

where $f(x, y)$ is the objective function, like system cost, $g(x, y) = 0$ are equations describing the performance of the energy system, like the relation between the mass flow through a process and the corresponding energy demand, $h(x, y) \leq 0$ are inequalities describing for example limits in capacity for the components in the system. The variable x is continuous and corresponds to such aspects as energy and material flows, while y is discrete (binary) variables [25]. In the third step, an appropriate optimization routine should be applied. reMIND is normally using CPLEX. In CPLEX a variety of different algorithms may be chosen [26]. Normally in reMIND CPLEX uses simplex to solve the linear programming problems and branch and bound to solve the integer programming problems. In the last step, the model is validated and results are analysed. This should include verifications of the solutions from the model. Furthermore, a continuous dialogue with representatives from the company, primarily for discussion and verification of input data to and output data from the model, is important in order to create a valid model based on reliable data.

3. The modelled system

3.1 The foundry under study

The analysed medium-sized iron-foundry is located in the south east of Sweden and produces bearing housings and castings, mainly for the automotive industry. The annual turnover at the foundry is approximately EUR 85 million

and the foundry currently produces about 19,000 tons of housings and castings annually. The annual energy use is almost 40 GWh, most of which in the form of electricity. A minor portion of the energy use at the foundry consists of LPG which is used for preheating the ladles. Please refer to [5, 27] for a more detailed overview of the energy use in the different processes at the foundry, and Fig. 2 for a general overview of a foundry's production line using sand moulds.

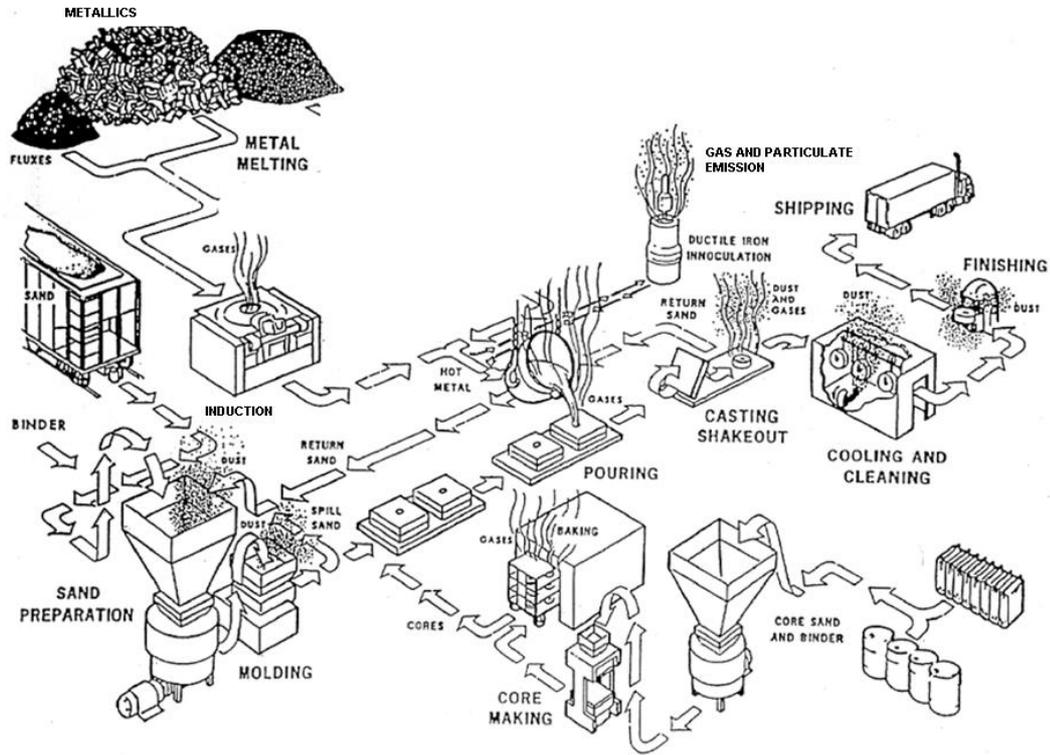


Fig. 2. General overview of a foundry with sand moulds. Holding furnaces not included in the figure [34].

3.2 Investment background

The foundry's five melting furnaces were installed in the late 1950s and are therefore fairly old. The furnaces' different melting capacities and power demands are shown in Table. 1.

Table 1

Data from the different melting units used in the different cases

Melting units	Approx. electricity demand (kWh/ton)	Capacity (ton)	Melting time (h)
Furnace 1	750	12.0	5.0
Furnace 2	750	12.0	5.0
Furnace 3	750	6.0	3.0
Furnace 4	750	6.0	3.0
Furnace 5	750	6.0	3.0
New twin furnaces	525	11.0	1.0

The new furnaces being studied by the foundry, with a total investment cost of about EUR 3.9 million has a melting capacity of 11 tons/h and use about 30% less electricity per ton of melted metal. The aggregated melting capacities for the new furnaces are approximately the same per hour as the five current furnaces. In addition, the investment in new furnaces would also include charging the new furnaces by means of a charging wagon. Today the five furnaces are charged manually. In the foundry's own study of the potential investment, the current holding furnaces are planned to be removed. The reason for removing the holding furnaces, from the point of view of the foundry's management team, is that the overall operating energy costs are then lowered enabling a better investment figure to be presented for the corporate board.

3.3 Assumptions regarding prices and costs

In the foundry's own investigation of the potential investment, the electricity prices are assumed to remain stable, i.e. current prices are used which do not fluctuate on a daily basis. Swedish industry has previously enjoyed one of the lowest electricity prices in the European Union [28] and will most probably experience electricity price increases due to liberalisation of the electricity market within the European Union [3-7, 29-30]. A study by [30] indicated that future electricity prices in Sweden are expected to converge towards about 80 €/MWh Monday-Friday 6 am to 6 pm and about 44 €/MWh during the rest of the week [30]. The reason why the calculated prices are higher during the day is that the demand is higher, leading to the use of more costly top load production units [30]. Two assumptions, among several, in the cited study were perfect market mechanisms and a CO₂ price of €10 per ton. A sensitivity analysis indicated that the CO₂ price does not seem to have a very large impact on the electricity price with a decrease in price of only 3–4 €/MWh if the CO₂ price was excluded [30]. A report that investigated electricity price elasticity showed similar results [29]. The average electricity prices in the previously cited study [28] corresponds quite well to the above prices from [30], taking the average price on a 24-hour weekday. The future electricity prices derived from [30] are used in the calculations of the foundry's energy costs. LPG represents a very small share of the aggregated energy use at the plant and has therefore been assumed to remain on the same level, i.e. only present (2007) prices have been used.

The prices of virgin or scrap iron have not been taken into consideration as the price of iron does not significantly change the results between the technological options considered. This is a result of the aggregated weekly production in the different analysed cases being the same and that the yield for a new melting unit, in terms of melted iron out in relation to charged scrap iron into the furnace, does not change significantly compared with the current melting unit. Consequently, the amount of purchased raw material is the same in the different cases and so are the related material costs. When comparing the different analysed cases, the cost of iron thus levels out. The metal that for various reasons not pass the quality control are assumed to be re-melted. Also, labour and maintenance costs have not been included in the actual modelling but have been included in the figure presenting the optimization results (Fig. 4). This is based on the fact that labour and maintenance costs may very well be calculated without the use of investment decision support such as the MIND

method. The current melting unit demands five employed staff and, a new melting unit demands four employed staff. The reduction in personnel is achieved in the more efficient charging of the furnaces. In addition, the two holding furnaces, when used, demands about 20 man hours per week to operate. A cost of about 30 EUR per man hour has been used when estimating the labour and maintenance costs. The maintenance cost estimations have also been inspired by [31].

3.4 Sensitivity analysis

A sensitivity analysis was made for the new furnace cases using current electricity prices, i.e. CASE 1C and CASE 2C. Electricity prices from the Nordic spot exchange from one week were also used to complement the analysis of the future electricity prices derived from [30]. The average Nordic electricity spot prices during week 49 in 2007 were chosen as representative of the average prices during the 4th quarter of 2007, i.e. from October 1st to December 31st. In order to enhance the analysis, prices from the German spot exchange for week 44 were also used, using the same evaluation criteria as for the Swedish spot prices.

In order to improve the sensitivity analysis even further, the company's current power charges were also included in the analysis as these charges are not included in the spot prices. Furthermore, an analysis of the possibility to lower the peak load was also conducted by setting constraints on the power load. The minimum load was then found by lowering the constraint in the model until an optimization was unfeasible. Using the same reversed procedure, the weekly production was increased successively in order to spot the possible maximum weekly production for the different cases.

4. Model description

The model has been developed to represent an investment in a new melting unit. The different modelled production processes are connected together by energy and material flows. Production involves about 120 different batches per week consisting of primarily two types of iron: grey iron and ductile iron. The present production line consists of five open inductive-melting furnaces, two holding furnaces, ladle heating, sand preparation, and two major moulding processes, FA68 and DISA, with subsequent sand blasting and cleaning. The major material and energy flows within the system are shown in Fig 3, where sand blasting and cleaning are grouped together as "Finishing". In Table 1, the furnaces' different melting capacities and power demands are shown. For the two holding furnaces, which can store iron for the whole modelling period, i.e. a whole week, there is a maximum storing capacity of 60 tons and 30 tons demanding about 125 kW and 115 kW respectively.

The production process, which has a maximum capacity of 24.000 tons/year, begins when the melting furnaces are charged with iron. After the melting procedure, the iron is transported via ladles either to the holding furnaces or directly to the pouring procedure from where the moulds are supplied from the two major moulding lines, DISA and FA68. The maximum hourly capacity for the DISA moulding line is 3.11 tons/hour for both ductile and grey iron, and 4.92 for ductile iron and 6.13 for grey iron for the FA68 moulding line. Finally, the products are cooled and finished. Each production

unit, shown in Figure 3, is connected to the next unit by the flow of iron. It should be noted that the energy use for sand preparation in the model is included in the pouring and cooling procedure.

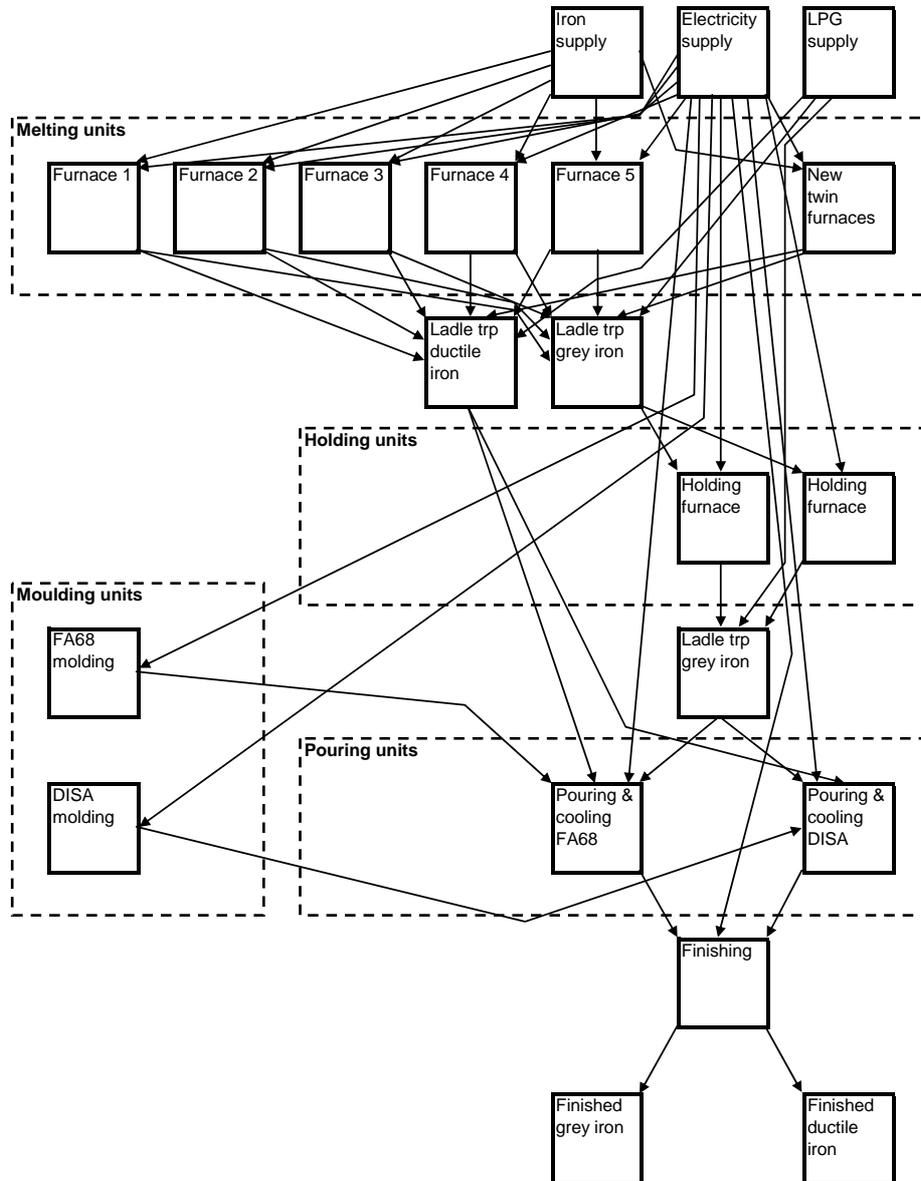


Fig. 3. A schematic outline of the modelled system derived from reMIND. The arrows represent different flows of electricity, LPG, iron for melting, ductile/grey iron and sand. It should be noted that it is solely for logistical reasons, and not for e.g., quality reasons, that ductile iron only is melted in two furnaces.

The demand for finished products was based on a representative production week at the foundry of about 420 tons of grey iron and 70 tons of ductile iron, which is the driver in the model and will thus implicitly determine the production rate in the different units, such as the two moulding lines and the hot metal rate in the melting furnaces. The efficiencies and specific production unit related data used were based on actual production data from the foundry. The development of the model required input data which was obtained from a

previous energy audit at the plant, the audit is further described in [5, 27], and production figures obtained from the manager of the melting department. For example, in the different units, the use of electricity was aggregated from actual data of the different unit processes taken from previous measurements from the energy audit, i.e. compressed air, ventilation, lighting and production-related energy users such as electric motors in the moulding lines.

The model was split into several time periods determined with respect to the production unit activities. One production week was modelled, using 120 time steps, representing the current 120 production hours, based on hourly averages.

4.1 Objective function

The objective function was formulated to minimise the system cost and include the energy flow variables that affect the system and its related costs. The costs for the different flows are based on current energy prices at the foundry and/or future prices. The unit for the objective is €/week.

4.2 Analysed cases

In order to investigate the usefulness of investment decision support, six different cases were devised, three which use current electricity prices and three which use future electricity prices, see Table 2. The different cases are described further in table 3.

Table 2

Current and future electricity prices used in the different cases [electricity prices include network and power charges].

Cases	Electricity price [Mon - Fri, 6 am - 6 pm] [€/MWh]	Electricity price [6 pm -6 am, and Sat 6 am - Mon 6 am] [€/MWh]
BASE C, CASE 1C, CASE 2C	71.0 ^{1, 2}	71.0 ^{1, 2}
BASE F, CASE 1F, CASE 2F	80.5	44.3

¹ 1 € = 9.3 SEK

² Arithmetic mean value [tradable green certificates (TGC) are not included in the price]

Table 3

The six different cases analysed

Analysed cases	Investment in new melting units	Use of the existing holding units	Electricity prices
BASE C		X	Current
BASE F		X	Future
CASE 1C	X	X	Current
CASE 1F	X	X	Future
CASE 2C	X		Current
CASE 2F	X		Future

5. Results

The results from the optimization of the six different cases are shown in Fig. 4. A comparison of the two cases representing the current production units using current and future electricity prices shows that the energy cost would decrease (BASE F compared to BASE C), due to the fact that the optimal melting procedure mainly takes place at night when prices are low. A comparison of CASE 1C and CASE 1F, i.e. an investment in new melting furnaces with future and current electricity prices, shows similar findings. When CASE 2C is compared with CASE 2F, i.e. new melting furnaces excluding the holding furnaces using current and future electricity prices, it can be seen that the optimal production cost is still lowered with future electricity prices but not nearly as much. The difference is thus much lower than in the previously outlined comparisons as a lack of holding furnaces, with future prices, precludes storage of iron melted during low-cost hours. A comparison of the weekly energy use for the six cases investigated shows that energy use will decrease by about 20% with a new melting unit and an additional 6% if holding furnaces are not included in the model's production systems. The latter is due to the fact that the use of holding furnaces increases the aggregated energy use at the foundry. With fluctuating electricity prices, however, this does not necessarily lead to increased electricity costs as one may shift the use of the largest electricity consuming unit, namely the melting unit, to hours when electricity prices are lower.

When the results from the model of the current system are compared with the model with the new furnace – holding and new furnace – no holding investment options, it is clear that the system costs for the cases with no or very small fluctuations in electricity prices are lowered (BASE C compared with CASE 1C/2C and SWE compared with SWE 1 and SWE 2). For the cases with larger daily electricity price fluctuations, however, the planned investment, i.e. new furnace - no holding, does not in fact seem to lower the costs to any great degree (BASE F compared with CASE 2F and GER compared with GER 2). This is a consequence of how the possibility of production planning and the reduced energy use at the foundry are enabled in the different cases.

When the results from the models of the new furnace with no holding furnaces are compared with the models of a new furnace with holding furnaces it can be seen quite clearly that for the two cases with fluctuating electricity prices (CASE 2F with CASE 1F and GER 2 with GER 1), the use of holding furnaces reduces the system cost while the other two cases with no or minor electricity price fluctuations do not differ as much. Thus, when holding furnaces are available it is possible to utilise the daily fluctuating electricity prices to decrease costs.

5.1 Sensitivity analysis

The optimization results from the cases using Swedish and German spot prices are included in Fig. 4. Fig. 4 shows that when modelling the current system, approximately the same system costs were spotted for the case using future prices (BASE F) and the cases using Swedish (SWE) and German (GER) spot prices. For the cases with new melting furnaces and existing holding furnaces being retained, a comparative analysis shows similar findings for the

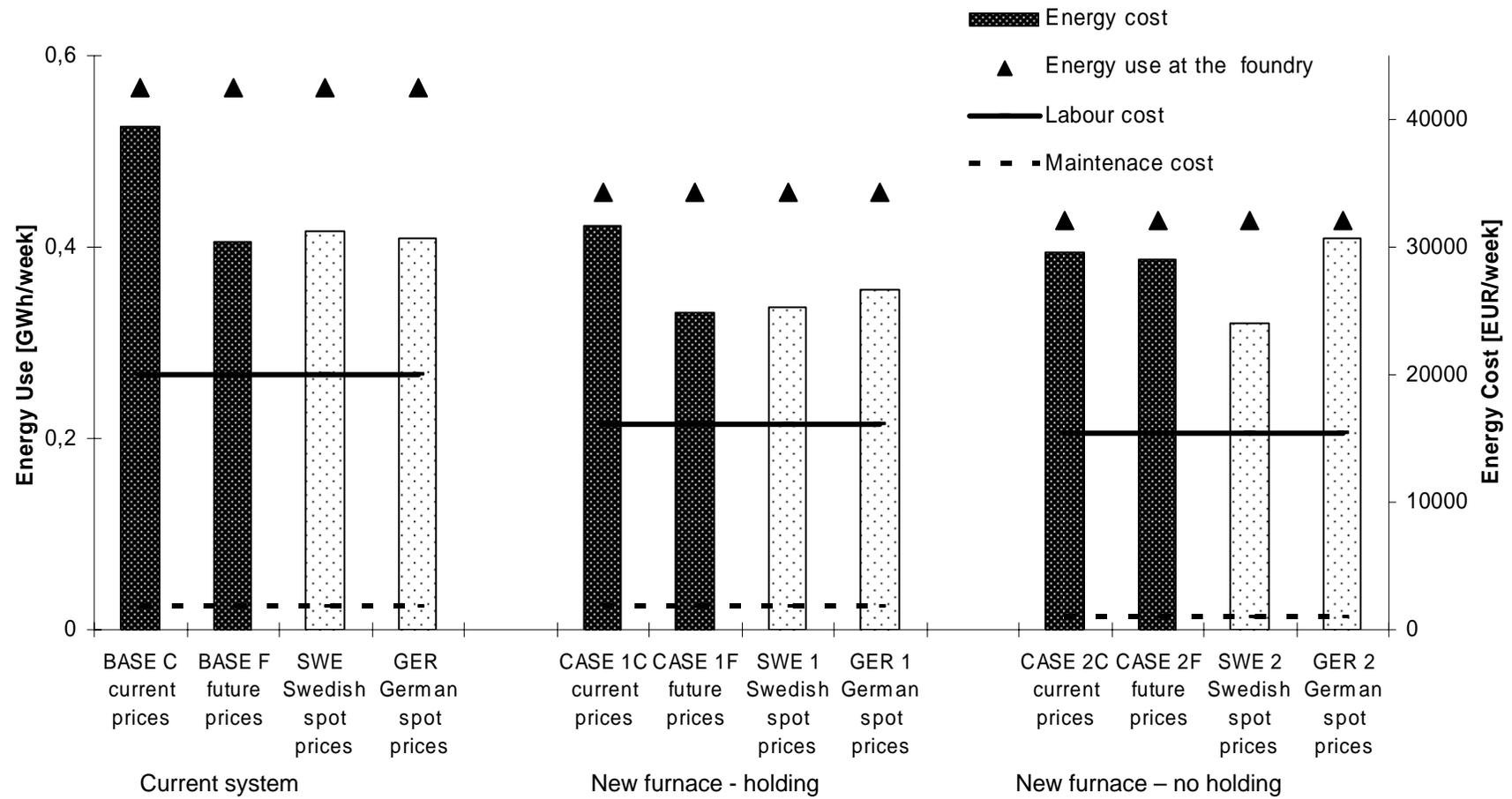


Fig. 4. Optimization results for the six different cases including cases using Swedish and German spot prices from weeks 49 and 44 in 2007 respectively. Also, weekly labour and maintenance costs, inspired by [31], are included in the figure.

CASE 1F and SWE 1 cases while the GER 1 case's system cost was slightly higher. For the cases with the new furnaces and no holding furnaces the system cost is lower for the SWE 2 case compared with the cases using current prices (CASE 2C) and future prices (CASE 2F) while the GER 2 case's system cost was slightly higher than CASE 2C and CASE 2F. This is explained by higher daily electricity prices resulting in higher system costs as the removal of the holding furnaces precludes storage of melted iron.

A sensitivity analysis of the electricity prices indicate that the system cost for CASE 1C is similar to the system cost for CASE 2C if the electricity price for the latter case rises with 5.4 €/MWh. If the electricity price remains on the same level daytime, Monday-Friday 6 am to 6 pm, but is reduced during the rest of the hours with 7.0 €/MWh, the system cost for CASE 1C turns out to be equal to CASE 2C's system cost. It should be noted that it is difficult to conduct such an analysis for the SWE and GER cases as these cases include hourly electricity price variations.

A sensitivity analysis of the power demands showed that the case representing the new melting unit with holding furnaces was able to decrease the power demand from 7.9 MW to 4.0 MW when setting constraints on the power load, while the new melting unit without holding furnaces was able to decrease the power demand from 7.9 MW to 5.5 MW when setting constraints. For the cases representing the current melting unit, the power demand could be lowered, when setting constraints on the power load, from 8.7 MW to 6.0 MW. The above findings are a result of the lower power demand for the new furnaces. A sensitivity analysis of the studied cases showed that the aggregated weekly production could be increased in all the studied cases by about 25%.

The new melting unit, consisting of only two furnaces, is much easier to run as the furnaces are charged by means of a charging wagon and not manually during the melting process leading to a reduction in personnel of one person. The working environment will also be significantly improved, i.e. made safer, as the charging of the furnaces is not made manually. However, retaining the two existing holding furnaces will lead to higher maintenance costs than if these holding furnaces were not used at all, as shown in Fig. 4. The production planning process also becomes easier as the new furnaces' melting times are shorter than the existing furnaces' even though the aggregated melting time for the two cases hardly differs. Even though the above parameters affect the investment figure, this has not been included in the actual model of the foundry as such parameters can be obtained without using investment decision support and this study has only studied the use of the latter. However, some primary figures related to the investment have been included in Fig. 4.

6. Concluding discussion

Previous research at the foundry showed that energy efficiency measures, spotted through energy auditing, might be of great importance in reducing the threat of increasing energy prices [5]. An evaluation of the outcome of the

energy audit revealed that mainly low-cost measures related to the support processes were undertaken [13]. This supports the importance of this study as energy audits focussing on cross-cutting-technologies alone may not provide the necessary means of stressing more costly strategic investments, i.e. energy audits in combination with investment decision support may be a means to further enhance the undertaking of measures, especially production-related measures, leading to reduced energy costs, greater competitiveness and higher productivity.

The initial investment plan for the studied foundry was to exclude holding furnaces since the overall operating energy costs in such a case are lowered, enabling a better investment figure to be presented for the corporate board. However, in the light of the findings from the optimization of the cases, one can conclude that, even though the energy use would be higher retaining these furnaces, it would not be so cost-effective to make the planned investment, even when taking the increased maintenance and labour costs for the holding furnaces into account, see Fig. 4. It would not have been possible to achieve this finding without the use of investment decision support such as MIND. One conclusion from this, stated in more general terms, is that Swedish foundries, from an energy cost point of view should try to retain their existing holding furnaces. From an energy use point of view, however, it is more efficient to remove holding furnaces as the energy use is then lowered. It should be noted that the optimal outcome is related to the foundry's specific abilities and commitment to planning production efficiently and therefore does not necessarily need to be the real outcome. It should also be noted that the foundry already uses shifts for the melting unit. For foundries with staff employed 24-hours a day, such as the investigated foundry, such a change in electricity prices would thus affect the energy related costs positively, assuming that production planning is carried out effectively. However, these results may not apply for all Swedish foundries as not all foundries operate round the clock.

Linking the above results to the aim and research question of this study, it is clear that the use of investment decision support is useful and provides company managements with additional information for the type of investment studied. Using MIND, the energy-intensive medium-sized foundry's management team is able to obtain more basic data for decision-making and thus also additional information for the production-related investment being studied, in this case investment in a new melting unit. For energy-intensive SMEs, the use of investment decision support when considering strategic investments - not least for the foundry industry with complex interactions between different production units - thus seems greatly needed. If not, the industry will instead face a risk of costly reinvestments if prices begin to fluctuate widely on a daily basis, which most likely will occur before long. Investment decision support may thus be one means of emphasising energy efficiency for energy-intensive SMEs beyond the level of traditional energy auditing when more costly, strategic, production-related investments are to be made.

7. Further work

Further research is needed to determine whether the results from this case study hold for other types of production-related investment decisions in foundries and other industrial sectors. Furthermore, it would be useful to use the optimization results as input to manufacturing simulation models to test whether the optimal outcome found in this study could actually be practiced and if not, what the bottlenecks and limitations in the production line are.

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