Publication II

Leena Sivill, Jussi Manninen, and Pekka Ahtila. 2009. A combined approach to energy efficiency monitoring in the pulp and paper industry. In: Proceedings of the 22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2009). Foz do Iguaçu, Paraná, Brazil. 31 August - 3 September 2009. Brazilian Society of Mechanical Sciences and Engineering. Pages 1513-1521.

A COMBINED APPROACH TO ENERGY EFFICIENCY MONITORING IN THE PULP AND PAPER INDUSTRY

Leena Sivill, leena.sivill@tkk.fi
Helsinki University of Technology, Department of Energy Technology, P.O.Box 4400, FIN-02015 TKK, Finland

Jussi Manninen, jussi.manninen@vtt.fi
VTT Technical Research Centre of Finland, P.O.Box 1000, FIN-02044 VTT, Finland

Pekka Ahtila, pekka.ahtila@tkk.fi
Helsinki University of Technology, Department of Energy Technology, P.O.Box 4100, FIN-02015 TKK, Finland

Abstract. *This paper discusses the aspects to be considered in the development of key performance indicators (KPI) for the management of energy efficiency at a corporate level in the pulp and paper industry. The term 'combined approach' refers to linking energy efficiency monitoring with business strategy and combining technology, operation and process integration perspectives into the development of the KPIs. We address the tasks, methodological issues and setting of objectives related to energy efficiency monitoring. A case study demonstrating the use of the KPIs for fault detection and the indication of operational improvement and process integration opportunities is presented. In the case study, monitoring is applied to the heating of process water in an integrated thermomechanical pulp (TMP) and papermaking line based on data from an existing mill. The results encourage the use of process systems engineering methods and tools for energy efficiency monitoring.*

Keywords*: energy efficiency, energy management system, key performance indicator, pulp and paper industry, balanced scorecard*

1. INTRODUCTION

The long-term objective of a company is to make profits for its shareholders. In this respect, the purpose of energy efficiency improvement is to increase profitability through cost-effectiveness. In the future, this may also include the growth of revenues if eco-efficiency increases the demand or the customer's willingness to pay. To meet these business goals, a company can carry out an energy efficiency program (EEP). This is described as a continual cycle of setting an energy policy, planning, implementing, reporting, reviewing and improving a company's systems (Connaghan and Wunderlich, 1999). Several frameworks have been specified for the EEPs. Among others, these include frameworks defined in voluntary energy efficiency agreements (see Motiva, 2007) and standards on energy management systems (EMS). The voluntary agreements and the EMS are policy incentives which aim at integrating energy efficiency practices. Today, standards on the EMS already exist at a national level, for example, in Denmark (DS 2403), Germany (VDI 4602/1), Ireland (I.S. 393), Sweden (SS 627750) and the U.S. (MSE 2000). A common European standard will be launched by the end of 2009 (CEN, 2005) and an international standard ISO 50001 by the end of 2010 (ISO, 2008).

The EMS standards require energy efficiency objectives to be determined and energy efficiency information to be measured and monitored on a regular basis (Desai *et al.,* 2008). However, the standards only address the general guidelines for energy efficiency monitoring. At the detailed level, the individual companies applying the EMS have to decide how the measurement and monitoring are carried out, including setting of the objectives and defining the important variables to be monitored. Consequently, there can be very different interpretations as to what should be monitored and how the information should be expressed depending on the company policy, the available information and the experience of the personnel. Arguably, it would be beneficial to have specific guidelines on energy efficiency indicators in such industries where the main processes, technologies and business processes are similar.

Performance monitoring systems (PMS) are widely used for day-to-day operational improvement in the process industry. In these monitoring systems, process systems engineering (PSE) methods and tools (see e.g. Grossman and Westerberg, 2000) are applied to assess the actual process status by calculation, visualization and monitoring of key performance indicators (KPI) (Klatt and Marquardt, 2009). Once the strategically relevant KPIs have been identified, the monitoring concepts can be tailored to the specific process and plant. As one example of these applications, energy monitoring and targeting (M&T) is a concept which originates from the 1980s. The basic technique of the M&T is to produce energy consumption information, link this information with the most important explanatory factors, and forecast the expected energy consumption of a process based on a model derived from the historical process data. Deviation from the modeled behavior indicates improvement or a fault to be diagnosed and acted upon. Today, there are a number of energy service companies operating internationally in the M&T field, but the basic concept has remained the same. Despite its availability, the M&T is still not commonly applied in the pulp and paper industry.

In this paper, we discuss the aspects to be considered in the development of the KPIs for the management of energy efficiency at a corporate level in the pulp and paper industry. These include defining the linkage between strategy and energy efficiency and determining the tasks and the methodological issues related to the development of the KPIs. We highlight that energy efficiency monitoring should cover the technology, operation and process integration perspectives when setting objectives. Hence, we argue that in the process industry, the measurement and monitoring could be developed beyond the traditional M&T. In addition, we present a case study which demonstrates the use of KPIs for fault detection and the indication of operational improvement and process integration opportunities. In the case study, energy efficiency monitoring is applied to the heating of process water in an integrated thermomechanical pulp (TMP) and papermaking line based on data from an existing mill.

2. LINKAGE BETWEEN STRATEGIC MANAGEMENT AND ENERGY EFFICIENCY

A company needs to define and refine its strategic objectives in order to remain profitable and competitive under changing operational conditions. In addition, a balance between different objectives needs to be maintained.

Wagner (2007) has found that there are benefits from integrating environmental management into strategic management and operational planning. The integration enables the establishment of a better connection between the actions of environmental management and financial performance or its drivers. The integration also reduces inefficiency caused by possible conflicting objectives. In this paper, we assume similar benefits from the integration of energy efficiency management into strategic management.

In the following, we refer to the Balanced Scorecard (BSC) as the most commonly used strategic management system to establish a link between energy efficiency monitoring and strategy (Kaplan and Norton, 1996). The aim of the BSC is to translate the vision and strategy of a company into action. The strategic objectives are associated with one or more measures, each assigned to one of four perspectives: financial, customer, internal business process, and learning and growth. The measures are expected to foster a balance between short- and long-term objectives, between preferred outcomes (lag performance measures) and the performance drivers of these outcomes (lead performance measures), and between quantitative and qualitative measures.

In Figure 1, we present a hypothetical BSC approach to energy efficiency management. This example is intended for illustration only since the details of each BSC are company-specific and we have not carried out research to generalize a common approach or to validate the illustration. The role of energy efficiency indicators in this example is to enable the internal processes to function more efficiently and to ensure that the customer's specifications on energy efficiency as a quality factor are achieved. However, Figure 1 points out one interesting feature similar to the ISO 14031 standard on energy performance evaluation: management performance indicators (MPI) can be separated from operational performance indicators (OPI) (ISO, 1999). The MPIs are intended for measuring the carry-out rate of energy efficiency programs and actions, whereas the OPIs measure the actual quantifiable performance related to energy efficiency. Both the MPI and the OPI indicate how energy efficiency management has been adopted within an organization. Hooke *et al.* (2004) present a list of success factors for the managerial performance of an energy efficiency program. This list could be applied in the development of the MPIs.

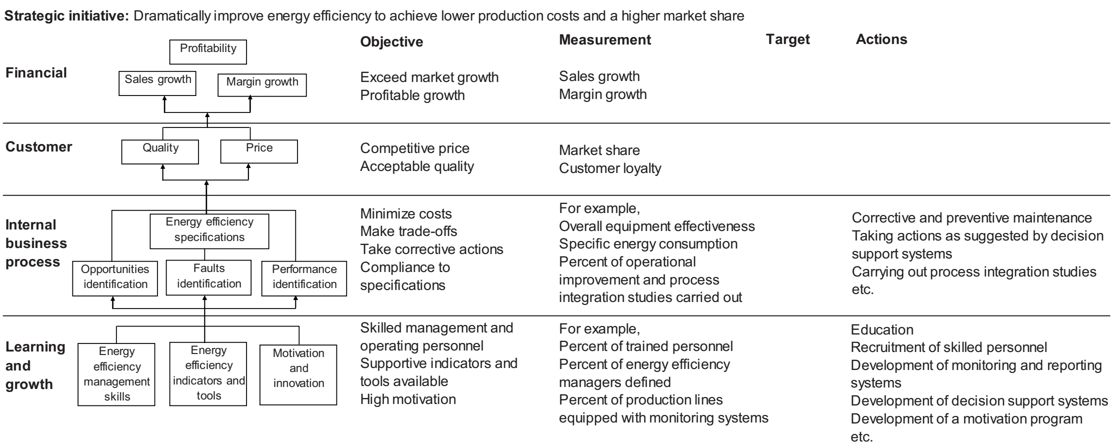

Figure 1. An example of a Balanced Scorecard approach to the strategic management of energy efficiency

3. OPERATIONAL KEY PERFORMANCE INDICATORS FOR ENERGY EFFICIENCY

In the following, we discuss the aspects which have to be taken into account in the development of operational KPIs for energy efficiency in the pulp and paper industry. To serve the strategic business goals, the operational energy efficiency indicators should assist in the following four tasks

- Indicate performance and progress,
- Identify the need to take corrective or preventive actions,
- Enable benchmarking to assess competitiveness, and
- Identify opportunities for performance improvement

Each of these four tasks requires a reference or a target to be defined. The performance of a process may be compared to a target based on the historical achievement of the process, another similar process under same operating conditions or a modeled target (Hooke *et al.*, 2004).

Economic energy efficiency improvement can be achieved through the three main classes of means described in Fig. 2. The term 'technology' refers to the equipment and the selection of a manufacturing process for a product. Operational improvement opportunities relate to the way in which the process is operated and maintained. It includes sub-tasks such as selecting set points and other operating parameters, the control of production and quality, and the scheduling of production, resources and maintenance. 'Process integration' refers to taking advantage of interactions between processes. The classification in Fig. 2 is not intended to be definitive; it is only a matter of interpretation.

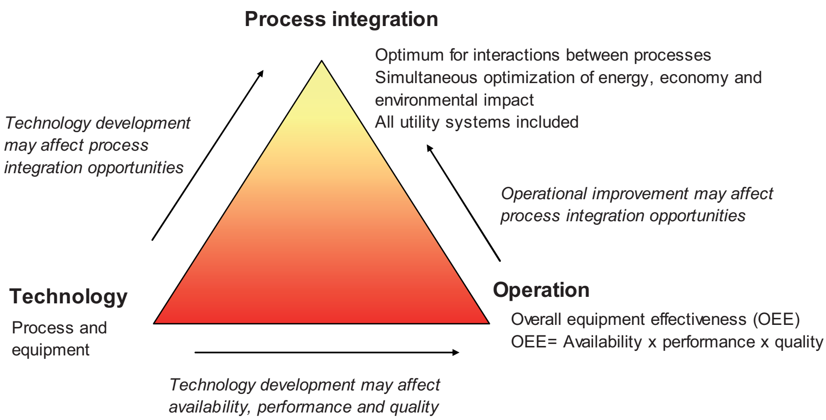

Figure 2. Means to improve energy efficiency in an industrial plant

A change (internal or external, momentary or permanent) within the processes or the way in which they are operated may have effect on the opportunities for economic energy efficiency management. Hence, energy efficiency management is a continuous task and requires adaptive indicators. This can be achieved by updating objectives manually, or automatically by creating adaptive models, or using a combination of the two. In the following, we discuss the state-of-art in energy efficiency indicators, their methodological issues and setting of objectives for the operational KPIs.

3.1. Existing energy efficiency indicators

The fundamental challenge in the measurement and monitoring of energy efficiency is that it is constantly affected by numerous internal and external variables and their dynamics. The internal and external variables include factors such as ambient conditions, the occurrence of breaks and shutdowns, the production rate, the quality of the materials and the end products, the operation of the control system, and the actions of the mill personnel. Information on all the relevant variables may not be available or their measurement not reliable, and the information may be qualitative by nature. It is therefore difficult to assess performance, relate actions to consequences, or find potential for improvement only by analyzing data. In addition, there are many methodological issues which need to be addressed before an assessment. For example, a product's energy efficiency should be considered throughout its lifecycle in policy analyses, whereas at a corporate level, the aim is higher profitability (Tanaka, 2008). Macro-economic indicators are therefore different from indicators at the corporate level, even though many of the methodological issues are similar. According to Patterson (1996), the issues related to macro-economic indicators are: the role of value judgments in the construction of the energy efficiency indicators, the energy quality problem, the boundary problem, the joint production problem (multiple products) and the question of isolating the underlying technical energy efficiency trends from the aggregate indicators.

Energy efficiency indicators can be divided into descriptive and explanatory indicators (Patterson, 1996). The role of the descriptive indicators is to express the absolute value of performance and the explanatory indicators to provide information explaining the behavior of the descriptive indicators. A commonly used descriptive indicator for energy efficiency is the following ratio (Patterson, 1996)

$$\text{Energy efficiency} = \frac{\text{Useful output of a process}}{\text{Energy input into a process}} \tag{1}$$

The specific energy consumption (SEC) is the inverse of this definition. The energy input can also be expressed in monetary terms linking energy efficiency with economy. However, Equation 1 does not yet address the variability aspects of energy efficiency. We illustrate this by presenting the SEC as a function of its explanatory factors as follows

$$SEC = \frac{E(x_1,...,x_n)}{P(y_1,...,y_m)} \tag{2}$$

where E describes the energy consumption as a function of its explanatory variables x and P the production as a function of its explanatory variables y. The effect of some explanatory variables is more dominant than others and many of the variables are interdependent. Equation 2 therefore points out two important aspects: firstly, we need modeling and process data on a momentary basis to be able to quantify the relationships between a specific action and the energy efficiency, and, secondly, the SECs measured over time are not able to catch the underlying variability and can therefore only be used to describe long-term trends.

Two commonly used indicators are derived from the SEC: the best available technique (BAT) for benchmarking and the energy efficiency index (EEI) for expressing changes (IPPC, 2008). The major restriction of BAT is that there may be a gap of several years between the updates of the publicly available values (see e.g. Vasara *et al.*, 2001; IPPC, 2000). Other methodological issues concerning the BAT include the definition of similar process boundaries and operating conditions, which restricts the applicability of this indicator. As a solution to the boundary problem, Francis (2007) has presented guidelines for reporting energy use in pulp and papermaking operations by process area. The KPIs to be reported include the use of fuels per type, steam, condensate, hot water, electricity and production by type. These guidelines are used by CIPEC (2008).

There exists, however, no common practice for the KPIs to be monitored within a company. TAPPI (2006) TIP 0404-63 lists so-called energy performance indices (EPI) which give targets not only to the SECs but also to other KPIs in a papermaking line such as uptime, overall machine efficiency and the dry solids content at each stage of the drying process. In addition, these guidelines recommend the monitoring of the specific consumption of compressed air, the rate of condensate return and the total energy cost per ton of paper produced. Along with this type of KPIs, Connaghan and Wunderlich (1999) list KPIs which are actually intended for supply-side energy management. The KPIs can also be defined strictly as indicators of energy performance. With this definition, API (2009) uses the term ‘key energy parameters’ (KEP) to describe the process variables that the operating personnel must pay attention to in order to maintain efficient energy performance in terms of these KPIs. This definition subdivides explanatory energy information into the controllable and the non-controllable, and thereby already requires a judgment to be made as to the nature of each explanatory variable.

Figure 2 refers to overall equipment effectiveness (OEE) as a measure of operational performance. The OEE is a product of three operational performance indicators: the availability, the performance rate and the quality rate. These are used as metrics in total productive maintenance (TPM) (Nakajima, 1989). The OEE is included here as an energy efficiency indicator because efficient production typically reflects positively on energy efficiency and overall profitability, although in certain situations there may be trade-offs between energy efficiency and profitability (Sivill and Ahtila, 2009).

In conclusion of our literature review on the existing KPIs, a clear framework has not been presented for the classification, definition and interpretation of KPIs in the pulp and paper industry. Furthermore, only a few of the existing indicators associated with energy efficiency have been subjected to critical analysis. The lack of these specifications implies that the existing performance indicators may have unknown consequences, can be misinterpreted or important indicators may be lacking since each indicator is only able to describe part of the process properties and behavior.

3.2. Setting objectives for operational KPIs

A target for an operational KPI can be hypothetical or a specific value considered as achievable by the means presented in Fig. 2. The difference between a target and the actual performance highlights an improvement potential.

The improvement potential includes several levels. It may describe a theoretically, technologically or economically achievable future potential (Tuomaala, 2007) based on what-if scenarios. It can also describe a potential based on the analysis of past information such as the expected modeled behavior or the historically achieved best performance.

The targets need to be adjusted in relation to the variable conditions expressed in Equation 2. Typically, this requires the use of modeling. Recently, a state-of-art review has been published on the use of modeling and simulation in the pulp and paper industry (Dahlquist, 2008). This work also critically reviews the benefits and downsides of modeling and the criteria for models to be viable and applicable in decision-making. The aspects of operational decision-making in the process industry have also been reviewed recently by Mätäsniemi (2008).

Due to the limitations of information and modeling, all targets cannot be expressed quantitatively. A lot of information exists on factors which are known to contribute to energy efficiency, even if measuring or modeling them is either impossible or otherwise not meaningful. The challenge of taking advantage of such information is being able to determine preferable targets since the effects on the whole can be defined only by trial-and-error. For example, improving the dryer economy of a paper machine may result in more breaks unless the operating personnel are able to find a correct balance between certain operating parameters. These trade-offs emphasize the expertise of the operating personnel. Part of this empirical knowledge may be utilized by creating appropriate expert systems.

Many profitable energy conservation opportunities are related to the design of the processes: the dimensioning, the structure and the integration. The purpose of energy analyses, process integration and process intensification studies is to remove these possible design imperfections. Methods are presented widely for both greenfield and retrofit design (see e.g. Tjoe and Linnhoff, 1986; Yee and Grossmann, 1991; El-Halwagi, 1997; Kovač Kralj *et al.*, 2000; Kovač Kralj *et al.*, 2005; Uerdingen *et al.*, 2003; Reay, 2008). The use of these methods has traditionally been associated with off-line design. In this paper, we wish to challenge this by considering whether the results of these design analyses, i.e. their design scenarios, could be used for energy efficiency monitoring. The classic approach in the analyses is to perform a detailed study periodically or by case-by-case consideration based on the available data, engineering knowledge and assumptions on uncertain factors. For example, resources are allocated to such energy conservation investments which are considered the most profitable under price uncertainties (Svensson *et al.*, 2009a; Svensson *et al.*, 2009b). A gap therefore exists between the actual and the estimated performance of designs which are theoretically, technologically, financially or empirically optimal in each operating situation. These scenarios indicate an improvement potential which assists in the scheduling of the future detailed analyses and investments. For the use of energy efficiency monitoring, the design scenarios will have to be simple and may therefore not take all the design criteria into account. The scenarios also require updating if the design assumptions change over time. The need for detailed analyses therefore remains, but the decision-makers are better informed about the magnitude of the improvement potential related to design.

4. CASE EXAMPLES

In the following, we demonstrate a new monitoring approach for the process water heating of an existing integrated TMP and a papermaking line based on the development of KPIs for fault detection, operational improvement and process integration. The primary objective is to minimize the overall steam consumption in two cases: with or without investment in the existing heat exchanger network (HEN). The objective without investment is to maximize heat recovery from the dryer section's exhaust air to the process water. By allowing for HEN retrofit, there is also an opportunity to increase heat integration between the TMP plant and the paper machine (PM).

The procedure to develop the KPIs is presented in Fig. 3. The KPIs for fault detection and operational improvement express the deviation between the measured and the modeled recovered heat, and the KPI for process integration describes the deviation between the measured and the modeled steam consumption.

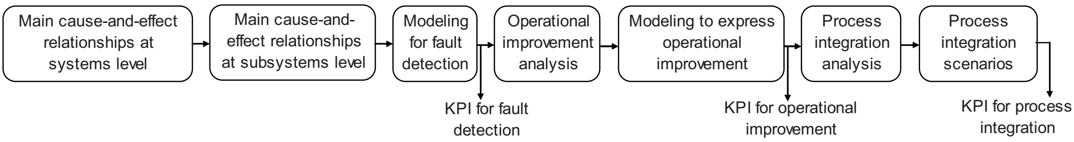

Figure 3. Procedure to derive KPIs for fault detection, operational improvement and process integration

Figure 4 presents a simplified flow chart of the cause-and-effect relationships affecting the heat consumption in the PM. The arrows show the direction in which changes in one section affect each other.

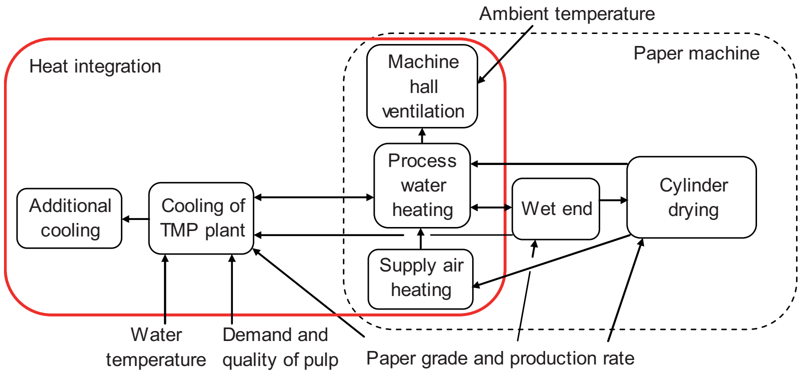

Figure 4. Main cause-and-effect relationships in the primary heat consumption of a paper machine

Figure 5 presents the results of momentary pinch analyses for the integrated system as duration curves. The figure illustrates the deviation between the actual steam consumption and theoretical steam use with a HEN which changes its structure depending on the calculated minimum energy requirement (MER) at every operating hour. The pinch analyses include 11 streams to be heated and 11 streams to be cooled or being available for heat recovery. The actual steam consumption includes the steam consumption of process water, machine hall ventilation and supply air. In the pinch analyses, the dryer section's exhaust air is treated as a soft stream because the air can be exhausted outdoors whenever there is a surplus of heat (Kemp, 2007). According to the MER analysis, the primary steam consumption could be reduced by 32 GWh (65 %) compared with the performance of the existing HEN in 2004. The estimated MER crosses over the actual heat consumption in the beginning of the curves because during start-ups all the relevant process units contributing to the additional heating demand have not been taken into account and there are always inaccuracies in live data even though it has passed through initial filtering. Interestingly, there exists no pinch point between the composite curves of the hot and cold streams during normal operation, indicating that the heat exchangers could be designed for large temperature differences.

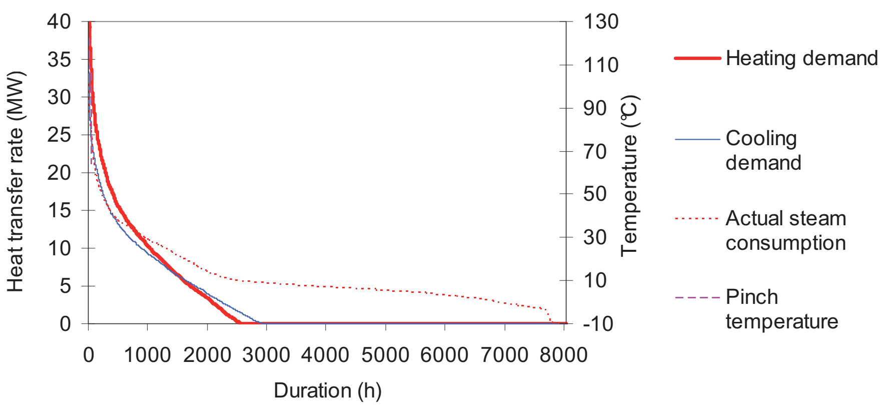

Figure 5. Pinch analyses of an existing integrated TMP and paper machine line based on hourly data in 2004

In Figure 6 the hourly pinch analyses show that the MER between the paper machine and the TMP plant would have brought about a 40 % saving in steam consumption compared with the measured consumption in the heating of supply air, machine hall ventilation and process water in January 2004. The occasional cross-over of the MER is also presented, which is an effect that can easily be removed from actual monitoring applications. The existence of a large gap between the MER and the actual steam consumption during normal operation gives an incentive to start up a detailed process integration analysis. Figure 6 also shows the actual steam consumption of process water heating. According to MER, no steam is required for process water heating when the TMP plant and the PM are simultaneously in production.

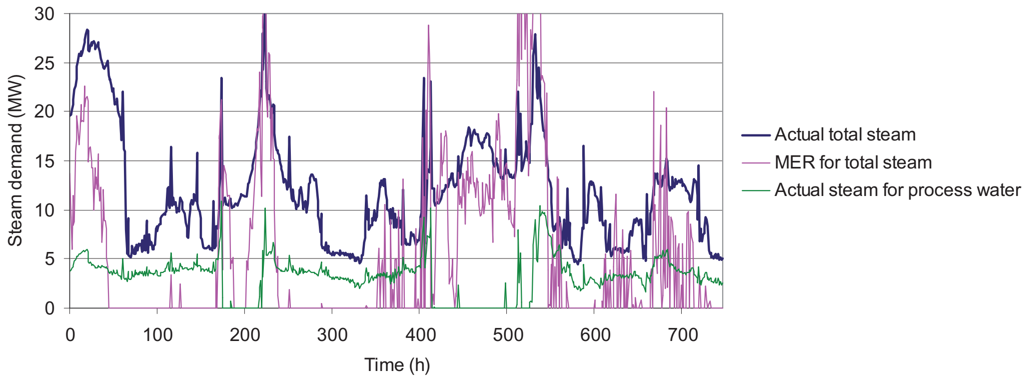

Figure 6. Process integration potential between a thermomechanical pulp plant and a paper machine in Jan. 2004

Figure 7 shows how much heat is recovered in the dryer section's heat recovery system. With a simulation model of the existing dryer section's heat recovery system (heat exchanger model presented by Sivill *et al.*, 2005), we can produce an estimate for the heat transfer rate in the case of a leaking valve. According to Figure 7, if 10 % of the flow rate of process water passes by the heat recovery, the steam consumption would have increased by 9.5 %. Similarly, we can use the heat recovery model to estimate the effects of possible operational improvements that have been identified in an operational improvement study. Two opportunities are considered as targets: to connect the process water to the dryer section's heat recovery system in a thermodynamically correct way by not mixing the water with streams that have already been heated at a set point prior to heat recovery, and to increase the humidity of the exhaust air by 10 $g_{H2O}/kg_{d.a.}$ by adjusting the dryer section's ventilation. As a result of these modifications, the steam consumption would have been reduced by 8 %.

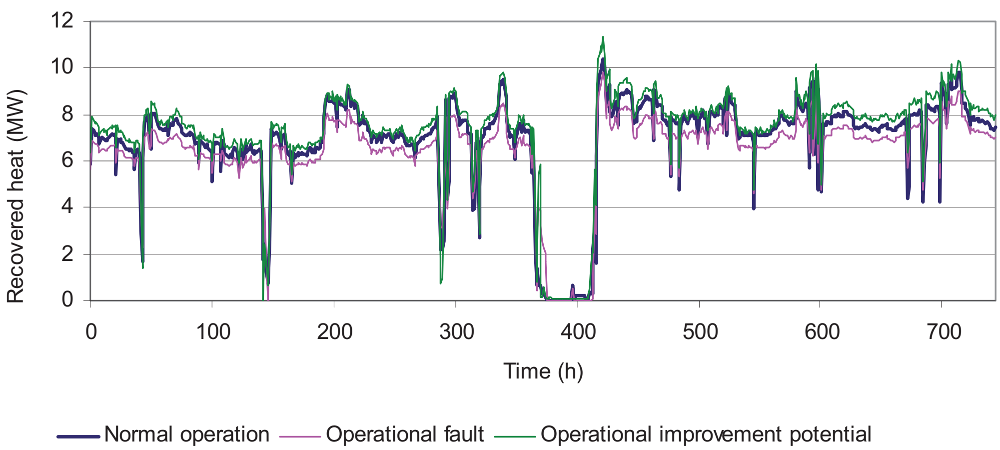

Figure 7. Fault detection and operational improvement potential of process water heating in a case paper machine on an hourly basis in Jan. 2007

5. CONCLUSIONS

Energy efficiency management in the pulp and paper industry is a challenging field for performance monitoring because of its complexity and the methodological issues involved. Information should be produced in a way that allows us to be aware of the different choices of actions and their consequences. In this paper, we viewed energy efficiency monitoring from the strategic and the operational perspectives and demonstrated that it is possible to provide information on the potential for energy efficiency improvement. Many research areas in this field require further development. These include demonstrating the BSC approach, analyzing the existing KPIs and their relationships in detail, systematically developing new KPIs, removing the possible overlap of the KPIs, determining procedures for reporting and most importantly, bringing in the mill personnel as part of the development process. This paper also indicates great potential for the use of PSE tools and methods in energy efficiency monitoring.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Pekka Ruohonen and Ilkka Hippinen from Helsinki University of Technology, Emilia Pentti from the Helsinki School of Economics and the personnel of the case mill for valuable comments.

REFERENCES

API, 13 Mar 2009, "Energy Targetter™", American Process Inc., <http://www.apiweb.com/EnergyTargetter.aspx>.
CEN, 2005, "CEN/CLC BT JWG "Energy Management": Final Report", European Committee for Standardization (CEN), 102 p.
CIPEC, 2008, "Benchmarking Energy Use in Canadian Pulp and Paper Mills", Canadian Industry Program for Energy Conservation (CIPEC), Pulp and Paper Research Institute of Canada, Ottawa, 60 p.
Connaghan, C. and Wunderlich, R., 1999, "Developing, Implementing and Maintaining an Energy Efficiency Program", In: Browne, T.C. and Williamson, P.N. (Eds.), "Energy Cost Reduction in the Pulp and Paper Industry: A Monograph", Pulp and Paper Research Institute of Canada (Paprican), Montréal, 234 p.
Dahlquist, E. (Ed.), 2008, "COST Action E36: Use of Modeling and Simulation in Pulp and Paper Industry", European Cooperation in the field of Scientific and Technical research (COST), 330 p.
Desai, D., Meffert, W.A., Grell-Lawe, H. and McKane, A., 2008, "Summary Comparison of National Energy Management Standards", United Nations Industrial Development Organization (UNIDO), United States Department of Energy (DOE), 42 p.
El-Halwagi, M.M., 1997, "Pollution Prevention through Process Integration: Systematic Design Tools", Academic Press, San Diego, 318 p.
IPPC, 2000, "IPPC Reference Document on Best Available Techniques in the Pulp and Paper Industry", Integrated Pollution Prevention and Control Bureau (IPPC), European Commission, 509 p.
IPPC, 2008, "IPPC Reference Document on Best Available Techniques for Energy Efficiency (ENE-BREF)", Integrated Pollution Prevention and Control Bureau (IPPC), European Commission, 430 p.
Francis, D.W., 2007, "Reporting Guidelines for Energy Use in Pulp and Paper Operations", FPInnovations, Vancouver, 110 p.
Grossmann, I.E. and Westerberg, A.W., 2000, "Research Challenges in Process Systems Engineering", AIChE Journal, Vol. 46, No. 9, pp. 1700-1703.
Hooke, J.H., Landry, B.J. and Hart, D.M.A., 2004, "Energy Management Information Systems: Achieving Improved Energy Efficiency", Canadian Industry Program for Energy Conservation (CIPEC), Ottawa, 93 p.
ISO, 1999, "Environmental Performance Evaluation – Guidelines (ISO 14031:1999)", International Organization for Standardization, Brussels.
ISO, 15 Sep 2008, "ISO Launches Development of Future Standard on Energy Management", International Organization for Standardization, 26 Jan 2009, <http://www.iso.org/iso/pressrelease.htm?refid=Ref1157>.
Kaplan, R.S. and Norton, D.P., 1996, "The Balanced Scorecard", Harvard Business School Press, Boston, 322 p.
Kemp, I. C., 2007, "Pinch Analysis and Process Integration", Elsevier Ltd., Oxford, 396 p.
Klatt, K.-U. and Marquardt, W., 2009, "Perspectives for Process Systems Engineering – Personal Views from Academia and Industry", Computers and Chemical Engineering Vol. 33, pp. 536-550.
Kovač Kralj, A., Glavič, P. and Kravanja, Z., 2000, "Retrofit of Complex and Energy Intensive Processes II: Stepwise Simultaneous Superstructural Approach", Computers and Chemical Engineering, Vol. 24, pp. 125-138.
Kovač Kralj, A., Glavič, P. and Kravanja, Z., 2005, "Heat Integration between Processes: Integrated Structure and MINLP Model", Computers and Chemical Engineering, Vol. 29, pp. 1699-1711.
Motiva, 2007, "Energy Efficiency System (EES)", Motiva, Helsinki, 12 p.
Mätäsniemi, T. (Ed.), 2008, "Operational Decision Making in the Process Industry: Multidisciplinary Approach", VTT Research Notes 2442, VTT Technical Research Centre of Finland, Edita Prima Oy, Helsinki, 138 p.
Nakajima, S. (Ed.), 1989, "TPM Development Program: Implementing Total Productive Maintenance", Productivity Press Inc., Cambridge, 403 p.
Patterson, M.G., 1996, "What is Energy Efficiency? Concepts, Indicators and Methodological Issues", Energy Policy Vol. 24, No. 5, pp. 377-390.
Reay, D., 2008, "The Role of Process Intensification in Cutting Greenhouse Gas Emissions", Applied Thermal Engineering, Vol. 28, pp. 2011-2019.

Sivill, L. and Ahtila, P., 2009, "Paper Machine Production Efficiency as a Key Performance Indicator of Energy Efficiency", Proceedings of the 12th International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Prevention (PRES'09), Rome, 6 p. (in review)
Sivill, L., Ahtila, P. and Taimisto, M., 2005, "Thermodynamic Simulation of Dryer Section Heat Recovery in Paper Machines", Applied Thermal Engineering, Vol. 25, No. 8-9, pp. 1273-1292.
Svensson, E., Berntsson, T., Strömberg, A.-B. and Patriksson, M., 2009a, "An Optimization Methodology for Identifying Robust Process Integration Investments under Uncertainty", Energy Policy, Vol. 37, No. 2, pp. 680-685.
Svensson, E., Berntsson, T. and Strömberg, A.-B., 2009b, "Benefits of Using an Optimization Methodology for Identifying Robust Process Integration Investments under Uncertainty – A Pulp Mill Example", Energy Policy, Vol. 37, No. 3, pp. 813-824.
Tanaka, K., 2008, "Assessing Measures of Energy Efficiency Performance and Their Application in Industry", International Energy Agency (IEA), Paris, 40 p.
TAPPI, 2006, "TIP 0404-63: Paper Machine Energy Conservation", Technical Association of the Pulp and Paper Industry (TAPPI), Norcross, 21 p.
Tjoe, T.N. and Linnhoff, B., 1986, "Using Pinch Technology for Process Retrofit", Chemical Engineering, Vol. 93, No. 8, pp. 47-60.
Tuomaala, M., 2007, "Conceptual Approach to Process Integration Efficiency", Doctoral Dissertation, Helsinki University of Technology, Espoo, 225 p.
Uerdingen, E., Fischer, U., Hungerbühler, K. and Gani, R., 2003, "Screening for Profitable Retrofit Options of Chemical Processes: A New Method", AIChE Journal, Vol. 49, No. 9, pp. 2400-2418.
Vasara, P., Jäppinen, H. and Lobbas, P., 2001, "A Strategic Concepts for Best Available Techniques in the Forest Industry", Report 425, Finnish Environment Institute, Oy Edita Ab, Helsinki, 73 p.
Wagner, M., 2007, "Integration of Environmental Management with Other Managerial Functions of the Firm: Empirical Effects on Drivers of Economic Performance", Long Range Planning, Vol. 40, pp. 611-628.
Yee, T.F. and Grossmann, I.E., 1991, "A Screening and Optimization Approach for the Retrofit of Heat-Exchanger Networks", Industrial & Engineering Chemistry Research, Vol. 30, No. 1, pp. 146-162.

RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.