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ENERGY EFFICIENCY INDEX AS AN ENERGY EFFICIENCY INDICATOR FOR INTEGRATED PULP AND PAPER MILLS – A CASE STUDY

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ABSTRACT:

Energy efficiency indices (EEI) can be used for process energy efficiency monitoring in industry. The EEI reflects energy efficiency performance by comparing the energy consumption over a follow-up period to a reference value that is calculated at the same production rate with a baseline function determined in advance for each production department. Consequently, the EEI is able to detect changes in energy efficiency at any production rate. This is very important in production lines with different product grades and varying production rates because, in contrast to EEI, the specific energy consumption (SEC) typically has a minimum at a fixed operation point. In this paper we present definitions for EEI in the processes of the pulp and paper industry. We discuss several methodological issues, such as how to determine appropriate baselines for EEI in each process, how to combine the baselines of an integrated mill with multiple products, and what type of information needs to be evaluated to explain the behaviour of the EEIs. We present a case study which indicates that EEI is a suitable supplementary performance indicator for process energy efficiency monitoring in the pulp and paper industry.

KEYWORDS: Energy efficiency; Efficiency indicator; Efficiency index; Energy conservation; Pulp and paper

1. INTRODUCTION

Energy efficiency indicators were originally developed for the evaluation of energy policies. These energy efficiency indicators are used for assessing the effectiveness of policy measures, monitoring trends and comparing performance at a national or sectoral level. Definitions and methodologies for this are widely presented in the literature and in scientific papers (see e.g. Bor [1]). Today, the concept of energy efficiency indicators is being extended to individual production sites and processes to quantify and explain the behaviour of energy efficiency.

The International Energy Agency (IEA) [2] has described the hierarchy of energy efficiency indicators with a pyramid model. Our focus is on the ground level of this pyramid: process energy efficiency. We examine how the energy efficiency index could become a tool for energy efficiency monitoring in industrial sites and individual processes.

1.1. Definition of energy efficiency index

An energy efficiency index is an energy efficiency indicator reflecting changes in energy efficiency. The term energy efficiency index itself is generic. Indices can be derived from many types of energy efficiency indicators, depending on the analyses to be undertaken. In this paper we use a definition for energy efficiency index that dates back to the Canadian Industry Program for Energy Conservation (CIPEC) and has been further developed by Siitonen et al. [3]. The energy efficiency index for process performance monitoring is defined as

$$EEI = \frac{E_{mes}}{E_{ref}} \quad (1)$$

where E_{mes} describes the measured energy consumption of a process during a follow-up period and E_{ref} the value of a reference baseline function for energy consumption at the same production rate as recorded in the follow-up period. The baseline function is determined in advance based on the characteristic behaviour of energy consumption in the process. A fixed period in the process history is selected for the determination of the baseline function. This reference period should be long enough for the characteristics of energy consumption to appear in the data correctly. Siitonen et al. [3] have described how the characteristic behaviour of energy consumption in an industrial process can typically be divided into basic energy consumption and variable energy consumption (Figure 1).

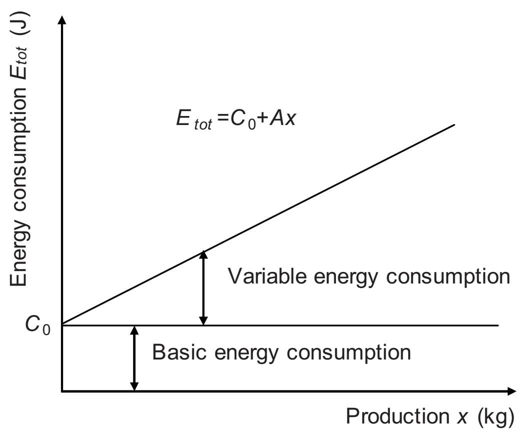

Figure 1. Division of basic and variable energy consumption (reproduced from [3])

The basic energy consumption includes all energy use that is not dependent on the production rate, e.g. lighting and energy use during shutdowns. In process industries the variable energy consumption has a characteristic linear relationship to the production rate. Although there are a number of other factors such as ambient temperature and changes in product quality affecting the energy consumption, the effect of the production rate on energy consumption is by far the greatest. The dependence between energy consumption and the production rate is not strictly linear as the lowest specific energy consumption is typically achieved at a fixed operation point near design capacity, as presented in Figure 2. As a result, changes in energy efficiency in processes that produce several different product grades with differing production rates remain unrevealed, since the specific energy consumption (SEC) is sensitive to changes in the production rate. This problem can be avoided by defining the behaviour of energy consumption as a function of the production rate with an energy efficiency index.

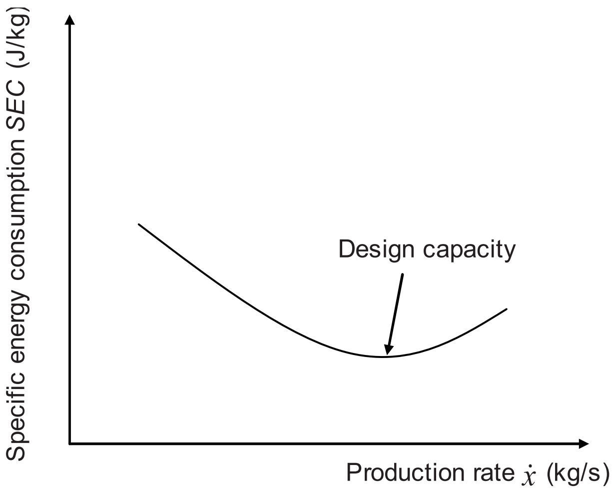

Figure 2. Specific energy consumption as a function of the production rate

1.2. Methodological, operational and practical problems

The energy efficiency index is subject to the same methodological and operational problems as other energy efficiency indicators. Patterson [4] has described these as subjective value judgements in the construction of energy efficiency indicators, the energy quality problem, the boundary problem, the joint production problem and problems in isolating the underlying technical energy efficiency trend from aggregated indicators. Among the practical problems concerning the energy efficiency index is the requirement for baseline updates when major changes are made to the process structure. In addition, field instrumentation and information systems in existing industrial plants were not originally designed for energy efficiency monitoring, which limits the available data.

1.3. Research aims

The key to the energy efficiency index is in the determination of an appropriate baseline function E_{ref} able to describe the process characteristics correctly. To define an energy efficiency index, three fundamental questions need to be answered: 1) what is the proper form and coefficients for a baseline function, 2) should other characteristic variables in addition to the production rate be taken into account and 3) what is the correct time scale to be used for determining baselines and calculating indices. Our aim in this paper is to provide answers to these questions in the processes of the pulp and paper industry.

2. METHODS

2.1. Determination of baseline equations for the pulp and paper industry

For the pulp and paper industry, Siitonen et al. [3] have proposed a baseline function defined as

$$E_{ref}(x) = C_0 + \sum_j A_{0,j} x_{j,k} + \sum_i M_{i,k} \tag{2}$$

where C_0 is the base load in the reference period, $A_{0,j}$ is the specific energy consumption of production line j, $x_{j,k}$ the production of production line j in the follow-up period k, and $M_{i,k}$ is the effect of such changes i on the process or its operating conditions that need to be corrected to the baseline function case-by-case in the follow-up period k. Such conditions include the operation rate, outsourcing and changes in production line structure.

Equation 2 generally applies well to the electricity consumption of paper machines, but for mechanical pulping the quality of the produced pulp, e.g. freeness (CSF), is a significant factor: the lower the CSF, the higher the specific electricity consumption. For example, the specific electricity consumption can vary from 2.2 to 4 MWh/t for dry thermomechanical (TMP) pulp [5]. Ambient temperature has little effect on electricity consumption in the pulp and paper industry, apart from seasonal changes to machine hall ventilation and the use of cooling towers.

Heating demand depends heavily on both the production rate and the ambient temperature. However, the degree of process integration has an important role in how seasonal changes in heating demand reflect on the use of primary heat. In this paper, we argue that the heat consumption of paper machines should be independent of changes in ambient temperature. Several reasons exist for this. For example, paper machines are equipped with heat recovery systems designed to satisfy the whole heating demand of machine hall ventilation and process water during normal operation [6]. In cold climates, primary heat should only be used for these purposes during shutdowns and the highest winter peaks. If this is not the case, process control, process equipment and heat integration should be checked and modified. To summarise, seasonal changes in paper machine heat consumption afford opportunities for energy efficiency improvement. To show this potential in the energy efficiency index, baseline equations for heat consumption in paper machines should be determined without seasonal effects, and ambient temperature should not be compensated for in the follow-up periods.

Another important factor is to define how the operation rate (operation time divided by follow-up period) and the production rate (kg/s) are taken into account in the baselines. In Equation 2, Siitonen et al. [3] use a constant SEC for the reference period and suggest using correction terms M_i for changes in the operation and production rates in the follow-up periods. However, the definition for M_i is missing. Therefore, we wish to replace Equation 2 with another definition. For paper machines, we define the baseline as

$$E_{ref}(x) = (A_0 \dot{x} + B_0) t_k \tag{3}$$

where A_0 is the coefficient for the production rate $\dot{x}$, B_0 is a constant and t_k denotes the operation time in the follow-up period k. The values for A_0 and B_0 are determined with the partial least squares method directly from process data during normal operation in the reference period.

Equation 3 can be replaced with a more complex equation if such a correlation is detected in the process data. The reason why we suggest omitting the base load term C_0 is that this effect is already part of B_0 during the operation time. Consequently, Equation 3 leaves out a term for reference base load during breaks and shutdowns and emphasizes the importance of a high operation rate for energy efficiency.

In this paper, all index baselines are calculated based on gross production including packing and shells. Differences between gross and net production (defined as production in reel) are therefore included in the results.

2.2. Definition of aggregated energy efficiency indices

The energy efficiency indices of individual processes can be aggregated to higher levels. The reference periods used for each production line do not have to be the same. This outline is practical, for example, when baselines for individual production lines cannot be determined at the same time due to lack of information. The measured energy consumption of a production line can replace the missing baseline until it becomes available. In this paper, we define the aggregated energy efficiency index as follows

$$EEI_{tot} = \frac{E_{mes,tot}}{\sum_i E_{ref,i}\left(\dot{x}_{mes,i}\right) + E_{ref,other}} \tag{4}$$

where EEI_{tot} denotes the aggregated energy efficiency index, $E_{mes,tot}$ the measured total energy consumption and $E_{ref,i}$ the calculated reference energy consumption of process i with the measured production rate. $E_{ref,other}$ refers to total site steam consumption not related to the production lines, e.g. district heating of office buildings. By definition, this aggregated energy efficiency index shows the effect of changes in the energy efficiency of individual production lines relative to the energy consumption as a whole.

2.3. Data analysis methods

We use the partial least squares projection to latent structures (PLS) method for data analysis (see e.g. Eriksson et al. [7]). PLS is a statistical multivariate method which enables regression modelling between two data sets selected as the predictors (X) and responses (Y) of a linear system. One of the major advantages of the PLS method is that it is able to handle multicollinearity. For software, we have used Simca-P version 10.0 developed by Umetrics AB for the PLS analyses.

3. CASE STUDY

We carried out a case study with data from an existing integrated pulp and paper mill located in Northern Europe. The mill produces TMP and groundwood (GW) pulp and both uncoated and coated papers from mechanical and chemical pulps. We divided the case mill into production departments according to the division used in the energy and materials reports of the case mill. Monthly reports were available from 2005 to 2007. In addition, we selected one paper machine as a case example to explain changes in energy efficiency indices based on hourly average data collected in 2004 and 2007. Hourly averages were used to filter the effects of process delay, white noise and control system operation from the data.

3.1 Mechanical pulping

We attempted to create energy efficiency indices for GW and TMP pulp plants based on monthly reports without information on the behaviour of freeness. We found this method unreliable because the changes in freeness distorted the baseline definition. In conclusion, baselines for electricity consumption should include freeness as a variable and this requires process data. Figure 3 presents the behaviour of monthly specific electricity consumption in two mechanical pulp plants over five years. The curves show short-term variation due to freeness and long-term changes due to energy conservation investments and quality requirements.

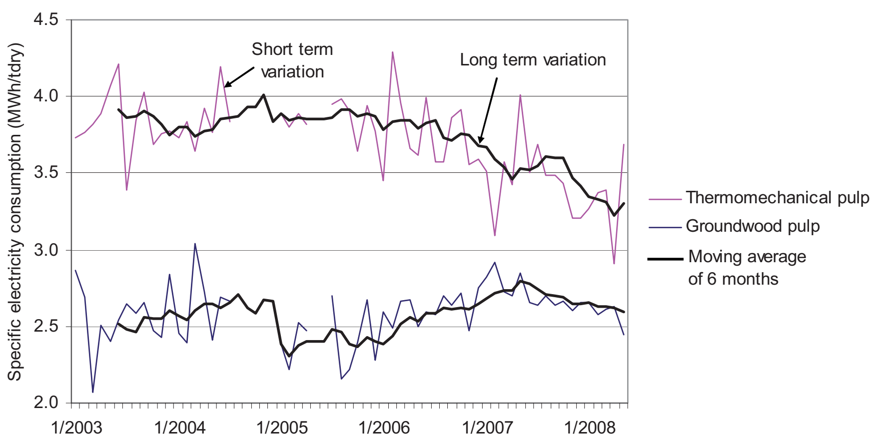

Figure 3. Moving averages of specific electricity consumption of two mechanical pulp plants

3.2 Paper machines

We determined the baseline for electricity consumption in the case paper machine according to monthly electricity consumption, operation times and gross production in 2005. For heat consumption we selected 2004 process data as hourly averages for the baseline. We transformed the production rate in reel to a gross production rate and removed the effect of machine hall ventilation from the total heat consumption. The correlations are presented in Figure 4. The standard deviation in heat consumption was +/-1.8 MW equal to +/-4 % standard deviation in the values of energy efficiency indices. Consequently, the deviation does not significantly affect the energy efficiency indices.

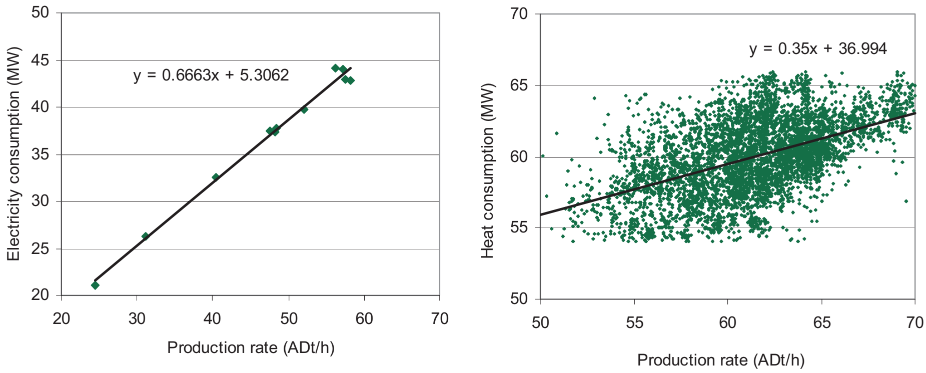

Figure 4. Correlations between energy consumption and the production rate in the case paper machine

Figure 5 presents the calculated energy efficiency indices. The shape of specific heat consumption (SEC_h) is different from the energy efficiency index for heat consumption (EEI_h) due to SEC_h being dependent on the production rate. The production rates for EEI_h are calculated based on reported monthly production divided by operation time. Figure 5 reveals that the energy efficiency indices are dependent on seasonal changes. The heat consumption in winter has been up to 50 % higher than the baseline, indicating a major potential for heat integration.

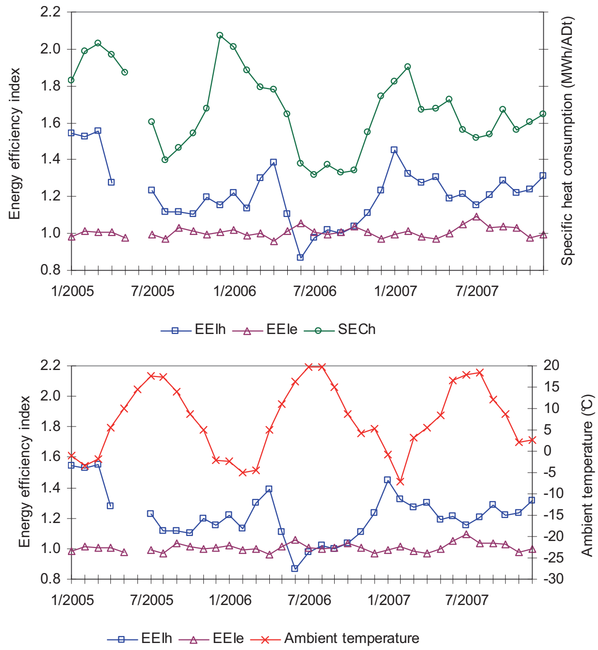

Figure 5. Monthly energy efficiency indices of the case paper machine

In the following we explain the reasons for the decrease of energy efficiency in heating 2007 compared to the 2004 baseline with PLS. Table 1 shows the variables used in the PLS model to describe the production rate, produced paper grades and the temperatures of incoming water and ambient air.

Table 1. Variables in the PLS analysis of the case paper machine

Symbol		Unit	Variable
Ambient temp	X	°C	Ambient temperature
Water temp	X	°C	Temperature of preheated chemically purified water from TMP plant
Grammage base	X	g/m2	Grammage of base paper
Reel speed	X	m/min	Reel speed
Grammage reel	X	g/m2	Grammage in reel
Water flow	X	kg/s	Flow rate of chemically purified water from TMP plant
Chpulp f	X	kg/s	Flow rate of chemical pulp
Water_ch f	X	kg/s	Flow rate of chemically purified water from water preparation
Mpulp f	X	kg/s	Flow rate of mechanical pulp
Mpulp cs	X	%	Consistency of mechanical pulp
Chpulp cs	X	%	Consistency of chemical pulp
Ash base cs	X	%	Ash content of base paper
Steam box	Y	MW	Steam box
Supply air	Y	MW	Supply air heating
Dryer section	Y	MW	Drying cylinders
Shower water	Y	MW	Shower water
AHR	Y	MW	Machine hall ventilation

This PLS model explains 88 % of the variation of response variables in 2004, breaks and shutdowns included. We predicted the heat consumption in 2007 with the 2004 PLS model using 2007 data as input. The actual heat consumption compared to modelled values revealed a significant increase in the heat consumption of the dryer section and the shower water. To analyse the magnitude of this change during normal operation, we removed breaks and shutdowns from the PLS model and compared only the operation time data presented in Figure 6. The explanation rate for the operation time with the 2004 PLS model is 75 %. The results indicate an increase of over 10-20 % in dryer section steam demand compared to the expected value. Direct comparison with SEC_h in the dryer section as a function of the production rate confirmed these findings.

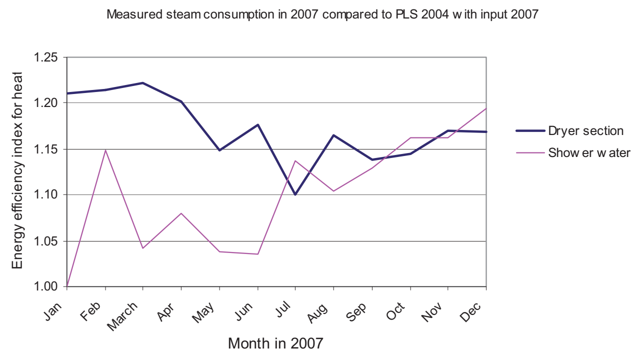

Figure 6. Operation time energy efficiency indices for heat consumption in the dryer section and shower water heating in 2007 using the 2004 PLS model as the baseline

A comparison of the PLS models for 2004 and 2007 in Figure 7 reveals that the increase in dryer section heat consumption is linked to the flow rate of mechanical pulp and the basis weight of the base paper, which have become dominating predictors in 2007. These reveal a shift in the produced paper grades and the operating conditions of the dryer section.

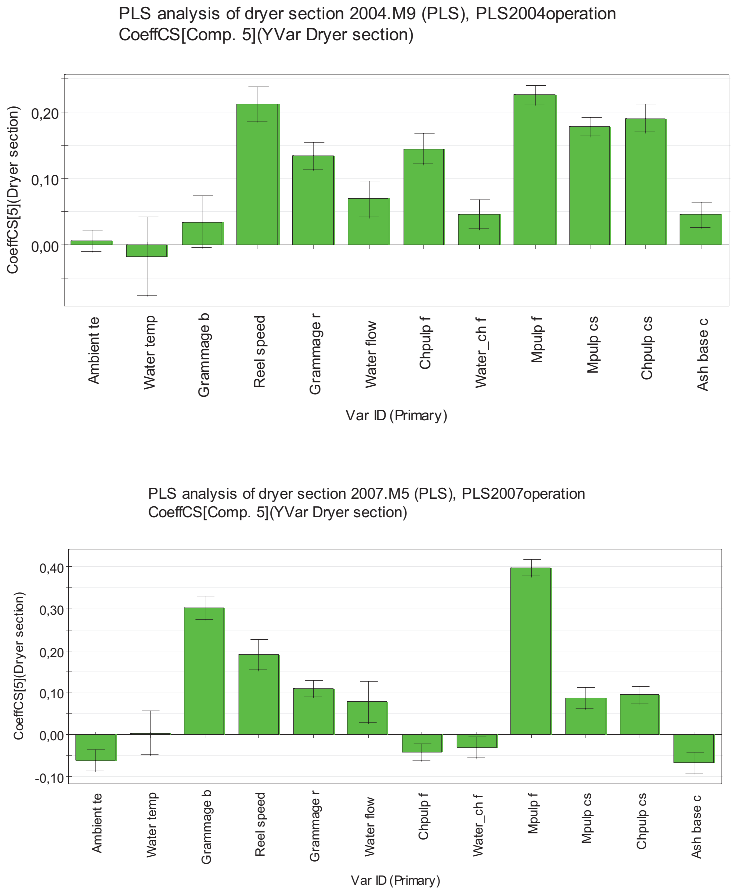

Figure 7. Scaled predictor coefficients in 2004 and 2007 PLS models for the paper machine dryer section during normal operation

3.3 Aggregated energy efficiency index

As an example of aggregated indices, Figure 8 presents the electricity consumption of four paper machines. Each production line has a different weight in the aggregated index because of differences in individual baselines. For example, the aggregated energy efficiency declined in 2007 because of four consecutive peaks in the EEI_e of three different paper machines. This highlights the necessity to break down aggregated information to explain the reasons for changes.

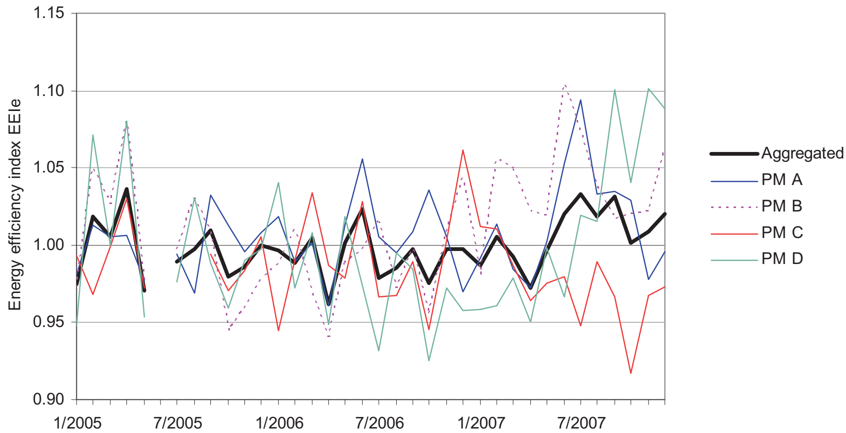

Figure 8. Aggregated energy efficiency index of electricity consumption for paper machines

4. DISCUSSIONS

The purpose of process monitoring is to quantify performance and to detect positive and negative changes in a process, thereby enabling appropriate corrective actions. Until now the possibilities to monitor process energy efficiency in industrial sites have been scarce. The role of the energy efficiency index is to provide information explanatory to SEC. The energy efficiency index is able to detect true changes in SEC that are not solely caused by changes in the production rate. This enables the discovery of potential for energy conservation, for example, by revealing the seasonal behaviour of heat consumption.

By definition, the energy efficiency index is suitable only for analyses of the process in question, not for benchmarking. The drawbacks of the energy efficiency index are its subjective nature and the lack of information on how to establish the baseline equations. Standardized methods and definitions should be developed for each branch of the process industry. We found that the operation time and the production rate are not the only important process variables that need to be included in the baseline equations. For example, processes may have cyclic behaviour, as in mechanical pulping with CSF. The effect of these intrinsic process variables must be taken into account in the baselines.

When determining appropriate time scales to be used for baseline definition, we found process data transformed into hourly averages to be the best information source. Monthly reports on energy consumption, production and operation time provided enough information only for the baselines of electricity consumption in paper machines.

How far an analysis can go to explain the behaviour of energy efficiency indices depends ultimately on the availability of information. In the case study the amount of available data varied significantly between production lines. However, this limited mainly the opportunity to explain the reasons for changes in energy efficiency. Process measurements necessary to construct the energy efficiency indices were already available, including direct process measurements of the production rate and energy consumption. We found PLS useful in explaining the behaviour of the indices. Information on investments and other changes to the processes should be made available for personnel responsible for analysing energy efficiency.

Modern automation systems enable access to data exploration, which is an opportunity not yet fully exploited in energy efficiency monitoring at the process level. The major obstacle today is the lack of properly defined methodologies and energy efficiency indicators which would enable the process data to be critically analysed.

5. CONCLUSIONS

Energy efficiency indicators can be used for process energy efficiency monitoring in industry provided that reference baselines for the process energy consumption are accurately defined. The baselines have to include all intrinsic process variables that affect process-specific energy consumption during operation. In the pulp and paper industry, these are the production rate, operation time and product quality.

We conclude our paper in the realisation that it is important for the improvement of process energy efficiency not only to be able to detect changes but also to explain the underlying reasons for changes. Energy efficiency monitoring should quantify objectives reached and define objectives to be reached with guidance to the right measures to improve energy efficiency. To meet these objectives, we need to initiate more research in the field of energy efficiency monitoring in industry.

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