Challenges of Energy Management in Industry

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Abstract

Energy Management is vital to reducing industry energy costs, which improves viability of enterprises and enables the fulfilment of energy/CO_2 reduction targets. Knowledge of energy use is paramount, however often expensive sub-metering is not in the correct location as time of machine operation and profile of energy use is not understood. Subsequently understanding and correcting this data error is difficult to perform in an environment where production cannot be interrupted.

The challenges of data collection and management are addressed through the development of production models and machine profiles that build up a picture of factory operations based on existing data. A two-dimensional picture of factory line operations using machine profiles utilises the real data from sub-meters as a validation mechanism with the completed process model utilised as an indication of arising production inefficiencies. This work outlines the developments in this approach.

Keywords: Energy Management, Production, Modelling, Machine Profiles

1. Introduction

On a global basis, industry accounts for almost a quarter of all jobs and it is therefore important for employment and wealth creation. However the industrial sector places pressure on the environment; it consumes renewable and non-renewable materials, energy and water, and produces solid, liquid and gaseous wastes and in Europe, industry accounts for a quarter of energy end consumption. (1,2).

Energy Management is a systematic approach for energy conservation efforts within an organisation and it widely acknowledged that energy management is a vital component in reducing industry energy costs which in turn improves viability of enterprises and assists in the fulfilment of wider energy reduction/CO_2 reduction targets.

Previous works have suggested that although energy efficiency will be an important competitive factor in the near future, in some instances, especially in energy intensive industries, it is not given a high enough priority, (3,4). Some barriers to energy efficiency in industry have been listed in (4) and can be summarised as cost and risk of production disruptions, a lack of access to funding and a lack of sub-metering. A requirement of effective energy management is the accurate quantification of energy use (5).

For manufacturing sites, there are two levels of energy consumption analysis; plant and process. High level services such as heating, lighting and ventilation, i.e. the services that control the production and environment conditions are at plant level. The process level is concerned with the energy consumption of the machines and equipment used to process materials (6).

In the embedded product energy framework presented in (6), energy is split into direct and indirect energy. The indirect energy includes the high level plant services.

The direct energy is the process energy and is split into two subgroups; theoretical and auxiliary energy. Theoretical energy is defined as the minimum amount of energy required to carry out the process. Auxiliary energy is the energy that the supporting equipment consumes and it includes the energy consumed by production equipment in non-production states. In this work, the direct energy will be determined via the use of a power study to acquire machine power profiles. Therefore it is the measured energy consumption used to process a manufactured component or a batch of such components and will now be referred to as value added energy, i.e. it is the energy that adds value to the product.

The energy consumption of production machines fluctuates over time with the changing machine states as noted by data logger power profiles. Generally energy profiles can be subdivided into fixed and variable energy consumption. The fixed consumption can be considered as auxiliary energy in non-production states and as process energy in the process state. The variable energy consumption of a production machine encompasses the required energy for tool handling, positioning and the actual operation (7).

It has been contended that energy metering and sub-metering is required to quantify current energy consumption, provide energy transparency within a facility, and provide a broad quantitative perspective on day to day consumption and also to fully support the potential smart grid pricing infrastructure (5). However energy monitoring systems are usually installed to quantify the proportion of energy relative to the entire energy consumption that a particular value stream consumes or to facilitate understanding of energy loads on particular circuits to prevent overloading. Thus secondary energy sub-metering is often not in the correct location as time of machine operation and profile of energy use (relationship between standby and machine under load operation) is not understood. For those sub meters that monitor an individual machine, the resolution of the data collection is often too low e.g. around 15 minutes to determine the machine profile and the identification of machining stages, (idle, machining, unloading etc.). Low resolution measurements or small sampling rates only gather basic information such as average, minimum and maximum power values. To identify transient events that occur in very short time periods, high resolution data is required (5). Some of the issues with respect to data collection have been discussed in (8) noting that the data needs to be appropriate to the modelling in terms of what is actually collected and its granularity.

The subsequent understanding and correction of the data error is difficult to perform in an environment where production cannot be interrupted for output, technical or cost reasons. The utilisation of rated power on each machine will over-estimate the electricity consumed per machine as installed power is never fully exploited because the mean power is less than half the power available at a rate of 60% of the total time spent actually machining (9).

This paper addresses the challenges of data collection and management through the development of production models and machine profiles that build up a picture of factory operations based on existing data where appropriate. A two-dimensional picture of factory line operations using the machine profiles utilises the real data from sub-meters as a validation mechanism with the completed process model being utilised to give an indication of arising inefficiencies in production.

2. Challenges with Data

Figure 1 shows a day’s data from an energy monitoring system of a milling machine. The resolution is 15 minutes, fundamentally, the energy consumption over 15 minutes is summed and logged and the clock resets to zero. Although the data allows for allocation of energy costs, the information it provides is not sufficient in order to attain the machine profile to understand the energy relationship between different machine states.

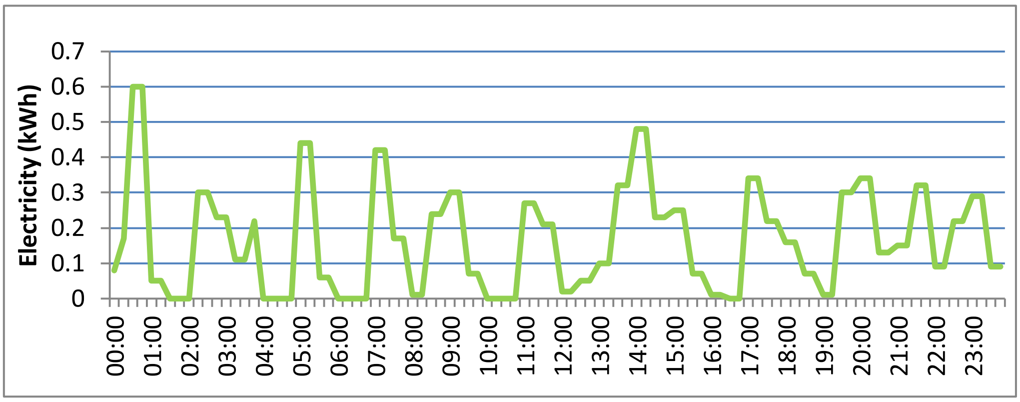

Figure 1: Energy Data for a Mill Machine with a 15min Resolution

The monitoring of production machines at a one second resolution would produce over 86,000 data entries per machine per day and thus would be unrealistic from a data management perspective. Furthermore it may be quite unnecessary due to the repeating pattern of demand for machines producing the same component. Developed software tools such as life cycle assessment software, are often not available, not representative of the situations faced by manufactures, due to non-site specific models, or are based on unrealistic assumptions. Therefore it is prudent to use life cycle analysis with other analytical tools to fully explore environmental and economic impacts of manufacturing (1,10). A power study of each machine within a production line of a product, using a portable power meter, will provide the machine profile and enable its analysis. Promotion of the use of portable equipment due to the repeating cycles of manufacturing equipment to avoid the high costs of permanent equipment is found in (8,11).

3. Process Description

A typical value stream within a manufacturing facility consists of a range of processes that induce material change. A batch enters the value stream and follows the sequence of machining operations for the product. Figure 2 shows a value stream, at each machine stage the energy, both direct and indirect, is required to process the batch. At each stage a number wastes are also produced.

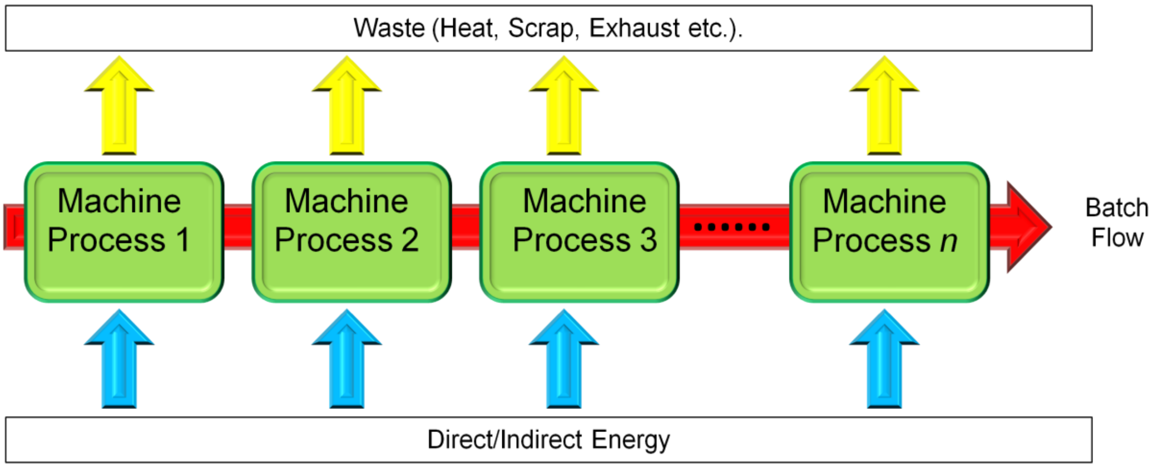

Figure 2: Product Value Stream

4. Eclipse

Following the modelling of the selected manufacturing process and the identification of machine energy profiles, a simulation package called ECLIPSE developed by the University of Ulster, as shown in Figure 3, is used to simulate the working process to provide a consistent basis for energy performance evaluation and comparison. The Eclipse simulation tool was originally developed to technically and economically model large scale power stations and chemical processes. Its development has since evolved to portray numerous technical processes. ECLIPSEi is the latest development, which is concerned with industrial processes in value streams, with both batch and continuous product flow. ECLIPSEi is a personal-computer-based package containing all of the program modules necessary to complete rapid and reliable step-by-step technical, environmental and economic evaluations of chemical and allied processes. ECLIPSEi uses generic engineering equations for power plant and manufacturing cycle analysis. A techno-economic assessment study is carried out in stages; initially a process flow diagram is prepared, technical design data can then be added and a mass and energy balance completed. Consequently, the system's technical impact is assessed, capital and operating costs are estimated and an economic analysis performed.

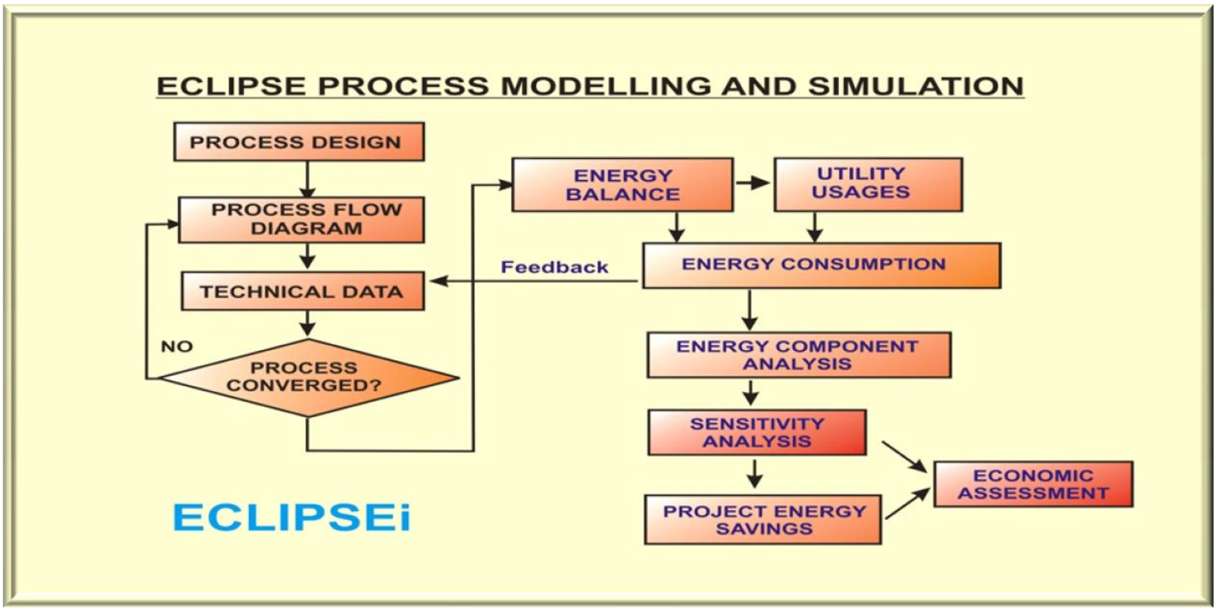

Figure 3: Eclipse Architecture

5. Methodology

A Fluke1735 energy meter, along with voltage clips and current transducers is used to measure the power consumption for each machine. The measured power is then used to construct power profiles from which the energy consumption can be determined and used to populate the ECLIPSEi model to simulate the product line. During the power study the energy consumed by supporting services such as compressed air and cooling pumps, is estimated to determine the indirect energy at each machine stage this is then added to the auxiliary energy consumed during the idle machine stage.
Figure 4 shows the analysis of a machine profile, were the power is plotted against time. The area under the power curve is the energy consumption, Equation 1. The characterisation of the energy consumption is detailed in Equation 2 to Equation 5. The value added energy is the sum of the fixed and variable energy and is the area under the power/time curve when the machine is processing, thus it’s processing stage. It includes part handling, start up from idle, processing and unloading, Equation 2. The fixed proportion of the value added energy is the energy that equates to the energy that is required regardless of machine state; ready/operating, Equation 3. Thus when the machine is not processing a part the fixed energy is termed the auxiliary energy, Equation 5. The auxiliary energy is the energy used by the machine when it is not machining, Equation 4. When the machine is in an idle state the fixed energy is termed auxiliary; it is not value adding.

Equation 1

$$\text{Energy Consumption} = \int_{a}^{d} P(t)dt$$

Equation 2

$$\text{Value Added Energy} = \int_{b}^{c} P(t)dt$$

Equation 3

$$\text{Fixed Energy} = \int_{b}^{c} f(t)dt$$

Equation 4

$$\text{Variable Energy} = \int_{b}^{c} P(t)dt - f(t)dt$$

Equation 5

$$\text{Auxiliary Energy} = \int_{a}^{b} P(t)dt + \int_{c}^{d} P(t)dt$$

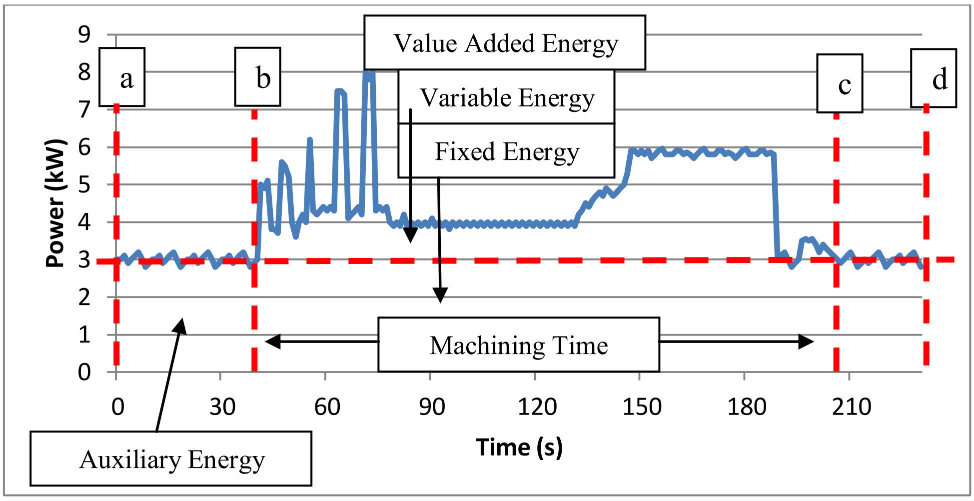

Figure 4: Machine Profile Analysis

Multiplying the number of products/batches that a machine processes in a fixed period of time by the area under the curve between the start and end of operation, the value added energy (fixed and variable) consumed during production is known. The amount of time that it takes to process a part/batch is the machine time and multiplying this by the number of batches processed within a fixed period of time e.g. a day, equates to the production time and hence the non-production/standby time for the studied period of time is also known. Multiplying the standby power consumption by the standby time will allow for the energy consumption to maintain machines in non-production stages. If the planned production schedules are known, an estimation of the energy expenditure can be made. Data for the same time period from the value stream sub-meter is then compared to the energy consumption estimated by ECLIPSEi.

6. Results

For the purpose of this study to predict energy consumption in the selected industrial process, a value stream with three machine processes is considered and three different cases have been examined:

Case study one - The “ideal working” case considers the process without any operation delay caused by the bottle-neck problem. The modelling assumes that the process capacity has little impact on energy consumption in the process.
Case study two - The “practical working” case takes into account a limited capacity determined by the working batch size of the machine, operational times and cycles of the process.
Case study 3 - The “capacity expanding” case adds new capacity in the congested location to ease production delays.

Figure 5, Figure 6 and Figure 7 show the power profiles per component for three different machines. In the discreet interval process, the time between a batch being unloaded and the next batch being loaded varies for a number of reasons; speed of operator, break schedules, maintenance, bottlenecks and production schedules, to name a few. Although this variable is not key for the steady state simulation, and hence the current work, it will be a vital parameter for dynamic modelling.

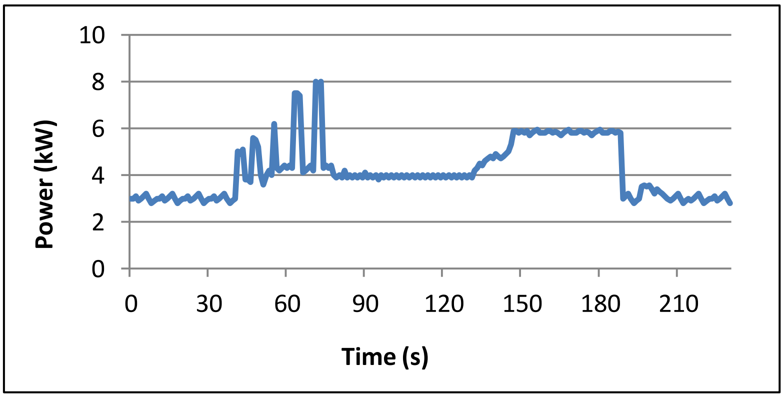

Figure 5: Machine Process 1

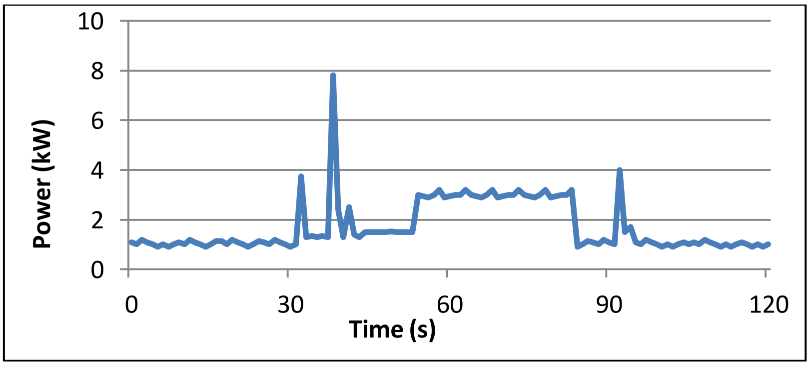

Figure 6: Machine Process 2

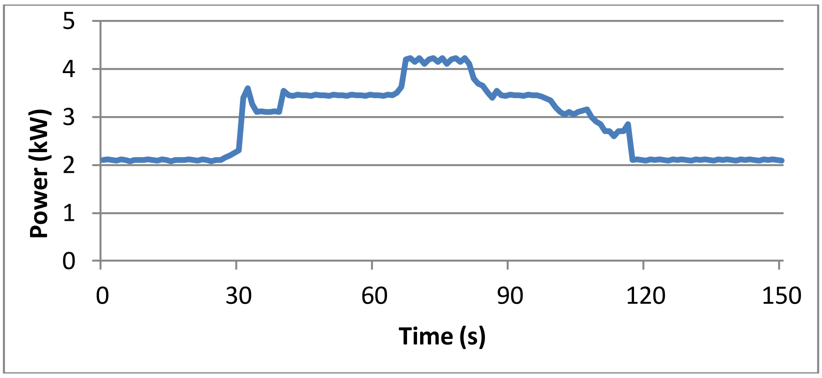

Figure 7: Machine Process 3

The energy and time information extracted from the power profiles is then used to simulate the value stream in ECLIPSEi. Table 1, Table 2 and Table 3 details the results for each of the case studies.

Scenario one				
	Machine 1	**Machine 2**	**Machine 3**	**Total**
Parts/Batch	20	19	19	
Cycle time, seconds/part	165	67	92	
Idle period, %	0	0	0	
Rework	0	1	1	
Fixed energy, kWh/batch	2.90	0.38	0.94	
Variable energy, kWh/batch	1.53	0.48	0.66	
Direct energy, kWh/batch	4.43	0.86	1.60	6.9
Percentage of Fixed Energy, %	65	44	60	
Indirect energy consumption, kWh/batch	7.70	5.14	1.80	14.64
Total energy consumption, kWh/batch	12.13	6.00	3.40	21.53
Overall energy consumption, kWh/part	0.61	0.32	0.18	1.10

Table 1: Case study one

Scenario two				
	Machine 1	**Machine 2**	**Machine 3**	**Total**
Parts/Batch	20	19	19	
Cycle time, seconds/part	165	67	92	
Idle period, %	0	61	47	
Rework	0	1	1	
Fixed energy, kWh/batch	2.90	0.95	1.87	
Variable energy, kWh/batch	1.53	0.55	0.70	
Direct energy, kWh/batch	4.43	1.50	2.56	8.5
Percentage of Fixed Energy, %	65	63	73	
Indirect energy consumption, kWh/batch	7.70	5.14	1.80	14.6
Total energy consumption, kWh/batch	12.1	6.6	4.4	23.1
Overall energy consumption, kWh/part	0.61	0.35	0.23	1.19

Table 2: Case study two

Scenario three				
	Machine 1 x 2	**Machine 2**	**Machine 3**	**Total**
Parts/Batch	40	38	38	
Cycle time, seconds/part	165	67	92	
Idle period, %	0	25	0	
Rework	0	2	2	
Fixed energy, kWh/batch	5.80	0.95	1.97	
Variable energy, kWh/batch	3.06	1.03	1.33	
Direct energy, kWh/batch	8.86	1.98	3.30	14.1
Percentage of Fixed Energy, %	65	48	60	
Indirect energy consumption, kWh/batch	15.40	8.88	2.21	26.5
Total energy consumption, kWh/batch	24.3	10.9	5.5	40.6
Overall energy consumption, kWh/part	0.61	0.29	0.15	1.04

Table 3: Case study three

By adding additional capacity in case study three, Table 3, the bottleneck due to the cycle time of Machine 1, is removed and therefore the idle time for machine 2 and 3 is also reduced. The added capacity not only increases production but reduces the embedded energy per product. In each case, the power profile of the machines has remained constant. It is the capacity and the production schedule that has been altered. Increasing the capacity with a machine higher efficiency will change the power profile and thus reduce the value added energy consumption. However in this work, idle time has been reduced and the energy consumption per part has decreased.

7. Discussion and Conclusions

Machine level energy monitoring at an appropriate resolution is expensive and for an entire manufacturing facility may cause issues for data handling due to the sheer quantity of data. Machine ratings plates will over estimate energy consumption as the majority of the time the power consumption is much less than the rated power. Without simulation and modelling it would be difficult to determine which configuration would result in a lower embedded energy product. By performing standard steady state and dynamic simulations the identification of potential energy consumption reductions and the determination of the margins for energy saving are quickly ascertained.
The higher the quality of the input data, the higher the quality of the modelling results. Using the power profiles garnered from the power study and the assumption of a repeating power pattern for each process stage for the same product increases confidence in the simulated results, as the energy data directly relates to the process under study.

Due to the ECIPSEi simulation tool considering the value stream as process stages, with the technical data at each stage being populated by directly measured data as a decision support mechanism. It is relatively easy to test different case studies to optimise production schedules with respect to energy consumption.

Currently the steady state modeling and simulation results are predicted by using mean energy profiles of individual machines regardless of certain time intervals. To illustrate dynamic energy consumption in the whole manufacturing process it is necessary to implement the dynamic modelling and simulation in terms of time dependent changes. The next steps are to consider the economics for each case, considering the capital cost of additional capacity and the operating savings achieved by the reduction in embedded energy.

8. Acknowledgements

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