Modelling energy consumption in a manufacturing plant using productivity KPIs

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Abstract
Energy efficiency initiatives in industrial plants are often focused on getting energy-consuming utilities and devices to operate more efficiently, or on conserving energy. While such device-oriented energy efficiency measures can achieve considerable savings, greater energy efficiency improvement may be achieved by improving the overall productivity and quality of manufacturing processes. The paper highlights the observed relationship between productivity and energy efficiency using aggregated data on unit consumption and production index data for Irish industry.

Past studies have developed simple top-down models of final energy consumption in manufacturing plants using energy consumption and production output figures, but these models do not help identify opportunities for energy savings that could achieved through increased productivity. This paper proposes an improved and innovative method of modelling plant final energy demand that introduces standard productivity Key Performance Indicators (KPIs) into the model.

The model demonstrates the relationship between energy consumption and productivity, and uses standard productivity metrics to identify the areas of manufacturing activity that offer the most potential for improved energy efficiency. The model provides a means of comparing the effect of device-oriented energy efficiency measures with the potential for improved energy efficiency through increased productivity.

Introduction
Many of the actions undertaken to improve the energy efficiency of a manufacturing company are aimed at getting energy-consuming devices to operate more efficiently or at conserving energy within a plant. Such actions could include, for instance, optimising boiler efficiency, installing energy-efficient equipment, retrofitting fixed-speed motors with variable speed drives, or improving insulation in plant and buildings. While these device-oriented energy efficiency measures can achieve considerable savings, greater energy savings may be achieved in many instances by improving the efficiency of manufacturing processes.

The simplest and most valuable measure of energy efficiency achievements in a manufacturing plant is unit consumption, or energy used per unit produced. Unit consumption provides the best indicator of how effectively the energy consumed by a plant is being put to use, and can be tracked over time to measure energy efficiency improvements. If we define *energy used per unit produced* as a measure of energy efficiency in a manufacturing plant, then there are two complementary approaches to increasing the energy efficiency of a plant: reducing energy consumption, and increasing productivity. Factors that reduce the productivity of a plant also reduce its energy efficiency. The greatest source of energy waste in any manufacturing plant could be an inefficient manufacturing process, a poorly planned production schedule, or poor product quality. An energy management policy that focuses only on improving the energy efficiency of energy-consuming devices or on energy conservation will not recognise or address these problems and will therefore have limited success. An effective energy management system should also incorporate energy sav-

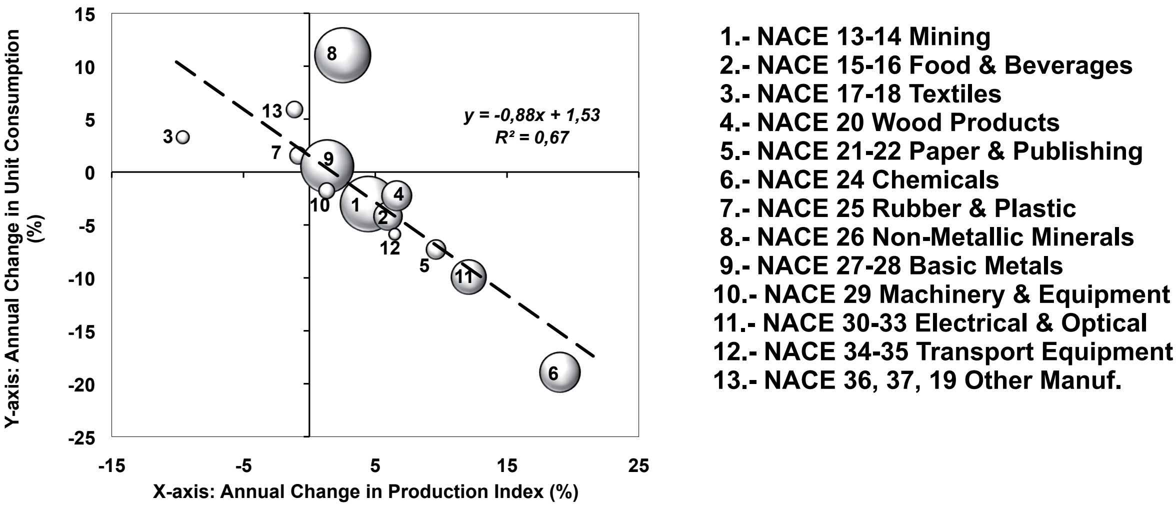

Figure 1: Relationship between production output and energy efficiency improvements – Irish industry 1995-2005

ings opportunities that can be realised by improving the overall production efficiency of a plant.

This paper proposes a simple method of modelling energy demand in a manufacturing plant using standard manufacturing Key Performance Indicators (KPIs). The model will help relate energy efficiency to productivity, and existing productivity metrics will help identify the areas of production activity that offer the most potential for improved energy efficiency. Other models incorporate productivity-related variables, but productivity is typically measured in terms of production output. If energy efficiency can be improved through increased productivity, these models give little indication of how the improved productivity could be achieved. Bieler et al (2003) use a simple linear model to relate energy consumption to production output. Carbon Trust (2008) explain how such a straight line model, using either production output or degree days as a driving variable, can be used to perform a CUSUM sequential analysis of change from expected consumption, to track energy performance over time. Kissock & Eger (2008) develop a model that disaggregates energy savings into production-dependent and weather-dependent savings, as well as production and weather-independent savings. Again, a simple quantity of production is used in the model. Boyd et al (2002) develop a model that uses the Malmquist productivity index to establish the relationship between productivity changes and changes in pollution. With this method, productivity changes can be disaggregated into technical and efficiency changes. However, at a plant level, this approach provides little information about opportunities for productivity improvement.

This paper introduces commonly used productivity metrics, and proposes that these existing methods of measuring the productivity of a manufacturing process can be applied to plant energy model to better understand energy consumption patterns and to identify productivity-related opportunities for improving energy efficiency.

Industry-wide relationship between productivity and energy efficiency

Using aggregated national statistics for industrial output and energy use, it can be shown that a relationship exists between productivity and industrial energy efficiency, measured as energy used per unit of production. Furthermore, the strength of the relationship can be determined and the rate at which energy efficiency improves relative to improvements in productivity can be quantified. This can provide a useful benchmark for individual companies to help them to determine the levels of energy efficiency that can be achieved in their manufacturing operations if productivity is improved.

Using indexed production output data for Ireland, published by the Central Statistics Office (2006), and energy consumption data provided by Sustainable Energy Ireland (2008), Ireland's national energy agency, an aggregate unit consumption value can be calculated for each of 13 NACE-coded sub-sectors that make up Irish manufacturing industry. To determine the relationship between productivity and energy efficiency at national level, the historical unit consumption values are calculated over the period of eleven years between 1995 and 2005 and the average annual change is determined. On a scatter plot, shown in *Figure 1*, the average annual change in production output for each of the 13 sub-sectors is plotted against the corresponding value for rate of change of unit consumption.

Generally, those industrial branches that demonstrate increased energy efficiency over the period also improved their production output over the same period, while sub-sectors with declining output show deteriorating energy efficiency. To establish the relationship for the Irish industry sector as a whole, a linear regression is performed on the displayed data points. The regression shows that, on average, a minimum growth rate of 1.7% in production output is required before any improvement in energy efficiency is achieved, and that on average a 1% increase in the production index growth rate results in a 0.88% improvement in energy efficiency for the sector. Boyd & Pang (2000) suggest that this relationship between productivity and energy efficiency varies substantially, depending on the energy intensity of the sub-sector. However, the diversity of the sub-sectors analysed here and their relative proximity to the regression line would indicate that the relationship is similar for most sub-sectors, in Ireland at least. This provides a high-level view of the energy efficiency improvements that are likely to be achieved by an industrial sector that is becoming more productive.

In the following section, a model will be introduced that can be applied at an individual manufacturing plant level, to calculate the energy efficiency improvements that can be achieved through increased productivity. In contrast to the approach above and the more conventional approaches for modelling energy consumption in a factory, the proposed model will not use production output directly to model energy consumption. Instead, a productivity metric in common use in many manufacturing plants will be used as the driving variable for energy consumption.

Developing a productivity-related energy model for a manufacturing plant

UNIT CONSUMPTION

A simple top-down approach to modelling the energy efficiency of a plant requires only energy consumption data and production output data. The unit consumption value can then be calculated according to the following formula:

$$UC = EC/PO \qquad \text{(Equation 1)}$$

where *UC* is the unit consumption, i.e. a measure of the energy efficiency of a plant, *EC* is the energy consumed in a defined period and *PO* is the production output, or number of units, tonnes of product, etc., of mimimum acceptable quality produced in the same period.

Essentially, this approach treats the factory as one energy-consuming device. When calculated over time according to *Equation 1*, the unit consumption value can give some indication of improving or deteriorating energy efficiency. However, this method of modelling energy consumption at a factory level is unsatisfactory, as it doesn't reflect the complexity and interdependence of large variety of activities undertaken in the plant. Such a method provides no information about wastage or energy-saving opportunities in the plant.

A more useful calculation would differentiate between the energy consumed by the plant that is dependent on the quantity of units produced and the baseline energy consumption of the plant, i.e. energy demand of the plant that is independent of the level of production activity. Consider the following equation:

$$UC = B/PO + A \qquad \text{(Equation 2)}$$

where *UC* is the unit consumption, *PO* is the production output in the period analysed, *B* is the baseline consumption of the plant, and *A* is the amount of energy required to produce one additional unit of production output. To calculate the total energy consumed in the period, we can rearrange *Equation 2* as follows:

$$E_{tot} = A * PO + B \qquad \text{(Equation 3)}$$

where E_{tot} is the total final energy consumed by the plant during the period. The values of E_{tot} and *PO* are normally known. A typical value for *B* can be determined empirically, by measuring the power consumption of the plant at a given moment when nothing is being produced, and multiplying by the time period being measured to get an energy value. Alternatively, it can be estimated by performing a linear regression of production output data plotted against energy consumption and finding the point of intersection on the y-axis. If *B* can be determined, then a value for *A* can be resolved. In an ideal plant, variations in the unit consumption over a number of measured periods will be accounted for wholly by changes in the production output, *PO*, over the periods, i.e. the values of *A* and *B* in *Equation 2* will remain constant. In a real plant however, the values of *A* and *B* will also change over time depending on other productivity factors, on climatic conditions and on variations in the efficiency of energy-consuming systems. For the purposes of this paper we will assume the values of *A* and *B* to be constant.

MINIMUM UNIT CONSUMPTION

If the values of *A* and *B* are unchanging, then the unit consumption is at its minimum when production output is at its theoretical maximum. As actual production output divided by the theorectical production output is a measure of the overall efficiency of a manufacturing plant, a performance metric that measures this efficiency value could be used to determine the mimimum unit consumption value in *Equation 4* below

$$UC_{\min} = \eta * (B/PO + A) \qquad \text{(Equation 4)}$$

where UC_{min} is the minimum theoretical amount of energy required to produce a unit and η is the production output divided by the theoretical maximum production output. UC_{min} is the is the unit consumption value when product quality is perfect and product cycle times are at their maximum achievable. To calculate the minimum value, a means of determining η, the production efficiency, needs to be found.

OVERALL EQUIPMENT EFFECTIVENESS

Total Productive Maintenance (TPM) is a lean manufacturing programme that is aimed at maximising the productivity of manufacturing equipment. TPM, first put forward by Nakajima (1988) , incorporates Overall Equipment Effectiveness (OEE), a statistical measurement tool that determines the efficiency at which a machine or a manufacturing cell operates. OEE is calculated according to the following formula:

$$OEE = \%\ Availability * \%\ Performance * \%\ Quality \qquad \text{(Equation 5)}$$

Availability is a measure of actual running time versus planned production time. It accounts for losses due to downtime. *Performance* measures the actual number of units produced versus the theoretical maximum possible number of units that could be produced. It captures losses due to plant running at sub-optimal speeds. *Quality* measures number of units produced that meet minimum quality standards against the total number of units produced. It captures losses due to poor product or process quality, including losses due to rework. Normally, planned downtime is not included in the calculation. However, given that plants consume energy during planned downtime also, a minimisation of planned downtime will improve the overall energy efficiency. Ljungberg (1998) argues for the adding of planned downtime to the planned production time when calculating the *Availability*.

Data collection for calculation of OEE may be done manually or automatically, or a combination of both. When implementing OEE, the goal is typically to assess the impact and to address the so-called "Six Big Losses" which are the most common causes for loss of efficiency in manufacturing. They are:

- Breakdown and downtime losses caused by machine faults, unplanned maintenance and waiting times;
- Set-up losses caused by setting up of a line, retooling or product changeover;
- Minor stops caused by obstructed product flow or brief idle times;
- Reduced speed losses due to machines running below their maximum theoretical speed;
- Losses due to start-up rejects and quality losses due to production start-up;
- Production rejects and rework quality losses as part of normal production.

Each loss that occurs can be attributed to one of a number of causes. For instance, a breakdown loss could be attributed to a mechanical failure, a tooling failure, an electrical failure or a software failure. As well as being used to calculate the OEE for the production unit, this data can also be sorted to identify the most common causes for loss of efficiency, and consequently of loss of energy efficiency in the production unit, and corrective action can be taken.

FROM OVERALL EQUIPMENT EFFECTIVENESS TO OVERALL FACTORY EFFECTIVENESS

OEE is a useful tool for measuring the efficiency of a machine or production cell. However, any metric that we use to measure the energy efficiency of a complete production plant will need to take into account the complexity of manufacturing operations and the interdependence of the machines and production cells within it. For instance, a high efficiency statistic could be recorded at machine level, but the operation of the plant as a whole could be considerably less efficient. A factory-wide metric, or Overall Factory Effectiveness (OFE), is required. There is currently no standardised approach to calculating an OFE indicator. A number of methods are being developed and applied mainly in semiconductor fabrication. Some of these are presented and analysed by Oechsner et al (2003). Huang et al (2003) use OEE to develop another plant-wide metric, Overall Throughput Efficiency, (OTE). They show how *Equation 5* can be simplified to:

$$OEE = PO/PO_{\text{th}} \qquad \textit{(Equation 6)}$$

where PO_{th} is the theoretical attainable production output in the period analysed. This is applied at a factory level to get a definition for OTE, which is the ratio of total good production output from a factory to the theoretical attainable production output from the factory in a period of time. Muthiah and Huang (2007) then develop this further and propose a set of four defined manufacturing sub-systems to map out the manufacturing activities in a factory: *Series*, *Parallel*, *Assembly* and *Expansion*. Each sub-system is made up of a number of manufacturing cells for which OEE values can be calculated. They develop an equation for OTE for each sub-system, based on the OEE figures of the individual manufacturing cells that make up that sub-system. If a factory comprises a series of sub-systems, the OTE figures for the sub-systems can be combined in the equation for a *Series* sub-system to get an OFE value for the whole plant.

OFE is a measure of the production output of the whole plant and we can therefore use it instead of production output, used in *Equation 3,* to model energy consumption. The model would then be

$$E_{\text{tot}} = N * OFE + B \qquad \textit{(Equation 7)}$$

Figure 2 is a hypothetical example of a plant energy model where a weekly recorded OFE value is plotted against weekly energy consumption. A linear regression will yield the coefficients for *Equation 7*. Note that the value of *B* should be the same as the that given by *Equation 3* above, but that the slope of the line will be different.

Maximum theoretical production output can be calculated by replacing OEE with OFE in *Equation 6:*

$$PO_{\text{th}} = PO/OFE \qquad \textit{(Equation 8)}$$

The unit consumption value for any production output figure can now be calculated as follows:

$$UC = B/PO + N/PO_{\text{th}} \qquad \textit{(Equation 9)}$$

When the unit consumption is its miminum, *PO* is equivalent to PO_{th}. Therefore the lowest theoretically achievable unit consumption value is given by:

$$UC_{\min} = (B + N)\,/PO_{\text{th}} \qquad \textit{(Equation 10)}$$

This approach to modelling energy consumption in a manufacturing plant has two main advantages over the conventional approach of using production output. Firstly, it provides a mechanism for calculating the minimum theoretical unit consumption for a manufacturing plant, based on the maximum theoretical production output figure given by OEE/OFE, and thereby provides a best practice benchmark. Secondly, the minimum theoretical unit consumption can be compared to the actual unit consumption for any given period and the difference between the two can be apportioned to causes for loss of manufacturing efficiency recorded by the OEE calculation mechanism for that period. Thereby, the OEE/OFE metric will highlight the problems in production which, if they can be resolved, will offer the most potential for energy savings. Using hypothetical data, *Figure 3* shows how the difference between the actual unit consumption for a particular period and the minimum theoretical unit consumption could be attributed to the elements that are used in an OEE calculation, namely

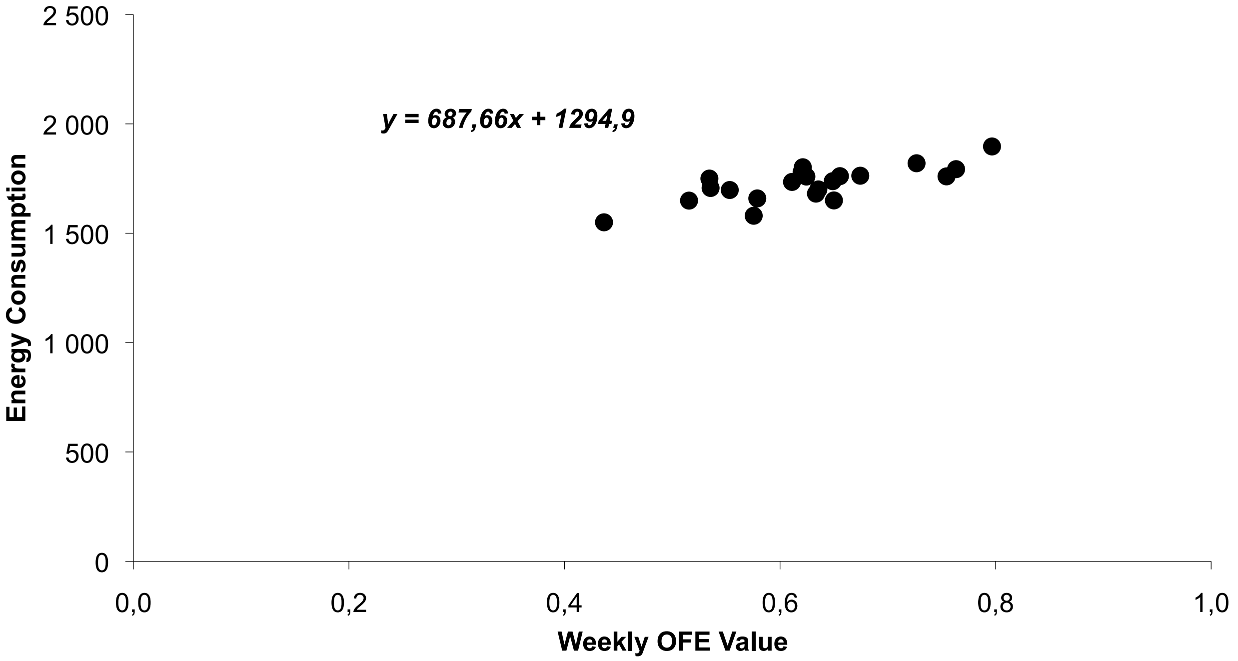

Figure 2: Plant energy model showing OFE versus energy consumption (hypothetical data source)

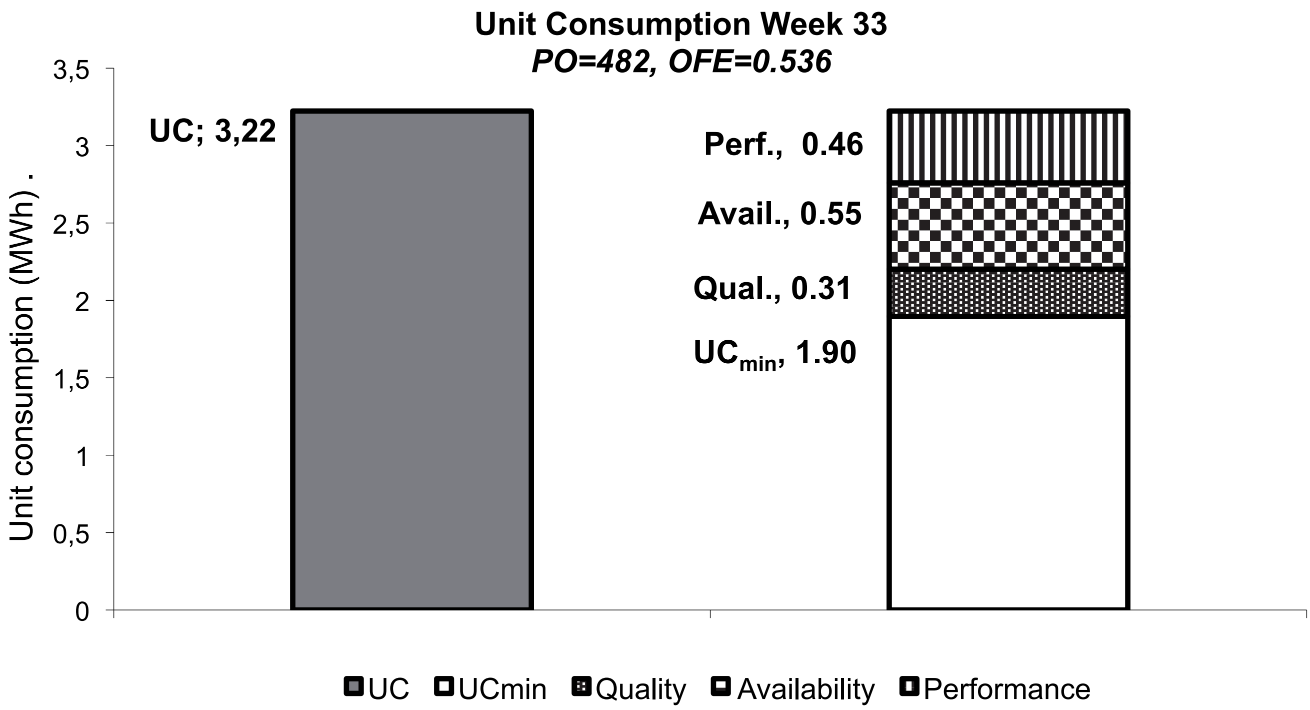

Figure 3: Using OFE to account for the difference between actual and minimum theoretical unit consumption (hypothetical data source)

Availability, *Performance* and *Quality*. With OEE, each of these elements is further broken down to specific production problems or losses. For instance, *Availability* includes losses attributed to machine breakdowns, set-up of machine or product changeover, missing paperwork, etc. Therefore, the amount of wasted energy attributable to each specific problem, or loss, can be quantified.

In the model, E_{tot} has been defined as a measure of the total final energy consumption in a plant for a particular period. In a similar manner, E_{tot} could be used to represent the consumption of a particular fuel type, such as electricity, gas or oil. The unit consumption value would then represent the amount of that particular type of energy consumed per unit produced. Similarly, E_{tot} could be applied to a particular type of energy-consuming utility. For instance, it could represent the amount of steam consumed in a period. Then the amount of steam lost due to products rejected due to poor quality, or due to a machine breakdown for example, could be calculated.

Discussion and Conclusion

A plant energy consumption model based on productivity KPIs helps us better understand the relationship between energy efficiency and production output. A model using OEE and OFE would additionally help us to identify the points in the manufacturing process that are contributing the most to a reduction of the production efficiency, and consequently of the production-related energy efficiency, of the plant. The model presented here will help explain fluctuations in unit consumption over time that were hitherto unaccounted for, and will point to the factors that lead to the variances.

Bieler et al (2003) attempted to model the energy consumption of a series of chemical batch plants using the formula in *Equation 3* above. When electricity consumption, for instance, was modelled as a function of the amount of chemicals produced per month, a linear relationship was found for some plants, while there was a poor correlation for others. The plants showing non-linear relationships were typically multipurpose batch plants, where different products and batch sizes were being produced from month to month, meaning that the level of equipment utilisation in the plants varied considerably over the period studied. A model such as that proposed in this paper, which takes into account the utilisation of equipment through a productivity metric, might help explain the poor correlation, and could potentially provide a better fit for the recorded energy consumption data. A model using OEE would identify which equipment is being under-utilised through the *Performance* statistic. Therefore, if the data had been available to model electricity usage in multipurpose batch plants using *Equation 7* instead, a linear relationship may have been observed despite the varying energy intensity of the products produced.

In some cases, a linear relationship between production output and energy consumption cannot be ascertained, due to the time lag that can exist between the input of energy into the product and the output of product from the plant. If the production process for a particular product stretches over a period of weeks, a plot of weekly production output versus weekly energy consumption is likely to be poorly correlated to the linear model. On the other hand, if weekly OFE is plotted against weekly energy consumption, then a stronger linear relationship is likely to exist, as the OFE value for any week is deterministic and represents the productivity of the plant in that week.

It should be noted that OEE/OFE is a measure of the operational efficiency of a manufacturing line or plant. It is constrained by the maximum theoretical output of that plant. The model gives a measure of the operational efficiency of the plant "as-is", and identifies opportunities for energy savings based on existing plant and procedures. However, the theoretical output of the plant could be further increased by technical changes, such as the installation of newer equipment. If such modifications are made, then the plant's energy consumption profile, represented by *Figure 2* for example, will change. Therefore, the minimum unit consumption, UC_{min}, must be recalculated based on the new configuration. The change in minimum unit consumption will give a measure of the improved theoretical energy efficiency resulting from the plant modifications.

Similarly, device-oriented energy savings measures, or measures to reduce baseload or improve energy conservation, will lead to a reduction in minimum unit consumption, UC_{min}. Therefore, the savings brought about by these measures can be quantified by measuring the drop in UC_{min}. To compare the energy savings brought about by these measures with the energy savings potential of increased productivity, one can measure the drop in UC_{min} against the difference between UC_{min} and the actual unit consumption.

While OEE is a well-established method of measuring manufacturing performance, there is no standardised approach to calculating OFE at this time. Current developments include applying the OFE metric at the factory design stage to optimise production efficiency and avoid potential bottlenecks. Similarly, the metric could be used at the design stage to model the plant's energy performance and to design a more energy-efficient plant. The model could be further refined by applying the formula to individual fuel types, such as gas, oil and electricity, or to energy consuming applications or utilities such as heating, lighting and cooling.

The model needs to be tested on a production plant for which energy consumption, production and OFE statistics are available. As the concept of an OFE is still relatively new, it's unlikely that there will be many plants that can apply the plant-wide model in its current form. However, a smaller model using OEE instead of OFE could be applied to a production line or cell. This would not capture energy losses due to inefficiencies of plant-wide manufacturing processes.

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Glossary

CUSUM	Cumulative Sum – sequential analysis technique
KPI	Key Performance Indicator
NACE	Nomenclature Generale des Activites Economiques dans I`Union Europeenne – European standard for classification of business activities
OEE	Overall Equipment Effectiveness
OFE	Overall Factory Effectiveness
OTE	Overall Throughput Effectiveness
TPM	Total Productive Maintenance

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