Tools for Energy Efficiency in Industrial Processes

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Abstract:

An important facet of sustainability is energy consumption. Simple thermodynamics states that all processes conserve energy — that is, the total amount of energy present in the world is unchanged by any particular process. What is significant, however, for sustainability is the form in which energy is embodied. A sustainable process is one that transforms the least amount of energy from high quality forms, like fuel, to low quality forms, like heat. A sustainable process is therefore an efficient one, and the evaluation of energy efficiency is ultimately a comparative exercise; to make meaningful decisions about energy efficiency the measured efficiency of a process must be compared to a benchmark. Then, once the energy efficiency of a process has been measured and benchmarked, control or design actions may be taken to improve the process. This requires that energy efficiency data is presented in a timely and apt manner to personnel, whether they are plant operators, technical management, design engineers, or financial controllers. To this end, it is important that energy efficiency data is presented from a critical perspective, that not only identifies what energy use was achieved, but also indicates why energy use occurred and how it could be used more efficiently. The final step is to ensure, via on-going monitoring, that energy efficiency gains have in fact been realised and to identify new opportunities. Using a case study in industrial refrigeration plants, this paper examines some of the technical and managerial issues that arise in measuring, benchmarking, and monitoring energy efficiency and in consequent decision making.

Introduction:

Industry is responsible for a large proportion of the energy consumed in New Zealand, after domestic transport. In 2004 industry in New Zealand consumed 168.6 PJ of energy, which was 32.7% of the national energy consumption (Hang, 2006). This represents a decrease from 35.5%, in 1995, but it is an increase in the total energy use (149.7 PJ in 1995). Of course, the output of industry also increased over this time period: New Zealand's GDP increased by 58% between 2004 and 1995. This sort of long-term growth is obviously unsustainable as finite resources like oil and coal will eventually be depleted and renewable resources like wind and hydro-power are only accessible for consumption at finite rates. To ensure that the sustainable size of the New Zealand economy is as large as possible, it is imperative that the energy use by all sectors, including industry, is used as efficiently as possible. Industrial energy efficiency is also important for meeting New Zealand's international obligations to decrease greenhouse gas emissions under the Kyoto Protocol (UNFCCC, 1997). For example, in 2003, the industrial sector directly produced only about 5% of New Zealand's greenhouse gases, but another 16% of the country's emissions were indirectly emitted via industry's consumption of energy (Ministry for the Environment, 2006).

Of course, industrial users of energy are normally businesses for whom energy efficiency might be important for economic reasons. A process that uses less energy, may cost less money to run, and therefore has the potential to make larger profits for the business. However, care has to be taken when analyzing or promoting energy efficiency via purely economic considerations. A very efficient process may be used to replace other more expensive business resources, like labour or capital, leading to economic benefit but increased total energy use by an industry due to a greater production level, which is not desirable from a sustainability point of view (Brookes, 2004)

Measuring Energy Efficiency:

There are a number of indicators used in the literature to measure energy efficiency. Essentially these reduce to theoretical thermodynamic efficiencies, and various "economic" measures of efficiency such as, energy per output (energy per tonne of butter, etc), this is sometimes called energy intensity or technical energy efficiency, energy per $ of GDP (or profit, etc), or energy cost ($) per $ of GDP (or profit, etc) (Patterson, 1996).

Thermodynamic measures of energy efficiency can be misleading as simplistic thermodynamic analysis based on energy balances alone may not account for the quality of energy (Patterson, 1996). On the other hand, thermodynamic analysis that does account for energy quality (exergy analysis, for example) may also not be appropriate in all circumstances, particularly as there are often difficulties justifying the assumptions required for the analysis with regard to real machinery (Patterson 1996; Hammond, 2004). The various economic indicators are of some use when examining large aggregates, like an entire industrial sector. For example, Farla et al (1997) compared the aggregated energy efficiency of the pulp and paper industry between eight countries; Lansink and Ondersteijn (2006) measured the trends over a period of years in energy productivity ($ of energy / $ of product) in the Dutch greenhouse flower industry; and Golove and Schipper (1997) measured the energy intensity (J / km-travelled, or tonnes of product) of various sectors in the US economy. Even when applied to aggregates these measures are not without problems, as the choice of "product" is sometime ambiguous, and those measures based on value of product ($) may, partly due to economies of scale, exaggerate changes in efficiency made while production and or profits are also increasing (Freeman et al, 1997). However, aggregate measures like this are of little use in actually doing something about energy efficiency on the factory floor. Certainly, it might be possible to calculate the energy intensity ($ of energy per tonne of product) for a single factory, or a production line within the factory, and such a strategy can help to identify plant that was performing badly when the data was gathered, but this is purely a functional, retrospective measure of energy efficiency. It is a functional measure because it just measures what energy was used, and does not seek to encourage questions about the process, about how the energy was used and why it was used in that way. It is retrospective because it is based on what was achieved not what could be achieved.

A functional measure of energy efficiency is not very helpful to a factory manager who wants to improve the efficiency of plant, or equally importantly wants to identify plant that is about to degrade and become inefficient. What a factory manager needs is a critical analysis of energy efficiency. A critical analysis of energy efficiency not only reveals what energy was used, but also answers why energy is used and how it could be used. In order to move towards a critical analysis of energy efficiency, more than just simplistic measures of energy use must be made, and the energy analyst needs to examine and measure other factors within the plant that contribute to the use of energy. For example, it is not enough to just relate energy use to the tonnes of milk processed by a factory, the operating conditions (pressures, temperatures, flow-rates, etc) of the plant equipment must also be monitored. Such a strategy was used by Wee and Stockwell (1989) to manage the energy use of three food processing plants (meat, dairy, and vegetable processing). They found that while energy could be saved, large volumes of data needed to be continuously processed and that analysis required specialist engineering knowledge. This is an important point as many industrial managers, cannot rely on the presence of suitably qualified staff. Utilities, for example, are often large consumers of energy on an industrial site, yet utilities are frequently seen as a non-core competency that can be outsourced to contractors, but those contactors, or analysts employed at energy companies, often lack the specialist knowledge needed to interpret site operating data correctly. Linden and Carlsson-Kanyama (2002) note that in the Swedish energy efficiency program education was an important factor in energy saving achievements by industrial groups. The availability of suitably qualified staff to perform such analysis is unlikely to increase in the short term as both the number of engineering graduates with relevant qualifications has declined, and more than a third of current, suitably qualified, engineers are due to retire in the next decade (Joos et al, 2004).

Generating a comparison benchmark:

Regardless of how it is measured, any thermodynamics text book will note that there is a limit to the energy efficiency of a process (Turns, 2006). That is, the energy efficiency of a process cannot be improved indefinitely. Exactly what that limit is for a particular process can be calculated by applying theoretical thermodynamics, but it is unrealistic to expect real machinery to actually achieve these efficiencies. For example, using an electrical heater to heat water from 20°C to 80°C (a First Law process) might consume about 250 kJ of electrical power per kg of water. On the other hand, a heat pump (a Second Law process) which transfers heat from a low temperature source (say at 20°C) to a high temperature sink (say at 90°C) can theoretically (according to the Carnot cycle) operate with a Coefficient of Performance (COP) of 5.2 and therefore consume only about 50 kJ of power to heat each kg of water. A real heat pump, however is unlikely to have a COP greater than 2.5 under these conditions, and so will in fact consume about 100 kJ of electrical power to heat each power. Clearly, the heat pump uses less energy than the electrical heater, but how plausible it is to improve the real heat pump performance towards the theoretical performance is usually unclear from theoretical calculations alone. Instead, determining the practical energy efficiency of a process is often best treated as a comparative exercise. The essential question is how does the efficiency of a particular existing or proposed process compare to the efficiency of a "good" or "best practice" process. That is, the energy efficiency of the process must be compared to a benchmark, or a target. The theoretical performance is a possible benchmark, but there are several other approaches that can be taken to the generating the benchmark. How the benchmark is generated has an important influence on what can be achieved with an efficiency measure.

One method is to survey similar processes, tabulate the results, and pick the best performing processes as "best practice" standards to which others must strive to achieve meet. Such an approach was used extensively by the New Zealand Dairy Board, which carried out periodic surveys of fuel and electricity use between the 1950s and 1980s. For example, researchers found that 20% of the energy used by the dairy industry in 1985 could have been saved if all dairy factories had operated at the energy efficiency of the top five (Lovell-Smith and Baldwin, 1988). Another example of this approach is a more recent survey of energy use in cool-stores in New Zealand (Werner et al, 2006). This survey found that 17% of energy consumed by the cold stores in 2004 could be saved if all storage facilities operated at best practice levels. This approach relies on a large, relatively homogenous, and co-operative industry, and is most valuable for identifying (and correcting) the worst performing processes. However, this approach offers little benefit for those processes that are already operating at or close to "best practice", as it does not reveal significant information about the potential for the best operators to improve further. This is a functional measure of energy efficiency rather than a critical measure.

Another method that can be taken to generating a benchmark is to compare the current performance of the plant to its past performance, which then allows management to set a goal — like being 10% better than last year. This approach often involves fitting regression equations between production and energy use (for example, Boyd and Pang, 2000). Despite the use of a regression equation the reliance on past data is problematic if production changes, a new product is introduced, or the product mixture changes. The regression model may also become rapidly invalid if the factory actively tries to be more efficient. For example, if the operators of a refrigeration plant lower the condenser discharge pressure to improve performance (Love and Cleland et al, 2005), then the regression model will not be useful to evaluate further changes — until enough data is accumulated to create a new regression model. Some of these issues can be mitigated by using more complex, adaptive forecasting statistics (Congdon, 2003). However, these still leave questions over how management can set a target. Why is the goal "10% better than last year" — is this the best that can be achieved, is it even achievable at all? The process of setting this target *could* be an opportunity for critical evaluation of the energy efficiency of the factory — but it seems as likely that the goal would be set arbitrarily without inviting examination of why and how energy is being used.

A third option for benchmarking energy efficiency is a performance model. This strategy feeds site operating data into models of site equipment that attempt to model what the equipment can actually achieve. Comparing the site operating data to the model allows opportunities for energy efficiency to be identified. A performance model can also be used to identify plant that is degrading in performance, and so loss of energy efficiency can be prevented by maintenance intervention. Finally, the model can be used to speculate on the effect of changes in operating procedures, or the effect of capital projects (to install alternative equipment, for example). A performance model could be the tool that management uses to generate a target for the site, as described above, rather than a regression approach. The use of performance models to evaluate energy efficiency has been an approach utilized at large manufacturing sites: this is the basis behind techniques such as "pinch analysis" (also called "process integration") and some recent published examples of these techniques include Andersson et al (2006) and Fritzon and Berntsson (2006). This approach lends itself to a critical evaluation of energy efficiency, particularly if the use of the performance model is on-going and routine. Although unfortunately performance models are often used in a special effort made for one-off audits, which decreases their utility as tools to critically examine energy efficiency.

Case Study: Industrial Water Chilling

During 2005, sixteen models of industrial chilled water utility plants at ten different manufacturing sites were prepared. The modelling strategy is described in Love and Cleland (2006), and the models were quasi-steady state in nature and based on the approach of Cleland and Cleland (1989). The models were used to compare the observed performance for a week's worth of plant operation (or when the data was available a season's worth) to what the plant could have achieved if it was operated in an optimal state, with all components operating according to the equipment manufacturer's specifications. The major performance criterion considered was the energy use of the chilled water plants, however temperature control, and capacity to respond to fluctuations in cooling demand, was also considered. Earlier, a pinch analysis project had focused on minimising the total use of cooled water, so this aspect of reducing energy use was not examined in this study. The main energy saving opportunities found are noted in Table One.

Table One: Energy savings opportunities at sixteen chilled water plants (not cumulative).

Opportunity	% Energy Saving
Discharge pressure set-point too high	6-15
Water chiller heat exchanger performing below specification	3-11
Convert chilled water storage tank to a stratified tank	16-30
Improved control strategies	15-22

It was found that almost all of the sites needed to improve their monitoring and data collection systems for the chilled water utility. Major problems included data that was either not archived or was not archived correctly (thresholds on data storage algorithms incorrectly set, for example), lack of clarity about what a particular meter measured, meters that had not been calibrated (particularly flow meters and meters that monitor loading on refrigeration compressors), and important meters that simply were not present. These problems seemed to stem from a combination of chilled water being a low priority, and the fact that the chilled water data that was collected was not routinely analysed.

The energy savings opportunities were of two types: operating changes and capital projects. The major operating change that was identified was that the discharge pressure of the refrigeration compressors was invariably operated at too high a level. Essentially, the lower the discharge pressure the less electrical power that the compressors consume, but an upper limit is set by the ambient conditions and the physical size of the chilled water condensers: lower ambient temperatures and bigger condensers mean that the discharge pressure can be lowered. The energy consumption of the condenser fans is also important, as lower discharge pressures increase the condenser fan energy use; however, as lowering the discharge pressure saves energy use on the much larger compressor motor it is generally worthwhile to incur this energy cost. The theoretical energy saving benefit of lowering the discharge pressure is well known to refrigeration engineers (Love and Cleland et al, 2005), but it was found that the discharge pressure was deliberately operated at an elevated level by the control system. In fact, the control system was usually operating at the pressure prescribed by the design documents. The problem with this strategy is that the standard design procedure for a refrigeration system aims to produce a design that will perform the cooling duty at a high, extreme ambient temperature (ASHRAE, 2006). When ambient temperatures are lower than the design (as is typical for most of the year) there is capacity to lower the discharge pressure — that is, the control systems were programmed under the mistaken assumption that the design conditions were standard operating conditions, rather than an extreme condition. Another possible reason for operating condensers at an elevated discharge pressure is that the condensers have degraded, are no longer functioning at their design specification, and are effectively acting as if they are smaller than they really are. Such degradation can be corrected by regular cleaning of the condensers, if the degradation is due to the fouling of the condensers, which commonly occurs due to air-borne particulate matter on an industrial site. Degradation of condenser performance due to fouling occurs relatively slowly and as it becomes a problem it might not be initially noticed by an analysis of energy consumption alone. However, an on-going monitoring regime that also monitors changes in the discharge pressure and condenser fan loadings would allow a site to properly assess and identify this energy saving opportunity *before* significant energy costs were actually incurred. Condenser performance degradation can also occur due to poor installation (particularly if buildings are subsequently constructed around the chilled water plant), which should be identified as an issue in the planning of site construction.

Water chiller heat exchangers likewise commonly degrade in performance due to fouling. Again, this energy saving opportunity could have been identified, before significant energy costs were incurred, via a monitoring system that examined the performance of the heat exchangers and allowed site operators to note when performance began to degrade. It was also noted that the installed size of the chiller plate heat exchangers was quite variable in comparison to their expected duty (illustrated in Figure One). In general, the greater the chiller surface area (further to the right on Figure One) the less cost there is to operate the refrigeration plant. Some chillers had a high amount of chiller surface area per kW of cooling duty ($> 0.16\ m^2 / kW$), whereas other chillers had a less than a third as much chiller surface area (as little as 0.05 m^2 / kW) — a value of around about 0.08 m^2 / kW is typical for a "good design" (Holman, 1992). The wide discrepancy is partly due to some equipment being salvaged from other uses, but it primarily represents a decision made during plant specification to trade lower capital cost for higher operating cost. That is, a small chiller costs less to purchase, even though it has a higher life-time operating cost. This demonstrates that it is crucial to consider energy efficiency at design and specification, as decisions made by designers can restrict the energy savings opportunities during plant operation. The lowest capital cost plant is unlikely to be the best from a sustainability perspective.

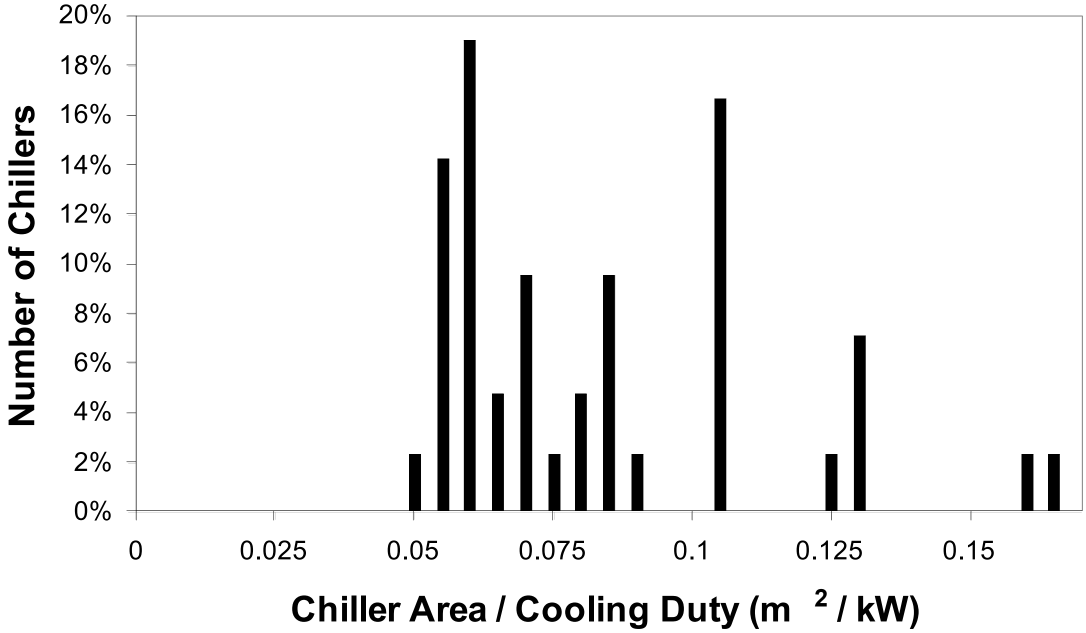

Figure One: Frequency of water chillers with a given heat exchanger area per cooling duty.

The other notable savings opportunities were capital projects that require significant site expenditure to implement. Operating chilled water storage tanks as stratified tanks allows the buffering capacity of the existing chilled water tanks to be more usefully utilized, similar to the way that a hot water tank in the home can be stratified (Nelson et al, 1999). This would act to lessen the need for the refrigeration system to operate inefficiently in a partly loaded mode, where the cooling capacity of the energised equipment greatly exceeds the required cooling duty. This capital project is mostly a re-plumbing issue, but is costly in terms of skilled labour and plant down-time.

The control strategies in the chilled water plants were also frequently inefficient. Most control systems were focussed on maintaining very tight temperature control, despite the fact that often the processes where the chilled water was used could tolerate wide swings of temperature. In addition, the control systems had time delays built into them; ostensibly, to prevent frequent starts and stops of equipment. The combination of tight temperature control and time delays often meant that chiller equipment was running inefficiently (part loaded), and yet still cycled on and off on a regular basis. On the other hand, one site had a control system that tolerated swings in chilled water temperature and therefore ran very efficiently.

Again, to identify energy efficiency opportunities it is necessary to look beyond measurement of energy use and to analyse the energy consuming process in detail. Other control issues included ensuring that the operating capacity of the chillers matched the cooling duty as close as possible. Technical modifications to improve chiller efficiency were also possible, for example, installing compressor motor variable speed drives (VSD) to reduce the part load inefficiency when part loading is unavoidable.

Once energy efficiency opportunities have been identified, they must be implemented on the site. In this study, there was often reluctance from site personnel to make operating changes (like lowering the discharge pressure set-point), particularly when the operation of the chilled water plant was controlled by a contractor. This is fundamentally an issue of education, needed to overcome institutional inertia resisting change. It also suggests that contractor maintenance contracts could be re-written so that contractors have a financial incentive to save energy on site. Capital cost measures to save energy must pass through a financial analysis process — which means that they take time considerable time to implement, and will not be implemented on a pure sustainability criteria.

An attempt was made, at one chilled water site, to implement a detailed monitoring regime, which via weekly reports could allow plant operators to clearly see the impact of operational changes. The intent of the weekly reports was to remind and educate operators about savings opportunities, and through the on-going analysis of the plant identify new savings opportunities. The reports were also intended to act as a summary to inform technical management about on-going energy use in the chilled water plant. The particular chilled water plant for this part of the study was chosen because it was relatively modern and well-monitored, but even so there were considerable difficulties in making monitored data accessible to off-site analysts in a timely manner. The issue was complicated because data was transmitted from the manufacturing site, to a data processing centre, and then to an external data centre for analysis. The use of specialist data processing facilities did allow the large amount of monitoring data to be collated, and stored competently, but the multiple handling of the data meant that several systems had to be configured, by different technical staff, whenever modifications were made to the set of monitored data. Problems with instrument calibration were also encountered, along with questions about exactly what certain instruments were measuring. Due to poorly documented modifications to the plant, it was unclear where some chilled water streams were actually used on site. Data collection, and insurance of data integrity is a crucial component of an energy monitoring system, and should be carefully planned.

While the chilled water reports were circulated, and as more data became available, incremental modifications were made to the reports. Near the end of the pilot study a focus group was held with report recipients (and plant operators at two other sites, who had not received the reports) to provide feedback on the reports and to discuss how they had been used for energy management. The focus group noted that they appreciated a concise report (each weekly report was two A4 sides), but there was a lack of clarity from the report recipients about what the energy target meant. In this case, the target was a simple regression model of the previous year's energy use as a function of several measures of production, which was chosen to show the benefit of changes (even though it would be less useful to identify new savings opportunities). In addition, several targets were displayed in the report — one for energy use, another for temperature control. This seemed to confuse the report recipients, with some operators believing temperature stability was paramount, whereas others believing that energy use was more important. The performance of some plant equipment was plotted alongside "targets" that had been set on the basis of analyst experience — however, it was found that the focus group did not agree with the analyst on what the failure to meet some performance targets meant. This highlights the importance of both site education and the requirement for the energy analyst to be technically informed about the energy using process. Finally, the focus group was split on whether providing energy use data as $ or kW h values was more informative. A participant from technical management noted that demonstrating a failure to meet a budgeted $ value could be used to critique and increase the operating budget (which may actually encourage energy *inefficiency*).

Conclusions:

A critical analysis of energy efficiency is one that allows site operators and managers to identify why energy use on an industrial site is the way it is, and how they can act to improve energy efficiency. Functional measures of energy efficiency, particularly aggregate measures of energy use against production volume, do not really provide this information. The performance of energy consuming processes must also be examined by a technically informed analyst. For on-going energy savings to be identified and maintained, this analysis must also be on-going. A case study of energy use in the industrial generation of chilled water utility, at ten manufacturing sites was examined. It was noted that the integrity of data is very important to such an analysis. Several opportunities were noted for energy savings, some involved changes to operating practices, others involved significant capital expenditure. An attempt was made to monitor on-going energy saving at one of the sites, and to provide feedback in the form of weekly reports. It was found that site education and the clarity of the monitoring report, particularly with regard to what energy targets meant, would be critical for the successful use of such a report to improve energy efficiency, and hence sustainability.

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