PEER-REVIEWED PAPER

Energy analysis of a case-study textile mill by using real-time energy data

Ali Agha & David P. Jenkins
Urban Energy Research Group
School of the Built Environment
Heriot-Watt University
Edinburgh Campus EH14 4AS
United Kingdom
+44-131-4514447
aqa1@hw.ac.uk

Keywords

energy efficiency assessment, energy demand, textile manufacturing, peak and off-peak production

Abstract

The textile industry has relatively high energy consumption compared to other small and medium industries. More energy performance studies are required to improve process energy efficiency. For any energy efficiency study, measuring the energy consumption quantitatively is the first step. This paper utilises high-resolution empirical energy data of a vertical case study textile mill to estimate its overall energy use and to find out any underlying efficiency improvement opportunities. Average seasonal load profiles have been calculated against shift patterns and weekly and annual consumption trends are investigated. Despite winters being at a time of off-peak production, heating related gas use was found to be significantly high during this period, with high specific energy consumption (SEC) per unit of production. The study identified some actionable energy saving opportunities that consisted of reducing the weekend baseline load for both electric and gas through behaviour change and simple management. Some site-specific processes and technology-based energy savings were also identified. The paper reveals how a more detailed energy analysis of a process-specific non-domestic building (such as a textile manufacturer) can provide much richer and actionable information than more standard energy audits and surveys. The key methods and techniques used in this analysis are outlined in the paper, such that they may be extrapolated to other non-domestic buildings in similar industries.

Introduction

Emerging climate change and sustainability compliance is increasing pressure on businesses to reduce their energy use. Energy efficiency is one of the most promising ways. In the case of small and medium enterprises (SMEs) in the industrial sector, there is a difficulty in studying a large number of industry-specific technologies of this diverse sector (Energy Research Partnership 2011). Therefore, most of the energy efficiency practices carried out in the sector are based on commonly shared technologies, e.g. air compressors, boilers, etc.; this can underestimate the real efficiency potential of a specific industry. Representing a heterogeneous and fragmented industry in the SME sector, textile is a less energy-intensive industry than, for example, cement, steel, chemical, etc. The industry has specific characteristics mainly due to multiphase production processes involving multiple units per phase and each having different production rates (Karacapilidis and Pappis 1997) and, therefore, distinct energy requirements. This aspect of manufacturing can have a detrimental impact on the total process energy consumption. However, textile energy studies make up a relatively small share of all industrial energy studies (Hasanbeigi and Hasanabadi 2012). More energy studies in this sector will help to identify the energy efficiency potential for the industry itself as well as for the other similar industries.

Energy efficiency in a manufacturing environment can be achieved through two aspects: 1) a system approach, which appreciates energy efficiency opportunities lying both in the supply chain side as well as on the demand side (mostly outside the scope of this study), and 2) a component or technology approach which focuses on improving energy efficiency of individual technologies. Energy management, for example, may be carried out through equipment efficiency and controls development, and through change in behaviour and energy culture. These types of energy efficiency improvements are normally made possible through "Surveys" or "Audits", which are carried out by consultants and may consist of a one-off or a continuous improvement plan. Short-term energy audits and surveys do have limitations, such as only picking up a small number of improvement opportunities based on a one-off visit, but observations based on long-term energy studies can yield better results.

A different approach is that of Operation and Maintenance (O&M), involving timely maintenance of technology which encourages consistent efficiency. This might include, for example, changing the air filters on heating and air conditioning units, repairing air and steam leaks, oiling and greasing the moving parts of the machinery. Such a programme generally contains five distinctive components: Operations, Maintenance, Engineering, Training, and Administration, collectively called "OMETA". Studies have shown these measures working effectively (Richard, n.a.). Implementation of an energy management system can involve building upon different steps consisting of energy policy, planning, implementation and operation, checking and corrective actions, and a management review. The formation of an energy management standard ISO 50001 which provides a strong organisational framework for energy management is another way of implementing it. However, for any energy efficiency study, measuring the energy consumption quantitatively is the first step (Wang 2012).

Numerous methods are used to measure and estimate this energy consumption. For example, detailed methods for end-use energy consumption estimations in non-domestic buildings have been discussed elsewhere (Field at al. 1997, Bryant and Carlson 2002). An energy audit might be based on year-long monthly utility bills or, more reliably, daily demand meter readings. However, there may be chances of inaccurate estimate billing and risk of gaps and human error is involved with manual data. Inaccuracy related to estimate billing, for example, can cause ambiguity in industrial energy studies. The use of high-resolution automatic meter reading (e.g. every half-hourly for electricity in the UK) has reduced such risks considerably and provided an often under-utilised data source. Different visualisation techniques for such short-term time-series data have been discussed in Motegi et al. (Ferreria 2009) and have various applications and limitations. For example, Wijk and Selow (1999) used calendar profiles (cluster and contour plots) to identify consumption trends and patterns on multiple time scales (days, weeks, and seasons). Daily profiles (line plots) are commonly used for time series data and can be used to verify operation schedules, identify peak hours, and base load. The technique can lead to better consumption pattern understanding if the periods to compare are correctly chosen (Stuart et al. 2007). The analysis based on these plots helped to identify building system failures and opportunities for energy saving (Ferreria 2009, Kilpatrick 2012). As communication to the end-user is of paramount importance, reflecting the findings of such studies should increase the chances of theoretical savings becoming reality.

Studies focusing on technology aspects have shown efficiency improvements in all types of industrial activities. This can be from a change in technology, (such as replacement of an old iron melting furnace with a new electric arc technology), to technology alteration (inverter drives for motors), or reduction in energy waste (controls on air and steam leaks) (Gordic et al. 2010). Optimisation studies about production systems and process control in SMEs have shown notable efficiency improvement results (Mirade et al. 2012). Several energy studies in the textile industry have addressed different aspects, such as energy efficiency in a Toray textile mill case study (Best practice programme guide 148 n.a., Palainchamy and Babu 2005), energy intensity comparisons (Hasanbeigi and Hasanabadi 2012, Ines and Martinez 2010), and energy consumed per unit of production of a spinning unit (Koc and Kaplan 2007). To disseminate the scope of energy efficiency in this sector, several industry-focused organisations have produced reports (Department of Environment 1997, Hasanbeigi 2010, United Nations Industrial Development Organisation 1992). However, the actual implementation of energy efficiency measures can lag behind the theoretical calculations due to lack of implementation method, and lack of knowledge of the measures themselves.

In this study the total energy use, both for onsite production and operations, of a textile factory is estimated. Also, the energy efficiency improvement possibilities have been assessed therefore the main objectives are;

- To identify the major technology used and the potential for energy saving.
- To assess the impact of departmental energy consumption on the total energy use.
- To determine the effect of off- and on-season production on specific energy consumption.

In the following sections a review of industrial energy, particularly within the UK textile industry, is taken. The methods used for the data analysis will also be described and site-specific energy efficiency opportunities are discussed. Also, total energy consumption, SEC, and energy trends/patterns are identified.

Industrial energy and textile case study site

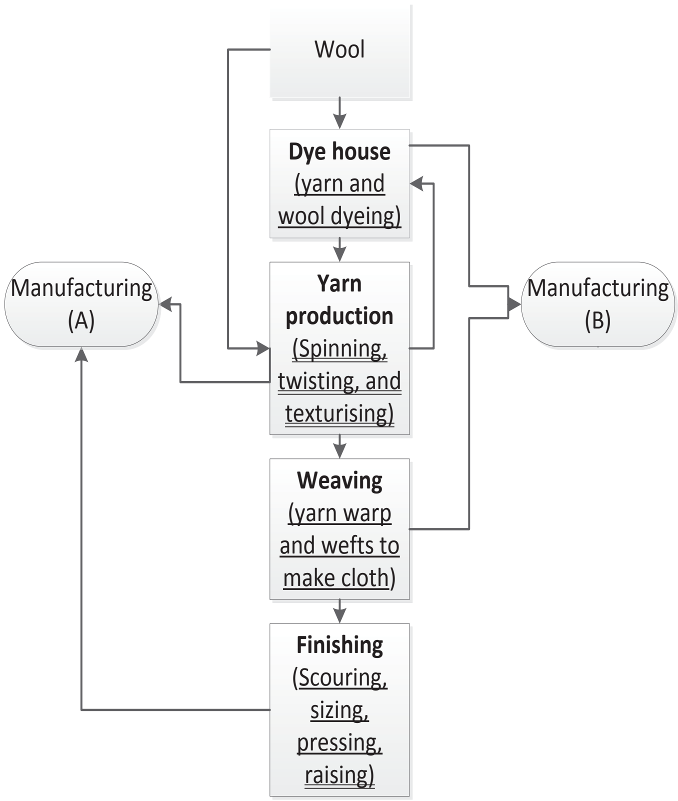
Industrial energy accounts for one-third of global energy (Greening and Roop 2007). In the UK, 57 % of industrial energy is used by more energy intensive industries i.e. iron and steel, cement, chemical, paper and pulp, etc. (Energy Research Partnership 2011). The textile industry in the UK uses 0.4 % of national energy and is responsible for 0.4 % of national greenhouse gas emissions (Allwood et al. 2006). 70 % of the industry's process energy requirement is met by low-grade, below 200 °C, thermal energy which is provided mostly by gas in the UK. However, some textile manufacturing processes, for example for synthetic fibres, use more electricity as compared to others processes.

The case-study mill is a vertical textile mill, which means it carries out all the production processes from raw material finishing to fabric producing onsite. The factory has over 45 buildings with 22,800 m^2 treated area. All production departments – Yarn production, Finishing (manufacturing "A"), Dye house, and Weaving (manufacturing "B") as shown in

Figure 1, and operations (administration) departments work alongside each other in the factory. The on-production season or "on-season" starts in March and ends in September, and off-production season or "off-season" starts in October and ends in February. In other words off-season generally represents the winter. The operations departments/sections consist of information technology office, human resources and administration offices, customer services, factory retail and coffee shops, factory warehouse and stock room. These sections work throughout the year, and the holidays are adjusted accordingly. Depending on the amount of work occurring in the production departments, shown (bold) in Figure 1, this can be completely or partially closed during the holiday periods. Some departments can also undertake night shifts and Saturday overtimes. As mentioned above, such a complicated work environment makes production processes and energy use more difficult to predict, which is also observed in the energy consumption analysis section. A generalised shift pattern is assumed and shown in Figure 3.

Depending on the nature of the fibre, e.g. cotton, synthetic, wool, production processes in the textile industry may vary, as will the energy demand and type of fuel. In this case, gas contributes towards 80 % of the total energy demand, shown in Table 1. It is worthwhile to mention that the factory is located in the north-east of Scotland, which has a significantly long and cold winter, the heating period in the factory spanning from early October through to end of May. Additionally, some of the buildings in the factory are up to 200 years old, and the factory runs a conventional steam heating system with a small number of buildings on electric heating. Figure 1 shows the process flow at the case-study mill. Each square box represents individual production department with the processes taking place within and are underlined to indicate major fuel type used.

Two main meters for electricity and gas supply energy to the whole factory, with no sub-metering around the production area in the factory. And the energy demand of individual department was estimated through profile analysis. Steam, which is produced by three conventional industrial boilers with a capacity of 3,000 kg/h. each, is the main heat carrier for both production and heating. The other main gas-based technology is a stenter frame, which consists of three large chambers in which hot air is blown to dry and set the size of the cloth in the Finishing section, which is further discussed later. Two compressed air units, 45 kW each (one of which is generally on standby), are utilised to meet the compressed air demands. The other users of electricity are mainly motors, industrial dryers, lighting, building services and small power and IT (information technology).



In brackets, single underlined text is predominantly gas based thermal energy and double underlined text is electric

Figure 1. Production process flow at the mill.

Energy technology and demand analysis

By carrying out a technology audit at the factory, major energy user technology was identified. A review of energy efficiency opportunities for both process and technology based on industry specific publications and onsite observations is discussed in the section below. Utility bills data for gas and electricity for the year 2011 were reviewed and analysed to establish baseline energy use. The individual sums obtained from these, shown in Table 1, were divided by the total production for the year to find out their share of SEC per metre of production. Time-series electricity profiles (Figure 2) were constructed which showed a rise (weekdays) and fall (weekends) in demand. Half-hourly electricity demand data was used to calculate weekday average "on-season" and "off-season" profiles against generalised weekday shift patterns as shown in Figure 3. Sections and departments with similar shift routines were identified and classified into three categories; i) Operations, ii) Manufacturing (A), and iii) Manufacturing (B) as mentioned above. A clear variation in energy consumption followed shift patterns and further analysis of these profiles confirmed increased energy demand in winter. It also quantified the expected reduction in demand during factory holidays. Through the analysis, it was also possible to find base load and manufacturing "B" demand in addition to the peak-demand. The estimated gas bills (from the energy supplier) were plotted against the manual data taken from the main gas meter and the discrepancies investigated (Figure 4). The gaps in the manual data, particularly for the weekends, were estimated by dividing the consumption with the number of days within the gap. The SEC was further reviewed on a monthly basis as shown in Figure 5.

Energy efficiency opportunities for the case study

Possible energy efficiency improvements for the factory are discussed below, with more detailed recommendations given in later sections.

BUILDING SERVICES AND IT

Lighting, heating, ventilation, and air-conditioning (HVAC), small power and IT equipment, in both the production and operations departments are significant. All the operations offices are lit, mostly, with T8 fluorescent tube lights. The production sheds use T12 8 ft. fluorescent tube lights. Replacement of these phased-out fluorescent tube lights with efficient lighting would be the most obvious recommendation. Most of the production sheds have north-facing roof lights and some buildings are only occasionally used, therefore these buildings would benefit from lighting-level controls and occupancy sensors. The HVAC in most of the buildings is controlled by a building management system (BMS). The running times and temperature settings on the system have never been changed since the installation of the system. A critical time and temperature review can help to reduce the HVAC's running cost. Also, a thorough review of the motors in the systems can highlight saving opportunities through proper sizing and other measures as discussed below. To reduce the weekend baseline load an equipment checklist for each building has been designed and is passed on to the designated members of staff to ensure everything is shutdown at the weekends. These checklists also include the canteen areas and small power and IT equipment. Numerous guidelines for the IT and building services have been published by energy efficiency focussed organisations e.g. The Carbon Trust, and US Department of Energy (DoE).

PRODUCTION PROCESS

Wet processes

These processes mainly involve dyeing in the Dye house and scouring (washing) in the Finishing area. These processes are mainly thermal and use steam. The technology used for these processes is simple consisting of large containers/vessels with closed coils for the steam flow. Programmable electronic control systems are used for water, washing chemical/dyes, cloth feeding in/out, process temperature and cloth/material dwell time control. Motors and pumps are used for pumping and agitation or some mechanical processes. The average daily demand of the water for the Dye house is 200 m^3 and roughly 30 % of this is used for dyeing process. The dyeing process in the factory, starting with water at 50 °C, achieves a maximum temperature of 98 °C and then the water is discharged without heat recovery. The daily water demand of scouring is also 200 m^3 and roughly 40 % of that is used for hot water washing at 40 °C. This hot water is also directed towards the drain without heat recovery, however water at this temperature is generally not suitable for heat recovery. Heat recovery and recycling from these processes could save significant energy and an account of heat recovery methods in thermal processes is given by (Hasanuzzaman et al. 2012). Both processes use hydro-extractors (spin dryers) equipped with heavy-duty motors, 25 kW each, for centrifugal drying. The energy efficiency opportunities for these motors can be reviewed against the options discussed below. Some microwave and infrared ovens are used for dyed raw material drying in the Dye house. Studies have shown this type of drying as reasonably efficient (Buyukakinci 2012), but a thorough study of the operation of the machines could highlight further avenues for savings. Investigations of the stenter frame have revealed some potential for improved efficiency. As discussed elsewhere (BREF 2000), optimising the exhaust air moisture, cloth dwell time, and heat recovery from the exhaust air could be explored further. Some manufacturers of these exhaust heat recovery systems claim up to a 30 % increase in efficiency. The machine also has a 55 kW burner and mechanical motors system and can offer efficiency savings through improved motors and variable speed drives. In addition to the technology side, some production process improvements are also achievable. These, according to (GPG 168), may consist of revising the dyeing and scouring programmes process times and reducing water usage to save overall energy input. Use of reactive dyes, needing lower temperatures (60 °C) for colour fixing, and the use of efficient mechanical drying, with suction slots, manglers, etc., can greatly reduce the drying energy cost on the stenters.

Other processes

These processes refer to Yarn manufacturing, Weaving, and the Finishing departments. Technologies in these departments mostly relate to rotation/vibration processes and conveyor belts, and extensively depend upon motors. This is reflected in the average power factor of the factory at 44 % for March through to July (2012), which is also subject to improvement. These machines are automated and programmed through electronic controls. Most of the technology in these departments/sections is between 10–50 years old therefore some of these machines are strong candidates for more efficient motors, for example as advised by International Electrotechnical Commission**.** Motors in some newer machines have built-in variable frequency drives (VFD), and these drives could provide significant savings for some technologies where suitable. Considering the age of the technology in the factory, a review of the sizing of the motors is critical and should prove to be a helpful measure for energy saving. Studies on industrial motor energy efficiency have shown considerable potential in this area (McKane and Hasanbeigi 2011).

UTILITY PLANTS

Compressed air and boiler units are common technologies across many different industries, with considerable guidance in published literature (such as Carbon Trust's energy efficiency guides). Air and steam leaks in the distribution systems are the very first step that could be addressed to improve efficiency, and in many cases simple measures like lowering the steam and compressed air pressure can be quite beneficial. The compressed air units were manufactured in 2008 and can execute many energy efficiency features, which have not been fully harnessed. A comprehensive review on achieving energy efficiency in compressed air systems is given in (Schmidt and Kelly 2005). Boilers also operate 24 hours a day, seven days a week even when steam for production or heating is not required; this was specifically monitored through simple weekend boiler shutdowns by the author. Detailed studies about improving energy efficiency in boiler systems (GPG 369) are available for guidance. Inbuilt timers on both the boilers and the compressed air systems can be utilised to control their weekend/off-peak loads to make some simple savings. Also, both the systems are a good candidate for exhaust air heat recovery (Hasanuzzaman et al. 2012).

Energy consumption analysis

Table 1 shows the total energy consumption for 2011. Despite the demand for electricity being only one fifth of the total energy, its cost equals to half of the total energy bill. Therefore, even modest electric energy efficiency improvements could make significant contributions to cost savings. The table also shows the SEC which is discussed in detail below. Figure 2 shows daily electricity consumption with the number of factory holidays (taken from the factory's holiday calendar) affecting the monthly demand, indicated with arrows. Reduced off-season demand can only be seen in October and November. This is when the production activity becomes slow and some sections in manufacturing (A) would either run smaller shifts or go on two-week holidays. The increased demand in December, January, and February, particularly representing the baseline and electric heating demand, indicates winter-related consumption. The on-season consumption is consistently high despite no heating being used from May through to end of September, indicating a production-related rise in demand. There are nine mechanical air handling units, 9.5 kW each, that are used for both heating and cooling in the major production buildings. There are 10 air conditioning units, 3.5 kW each, in the office buildings around the factory that are used for cooling only. This load considerably contributes towards demand in the summer.

In Figure 3, power demand profiles from Monday–Thursday are compared and peak-time for off-season shows a slightly increased demand, attributed to it being winter. However, off-peak demand, from 18:00 to 06:00, in off-season is relatively low indicating the reduced activity of manufacturing (B) as only the Weaving department works night shifts in winters. Another contributing factor is reduced activity in manufacturing (A) as discussed above. These factors happened to be the major contributors towards increased energy use and higher production costs in winter season as discussed in SEC calculations below. The fall of Friday curve at around 17:30 indicates the baseline demand. In spite of the reduced amount of off-season overtime between 06:00–12:00 on Saturdays, the curve looks similar to on-season. This also indicates winter related increase in demand and can also be observed through increased off-season baseline demand. The reduced demand between 20:00–00:00, for off-season Sunday, indicates that only one of the two departments of manufacturing (B) is working.

The analysis revealed an average peak-time demand between 850–950 kW whereas for off-peak time it was reduced to between 250–400 kW for both seasons, which represents the demand of manufacturing "B". The average baseline load was found to be 115 kW, which might be considered reasonably high. The energy trend and patterns assumed through these profiles helped to understand energy consumption on a daily and half-hourly basis. The in-depth understanding at such a resolution was never possible by an ordinary energy survey or audit as mentioned above. The analysis also pinpointed some areas of energy saving, such as reducing the baseline energy use that would not have been visible through information collected on a monthly basis.

Monthly gas consumption, both estimated/invoiced (esti.) and manually collected (man.), are shown in Figure 4. In addition to disagreeing with the manual consumption curve, the estimate gas curve is found to be too high for June and July, indicated with arrows. This was to compensate for the

Table 1. 2011 consumption.

2011 utility	Energy Consumption		Cost		Specific Energy Consumption (kW·h /metre)
	MWh/year	%	£/year	%	
Electric	4,147.61	19.69	378,361	48.65	3.68
Gas	16,924.66*	80.32	399,280	51.35	15.00
Total Energy	21072.27		777,641		18.68

** Based on supplier's estimate invoices.*

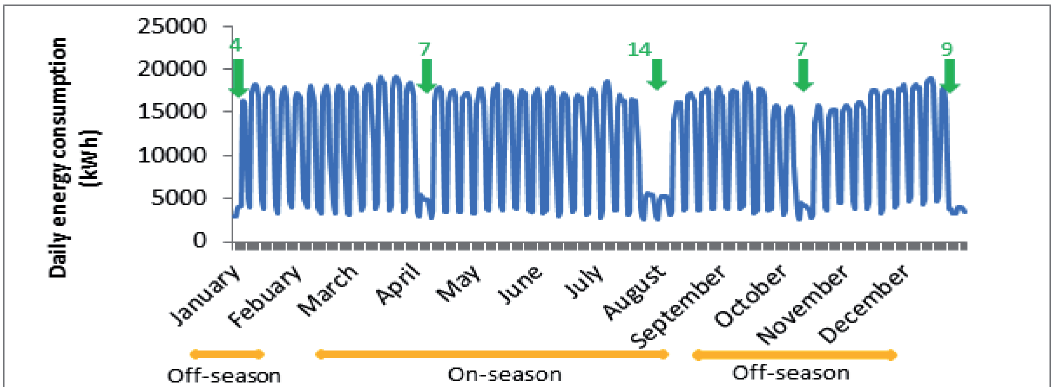
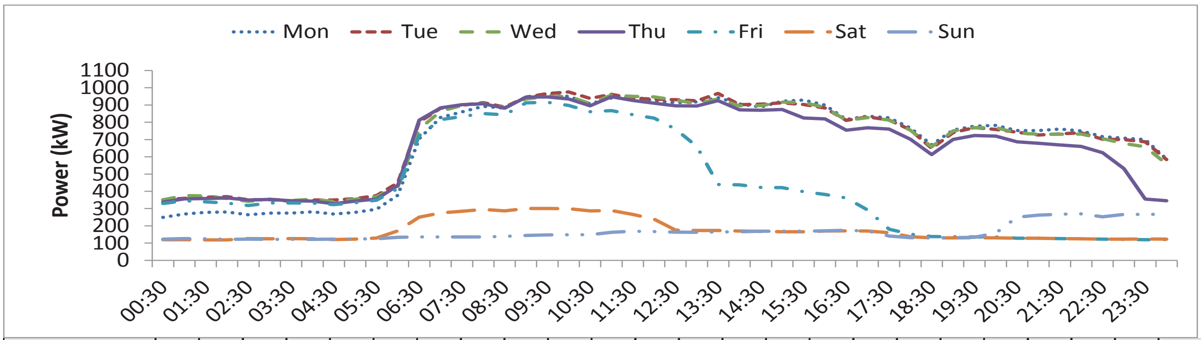


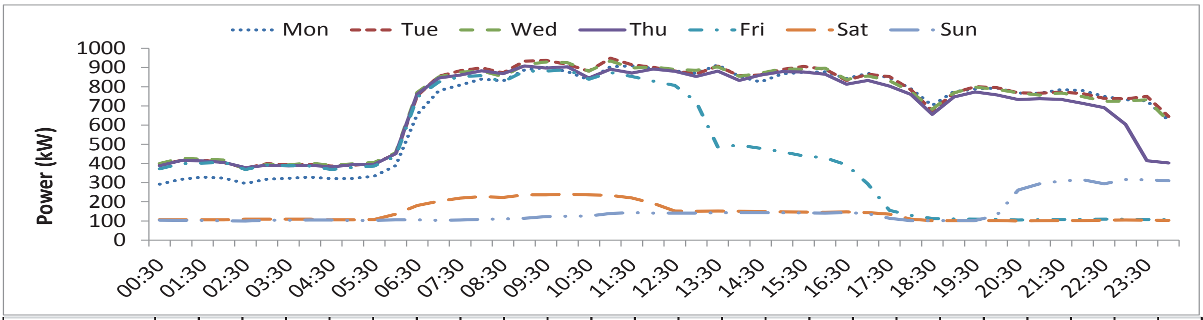
Figure 2. Daily electricity demand.

a. Off-season power demand.



	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
i)Operations						↓(1)	↓(2)	↓(2)	↓(4)								↑(1)	↑(6)						↑(2)
i)Mfg. (A)						↓																		↑
i)Mfg. (B)	→																							→
ii)Operations						↓(1)	↓(2)	↓(4)	↓(2)				↑(2)		↑(1)	↑(1)	↑(4)	↑(1)						
ii)Mfg. (A)						↓						↑												
ii)Mfg. (B)													↑(DH)				↑(W)							
iii)Retail (R)+OT						↓(OT)			↓(R.)			↑(OT)						↑(R.)						
iv)Retail											↓							↑	↓(W+DH)					→

b. On-season power demand.



	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
i)Operations						↓(1)	↓(2)	↓(2)	↓(4)								↑(1)	↑(6)						↑(2)
i)Mfg. (A)						↓																		↑
i)Mfg. (B)	→																							→
ii)Operations						↓(1)	↓(2)	↓(4)	↓(2)				↑(2)		↑(1)	↑(1)	↑(4)	↑(1)						
ii)Mfg. (A)						↓						↑												
ii)Mfg. (B)													↑(DH)				↑(W)							
iii)Retail (R)+OT						↓(OT)			↓(R.)			↑(OT)						↑(R.)						
iv)Retail											↓							↑	↓(W+DH)					→

Legend

→	↓	↑	i	ii	iii	iv
Continued	Starting	Finishing	Mon-Thursday	Friday	Saturday	Sunday

Figure 3. Power demand. The numbers in the brackets represent the number of sections starting/finishing. Manufacturing (A) includes Finishing and Yarn production, and the remaining sections of Operations finish an hour earlier before the midnight on Thursday. Manufacturing (B) includes Dye house (DH) and Weaving (W). R and OT symbolise Retail and overtime respectively.

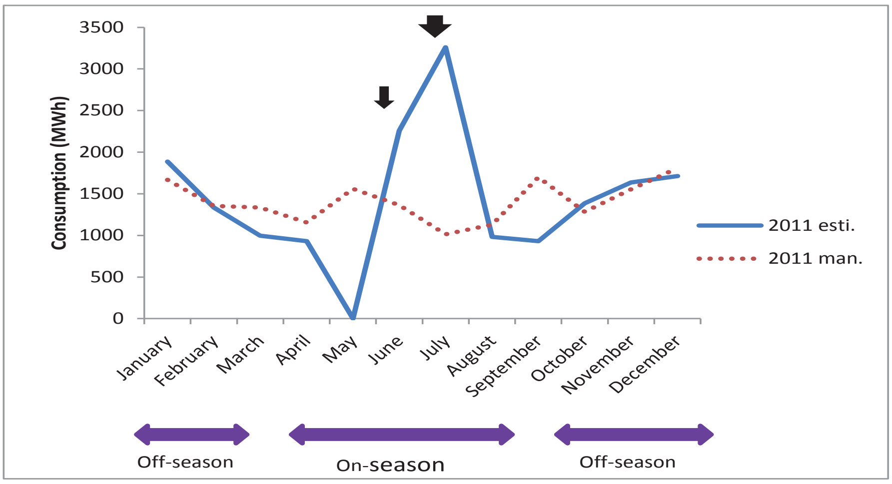


Figure 4. Manual and estimate gas demand.

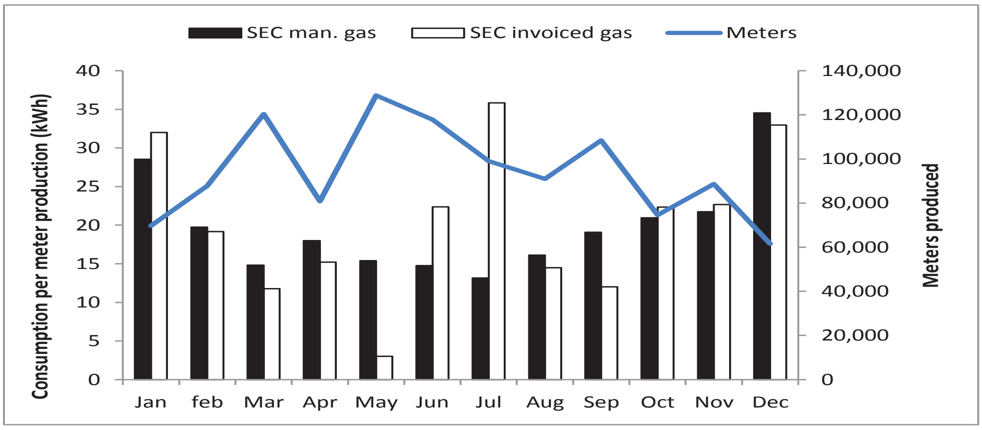


Figure 5. Estimate and manual SEC and monthly metres produced.

missing estimated bill in May. Such problems with estimated bills, though common, not only lead to unfair charges but can seriously affect the SEC calculations as discussed above and shown in Figure 5 (where the total estimated energy consumption for May only shows the electricity consumption). However, when the total estimate/invoiced and actual annual consumptions were calculated, negligible difference was noticed. The graph also showed increased demand in off-season which is due to increased heating demand in winter. This drives the need of investigating the efficiency of the heating system as well as improving the quality of building fabric insulation. This analysis also prompted an urgent need for accurate billing.

The effect of season and rate of production activity in the factory on SEC is shown in Figure 5. The SEC is low during on-season. It can be seen that higher monthly production rates improve the SEC, though increased heating demand in winter and slow production rates notably increase the SEC. It also shows that, other than the weather and season, there are more factors that could affect the SEC in such a complicated manufacturing process. Therefore, identifying these unknown factors (through sensitivity analysis and observing correlation with other parameters) and optimising their energy consumption through production management is another area that can potentially help to reduce and explain such patterns. The analysis based on higher resolution (daily meter readings) again offered a much better understanding of energy consumption, and energy saving opportunities, in the factory.

Conclusion

This study demonstrates that the textile manufacturing process is complex with a number of quite specific processes contributing to overall energy patterns. By using real-time energy data, the study attempted to estimate the energy consumption used in a case-study textile mill. The study revealed some technology and process efficiency improvements that might be feasible. Average energy demand profiles when compared to working patterns showed clear occupant- and activity-sensitive trends. Small differences in off- and on-season energy demand were attributed to winter related consumption in off-season. It was found that high monthly off- and on-season SEC variations were related to increased heating demand in winter.

Different areas of energy efficiency improvements in specific technologies were also identified. Waste heat recovery, improved performance of motors, and energy efficient lighting systems around the mill were found to be particularly promising. The energy audit and consumption analysis revealed some actionable measures directly supporting aims of energy saving. These included problems relating to a high baseline load, and investigations were made to benefit from this opportunity. The use of estimated gas bills was providing misleading information to the company (and their budgeting for energy), and this was highlighted as another area to address. The whole exercise proposed a thorough investigation of HVAC system and controls for possible opportunities of heating/cooling related savings. The study also suggested reviewing opportunities for building fabric insulation improvements. Some areas that were raised for further investigations include, disaggregating production and heating/cooling energy demands and the ways to reduce it, and identifying an optimum production rate for both off- and on-season for energy efficiency.

Such level of energy analysis is only possible through high-resolution real-time energy data and empirical observations that were made at the factory. This highlights the significance of energy data analysis for organisations wishing to improve energy efficiency and reduce production costs. The improved understanding of energy consumption that this can deliver can enable energy managers to make much better informed decisions on energy efficiency in an industrial workplace.

References

Allwood, J.M., Laursen, S.E., Rodriguez, C.M., Bocken, N.M. 2006. Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom. [pdf] GB: University of Cambridge Institute for Manufacturing. Available at http://www.ifm.eng.cam.ac.uk/uploads/Resources/Other_Reports/UK_textiles.pdf [Accessed 20 July May 2012].

Best Available Techniques for the Textiles Industry reference document (BREF). Available at http://www.ineris.fr/ippc/sites/default/interactive/bref_text/breftext/anglais/bref/BREF_tex_gb29.html#_Toc45680111 [Accessed 20 November 2012].

Best practice programme's good practice guide 148. Monitoring and targeting in the textile industry.

Brown, N., Wright, A. J., Shukla, A., Stuart, G., 2010. Longitudinal analysis of energy metering data from non-domestic buildings. Building Research & Information 38 (1), pp. 80–91.

Bryant, J.A., Carlson, K. 2002. Facilities Emerald Article: Short term energy monitoring: a road to long term energy savings? Short term energy monitoring: a road to long term energy savings? Facilities, 20 (10). pp. 303–313.

Buyukakinci, B.Y., 2012. Usage of Microwave Energy in Turkish Textile Production Sector. Energy Procedia 14, pp. 424–429.

Department of the Environment, 1997. Cutting your energy cost: a guide for the textile dyeing and finishing. Good practice guide (GPG 168).

Energy Research Partnership 2011. Industrial Energy Efficiency: Key Messages. [pdf] Available at www.energyresearchpartnership.org.uk/tiki-download_file.php?fileId [Accessed 09 August 2012].

Ferreira, V., G., 2009. The analysis of primary metered half-hourly electricity and gas consumption in municipal buildings. DeMontfort University PhD thesis, available online.

Field, J., Soper, J., Jones, P., Bordass, W., Grigg, P., 1997. Energy performance of occupied non-domestic buildings: Assessment by analysing end-use energy consumptions. Building Services Engineering Research and Technology 1997, 18: 39.

Good practice guide 369 (2004). Energy efficient operation of boilers. Action Energy.

Good practice guide 385 (2005). Energy Efficient compressed air system. The Carbon Trust.

Good practice guide 168 (1997). Cutting your energy cost: a guide for textile and finishing industry. Department of the Environment, UK.

Gordić, G., Babić, M., Jovičić, N., Šušteršič, V., Končalović, D., and Jelic, D., 2010. Development of energy management system – Case study of Serbian car manufacturer. Energy Conversion and Management 51 (2010) 2783–2790.

Greening, L.A., Roop, J.M., 2007. Modeling of industrial energy consumption: An introduction and context. Energy Economics 29 (2007) 599–608.

Hasanbeigi, A., 2010. Energy-Efficiency Improvement Opportunities for the Textile Industry. China Energy Group, Energy Analysis Department Environmental Energy Technologies Division. Available online: china.lbl.gov/staff/ali-hasanbeigi?page=1 [Accessed January 05, 2014].

Hasanbeigi, A., Hasanabadi, A. & Abdorrazaghi, M., 2012. Comparison analysis of energy intensity for five major sub-sectors of the Textile Industry in Iran. Journal of Cleaner Production [online] 23 (1), pp. 186–194.

Inés, C. and Martínez, P., 2010. Energy for Sustainable Development Energy use and energy efficiency development in the German and Colombian textile industries. Energy for Sustainable Development, [online] 14 (2), pp. 94–103.

Hasanuzzaman A., Rahim, N.A., Hosenuzzaman, M., Saidur, R., Mahbubul, I.M., Rashid, M.M. 2012. Energy savings in the combustion based process heating in industrial sector M. Renewable and Sustainable Energy Reviews 16 (2012) 4527–4536.

International Electrotechnical Commission in October 2008. IEC/EN 60034-30 standard.

Karacapilidis, N.I., Pappis, C.P., 1997. Production planning and control in textile industry: A case study. Computers in Industry [online] 30 (1996) 127–144.

Kilpatrick, R. 2012. Energy Consumption in Non-Domestic Buildings based on Empirical Data. PhD thesis Heriot Watt University, UK.

Koç, E., Kaplan, E., 2007. An Investigation on Energy Consumption in Yarn Production with Special Reference to Ring Spinning. [pdf] Fibres and Textiles in Eastern Europe , 15 (4), pp. 18–25. Available at www.fibtex.lodz.pl/2007/4/18.pdf [Accessed December 20, 2014].

McKane, A. Hasanbeigi, A. 2011. Motor systems energy efficiency supply curves: A methodology for assessing the energy efficiency potential of industrial motor systems. Energy Policy 39 (2011) 6595–6607.

Mirade, P.S., Perret, B., Guillemin, H., Picue, D., Dessere, B., Montel, M.C., Corrieu, G., 2012. Quantifying energy savings during cheese ripening after implementation of sequential air ventilation in an industrial cheese making plant. Energy 46 (2012) 248–258.

Palanichamy, C., Babu, N.S., 2005. Second stage energy conservation experience with a textile industry. Energy Policy 33 (2005) 603–609.

Richard, J.M., Maintaining the solution to operations and maintenance efficiency improvement. Pacific Northwest Laboratory, Safety Performance and Analysis Department Richland, Washington 99352. Available at www.pnl.gov/dsom/publications/26005.pdf [Access January 12, 2014].

Schmidt, C., Kissock, K., 2005. Modeling and Simulation of Air Compressor Energy Use. ACEEE Summer Study on Energy Efficiency in Industry 2005.

Stuart, G., Fleming, P., Ferreria, V., Harris, P., 2007. Rapid analysis of time series data to identify changes in electricity consumption patterns in UK secondary schools. Energy and Buildings 42 (2007) 1568–1580.

United Nations Industrial Development Organisation 1992. Output of a Seminar on Energy Conservation in Textile Industry.

Wang, S., Yan, C., Xiao, F., 2012. Quantitative energy performance assessment methods for existing buildings. Energy and Buildings, [online] 55 (2012) 873–888.

Wijk, J.J.V., Selow, E.R.V. 1999. Cluster and Calendar based Visualization of Time Series Data. IEEE Symposium on Information Visualization (INFOVIS'99), San Francisco, October 25–26, 1999.

Acknowledgements

This study is part of a PhD project funded by the textile company Johnstons of Elgin, in collaboration with Heriot-Watt University.