Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

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Karthik Pavan Kumar Gunturu, Krishna Koundinya Kota, Madhu Sharma

How to cite: Gunturu KPK, Kota KK, Sharma M. Energy Efficiency Improvement Opportunities in Indian Textile Industries. Textile & Leather Review. 2022; 5:296-326.
https://doi.org/10.31881/TLR.2022.13

How to link: https://doi.org/10.31881/TLR.2022.13

Published: 6 August 2022

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Karthik Pavan Kumar GUNTURU*, Krishna Koundinya KOTA, Madhu SHARMA

School of Engineering, University of Petroleum and Energy Studies, Dehradun, India
*karthikpavankumargunturu@gmail.com

Article
https://doi.org/10.31881/TLR.2022.13
Received 6 June 2022; Accepted 30 July 2022; Published 06 August 2022

ABSTRACT
The Textile Industry is one of the largest industrial sectors and the fifth largest exporter of the textiles employing 45 million workers in India. The Indian textile industry has changed its ways in the production of finished textiles, Energy is involved in each of stage processing. Thus, this study aims to evaluate the energy efficiency of the processes in the textile industry and identify opportunities for improvement in the process involving raw fabric to the finished textile product. The energy efficiency determination in an industry can be evaluated by the energy consumption of the respective process equipment in an industry which includes the performance evaluation of the textile manufacturing processes. This paper describes the operations in textile manufacturing such as weaving, yarn production, spinning, drying, and also the significance of PAT schemes in energy improvement opportunities for various industries, including the technical improvement studies and also provides the brief description on validating various unit operations and respective parameters that affect the performance of various process equipment such as stenter, heaters, compressors, motors, and other non-production equipment. This review paper also described the impact of PAT cycle 1 in validating the energy intensity of technologies used in textile industries and some important measures required to improve the energy efficiency of a process as this could improve the functioning of the system. The best available techniques in the process has also been discussed in the sections which can be implemented in practice for improving the energy efficiency of the processes.

KEYWORDS
energy efficiency, unit operations, textile industry, PAT scheme, process equipment

ABBREVATIONS

PAT	Perform Achieve Trade
SEC	Specific Energy Consumption
MTOE	Million Tonnes of Oil Equivalent
OHTC	Over Head Travelling Cleaning device
FAD	Free Air Delivery
KWh	Kilo Watt Hour
BEE	Bureau of Energy Efficiency
TPM	Total Productive Maintenance

INTRODUCTION

The Indian industrial sector is one of the largest end users of energy. It is the sector that needs to be focused to enhance energy efficiency. The Government of India has set up BEE, whose objective is to reduce the energy intensity of the economy. BEE has launched a Perform Achieve Trade scheme (PAT) to focus on energy efficiency in large industries in India [1]. The energy efficiency targets can be achieved by classification of industries as designated consumers in the Perform Achieve Trade scheme (PAT). The implementation of the PAT scheme is discussed in the next section.

PAT Scheme Implementation in India

Perform Achieve Trade (PAT) is a mechanism to accelerate improvements in energy efficiency in energy intensive industries. The objective of this is to enhance the cost effectiveness through energy savings by which the industries would be getting Energy Savings Certificates [1].

PAT Cycle - I had aimed to reduce the specific energy consumption (SEC) and obtain energy savings of 6.686 million Tonne of Oil Equivalent (MTOE). When the Cycle – I was completed the savings was 8.67 MTOE. PAT Cycle - II has set a target of 8.869 MTOE, and when the Cycle – II was completed the total energy savings was 13.28 million Tonne of Oil Equivalent. PAT Cycle – III has targeted to reduce the energy consumption of 1.06 MTOE, while PAT Cycle – IV has set a target to reduce energy consumption of 0.6998 MTOE. PAT Cycle – V has the energy savings of 0.5130 MTOE, and finally PAT Cycle – VI has also been set to achieve a savings of 1.277 MTOE [1].

India has about 3400 textile mills ranging in large, small, and micro scale industries [2]. The number of designated consumers which were identified were 90 units under PAT Cycle - I which is based on the minimum energy consumption of 3000 TOE (Tonnes of Oil Equivalent) [3]. The energy consumption of the designated consumers of the textile sector was 1.2 million TOE which was 0.73% of the energy consumption by the total designated consumers in PAT cycle - I.

Impact of PAT Cycle on the Textile Sector

Table 1 shows the lists of the designated consumers in each PAT cycle, where textile is the one of the sector which is targeted in each PAT cycle. From the Table 2 is visible that the energy intensity has decreased from the baseline year 2010. This shows that PAT has a significant impact on the textile sector.

The total energy consumption by the designated consumers was 1.2 MTOE in the year of 2010 and after the completion of the PAT Cycle - I it was identified that there was a savings of 0.066 MTOE [3]. This was about 0.99 % of the national energy saving target under the PAT Cycle - I. After the completion of the PAT Cycle – I, the PAT Cycle - II was launched where 99 units were notified with the energy saving target of 0.09 MTOE. In PAT Cycle - III, 34 designated consumers were notified with the energy saving target of 0.04 million TOE [3]. Under the PAT Cycle - I there was also a reduction of CO_2 emissions which was 0.62 million tonnes of CO_2 equivalent.

Table 1. Designated consumers under each PAT Cycle [1]

Timeline	Implementation of scheme	Sectors	Number of designated consumers
2012 – 2015	PAT Cycle – I	Aluminium, Cement, Chlor-Alkali, Iron & Steel, Paper & Pulp, Thermal Power Plant, Textile.	478
2016 – 2017 to 2018 – 2019	PAT Cycle – II	Aluminium, Cement, Chlor-Alkali, Iron & Steel, Paper & Pulp, Thermal Power Plant, Textile, Refineries, Railways and DISCOMS.	89
2017 – 2018 to 2019 – 2020	PAT Cycle – III	Thermal Power Plant, Cement, Aluminium, Pulp & Paper, Iron & Steel and Textile.	116
2017 – 2018 to 2020 – 2021	PAT Cycle – IV	Thermal Power Plant, Cement, Aluminium, Pulp & Paper, Iron & Steel and Textile, Petrochemicals and Buildings.	109
2019 – 2020 to 2021 – 2022	PAT Cycle – V	Aluminium, Cement, Chlor-Alkali, Commercial Buildings, Iron & Steel, Pulp & Paper, Textile and Thermal Power Plant.	110
2020 – 2021 to 2022 – 2023	PAT Cycle – VI	Cement, Commercial buildings, Iron and Steel, Petroleum Refinery, Pulp and Paper and Textiles.	135

The impact of the PAT cycle – I has brought significant change in the energy consumption in the textile sector by implementing the projects on energy efficiency. Table 2 describes how effectively the textile sector was being changing under the PAT scheme. PAT cycle schemes are generally evaluated based on energy intensity. Government has started investing in energy efficient technologies in various industrial sectors which made a significant improvement in the sector performance [1].

Table 2. Energy intensity of the textile sector [3]

Financial year	Total production (MT)	Total energy consumption (MTOE)	Energy intensity (TOE/million USD)
2010 (base line)	1.29	1.20	0.86
2015	1.56	1.24	0.59
2020	1.84	1.36	0.45
2025	2.17	1.49	0.35
2030	2.55	1.65	0.28

Note: Calculated energy intensity in the Table 2 doesn't include the energy consumption of non-conventional energy sources.

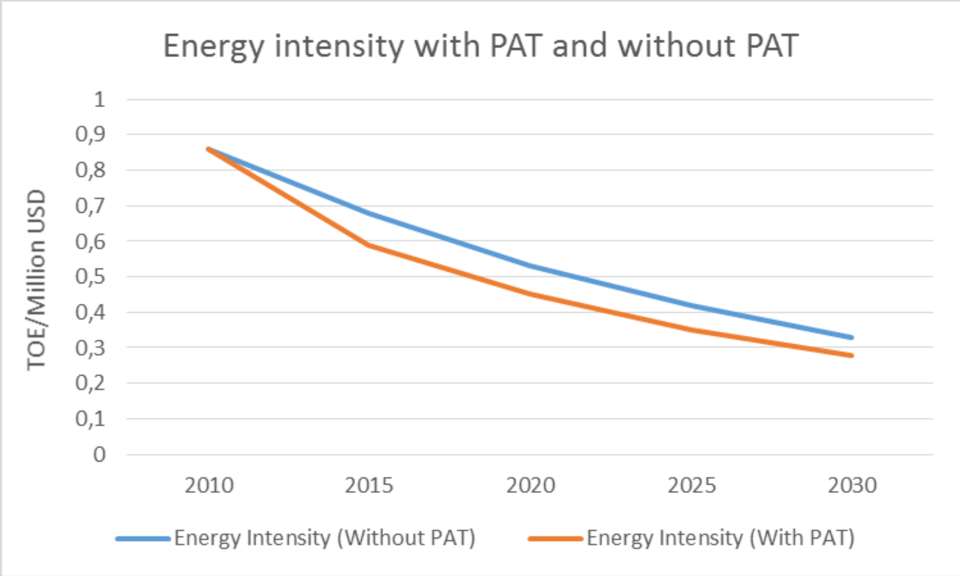

Figure 1. The energy intensity variation for the textile sector with and without PAT scheme from 2010 – 2030 [3]

As it can be seen from the Figure 1, there was a significant amount of decrease in the energy intensity with the implementation of PAT Scheme. PAT Cycle - I was implemented by taking into consideration 90 designated consumers for reducing the specific energy consumption. The energy consumption has been identified by the process in the textile industry in the respective sectors. The processes are listed in the Table 3.

Table 3. Process and technologies in textile industry [3]

Process	Sub-operations	Description	Technologies used
Spinning process	Opening or blending	The process of removing and separating the compact fibres in the bales.	There are four types of technologies that are used in the spinning process, mainly ring spinning, rotor spinning, Air-jet spinning and friction spinning. Mostly used technology in India for the spinning process is the ring spinning for many types of yarns [5].
	Cleaning	This is done to remove the dirt, seeds etc.	
	Carding	The process of producing a rope-like strand called the silver by passing the raw material through two press rollers.	
	Combing	The process of passing the silver through the needles or combs so to remove the short fibres so to ensure evenness.	
	Drawing	The process in which the strands of card silver are passed through a set of rollers which are responsible for combining the fibres into a single uniform strand.	
	Roving	The process in which the drawn silver is fed into a drafting arrangement in which the silver is stretched and twisted to strengthen the strand.	
	Spinning	Finally, the raw material is converted into yarn.	

Process	Sub-operations	Description	Technologies used
Weaving process	---------------	Weaving is the process of making fabric or cloth. Warp yarns and the filling yarns are the two ways for the weaving process.	Power looms are used for the weaving process.
Knitting process	---------------	Knitting is also preferred as a method for producing the fabric or cloth	Power looms and handlooms are for the Knitting process.
Processing	---------------	The processed fabric that is produced is sent for the wet treatment process in which the final fabric is prepared and then processed to dyeing, thereafter it is sent to the finishing process. The wet processing unit is the one which consumes large quantities of water and chemicals and where thermal energy in the plant is used [3]	There are mainly five types of machinery commonly used for dyeing the fabric. Jigger dyeing machine, winch dyeing machine, padding dyeing machine, mangle dyeing machine, jet dyeing machine [3].
Finishing	---------------	To make the fabric more attractive there are processes which need to be done in the finishing stage. The operations that are followed in the finishing are drying, dimensional stability, calendaring, softening. Note: calendaring and softening are the operations that are done so to make the fabric soft and attractive.	The stenter machines are used for the drying process and if the fabric has a deviation from its dimensions, to get appropriate fabric dimensions heat setting in a thermal fluid heater is used [3].

Process and Technologies in Textile Industry

The section will go through the production of fabric garment starting from fibre, along with the chemicals used in each process. The production will be going through various machinery operations, such as spinning, weaving, wet processing and finishing. Each of the operations will involve certain technologies which were identified in various studies.

The general process operations in a textile industry have been described in Figure 2 and the sub-operation in each process has been discussed in the Table 3 along with the technologies used.

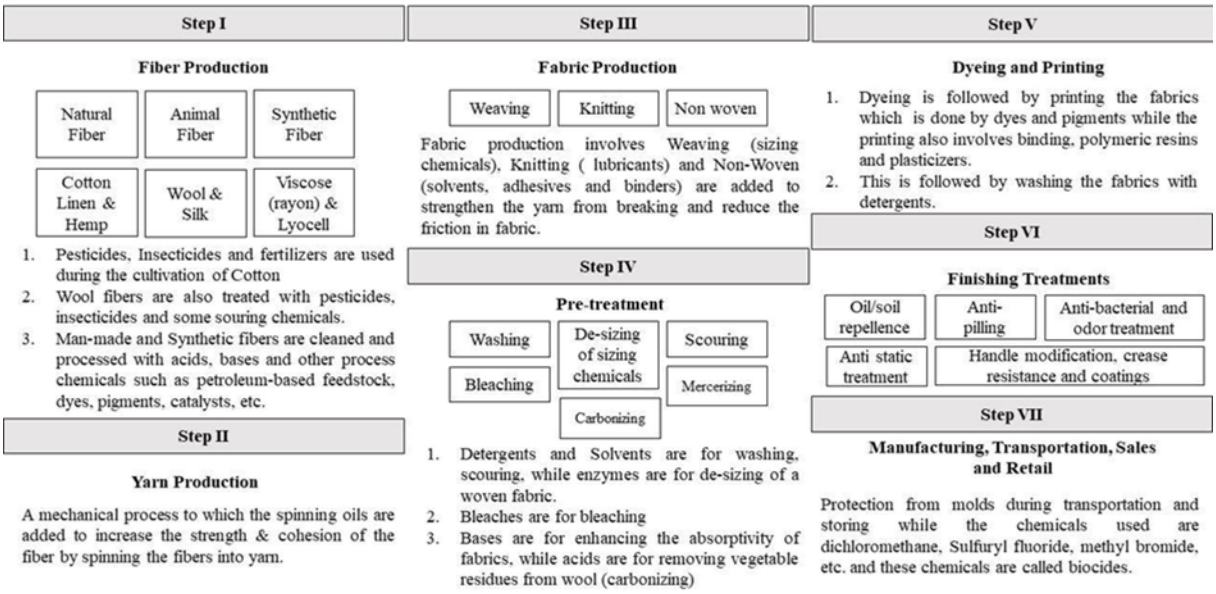

Figure 2. Operations in a typical textile industry [4]

Energy Consumption in a Composite Textile Industry

The textile industry will be needing both the thermal and electrical energy for its operation and the energy cost accounts for about 15 – 20% of the manufacturing cost [6]. The total energy intensity of a finished textile varies based on the fibre that is produced. For instance, cotton fibre needs 54 – 60 MJ/kg of fibre, nylon fibre production requires 120 – 140 MJ/kg of fibre [7].

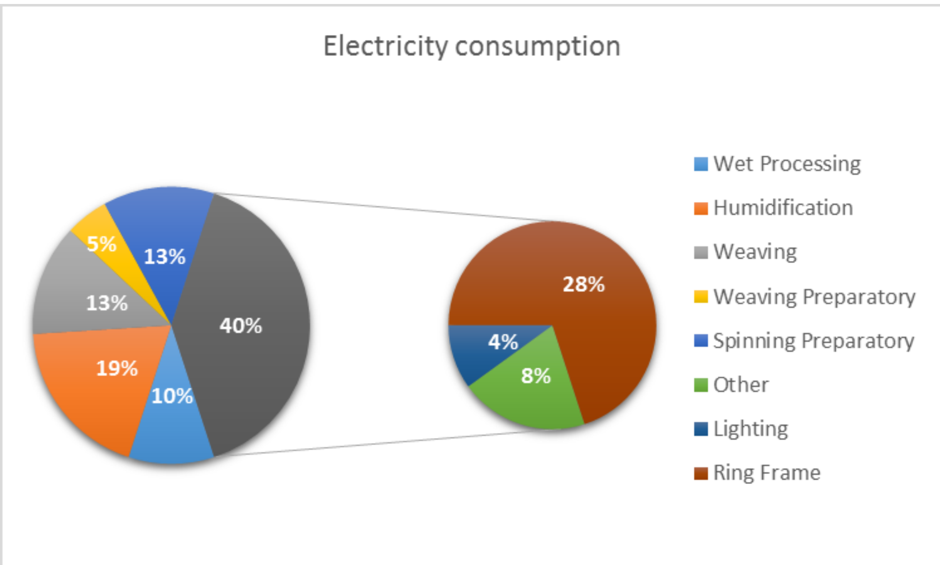

Figure 3. Share of electricity consumption in a composite textile industry [6]

The electricity consumption of the utilities that are installed in a composite textile industry is shown on the Figure 3. Process on the spinning ring frame is said to have a major electricity consumption followed by humidification.

As the fabric, which is formed after the weaving/knitting process, is processed to wet processing where the dyeing, bleaching and finishing takes place. Dyeing process involves adding colours to the fabric in an aqueous solution with thermal energy as steam. In the finishing process, for drying the textile fabric the steam is used as a thermal energy. During this process the steam is distributed throughout the respective process. There are losses which are incurred in the steam distribution network which is 10% (Figure 4).

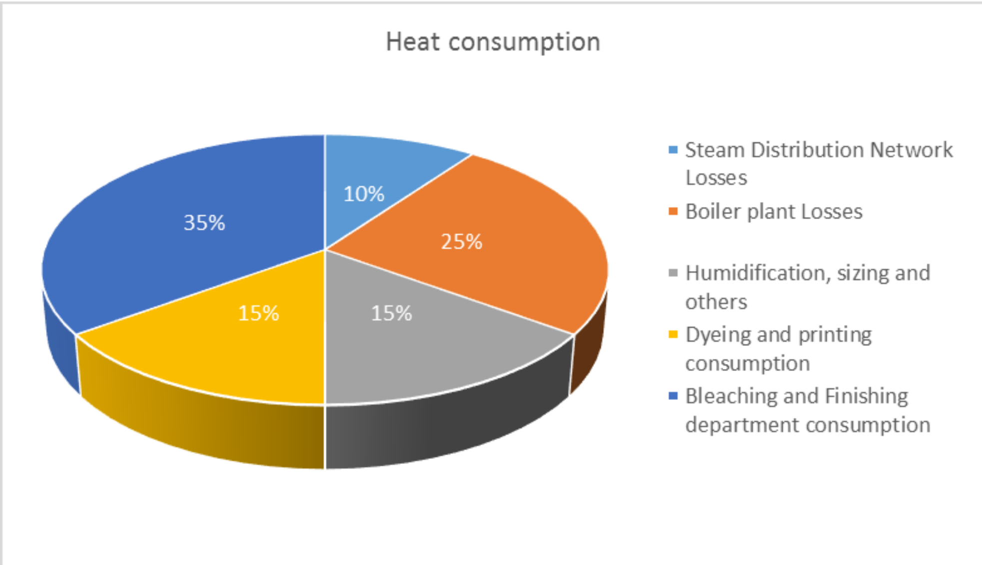

Figure 4. Share of heat consumption in the textile industry [6]

Figure 4 shows the electricity consumption of the utilities that are installed in a composite textile industry. Bleaching and finishing department have a major heat consumption followed by boiler plant losses.

Energy Use in Spinning Process and Wet Processing

From Figures 5 and 6, it has been observed that electricity consumption of the spinning process was 33% and the heat consumption of wet processing has been identified to be more when compared to other processes involving heat consumption. This consumption pattern is divided into respective processes in this section.

The energy used in the spinning process, ring machines account for more electricity consumption when compared to other machinery (Figure 5). Ring machines have consumed more energy than the openend machines. This is because in the open-end machines, draw frames and roving frames are eliminated and thereby their manufacturing costs are also less than ring machines [8].

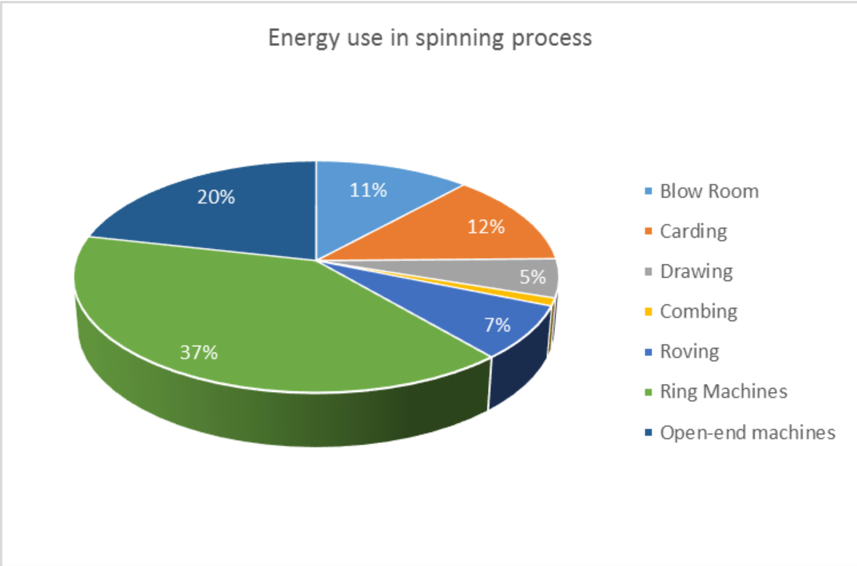

Figure 5. Share of electrical consumption in the spinning process [8]

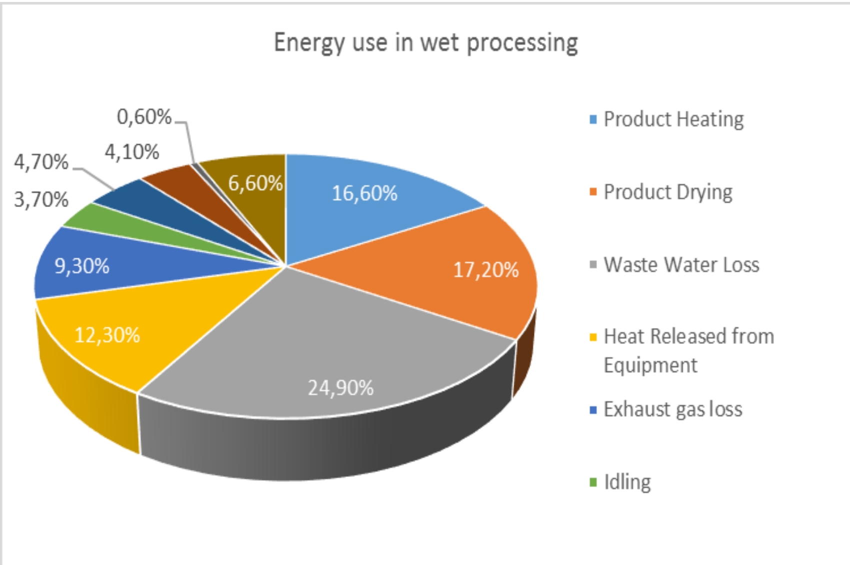

Figure 6. Share of Thermal energy usage in wet processing process [8]

From the Figure 6 it is evident significant losses are lost through wastewater along with that there are other losses which are accounted for that can be reduced using energy efficiency measures [8].

Table 4. Major energy consumption of the machinery technologies used in spinning and wet processing processes [7]

Process	Technology type	Energy consumption	Mode of energy consumed
Spinning process	Ring spinning	2.5 – 3.57 kWh/kg of yarn [9]	Electrical Energy
	Open -end spinning	2.44 – 3.56 kWh/kg of yarn [9]	
Wet Processing	Winch dyeing	6 – 17 GJ/tonne of output [9]	Heat Energy
	Jet dyeing	3.5 – 16 GJ/tonne of output [9]	
	Stenter	2.5 – 7.5 GJ/tonne of output [9]	

The consumption patterns of various processes are discussed in the above sections. So, to decrease the consumption and improve the performance of the industry, performance evaluation is being discussed in the next sections.

Performance Evaluation of Process Equipment in Textile Industries

The unit operations play an important role in the manufacturing unit of a textile industry, while their performances will be the main factor of achieving the desired quality of the product. With the change of time, the performance of the equipment will be depending on the heat and mass transfer occurred in the process respectively. The major energy consumption was evaluated from the previous energy and heat consumption section. As the motors of the ring frame in the spinning process consumer the more electricity, the performance evaluation is discussed below. Similarly, in the wet process, stenter-hot air dryers and dyeing machines are the largest consumers of heat. Performance evaluation is discussed below.

Performance Evaluation of an Electric Motor

Electric motors are the largest energy consumer in the spinning process. The energy consumption of the motors depends on various parameters such as yarn count, spindle speed, ring diameter, etc. This consumption is measured in terms of kWh per kg of yarn produced. For evaluating the performance of the motors there are some field tests which need to be performed.

Table 5. Summary of various parameters for testing the efficiency of motors

Parameter	Description	Equations
No load test	• The motors should be operated with no shaft attached to it • Input power, current, frequency and the voltage are to be noted. • From this test the no load losses in the motors is calculated.	$No\ Load\ Losses = (No\ Load\ Power) - ((No\ Load\ current)^2 \times Stator\ resistance)$ (1)[6]

Parameter	Description	Equations
Stator and rotor I^2R losses	• As the operating temperature of the motors and surrounding temperature are different, the resistance at the operating temperature must also be corrected, where t2 is the operating temperature and t1 is the ambient temperature, both in °C. • Stator copper losses at the operating temperature and the rotor input power is calculated from the equations shown, where I is the current motor input, S is the slip, Pr is the rotor input power, Pmotor is the power of the motor provided in the specifications.	$\frac{R2}{R1} = \frac{235+t2}{235+t1}$ (2) [6] $Stator\ Losses = 3 \times (I/\sqrt{3})^2 \times R2$ *(3)[6]* $Slip, S = \frac{Ns-Nr}{Ns}$ (4) [6] $Rotor\ Input, \mathrm{Pr} = \frac{Pmotor}{(1-S)}$ (5) [6]
Motor input power	• This is evaluated by adding all the losses with the rotor input power. Where stray losses can be calculated from IEEE-112 standard, it states that the stray losses can be in between 0.9% to 1.8% of the motor power (Pmotor).	$Motor\ input\ power = Pr + Stator\ losses + No\ Load\ Losses + Stray\ Losses$ (6) [6]
Efficiency of the full load motor	• It is the ratio of output power as per specifications (Pmotor) from the power to the input rotor power. This the efficiency at full load.	$Efficiency, \eta = \frac{Poutput}{Pinput} \times 100$ (7) [6]
Power factor evaluation	• The power factor at full load is to be also calculated when evaluating the performance, where V is the voltage of the motor and I is the current of motor. These two parameters are the specifications provided on the motor.	$Pf\ (Power\ factor) = \frac{Pinput}{\sqrt{3} \times V \times I}$ … …(8) [6]
Motor loading	• By the method of inline power measurements, the input three phase power is measured using in-line power meter. • Then, the input power at full load is measured. • The percentage of loading is then evaluted from the formula provided.	$Pir = \frac{Full\ rated\ power\ (As\ per\ specifications)}{efficiency\ at\ full\ load}$ (9)[6] $Load = \frac{Pinput}{Pir} \times 100$ (10) [6]
Rewinding of the motor	• If the motors have to be rewound then the efficiency of the motors before and after has to be evaluated.	

Performance Evaluation of a Stenter-Hot Air Dryer

The stenter should have a vast applicability for all types of fabrics such as light-weight, elastic, delicate, as well as strong, hard and heavy fabric materials. The fabric with moisture is passed through various chambers on the chain drive of a stenter held with pins, where the dry hot air from a thermic fluid heater is blown with the help of jets. The moisture present in the fabric will be absorbed by the air and the dry fabric is sent from the outer end of a stenter. Then after, the fabric is quenched at the cooling zone in which the cold air is blown to cool the fabric [10]. There are various factors that affect the drying mechanism where the sensitivity of the material will be considered to run or manipulate the operating parameters in a drying equipment (Table 6).

Table 6. Summary of various parameters affect the drying mechanism in a stenter hot air dryer

Parameter	Effect on drying rate
Humidity (moisture content)	• Initially the rate of drying is very slow in the warmup period. • The drying rate increases when the material gets heated up, till the moisture content reaches a certain stage till which the parameters like gas stream, temperature, flow rate, etc; will be dominating and then the falling rate period begins as the maximum evaporation rate could not be maintained which is known as critical moisture content. • After further heating the moisture inside the fabric could not be removed and this stage is divided into two phases, like 1st falling rate period which is the transition of constant rate period and 2nd falling rate period. • In the 2nd falling rate period, moisture and energy diffusion in the textile material will play the rate of drying. The falling rate phase is a very slow process as it takes a longer period to get dried.
Constant rate period and falling rate period	• Bulk diffusion (evaporation) of the moisture from the fabric surface to the hot dry air takes place in case of the constant rate period. Higher air velocities reduce the moisture film on the fabric surface. Initially the heat transfer is done by the mode of conduction within the fabric and the mode of operation is a forced convection, while in this process, at a certain point of time during the process, the surface temperature of the fabric exceeds the wet bulb temperature of the drying air, and this results in the radiation heat transfer. Thus, in practice, the drying rate in a stenter will be more than the calculated values. • The drying rate is gradually reduced due to the reduction of moisture content to its critical value, and then the molecular diffusion comes into picture within the fabric material. The evaporation rates previously the completely wetted fabric is exposed to the hot medium, while from the point of critical moisture content the wetted area is minimized and thus the rate of evaporation will be reduced gradually. Thus, in the falling rate period the capillarity and molecular diffusion play a major role in varying the drying rates.
Convective heat transfer rate	• The rate of heat transfer through convection is unsteady as the drying operation depends on the humidity of the mobile gas stream and inversion temperatures. Thus, obviously the drying rate will also be unsteady as mentioned above, while the product temperature and fluid properties also vary as they are the functions of humidity. The equation (i) shows the rate of heat transfer [61]. $Q = h \times A \times (\Delta T)$ *(11)*[10] where: *h* is the heat transfer coefficient of the convective heat transfer; *A* is the surface area or the heat transfer area; *ΔT* is the temperature difference between the drying medium and textile material in the stenter.

Parameter	Effect on drying rate
Equilibrium moisture content	• The determination of equilibrium moisture content is very important as the humidity depends on the type of material that is to be dried. If the textile material is hygroscopic, then it regains or absorbs the humidity from the ambience and so, the material is heated using super-heated moisture as it absorbs the moisture from the textile material and the effect of ambient humidity on the drying rate will be minimized

The other parameters that affect the drying rate are movement of bound water through the sorption diffusion, capillary motion of the moisture/free water within the fabric, heat and mass transfer of the moisture which are taking place in the drying process. Thus, the heat and mass transfer are to be determined to calculate the performance of a stenter drying system. A two-stage mathematical model has been developed by Nordon and David, where the made assumptions are diffusion of the water vapour through the inter-voids of the fibres, constant volume for varied moisture concentration, no moisture diffusion through fibres and negligible diffusion coefficient [11].

The mass balance and heat balance for diffusion of moisture through the air space is given by the following equation:

$$\varepsilon \frac{\partial C_a}{\partial t} + (1-\varepsilon)\frac{\partial C_a}{\partial t} = \frac{D_a * \varepsilon}{\tau} * \partial\left(\frac{\partial C_f}{\partial x}\right) \quad (12)\ [10]$$

Where ε is the porosity (dimensionless), D_a is the diffusion coefficient (m^2/s), C_a is the moisture content present in the air fabric pores (kg/m^3), C_f is the moisture content of fibres in a fabric (kg/m^3), τ is the effective tortuosity of the fabric.

$$C_v * \frac{\partial T}{\partial t} - \lambda * \frac{\partial C_f}{\partial t} = K * \partial\left(\frac{\partial T}{\partial x}\right) \quad (13)\ [10]$$

Where $$C_v = \rho \times C_p \quad (14)\ [10]$$

Where, C_v, C_p and λ are the volumetric heat capacity of the fabrics (KJ/m^{3}K), specific heat (KJ/kg K) and heat of sorption or desorption of water vapour by fibres or latent heat of evaporation (KJ/kg) respectively, while these are the functions of the water concentration in the fibres. The above equation was derived by assuming that the fibres and the gas stream are in thermal equilibrium. By applying the boundary conditions, the heat transfer equation and mass flow rate would be,

$$Q = \frac{q}{A} = h_e\,(T_e - T) \quad (15)\ [10]$$

And

$$M = h_m \left(C_e - C_A\right) \quad (16)\ [10]$$

Where M is the mass flow rate of the air (kg/m^{2}s), Q is the convective heat flux or convective heat transfer rate (W/m^2), h_e and h_m are the heat transfer coefficient (W/m^{2}K) and mass transfer coefficient (m/s), C_e and C_A are the moisture content of ambient air (kg/m^3) and moisture content of air in fabric pores (kg/m^3).

As the mass transfer also depends on the humidity, the rate equation for mass transfer will be,

$$\frac{1}{\rho*(1-\varepsilon)} * \frac{\partial C_f}{\partial t} = K * \left(Y_A - Y_f\right) \quad (17)\ [10]$$

"Y_a" and "Y_b" are the relative humidity of air in pores and in the fibre in the fabric. Under the ideal conditions, the air is considered as an ideal gas and so the relative humidity of air will be,

$$Y_a = \frac{C_a*R*T}{P_S} \quad (18)\ [10]$$

And

$$Y_b = \frac{C_P}{\rho*(1-\varepsilon)} \quad (19)\ [10]$$

R is the universal gas constant (KJ/kg K) and P_S is the saturation pressure (kg/m^2).

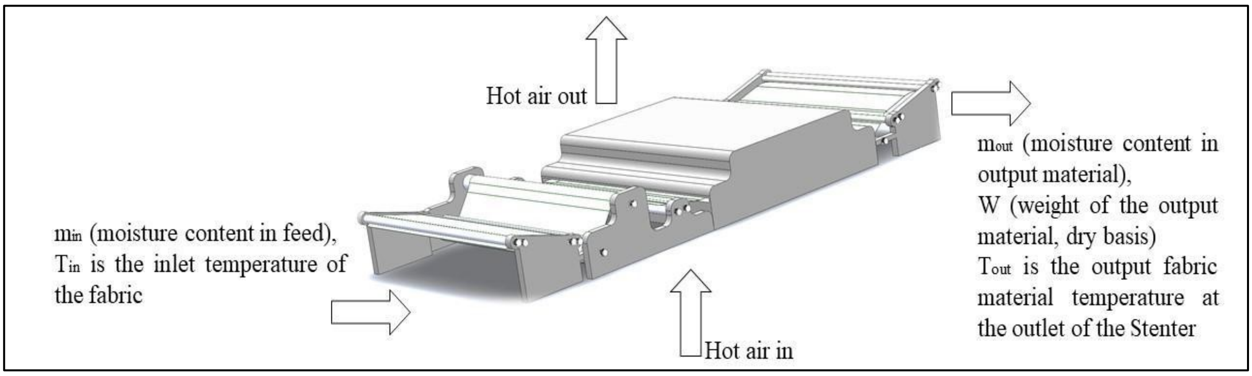

Figure 7. Outline of a stenter-hot air dryer with material balance scheme

When the thermal energy of Q_{in} is given to the stenter hot air dryer, then the dryer efficiency will be **Error! Reference source not found.**,

$$\eta(\%) = \frac{W*(m_{in}-m_{out})*(T_{out}-T_{in})+540}{Q_{in}} * 100 \quad (20)\ [6]$$

Performance Evaluation of Dyeing machines

The majority of the thermal energy used in the dyeing process is in the form of steam. The consumed steam depends upon the type of dyeing machine used. There are different types of dyeing machine such as jigger dyeing machine, winch dyeing machine etc. The temperature at which the dyeing machines will be operated depends on the dyed substrate. The amount of consumed steam can be evaluated from the energy balance equation. The steps for evaluating the performance of the dyeing machine is discussed in the Table 7.

Table 7. Performance evaluation parameters for dyeing machines [5]

Parameter	Notations	Equations
Energy input	• The Input energy can be calculated from the equation. Where, Hs is the total entalpy of the steam and can be found out from the mollier chart at the pressure of the steam supplied. Ms is the mass flow rate of the steam supplied at that specified timeperiod.	$Heat\ Input = Ms\ \times (Hs)$ (21)[6]
Energy output	• Energy output is the sum of the energy usage in the operation and the losses in the process. These losses incur due to the absorbtion of heat by the fabric, heat taken by the liquor. From the equation we will be calculating the mass of steam that is sent into the system.	$Heat\ Output = (Heat\ Usage\ in\ the\ process) + (10\%\ of\ (Heat\ Usage\ in\ the\ process)$ (22) [6]
Specific steam consumption	• Liquor ratio for every dyeing machine is specified for example, in terms of ratio 1:6 which means 100 kg of fabric will 600 litres of water. So, dividing the quantity of steam consumed with 100 kg of fabric we will be getting the steam consumed in the process.	$Specific\ steam\ consumed = \frac{Ms}{Kg\ of\ fabric}$ (23)[6]

Performance Evaluation of Other Utilities in the industry

Performance Evaluation of Air Compressor

Performance of an air compressor is affected by various parameters, where in the practice improper maintenance as well wear and tear, affect the parameters such as free air delivery, needed isothermal power, efficiency and specific power of both compressors and compressed air systems. Thus, there must be a regular performance assessment and evaluation on a time-to-time basis to deliver the air with appreciable economically efficiencies (Table 8). The measurement of air flow at compressor systems and nozzles were done according to the IS 10431:1994 and IS 5456:1985 codes. Depending on the delivery capacities, the size of nozzle is to be chosen. The sonic flow conditions (Mach No = 1) are seen for a particular ratio of pressure and ambient pressure receiver. The measurement of FAD of the compressor can be done by the Pump – up method in which the pressure inside the receiver is built up to a certain operational pressure capacity of the compressor. The time required for attaining the final pressure, by which the discharge of the FAD can be found, in required time interval. During the performance evaluation there are certain measures to be taken to prevent leakages in the compressor since leakages can effect the performance. Leaks in the compressors occurs in the air receivers, relief valves, pipe and hose joints as well as shut off valves [12].

Table 8. Steps for the performance evaluation of an air compressor [12]

Step	Parameter	Notations	Equations
I	Free air delivered (m^3/s)	• Nozzle Method: k is the flow coefficient, d is the diameter of the nozzle, P_1 and P_2 are the inlet pressures of compressor and receiver in kg/cm^2, T_1 is the temperature of the inlet air, P_3-P_4 is the pressure drop reading in the U-tube manometer occurred across the nozzle due to the flow of air, R is the gas constant of air (287 J/kg K), T_3 is the temperature at the inlet of nozzle	Free air delivered (FAD), Q_r $Qr = \frac{\pi * k * d^2 * T_1}{4 * P1} * \sqrt{(\frac{2\,(P_3 - P_4) * P_3 * R}{T_3})}$ (24) [12]
		• Pump-up Method: P_1 (kg/cm^2 a) is the initial pressure after bleeding, P_2 (kg/cm^2 a) is the final pressure after filling, P_0 is the ambient or atmospheric pressure in kg/cm^2, V is the total storage volume, T is the time taken for building up the pressure for filling (minutes)	$V = V_{receiver} + V_{cooler} + V_{piping}$ (25) 0 The free air delivery will be, $Qr = \frac{(P_2 - P_1) * V}{P_0 * T}$ (26) [12]
II	Isothermal power (KW)	• P_1 is the absolute intake pressure (kg/cm^2 a), Q_r be the free air delivered (m^3/hr), Compression ratio r	$Compression\ Ratio\ (r) = \frac{Absolute\ discharge\ pressure\ of\ last\ stage}{Absolute\ intake\ pressure\ (P_1)}$ (27) [12] $Isothermal\ Power = \frac{P * Q_r * ln(r)}{36.7}$ (28) [12]
III	Isothermal efficiency		$\frac{Isothermal\ Power}{Input\ Power}$ (29) [12]

Step	Parameter	Notations	Equations
IV	Specific power consumption	• This is measured at the rated discharge pressure	$\frac{Isothermal\ Power\ (KW)}{Q_r}$ (30) [12]
V	Volumetric efficiency	• C_d is compressor displacement (m^3/min), L is the cylinder stroke (m), D is the cylinder bore (m), S is the compressor speed in rpm, X is a constant, 1 for single acting cylinder and 2 for double acting cylinder, N is the no. of cylinders	$C_d = \frac{\pi * D^2 * L * S * \chi * n}{4}$ (31) [12] $Volumetric\ Efficiency = \frac{Q_r}{C_d}$ (32) [12]

Performance Evaluation of a Boiler System

The efficiency of a boiler usually depends on various factors as fuel quality, fouling, evaporation ratio, as well as operation and maintenance. Regular performance analysis of a boiler keeps the efficiency consistent which also improves the working of the boiler system. The boiler system efficiency can be enhanced by various techniques such as the additional installation of heat recovery equipment like super-heater, air preheater, feed water heating using economizer and regenerator (Figure 8). When it comes to the performance test of a boiler system, it can be done using two methods as indirect method and direct method [13].The direct method is done by determining the heat input and heat output from the boiler.

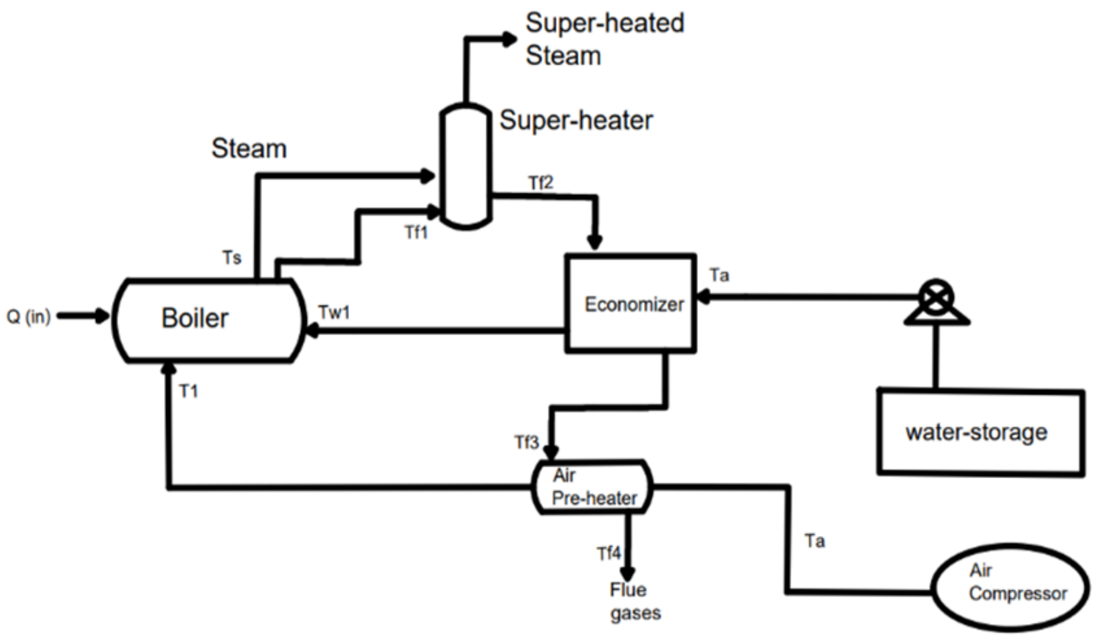

Figure 8. Boiler system scheme in a textile industry

Where $C.V$ is the calorific value of the fuel (KJ/kg), M is the mass flow rate of steam generated (kg/s), M_f is the mass of the fuel fed to the boiler in a unit time (kg/s), H is the Enthalpy of Steam (KJ/kg), H_{f1} (KJ/kg) is the Enthalpy of water at T_1 temperature (°C).

Whereas, the evaporation ratio (ER) is determined by, and this represents the economy of the boiler system, M is the mass flow rate from the economizer (kg/s), H_s is the enthalpy of the super-heated steam.

The H_{fo} is the enthalpy of water at the ambient temperature T_a, M_a is the mass flow rate of air to the economizer (kg air/s), T_1 is the temperature of air at the outlet of the air, C_p is the specific heat of air.

Direct Method

The efficiency of the boiler is given by,

$$\frac{\eta}{100} = \frac{M_s * (H - H_{f1})}{Mf * (C.V)} = \frac{Heat\ Input\ (Q_{in})}{Heat\ Output} \quad (33)\ [13]$$

$$ER = \frac{Steam\ Generated}{Fuel\ Consumed} \quad (34)\ [13]$$

But the indirect method is usually determined by considering the heat utilized and heat lost. The heat would be utilized by boiler, super-heater, and economizer as seen in the Figure 9.

Heat utilized by the boiler will be Q_{out},

$$Q_{out} = M_s * (H - H_{f1}) \quad (35)\ [13]$$

Heat utilized by the super heater will be Q_{sup},

$$Q_{sup} = M_s * (H_s - H) \quad (36)\ [13]$$

Heat utilized by the economizer will be Q_{eco},

$$Q_{eco} = M * (H_{f1} - H_{f0}) \quad (37)\ [13]$$

Heat utilized by the air pre-heater will be Q_{aph},

$$Q_{aph} = M_a * C_p * (T_1 - T_a) \quad (38)\ [13]$$

Heat Lost will be (Q_l),

$$Q_l = Q_{in} - \left[Q_{out} + Q_{sup} + Q_{eco} + Q_{aph}\right] \quad (39)\ [13]$$

Indirect Method

Indirect method, known as heat loss-method, where the performance evaluation is done by various losses that occur due to the presence of moisture, unburnt ash, incomplete combustion and water evaporation because of the presence of hydrogen in the fuel (Table 9).

Table 9. Indirect method for determining the performance of a boiler system [13]

Heat Loss parameters	Notations	Equations
Dry flue gas	L_f is the % heat loss due to the dry flue gas, m is the dry flue gas (kg flue gas/kg fuel) (proximate & ultimate analysis) C_p is the specific heat of the flue gas mixture (KJ/kg°C), T_f and T_a are the temperatures of flue gas and ambience respectively (℃)	$Lf = \frac{m*Cp*(Tf-Ta)}{GCV} * 100$ (40) [13]
Water evaporation	L_w is the percentage loss of heat due to the water evaporation, M_h is the mass of hydrogen in kg, present in 1 kg of fuel, C_p is the specific heat of the superheated steam (KJ/kg°C), Latent heat of water vapour is 584 KJ/kg	$L_w = \frac{9 * M_h * [584 + C_p * (T_f - T_a)]}{GCV} * 100$ (41) [13]
Moisture in fuel	L_m is the percentage heat loss due to the presence of moisture in the fuel, M is the mass of moisture in kg per 1kg of fuel, C_p is the specific heat of the superheated steam (KJ/kg°C), Latent heat of water vapour is 584 KJ/kg	$L_m = \frac{M * [584 + C_p * (T_f - T_a)]}{GCV} * 100$ (42) [13]
Moisture in air	L_{ma} is the loss of heat due to the presence of moisture in air, M_a is the actual air supplied per kg of fuel, f is the humidity factor is the kg water/kg dry air, C_p is the specific heat of the superheated steam (KJ/kg°C), Latent heat of water vapour is 584 KJ/kg	$L_{ma} = \frac{M_a * f * C_p * (T_f - T_a)}{GCV} * 100$ (43) [13]
Radiation and convection	L_{rc} is the percentage loss of heat due to the radiation and convection heat losses, V_m is the radiation loss (W/m^2), T_s is the surface temperature (°C)	$L_{rc} = 0.548 * \{\left(\frac{T_s}{55.5}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\} + 1.957 * (T_s - T_a)^\wedge 1.25 * \sqrt{\frac{196.5*V_m+68.9}{68.9}}$ (44) [13]
Unburnt fly ash	L_u is the percentage heat loss due to the presence of unburnt fly ash	$L_u = \frac{\frac{fly\ ash\ Collected}{kg\ fuel} * GCV of\ fly\ ash}{GCV} * 100$ (45) [13]

Heat Loss parameters	Notations	Equations
Bottom ash	*Lb* is the percentage heat loss due to the presence of bottom ash in the reactor	$L_u = \frac{bottom\ ash\ collected * GCV\ of\ bottom\ ash}{GCV} * 100$ (46) [13]

The other loss is due to the partial combustion as reduction takes place which stagnates the reaction at the formation of carbon-monoxide.

Boiler efficiency would be:

$$ŋ = 100 - \Sigma(Losses) \quad (47)\ [13]$$

The boiler sizing should be done depending on the operating conditions of the respective applications. Over-sizing the boiler reduces the optimum performance of the entire system as the heat energy input will be higher since the bigger system consumes more heat energy, but the required load will be minimum, which would affect the economy of the boiler.

Performance Evaluation of Thermic Fluid Heater

Thermic fluid heaters are used for high temperature applications which could be the better replacement for high temperature steam operations since fluids have wider operating temperature ranges than steam along with good physical, thermal and physical properties. A double coil, 3-pass shell and tube heat exchangers are provided with the jet system, deaerator, control panel and expansion tank (Figure 9). Depending on the system load, the operating temperature of the fluid vary, where the fluids have numerous advantages as minimum losses, compared to the boiler systems, operational flexibility and better thermal efficiencies than a steam heating system [14].

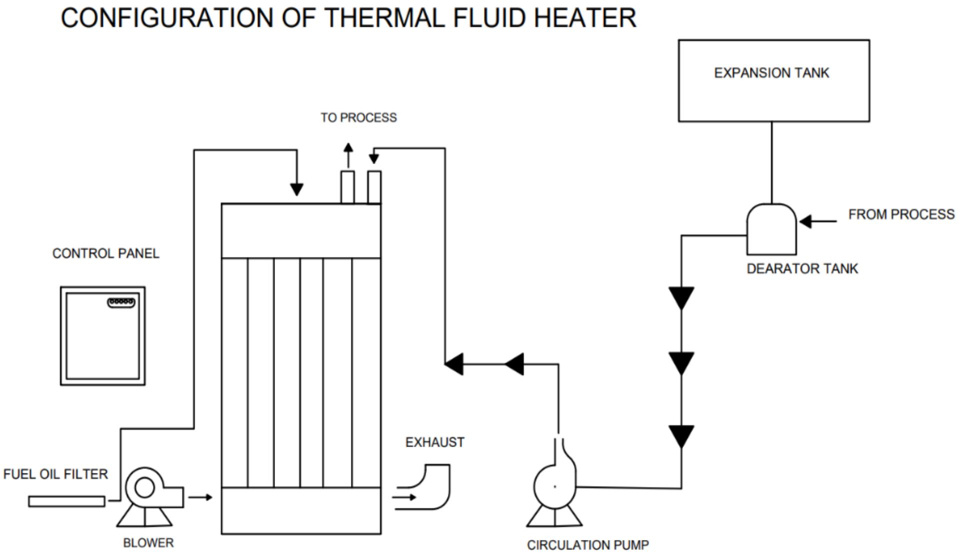

Figure 9. Thermic fluid heater working scheme

As same as the boiler, there are two methods used to evaluate the performance of a thermic fluid heater (described in the Table 10), while the indirect method of testing performance is as similar as the boiler's.

Table 10. Description of direct and indirect methods

Method	Description	Equations
Direct method	• This is also known as the input-output method in which the efficiency of the system is determined by the ratio of the heat input to the heat output. • Heat output (Q_{out}) would be the sensible heat of the thermic fluid and whereas the heat input (Q_{in}) will be the calorific value of the fuel multiplied to the feed rate of the fuel.	$Q_{out} = M * C_p * (T_0 - T_i)$ (48) [6] $Q_{in} = M_f * GCV$ (49) [6] $\eta = \frac{Q_{out}}{Q_{in}} * 100$ (50) [6]
Indirect method	• It would be the difference between the heat losses occurred and heat input given to the system. • This is also known as the heat loss method.	$\eta = \frac{Q_{in} - Q_l}{Q_{in}} * 100$ (51) [13]

Where M is the mass flow rate of the Thermic Fluid (kg/s), C_p is the specific heat of the fluid (KJ/kg °C), T_0 is the fluid temperature at the outlet of the heater (°C), T_i is the fluid temperature at the inlet of the heater (°C), M_f is the mass of the fuel fed into the heater (kg/s), Q_l is the heat loss occurred in the heater system, GCV is the Gross Calorific Value of the fuel (KJ/kg). Performance evaluation of various utilities would result in giving an actual picture of how efficient a textile industry is working.

Performance Evaluation of Humidification Systems

The humidification systems are installed in a textile industries in order to avoid problems of yarn breakage in dry and brittle condition as well to minimize the dry and fibre fluff. Generally spray air washers are used for humidification systems. The spray washer by spray water as medium gets evaporated by the air stream, thereby reducing the air dry bulb temperature and increasing its humidity [5]. So, for evaluating the humidification system performance saturation efficiency is calculated.

$$Saturation\ efficiency\ (\%) = \frac{Entering\ Air\ DBT - Leaving\ Air\ DBT}{Entering\ Air\ DBT - Entering\ Air\ WBT} \times 100 \quad (52)\ [6]$$

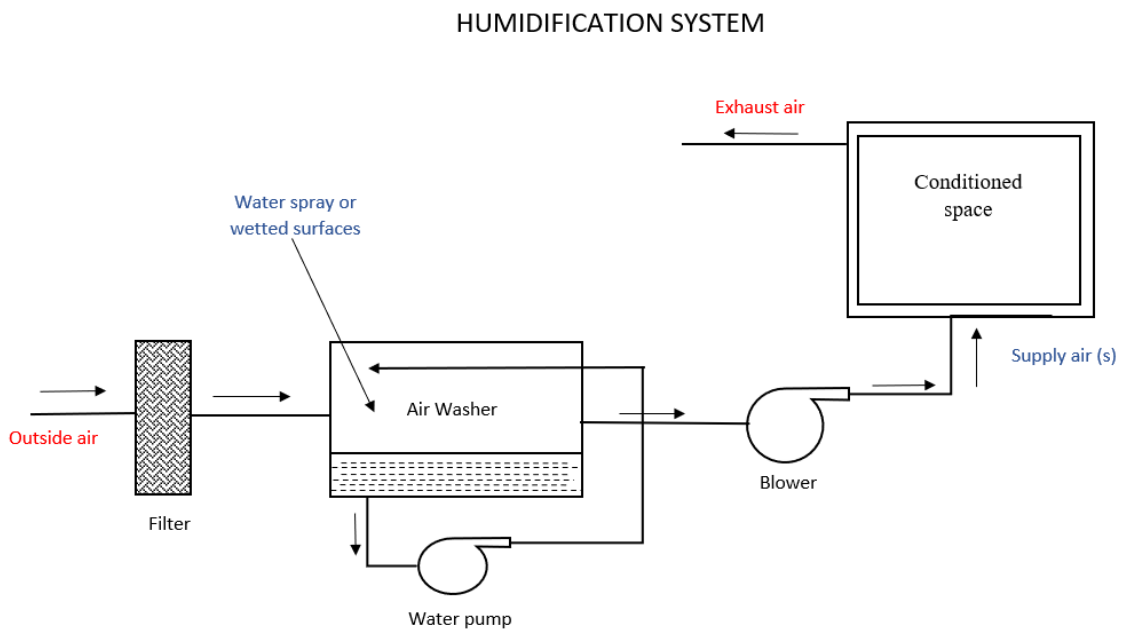

Figure 10. Working of humidification system

The saturation efficiency is improved by entering air in the air washer, where the cooled air circulated into the department area (Figure 10). The cold air will take out all of the heat leaving the operation area cold. This will increases the humidity in the operation area reducing the breakage of the yarn.

Identifying the feasible opportunities for reducing the consumption pattern of the machinery and improving the performance of the industry is discussed in the following section.

Technical Improvement Opportunities in a Typical Textile Industry

The opportunities of improving the energy efficiency in the textile industry can be done either by optimizing the operation or replacing the current machinery with the new one. In this case there is a need to concentrate on both, the cost of replacement and the energy savings after the replacement. Nafis Ahmad et al. has observed the ring frame section for the spinning process and suggested scientific approach for improving the efficiency of the machine using the TPM [15]. TPM is used as a supporting tool concentrating mainly on the maintenance, quality and efficiency [16]. Y. Dhayaneswaran and L. Ashok Kumar have observed the ring frame power distribution and plants humidification in the textile mills and found it to have a significant proportion when compared to other machines [17]. They have noticed that the ring frame machine is running with less efficiency of 91.5% on main motor so they have replaced it with the higher efficiency motor of 94.5%. The study had been conducted for energy savings where they had got a savings of 1122 kWh/month on the ring frame motor, 7260 kWh/month on the ring frame spindle speed and 9390 kWh/month on the ring frame OHTC. There also studied humidification of the plant, where it had been noticed that the motors had been loaded more than the rated load. The power factor is also observed to be poor. They have optimised the motors by servicing it and observed the savings of 10,230 kWh/month. S. Palamatuc has evaluated the electrical energy consumption in the cotton textile plant from both the production and non-production units [18]. The major deviation of the estimated electrical energy consumption was observed every month in the spinning plant of 6.5%, i.e. 30% in the warping and sizing department. The wet processing plant was found to account of 29.3% deviation from the estimated energy consumption. The reasons for deviations was investigated and found to be due to the maintenance as the repairs periodically increases and thereby accounting in the energy consumption. Saurabh Kumar Rajput investigated a textile industry located in Himachal Pradesh and found that the energy consumption is mainly in the spinning process and the motors need to be replaced by energy efficient motors of 94% [19]. The savings after the replacement of existing motors was 3202 kWh/year. The power consumption in spinning machines is accounted to be higher when compared to open – end rotor machine and ring frame. Open –end rotor machine consumes less power where ring diameter, balloon height, spindle speed and traveller mass increase power demand [19][20]. Ali Hasanbeigi and Lynn Price found that weaving machines account of 50-60% of total energy consumption in a weaving plant. Improvements of the energy efficiency can be done by the humidification, compressed air system and lighting [21].

The thermal energy majorly is consumed on heating and drying water operations. Processing operation seemed to consume more thermal energy. Textile sector is the energy consuming sector in India, where usage of solar energy for electricity and heating in textile mills can be more productive which will lead to faster payback on the solar investment [22]. Thermal energy is wasted in the process of removing the water from textile fabrics. Using heavy squeezing rolls during the water removal can reduce 15-20% of losses. Replacing the conventional system with vacuum impregnation for dyeing process can result in 60 – 65% fuel saving. Vacuum roll extractor usage can save energy up to 70% [23]. Chelmenciuc Corina has investigated how feed water economizers for the steam boilers, insulation of steam pipes improving, condensate and hot water tanks can reduce the boiler blowdown rate and improve result of efficient working of steam systems in the textile industry [24]. Energy efficiency is closely related to waste minimization where with implemented measures will result in savings [25]. The consumption in the textile industry is majorly used to heat up process baths [26]. Ciliz et al. has investigated energy consumption for cotton fabric process in a selected mill, identified overall energy consumption of finished textile is 1.5-1.7 kWh/Kg [27]. They calculated the average savings of 0.3-0.4 kWh/kg of finished plants which could achieve using a heat exchanger for bleach and dye wastewater process.

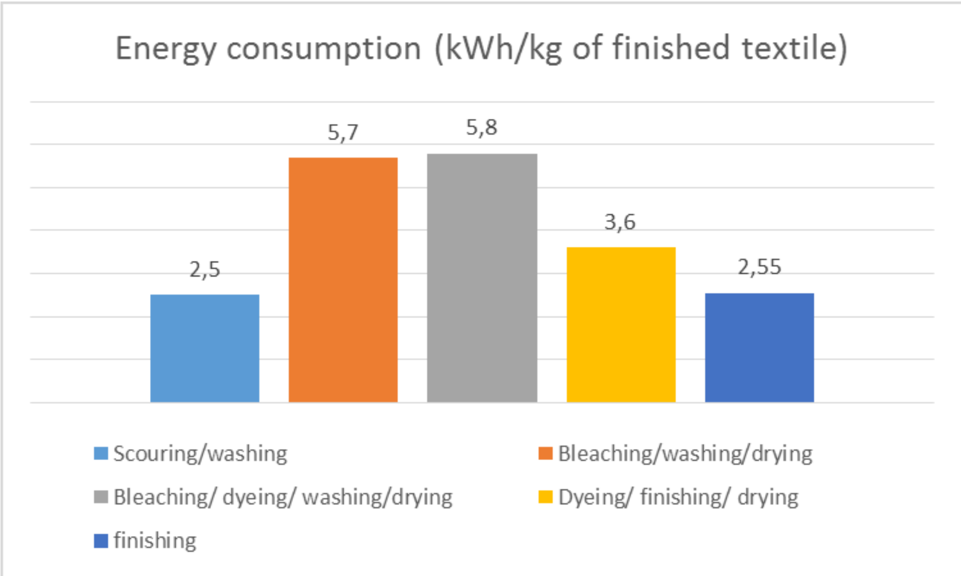

Figure 12. Energy Consumption in wet processing in the cotton fabric processes [27]

Ayse Merve Kocabas has observed that the energy efficiency in the finishing process can be improved by reducing the energy consumption in stenter frames, by optimising the exhaust airflow through the oven, heat recovery, insulation, heating systems and using burner technology [28]. Kalliala and Talvenmaa have found that implementation of best available techniques for textile wet processing can reduce energy consumption for 30% [29]. R. Tugrul Ogulata has done research on waste heat recovery in textile industry. The raw material in dye-printing is very humid, thus humid will be reduced by dryers. During the drying process the warm moist air is sent out to the surroundings, where this waste heat can be captured and then through the stream heat the fresh air in the drying system [30]. Water can be conserved during the scouring process, where the water can be deviated through another stream and used for heating the fabric during initial stages while separately the cooling water can be supplied to cool the dyeing machines, thus reducing the water consumption. Installing a computerized system in the dyeing process has resulted a 28% reduction in the water consumption [31]. ASM Monjurul

Hasan et al. had done their studies on the energy efficiency in textile industries of Bangladesh, identified that significant amount of energy has been consumed in the spinning process operation [32]. Additionally, they have listed out the opportunities from the research of Lihong Peng et al. for preparatory process, ring frame, winding, doubling, finishing, air conditioning and humidification system along wet processing unit [33]. C. Chullabodhi and S. Wangsupakukosol have done their research on the energy conservation in textile printing factory, observing that the modifications in boiler, cabinet dryers, hot water tanks and cylindrical dryers can increase the savings for the industry. Implementation of the measures have resulted in 30% decrease in the energy consumption [34]. Retno G.Dewi et al. have investigated that mitigating the factors incurred by combined heat systems, lightings, compressed air systems, motor systems, boilers, process integration, steam distribution systems will decrease the energy use for the selected textile industry [35]. After identifying the opportunities for improving the energy efficiency, the suggested measures required are discussed in the following section.

Energy - Efficiency Measures and Technologies

Improvement of energy efficiency and energy saving potential is the major area on which needs to be concentrated in industrial sectors, including the textile industries [36-38]. Aida Sa et al. have done investigations on energy management in industries. According to their research, energy efficiency means completing the given task with less energy demand [39]. Ali Hasan beige and Lynn Price have observed that energy efficiency can be improved by optimizing the process and by replacement of the current machinery [21]. J. Malinnauskaite et al. has described that the replacement of the new machinery should be justifiable after considering water savings, material savings and quality [40]. The energy efficiency measures have been discussed along with the technologies described below in the spinning process, weaving, wet processing and finishing process.

Energy Efficiency Measures in Spinning Process

After identifying the opportunities, measures has been implemented to improve the energy efficiency of the process. Y. Dhanayaneswaran and L. Ashok Kumar found that replacing the motor's efficiency of 91.5 % with higher efficient motor of 94.5 %, on trial basis, has achieved energy savings of 1122 units/ month [17]. Installation of the synthetic flat belts for spinning process, where sandwich tapes are stable and have good dimensional stability with soft and flexible tape bodies, can offer 5 – 10% of energy savings with a payback of 3 years [3]. The energy consumption in the spinning process varied, depending on the used type of spinning system, where producing yarn of middle count, the spinning process was consuming 80% of energy consumption per kg of single yarn [9,41].

Energy Efficiency Measures in Weaving Process

ASM Monjurul Hasan et al. has investigated the weaving process and found that power looms consume 50 to 60% of the total energy. For optimizing options of the process through measures are limited [32]. Ranjit Turukmane found that the energy consumption in air jet weaving, that energy consumption can be reduced by installing new technology machinery [42].

Energy Efficiency Measures in Wet Processing

Y. Dhayaneswaran and L. Ashokkumar has found that motors used in the humidification plant were loaded more than the rated load. After servicing the motor, the energy savings was 341.28 kWh [17]. Wet processing unit is the one which consumes most of the energy in the form of steam, i.e. heat energy [21]. The selection of insulation of the pipelines plays a critical role in maintaining the heat. Generally, the preferred materials for temperature below 650 ^{o}C are calcium silicate and rock wool, while for temperature range between 250 – 450 ^{o}C fiberglass is used [43]. Retno G.Dewi at al. has identified that the stream distribution lines have to be insulated well along with correctly placed steam traps [35]. Steam trap selection is the major keyway for uninterrupted operation [43]. Harun Kemal Ozturk has found that the heat recovery from wastewater can be trapped and then used to improve efficiency of the textile mill. He also observed that there was many areas with insulation without proper maintenance [44]. N Kiran Ciliz has observed that installing a waste heat exchanger for processed wastewater was able to produce energy savings of 300 Wh – 400 Wh /kg finished textile [27].

Energy Efficiency Measures in finishing process

Installing a waste heat recovery for stenters was able to result in energy savings with a payback period of 5 years. Replacing electric heating with the thermic fluid heating was more desirable and able to produce savings with a back-up period of 3 years [3].

Best Available Technologies

Technologies which are currently used in the textile industry are listed in the Table 11. These technologies are reviewed on basis of their energy consumption. Improvement in the processes can be done by changing the mode of operation through technology. The BAT have been listed in the Table 11. These technologies can be implemented in practice which can benefit the textile industry performance.

Table 11. Best available technologies in the world [45]

Technology	Description	Process
Vortex spinning and Jet spinning	• The energy costs are reduced when compared to ring and open end rotor spinning systems [45]. • Production speed is about 450 m/min which is 2 to 3 times more than open end rotor spinning and 20 to 30 times more than ring spinning which means greater productivity [45].	Spinning process
Multi-phase looms	• Multiphase looms can be used instead of single phase looms which consume less energy for the same output.	Weaving process
Ultrasonic treatments	• Low process temperature is maintained which results in energy savings [45].	Wet processing
Ultrasonic treatments	• Reduced dye consumption which resulted in 20-30% of reduction in the amount of effluent [45].	Wet processing
Real-time-on-line monitoring systems	• These systems can maintain good control on the textile production which will reduce the energy usage, reduce the water consumed and reduce excess usage of chemicals [45].	Control technologies

CONCLUSION

Textile industry is an energy intensive industry as consumption takes place in every operation from spinning to finishing processes where there are opportunities to improve the energy efficiency in the industry. Energy consumption is a key factor that affects India's textile sector. This paper has gone through the PAT scheme which is being implemented to reduce the energy intensity. Textile sector was being considered as a designated consumer in each cycle from 2012-2021. Performance evaluation for utilities has been discussed in the paper. So, for a typical industry after evaluating the performance certain measures need to be taken. Studies for improving the performance have shown that spinning operation has a significant amount of electricity consumption, mainly in the ring frame process. This consumption can be decreased by replacing the old inefficient motors with the efficient motors, practising this measure has resulted in energy savings which has been discussed in the above sections. The heat consumption was identified to be more in the wet processing process, mainly in the stenter machine. Studies have shown that replacing electric heating for drying purposes can be replaced by thermal fluid heating which has improved the wet processing process. Wastewater, which is drained out of the dyeing process, contains heat which can be captured and can be supplied back to the system through a heat exchanger for improving the efficiency of the process which is the solution to clean energy technologies. The emissions were observed majorly from dyeing and finishing process, where waste gases can be used as waste heat recovery option by installing a heat exchanger and using the heat as per requirement in a specific area, thereby incurring energy savings. This improves the processes involved in the textile industry reflecting on its performance. Solar power can be used as a power source for auxiliary systems such as lighting in the industry. Based on the results of the study, energy intensity variation estimated in the PAT scheme can be re-evaluated by also considering renewable sources which will reduce both the dependency on the traditional fuels and conventional methods which will result in energy savings. As most of the textile comes under micro, small medium sized enterprises, the cost-effective methods are not implemented due to the lack of resources. This paper provides information on evaluating the performance with suitable energy efficiency measures which can be followed based on the resources and economic factors for implementation in their respective production units. The best available technologies are discussed, and it can be followed in the textile industries which could impact on the energy efficiency performance.

Author Contributions

Conceptualization – Gunturu KPK, Kota KK and Sharma M; methodology – Gunturu KPK, Kota KK; formal analysis – Gunturu KPK, Kota KK; investigation – Gunturu KPK; resources – Gunturu KPK, Kota KK; writing-original draft preparation – Gunturu KPK, Kota KK; writing-review and editing – Gunturu KPK, Kota KK; visualization –Sharma M; supervision –Sharma M. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

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