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Modelling Energy Consumption with Value Stream Mapping and Dual Energy Stream Approach: Case Study of Tea Processing facility

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Abstract- The tea processing industry is fundamentally energy intensive, relying heavily on both thermal and electrical energy across manufacturing chain. Majority of tea manufacturing factories in Kenya under K.T.D.A management operate with sub-optimal energy management system, therefore missing opportunities for energy saving. Regular energy audits are insufficient in addressing high energy consumption. This research addressed high energy consumption in Kenyan tea manufacturing facilities using energy value stream map (EVSM) approach and by focusing on electrical energy. The main objective of the research was to model energy utilization using EVSM and dual energy stream approach for the purpose of optimizing section energy consumption. Using Kapkoros Tea Factory as a case study, the research systematically mapped energy consumed in production in order to visualize energy flows, section inefficiencies and bottlenecks. Electrical energy consumption was determined using data logger and energy smart meters. Efficiencies were determined using tachometers and rated motor torques. Modelling and simulation were then performed using Matlab for system optimization. The results were validated against EPRA, SLSEA and BEE benchmarks. The research determined that EVSM is viable tool for energy mapping in tea manufacturing facility. The case study facility had an energy use intensity (EUI) of 0.535Kwh/KgMT with an OEE of 85% and EER of 1.2. But through modelling and simulation the factory could operate at EUI of 0.437Kwh/KgMT with an OEE of 93% and EER of 0.92. This could be achieved through replacement of cast iron axial fans with alluminium VFDs. Installing continuous withering technology in withering section and updating maintenance procedures. The results obtained compared well with BEE benchmark of 0.47Kwh/KgMT and SLSEA standard of 0.51Kwh/KgMT. Under optimal consumption, energy efficiency ratio (EER) of the factory was determined to be 0.86 against SLSEA and 0.92 against BEE. The outcome of this research could become a base setter on how factories in Kenya should manage energy consumption in their utilities with potential scalability across the tea industry. The research highlighted key interventions through proposed energy saving strategies and demonstrated EVSM potential for energy efficiency management framework.

Keywords: Energy, Modelling, EVSM, EUI, EER

I. INTRODUCTION

The tea processing industry is energy-intensive, with significant energy consumption occurring during various stages of tea processing, such as withering, fermentation, and drying. According to (Improving Energy Efficiency in the Tea Sector - SNRD Africa, n.d.) to produce one kilogram of tea one needs approximately 3Kwh to 6 Kwh of thermal energy, supplied mainly from wood combustion and 0.2Kwh to 0.5 Kwh of electrical energy from the grid and diesel generators. About 12 to 15 % of total energy required in tea manufacturing is electrical energy while thermal energy accounts for over 80 %. However, the unit cost of electrical energy is much higher than thermal energy from wood products. According to (Energypedia, 2023), although electricity has a share of 15% of total energy consumption, it has a share of more than 50% of total energy cost. According to(Improving Energy Efficiency in the Tea Sector - SNRD Africa, n.d.), on average individual tea factories spend approximately 30 to 65 million Kenya shillings on electricity annually depending on factory size, crop level and other variable costs. Improving energy efficiency and cycle times in tea processing plants is crucial for reducing operational costs, minimizing environmental impact, and ensuring sustainable tea production.

Over the past view decades; lean manufacturing has been the pinnacle of strategies applied for cost and waste reduction. Manufacturing systems have evolved significantly over the years, with a growing emphasis on efficiency, productivity, and waste reduction. Lean manufacturing, a methodology that focuses on maximizing value by minimizing waste, has become increasingly popular in the industry. Lean manufacturing entails being responsive to change through the elimination of waste and focusing on quality during production process. Implementation of lean manufacturing practices has a key impact on attaining improved performance since it helps manufacturing firms manage their internal operations(Battistoni et al., 2013). Developed specifically for Toyota Production Systems (TPS) lean manufacturing is a popular instrument that is used in present day manufacturing industry and service sectors.

Value stream mapping (VSM) is a lean manufacturing tool used to visualize and analyze the flow of materials and information throughout a process. An improved version of value stream mapping is energy value stream mapping (EVSM). By applying EVSM to the tea processing plant, researchers can identify inefficiencies and opportunities for energy reduction. The dual energy signature approach, which combines both qualitative and quantitative data, provides a comprehensive understanding of energy usage and helps in developing targeted strategies for energy optimization. According to (Müller et al., 2014) they developed a dual approach for appraising the process-related input of energy using the criteria ‘value adding’ and non-value adding. This dual approach allows for the first time extending the proven VSM to an EVSM (figure 1) by following the principles of the Toyota Production Systems (TPS).

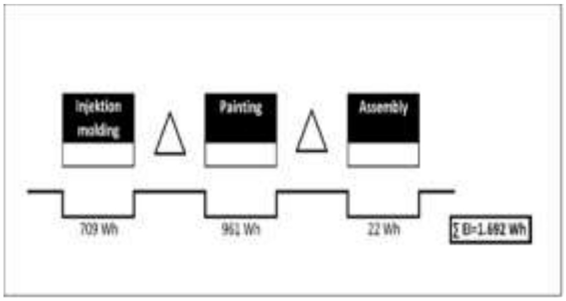

Figure 1: Extension of VSM to EVSM (Müller et al., 2014)

Despite advancement in energy efficient technologies, many plants operate with sub-optimal energy management systems. Conventional anergy audits often fail to provide a comprehensive understanding of energy flows across entire value chain. This gap results in missed opportunities for energy savings and high operational costs. Tea processing firms in Kenya are reporting severe financial position attributed to increased cost of production mainly attributed to energy cost. Majority of these manufacturing firms are staring at financial insolvency with very high risk of closing down if energy question is not addressed. It is for this reason that this research was carried out to visualize energy utilization signature, identifying bottlenecks and inefficiencies and recommending improvement action plan. Kapkoros tea factory is one of the tea processing plants located in South Rift region in Kenya. Their operations are strained by ever increasing cost of production attributed to high energy cost. This manufacturing facility is ideal approximation of several tea processing firms in Kenya under Kenya Tea development Agency which faces energy cost challenges. However, prudent utilization of energy within the plant cannot be realized unless there is better understanding of process’ energy utilization efficiencies. Energy value stream mapping is a lean methodology this research leveraged on using dual energy stream approach according to (Müller et al., 2014). This technique was used to map out energy and cycle time waste in tea processing plant, identify the wastes and develop improved energy utilization framework for tea industries. For this reason, this research proposed empirical study of processes and sub-systems in tea value chain by applying EVSM using dual energy stream approach in order to identify non-value adding processes and cycle times. The outcome of this research will be used to bridge energy audit gaps, energy budgeting and planning. Optimization strategies to improve energy utilization and cycle times in processes and sub-systems were developed.

II. METHODOLOGY

A. Research design

The research adopted a case study approach focused at Kapkoros Tea Factory. The approach adopted was quantitative involving determining electrical energy consumption and modelling using energy value stream mapping and dual energy stream approach. Data analysis was then performed with the help of statistical tools such as regression analysis and quantitative data analysis such as standard deviation, Z-score and relative position analysis. To optimize the process modelling and simulation was done using Matlab software. Model validation was then performed against internation Benchmarks such as BEE and SLSEA.

B. Scope of research

The research was carried out at Kapkoros Tea Factory, situated in Bomet County Kenya. The research focused on electrical energy consumption; process cycle time and waste associated with them. The processes involved were withering, CTC, drying and boiler operations.

C. Data collection

The primary data was collected as described in the scope of the research through measurement using data logging tools and tachometers. Previous data on energy audits on electrical energy consumption and energy intensity was studied and analyzed. Operational data provided process cycle times, consumption trends and throughput as well. Rated machine efficiencies for section were collected from the nameplates of each machine. Using tachometers, actual motor speeds were collected when machines are loaded in order to calculate actual motor efficiencies. The data logger was used to log data consumption in each section whereby section power demand and energy consumed were determined. For secondary data, the research scrutinized historical energy bills and load profiles as well as production reports. Technical manuals were reviewed for equipment specifications and manufacturer guidelines for energy consumption. Industry benchmark data from Energy and Petroleum Regulatory Authority (EPRA), SLSEA and BEE were studied in order to compare with plant’s energy performance.

D. Tasks and procedures

The tasks were arranged according to set objectives to be fulfilled. Each objective was performed before the next one. Each objective was broken down into tasks and procedures logically to collect and record required data.

E. Mapping out energy consumption

a. Starting with withering section, energy consumption data was collected on withering fans using data loggers and infrared tachometers.
b. Power consumption was collected when machines were loaded.
c. Power consumption load profile (graph of power-time) was then obtained from data logging systems for loaded status.
d. Using tachometers, the speeds of the motors were obtained while running in loaded status.
e. Power factors and motor efficiencies were collected from nameplates and manufacturer data sheet were obtained and studied.
f. Energy data box was created for further analysis.
g. Energy value stream map was then drawn.

F. Analysis of current energy state map

The current state map of all critical processes was then analyzed. Energy consumption and cycle time for each process cycle was determined. Using dual energy stream approach, value-adding energy and non-value-adding energy was determined. Value-adding and non-value-adding cycle times were also determined. Inefficiencies and bottlenecks were then identified. Opportunities for improvement were identified. This step formed the basis for creating a future state map.

G. Modeling and simulation of improved energy state map

Simulation was then performed using Matlab platform to visualize energy flows and forecast different energy scenarios by controlling the throughput and energy waste at different sections. Future state map with improved energy consumption was then created based on simulation experience. Validation was then done against industry benchmark data on tea manufacturing in Kenya from Energy and Petroleum Regulatory Authority (EPRA).

H. Validation of the model

To validate the model and evaluate improved energy consumption, the following key performance metrics were used:

a Energy use intensity (EUI)

This metrics measure the amount of energy used to make a kilogram of made tea. It is calculated as shown in equation 3.1.

$$EUI = \frac{\text{Energy Consumed in Kilowat} - \text{hours}}{\text{Made tea in kilograms}}$$

(3.1)

b Energy efficiency ratio (EER)

Using the standard EER methodology;

$$EER = \frac{\text{actual EUI}}{\text{benchmark EUI}} \tag{3.2}$$

where EER < 1 indicates high efficiency and where EER > indicates need for improvement. An when EER = 1 indicates match with standard.

c Overall facility efficiency (OEE)

To evaluate how well the facility converts energy consumed into useful form through value addition, overall facility efficiency was calculated using equation 3.3. It calculates the ratio of value adding energy to none value adding energy.

$$OEE(\%) = \frac{\sum E_{VA}}{\sum(E_{VA} + E_{NVA})} \tag{3.3}$$

These metrics evaluated the success of the proposed improved energy state map the factory may implement.

III. RESUILTS AND DISCUSSION

A. Factory energy consumption

Modelling based on withering shift of 70,000 Kgs (Table 1) of green leaf and cycle time of 7 hours, this section consumes a total of 2824.64Kwh as shown in figure 2. The section power demand is as shown if figure 3. Energy consumed in Kwh is calculated as in equation 4.1.

$$Energy = Power \times Time \times cos\emptyset \tag{4.1}$$

The factory achieved an out-turn of approximately 22.5% and based on 70,000 Kgs of green leaf, it translates to 15,750 Kgs of made tea (KGMT

Table1: Factory energy consumption

SECTION	THROUGHPUT(KG/H)	(KGMT)	PROCESSING TIME	POWER DEMAND(Kw)	ENERGY CONSUMED(KWH)	SECTION ENERGY INTESITY (Kw/Kg MT	ENERGY WASTE(Kwh)
WITHERING		15,750	7	403.52	2824.64	0.179	906
CTC	5400	15750	11	228.9	2517.9	0.160	228.25
DRYER	5400	15750	11	161	1771	0.112	55.8
BOILER	5400	15750	18	73	1314	0.083	54.36
			TOTAL	866.42	8427.54		1244.41
				ENERGY INTENSITY	0.535	0.535	

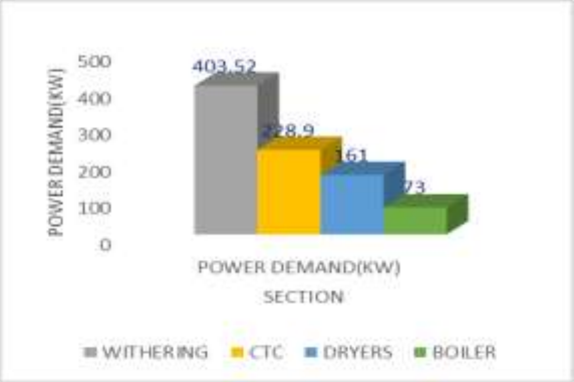

Figure 2: Section power demand

B. Overall energy consumption trends

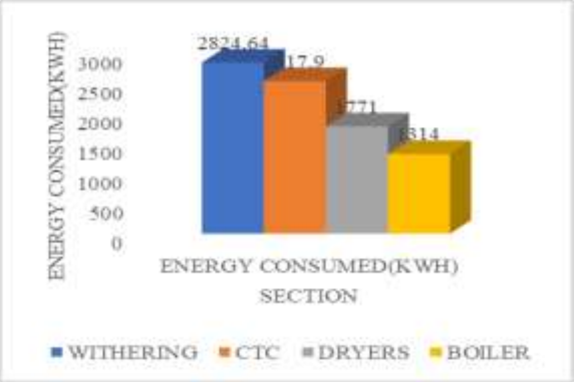

Figure 3: Section energy consumption

Weekly consumption trends are as shown in table 2. The weekly processing capacities varies with a low of 98, 300 KgMT to a maximum of 147, 986 KgMT.

Table 2: Weekly electrical energy efficiencies for the month of January, February and March 2025

Week Ending	Made Tea (Kgs)	Electrical Energy Used (KWh)	Energy Intensity (Kwh/KgMT)	Average through put
05/01/2025	129720	66947	0.52	5384
12/01/2025	117412	67766	0.58	5241
19/01/2025	147986	75182	0.51	5094
26/01/2025	140205	70308	0.50	5615
02/02/2025	116315	65101	0.56	5643
09/02/2025	106404	57544	0.54	5630
16/02/2025	108845	59693	0.55	5217
23/02/2025	99683	51158	0.51	5225
02/03/2025	98300	45175	0.46	5365

The electrical energy used varies proportionally as shown in figure 4. Energy consumed is a function of amount of green leaf to be processed. This indicates that an opportunity to save on energy used lies on waste elimination in sub-systems. One such opportunity exists in withering section and on machine efficiency management.

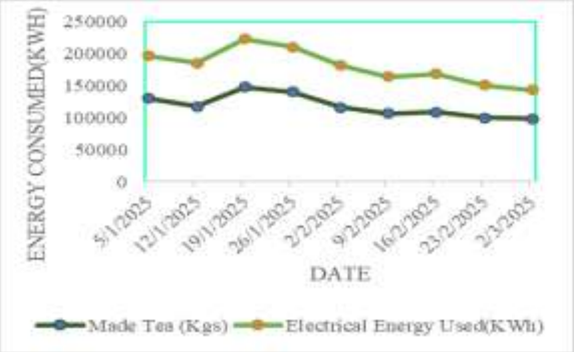

Figure 4: Weekly electrical energy consumption trends vs production trend

Energy intensity has been oscillating between 0.5 Kwh/KgMT) and 0.6 Kwh/KgMT except on week 9 as shown in figure 5. The drop in energy intensity suggests there is an opportunity for improvement if some critical decisions are made especially touching on withering section and factory maintenance regime.

Figure5: Energy intensity

C. Factory energy regression model

The factory regression model for Kapkoros Tea factory was created from the data collected and is as shown in figure 6 while the EPRA regression model is shown in figure 7. Comparing the two graphs, the factory has an opportunity for improvement in terms of energy intensity. Currently the factory is operating below the benchmark index. The factory exhibits some pockets of out-of-range intensities which are more than 0.55Kwh/KgMT suggesting the need to improve energy consumption in some critical sections.

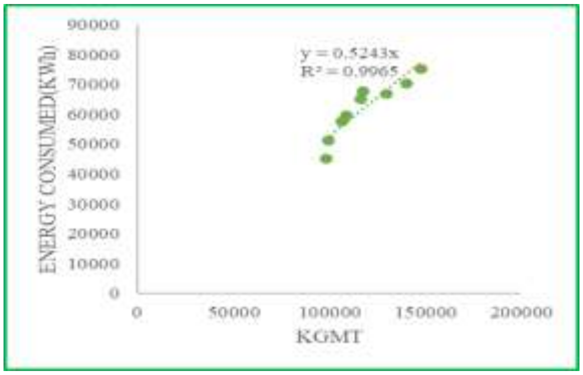

Figure 6: Factory energy regression model (Kapkoros)

Coefficient of determination of 0.9965 implies that 99.7 % of energy consumption is attributed to mass of processed made tea suggesting that the model is almost perfect representation of the true energy consumption in the tea manufacturing plant. However, this model is not perfect suggesting that energy consumption is due to other losses explained so far. These losses are efficiency losses, design losses such as withering fans, phase imbalance, cycle time losses and other factors. If compared with EPRA model in figure 7, one can deduce that energy inefficiencies exist in production process however, there is potential for energy savings. The factory is exhibiting energy intensity of 0.5243 against 0.5159 EPRA benchmark. This value could be slightly higher if other auxiliary consumptions is factored in. The plant is bleeding energy in critical processing sections.

D. Factory energy state map.

Figure 8 shows the energy value stream map of the factory. This map was created by combining all energy data boxes of withering, CTC, dryer and boiler sections. The purpose of this map is to depict immediate and precise status of energy consumption in manufacturing facility. The total energy consumed is 8427 Kwh, 7183.01Kwh is value adding energy while 1,244.53Kwh is waste energy. This map is therefore the current energy state map of this facility. It is quite obvious that withering section is the bottleneck in energy consumption followed by CTC. Other critical section such as dryers and boilers appears to perform optimally. Future energy state map will attempt to address the bottlenecks occasioned by the waste in respective section. The overall value adding efficiency of the factory is calculated according to equation 4.2.

$$\% \, \eta_{E_{VA}} = \frac{\sum E_{VA}}{\sum (E_{VA} + E_{NVA})} \tag{4.2}$$

$$\% \, \eta_{E_{VA}} = \frac{(1918.6 + 2289.65 + 1715.12 + 1259.64)}{(2824.6 + 2517.9 + 1771 + 1314)}$$

$$= \frac{7183.01}{8427.5} \times 100$$

$$= 85.2\%$$

85.2 % of energy being consumed is useful energy that goes into every kilogram of made tea. 14.8% is none value adding and is a waste reflected in energy intensity. Every effort should be made to minimize this waste.

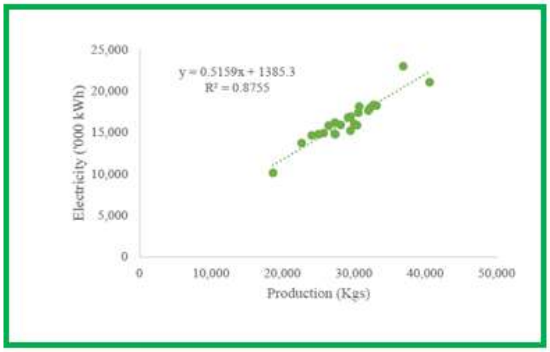

Figure7: EPRA energy regression model for tea factories in Kenya (Benchmark, 2024)

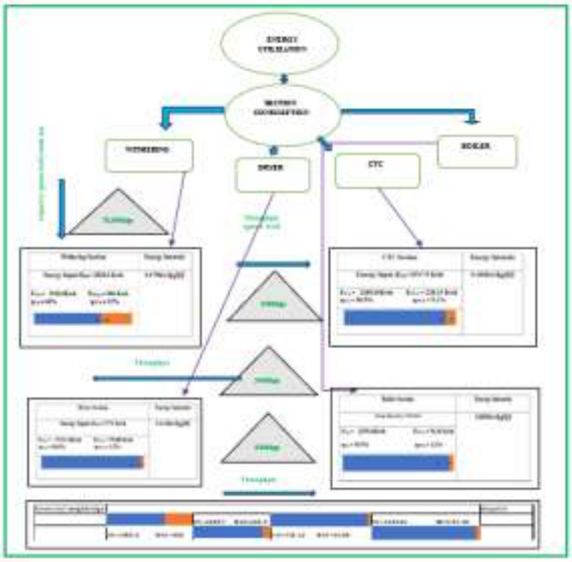

Figure 8: Energy value stream map of Kapkoros Tea Factory

Withering is the bottleneck as it shows having high proportion of non-value adding energy followed by CTC section.

E. Modelling energy consumption

To create improved energy state map, different scenarios of energy consumption and process cycle times were modelled and simulated using Matlab. The control parameters adopted were section power demand and section process cycle times. A desired state was obtained by eliminating possible wastes in critical sections, therefore creating a new power demand dynamic. Furthermore, reducing process cycle time resulted in desired state of energy consumption which was achieved through process reorganization and streamlining.

The number of sections to be modeled are four; withering, CTC, dryer and boiler section. The section power demands obtained from data logs (primary data) are as was modeled based data in table 1. Demands are 403.52Kw, 228.9Kw, 161Kw and 73Kw for withering, CTC, dryer and boiler section respectively.

The process cycle times obtained from factory secondary data were modeled based on data in table 8. Process cycle times are 7hr, 11hr,11hr and 18hr for withering, CTC, dryer and boiler section respectively. These cycles times were based on factory withering capacity of 70,000Kgs of green leaf.

Energy consumed per section is modeled using energy equation as shown in equation 4.3. The obtained model gives total energy consumed in a given section as a function of process cycle time.

$$\text{Energy consumed}\,(\text{Kwh}) = \text{Power}(\text{kw}) \times \text{time}(\text{hrs})$$

(4.3)

Value adding energy per section is modeled as a function of section efficiency as shown in equation 4.4. This is the actual energy that goes into value addition of each kilogram of made tea. This component of energy should be optimized at all times in order to section improve energy intensity.

$$\text{Value Adding Energy}\,(\text{Kwh}) = \text{Energy consumed}\,(\text{Kwh}) \times \text{efficiency}$$

To obtain none value adding energy(waste), the model was created by finding the difference between energy consumed in equation 4.3 and equation 4.4 and as shown in equation 4.5.

$$\text{None Value Adding Energy (Kwh)} = \\ \text{Energy consumed}(\text{Kwh}) - \text{Value Adding Energy (Kwh)}$$

(4.5)

This is the energy component (Eqn. 4.5) that add no value to made tea and is therefore considered a waste. The facility should minimize it in order to improve on energy intensity.

F. Modelling and simulation of current energy state for tea processing facility

At the moment, this manufacturing facility is consuming 2824.64Kwh, 2517.90Kwh, 1771 Kwh,1314Kwh for withering, CTC, dryer and boiler respectively. This consumption is based on withering capacity of 70,000Kgs which translate to 15750Kgs of made tea based on out-turn of 22.5% (table 1). The model showed that 903.88Kwh, 226.61 Kwh, 53.13Kwh, 52.56Kwh is wasted energy for withering, CTC, dryer and boiler respectively attributed to system inefficiencies. The section efficiencies are 68%, 91%, 97% and 96% for withering, dryer and boiler respectively. The total facility consumption is 8427.54Kwh of this 1236.19Kwh is wasted energy representing an overall facility efficiency of 85%. The facility energy intensity is 0.535Kwh/KgMT. This energy intensity is higher than EPRA recommended standard of 0.50Kwh/KgMT. Potential do exist of this manufacturing facility to improve this performance to 90% by eliminating section wastes and reducing process cycle times. The simulation of current energy state map is as shown in figure 8. The simulation shows that withering is the bottleneck followed by CTC section.

The poor performance exhibited by withering section is attributed to design wastes associated with cast iron axial fans, outdated withering technology and manual human handling of fresh green leaf which leads to extended cycle times. These factors contribute to more energy consumption and energy waste. These bottlenecks can be simply eliminated by introducing automation for example continuous withering technology. Optimizing fan design better designing fan blade orientation and using alluminium as fan blade material. Using carbon fiber as fan blade material should also be explored. Automation alone eliminates human errors during loading hence optimization of section cycle time. The subsequent energy states will leverage on these optimization strategies to continuously improve section energy consumption.

CTC section comes second in poor performance after withering. Aging CTC is the main contributor to this level of performance. Old motors which have been rewound many times was observed in this section. Phase imbalance was also observed which could damage motors. Loose pulley belt drives were observed which can lead to loss of power during transmission. These factors diminish level of performance in this section. Solution to these bottlenecks is straightforward. First, CTC modernization should be immediate intervention urgently needed. With modern CTC comes with new motors hence good performance in the section. The facility should adopt condition based and preventive maintenance regime on both electrical and mechanical components in this section. This will enhance quick and real time response to faults like phase imbalance and loose pully belt drives.

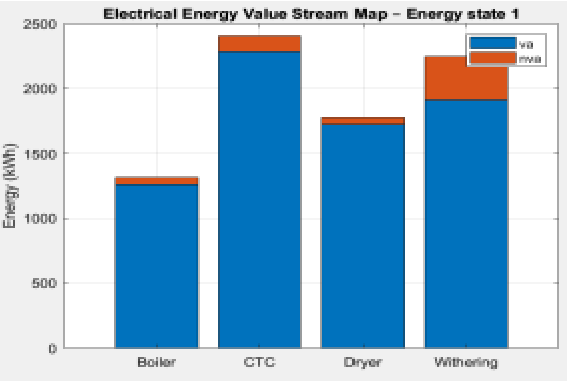

Figure 9: Simulation of energy state 1

The simulation shows that total energy consumed has gone down to 7172.37Kwh from 8427.54Kwh of previous state while the overall facility efficiency has gone up to 93%. Withering consumption has gone down from 2824.64Kwh to 2246.44Kwh reflecting interventions taken on fan design and efficiency improvement through proper maintenance. CTC consumption reduced from 2517.9Kwh to 2403.78Kwh. However, CTC consumption is higher than withering consumption, but still withering exhibit higher none value adding energy than all other sections (Figure 9). Withering overall efficiency however has gone up to 85% from 68% in the previous state implying that the implemented corrective action is bearing fruit. The facility energy intensity is 0.491Kwh/KgMT matching EPRA index. This energy intensity is approximately equivalent to EPRA recommended standard of 0.50Kwh/KgMT. The achievement implies that modernization through automation and investing in new systems and equipment is a major break though and this cannot be ignored.

H. Energy state 2

This state was achieved by reducing section cycle time combined with improvements made in energy state 1. This step yielded better results compared to results of energy state 1, that is energy state one. For example, a 5-hour withering shift could be achieved with continuous withering technology. However, if the facility retains the current technology and handling of green leaf is streamlined coupled with sufficient steam from the boiler, withering shift could be reduced to 6 hours shift on average. CTC could be optimized so that the throughput achieved is 6,000Kgs per hour from 5400Kgs per hour. If this is maintained, cycle time could be reduced to 10hrs from 11-hour cycle which represent a saving of 1 hour. One of the principles of TPS (Toyota Production Systems) is continuous improvement. TPS being one of the pillars of lean manufacturing demands continuous improvement. This principle is noticeable from how energy consumption is continuously improving from current energy state, energy state 1 and now energy state 2. Only when further improvement is not possible is when we shall call it an optimal system. Major improvement attributed to optimizing throughput from 5000Kgs per hour to 6000Kgs per hour (green leaf).

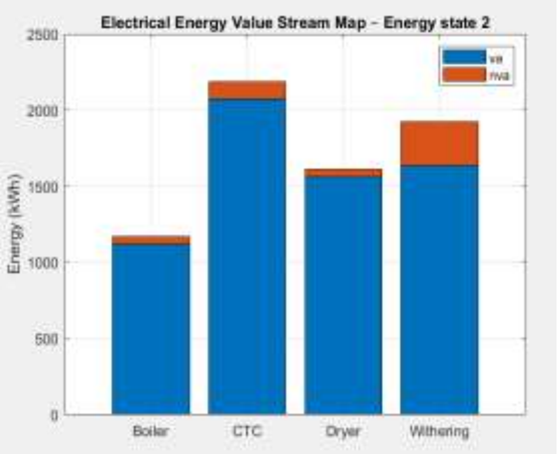

Figure 10: Simulation of energy state 2

The total energy consumed has gone further down to 6888.77Kwh from 7735.22Kwh of previous state while the overall facility efficiency has been retained at 93% suggesting optimal energy consumption as shown if figure 10. The facility energy intensity is 0.437Kwh/KgMT out performing EPRA index. This energy intensity is below EPRA recommended standard of 0.50Kwh/KgMT. The achievement implies that modernization through automation and investing in new systems and equipment is a major break though and this should be adopted by all tea industries. There is overall reduction in energy consumption across all the sections. This energy state is the most desired state the facility can adopt for sustainable production. Any further improvement beyond this performance demands new improved technology in tea manufacturing. This is therefore the desired future state map.

I. Projected energy intensities

Base on the simulation, the three energy states obtained (table 3) were 8427.54KWh,7735.22KWh and 6888.77KWh for current energy state, energy state 1 and energy state 2 respectively. The corresponding energy intensities were 0.54 Kw/KGMT, 0.49KW/KGMT and 0.44Kw/KGMT respectively. These findings showed that energy state 2 is the optimal state with least energy intensity of 0.44Kw/KGMT, a performance that far exceeds the industrial benchmark of 0.516Kw/KGMT(EPRA).

Table 3: Energy state and corresponding energy intensities

Energy state	Energy consumed (KWh)	KG MT	Energy intensity (KWh/KGMT
Current Energy state	8427.54	15750	0.54
Energy state 1	7735.22	15750	0.49
Energy state 2	6888.77	15750	0.44

Variations of energy intensities from simulation were as shown in figure 12. Summary of performance metrics was as shown in figure 11. An optima state with OEE of 93% and EUI of 0.437Kwh/KgMT was achieved.

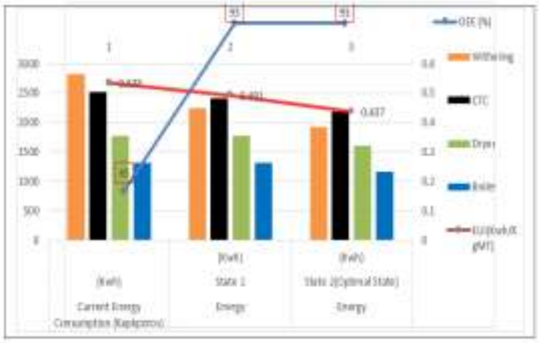

Figure 11. Factory performance metrics

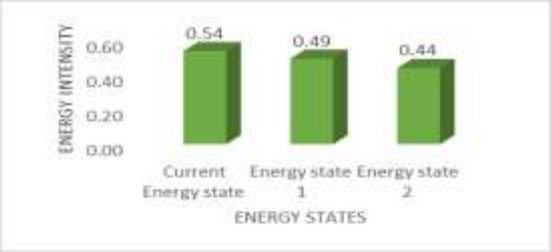

Figure12: Simulated energy intensities

Current energy intensity trend is not optimal as shown in figure 13 simply because the facility consumption is not optimized. However modelled energy intensity is stable because performance parameters have been optimized. There is therefore predictability in terms of energy consumption irrespective of daily processing capacity. The managers will be able to plan financial obligation related to energy use on time therefore enabling seamless operation. Abnormal energy consumption will also be detected on time and root course quickly identified and corrected. Energy value stream map being the cardinal principle of lean manufacturing enhances visibility.

Figure 13: The monthly trend of energy intensities

In order to gauge the viability of the model and optimal energy state 2, the performance must be compared with EPRA performance which is the Kenyan benchmark (Figure 7).

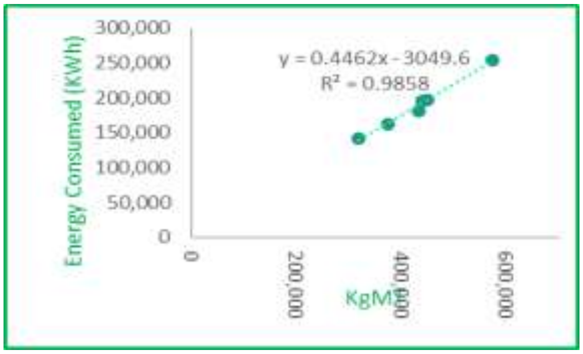

Figure 14: Optimized energy regression model of the facility

A coefficient of 0.4462 compared to 0.5159 suggest an improvement in facility energy consumption. Coefficient of determination of 0.9965 implies that 99.7 % of energy consumption is attributed to quantity of made tea suggesting that the model is almost perfect representation of the true energy consumption in the tea manufacturing facility. This performance is stronger than EPRA performance with coefficient of determination of 0.9858. If energy state 2(optimal state) operating conditions are implemented, the facility will achieve projected energy intensity as shown in regression model as depicted in figure 14. This implies the facility will operate within the EPRA standard, which is economical and sustainable.

J. Technical solution

Technical solutions must be sought in order to achieved energy state 2. Developed technical solutions target minimization of energy wastes but are subject to implementation cost. For short term, installation of alluminium VFDs and continuous withering is recommended. In the long-term total system automation is recommended.

K. Axial fan replacement

During the course of doing research, an interesting finding was uncovered in withering section. In this facility, withering axial flow fans were made of cast iron. As compared to alluminium type, cast iron axial fan is inefficient. As a result of this scenario alone, this facility is wasting 553Kwh per single withering batch of 70,000 Kgs. This is a huge waste considering associated cost. To optimize electrical energy consumption, the facility should consider replacing all the cast iron axial flow fans with alluminium type therefore saving 553Kwh for every 70,000 Kgs of green leaf processed. Axial fan performance was modelled as follows;

Mass moment of inertia was calculated using fan equation 4.6:

$$I_{CAST} = I_{hub} + \sum I_{blade} \qquad (4.6)$$

I_{hub} is estimated as 1/2Mr^2 and I_{blade} is estimated as 1/3ML^2 Therefore, the mass moment of inertia is calculated as follows:

$$I_{CAST} = \left(\frac{1}{2} \times 7 \times 0.19^2\right) + \left(\frac{1}{3} \times 3.5 \times 0.41^2 \times 6\right)$$

$$= 1.30305 kg.m^2$$

$$I_{AL} = \left(\frac{1}{2} \times 4 \times 0.175^2\right) + \left(\frac{1}{3} \times 2 \times 0.425^2 \times 7\right)$$

$$= 0.90417 kg.m^2$$

The funs run at 960 r.p.m equivalent to 100.5 rads/sec.

While starting the fun, $\omega_0 = 0\ \omega_f = 100.5$

The fun takes an average of 6secs to reach maximum velocity of 960 r.p.m.

Using the equation of uniform circular motion,

$$\omega_f = \omega_0 + \alpha t$$

$$100.5 = 0 + \alpha(6)\alpha = 16.76 rad/s^2$$

For cast iron fan, the axial fan torque requirement during starting is given as:

$$T = I\alpha$$

$$T = 1.30305 \times 16.76$$

$$= 21.84 N.M$$

(without considering fan blade aerodynamic drag and negligible bearing friction)

The axial fan power requirement is given as;

$$P = T\omega$$

$$P = 21.84 \times 100.5/1000$$

$$= 2.195 KW$$

For aluminum fan, the axial fan torque requirements during starting were calculated:

$$T = I\alpha$$

$$T = 0.90417 \times 16.76$$

$$= 15.15 N.M$$

(without considering fan blade aerodynamic drag and negligible bearing friction)

The axial fan power requirement was calculated as follows;

$$P = T\omega$$

$$P = 15.15 \times 100.5/1000$$

$$= 1.523 KW$$

Table 4: Performance characteristics of withering axial fans

Parameter	Cast iron axial fan	Aluminum axial fan
No. of blades	6	7
Mass moment of inertia (I_m)	$1.30305 kg.m^2$	$0.90417 kg.m^2$
Torque requirements	$21.84 N.M$	$15.15 N.M$
Power demand to during start-up	$2.59 KW$	$1.8 KW$

The summary of withering axial performance characteristics was as shown in table 4. The lower moment of inertia means the fan rotor accelerates and decelerates much faster. Implication is quicker start-up and speed changes especially when using VFDs for variable air flows. Directly contribute reduction in mechanical stress on the motor and drive system. Lower energy loss during frequent start/stop cycles common in batch withering process as in Kapkoros.

Looking at torque requirements, alluminium fan requires significantly less torque to operate. As a result, the use of lower rated motor is possible. The effect is reduced motor heating and higher efficiency. Withering usually run for very long time especially during increase supply of green leaf as well as during rainy season when air is saturated with moisture. Lower torques directly lowers energy consumption during this operating conditions.

As with regard to start-up power, start-up is the moment of highest power draw. Lower start-up power demand associated with alluminium fan implies less energy wasted during the frequent on and off cycles typical of withering process. Alluminium type axial fan is 30% lower in terms of energy consumption. Alluminium type axial fans are therefore recommended for installation. From this analysis, the following model holds;

Pick power demand(alluminium) = 1.8Kw
Process cycle time =7 hrs

$$\text{Total energy consumed by fan} = \text{Power} \times \text{Time} = (1.8 \times 7)$$

$$\text{Total energy consumed in withering (100 fans)} = 100 \times 1.8 \times 7$$

$$= 1260\,\text{Kwh}$$

To optimize energy use in withering section, the facility should consider installing variable frequency drives (VFD) on all withering troughs to complement alluminium axial fans performance. VFDs save energy when the connected motor is running at any speed below rated RPM which has direct relationship to frequency. The purpose if VFD drives together with controls is to optimize speed therefore saving on energy. In withering process, full flow of air is required only during 3 to 5 hours to facilitate quick removal of surface moisture from the leaves. Eventually, the air flow can be reduced for removal of moisture within the leaves to achieve partial wither for the next 4 hours. This dynamic demand in flow of air speed can be achieved by using VFD drives therefore optimizing energy use during entire withering process. Recent studies have shown that installing VFD drives saves up to 40% of energy consumption in withering section. From the withering energy consumption of 2824.64Kwh, 1130 Kwh could be saved by this technology. This is technically and economically attractive and it is feasible. The performance metrics were as shown in table 5.

Table 5: VFDs performance analysis

PERFORMACE METRICS	CURRENT PERFORMANCE	TARGET PERFORMANCE
Energy Saving	35%-40%	1130Kwh (40%)
Reduction in EUI	0.10-0.13Kwh/KgMT	0.122KwH/KgMT from 0.179)
Average power demand	1.8Kw	1.523Kw(start-up)

L. Installation of continuous withering

To achieve an EUI of 0.05-0.10 Kwh/KgMT, continuous withering technology which is modern in its sense should be installed in the short term. With this intensity, the following analysis holds.

Withering batch-70,000 Kgs of green leaf.
Factory out-turn (Kapkoros)=22.5%
Made tea =15,750Kgs
Amount of energy consumed based on EUI of 0.05Kwh/KgMT = 788Kwh

$$\%\text{ of optimized state (Energy state 2)} = \frac{\text{EUI(BEE)}}{\text{EUI (Energy state 2)}} \times 100$$

$$\%\text{ of optimized state (Energy state 2)} = \frac{0.05}{0.122} \times 100 = 40\%$$

Installing continuous withering lowers energy consumption to 40% of optimized state (energy state 2). It represents 60% energy saving compared to optimization techniques implemented in energy state

2 such as replacement of cast iron axial fans with alluminium type and process cycle time improvements. This performance represents significant leap in energy efficiency.

This explain the fact that adopting continuous withering is the best technique to achieving energy efficiency framework. Installing continuous withering is the only sure way to optimize withering process. The current withering technology at the facility is outdated and upgrade is begging. Other firms are becoming competitive by simply investing on the technology. Initial capital cost is high however; return on investment is worth it in the long term. The facility should consider investing in continuous withering process eliminating both human labor cost and cost of energy by lowering energy consumption. Continuous withering eliminates the need for monorail assembly and withering troughs; continuous withering is energy efficient

M. Improvement of maintenance procedure

It is best practice to always have proper maintenance policy in place in any manufacturing facility. The operation of the machine is as good as maintenance policy the firm has put in place for optimal performance of the systems. One such observation made was replacement decision to be made on old motors. If motors are not properly re-wound, efficiency can drop as high as 10%. A caveat should therefore be put in place by the management in this manufacturing facility in terms of number of re-wound cycles and when to purchase new one. Secondly, attention should be given to switchgears and contactors. Faulty contactors lead to sparks and motor heating up undermining its efficiency. Using the right size motor for given load must be determined because oversized motor affects power factor and eventually the energy cost. The maintenance teams in the facility should focus on system monitoring during entire production cycle. The use of AI and predictive analytics can also help in this endeavor. In addition, proper alignment and tightening of belts is necessary. Loose belts can lead to losses of up to 20% of energy which can drive up the energy cost. The matrix of critical focus areas and priority level to be adopted in energy management system at Kapkoros tea factory is as shown in table 6.

Table 6: Maintenance Priority level matrix

PRIORITY LEVEL	AREA	MAXIMUM ALLOWED LOSS	RECOMMENDED ACTION
HIGH	Motor Re-Winding	10% efficiency loss	Replace after every 2-3 winding
HIGH	Alignment & Tension	Upto 20% energy loss	Weekly checks
HIGH	Switch Gears & Contactors	Overheating and sparks	Weekly inspection
MEDIUM	Motor Sizing	Poor power factor	Proper load matching
STRATEGIC	Predictive Maintenance (AI)	Early failure detection	Management decision

IV. CONCLUSION

Judging from the simulation data, three energy states were created and evaluated. The current energy state shows total factory consumption of 8427.54Kwh and none value adding energy of 1236.19Kwh with overall facility efficiency of 85%. The second state showed total factory consumption of 6888.77Kwh and none value adding energy of 493.11Kwh with overall facility efficiency of 93%. The factory performance in energy state two is better than current state. State two is showing signs of optimal performance judging from stabilization of overall facility efficiency at 93%. So, this state was then considered future state map of this manufacturing facility with projected energy intensity of 0.44Kwh/KgMT. Research is recommending the factory to install alluminium VFDs in short term and installing continuous withering in the medium term. Furthermore, review of maintenance procedures should be implemented so that the machines perform at pick efficiency at all times.

V. RECOMMENDATION

In the medium term, the facility may adopt optimization strategies as depicted in future state map. The strategies include but not limited to change of withering fans from cast iron to alluminium type. Change of withering technology to continuous withering process is necessary. The facility should consider installing variable frequency drives (VFDs) in the withering fans to optimize energy consumption. The purpose of these medium-term strategies is to minimize energy consumption by eliminating possible energy wastes in the tea manufacturing value chain. These major steps will pave the way for optimizing energy use which in turn will provide a clear framework for electrical energy substitution with green energy which is cheaper. A lean factory is modest in terms of energy consumption. If achieved, green energy substitution becomes feasible. Furthermore, the facility should consider formulating comprehensive maintenance policy especially dealing with energy segment in the facility. The policy will respond to system inefficiencies eliminating them right on time before their occurrence.

Automation is the silver lining the facility should consider in the long term in order to remedy specifically energy cost and labor cost; automation is the present and future. Though the research findings attempted to provide optimization strategies, limitation do exist beyond which a better technology is needed. Automated system is a better alternative in terms of energy efficiency and economic sustainability. This milestone will be reflected in the cost of production per kilogram of made tea simply by lowering operation cost. The summary of recommendation is outlined as follows;

First, replace all existing cast iron axial fans in the withering section with alluminium fans. Alluminium fans have a lower mass moment of inertia, requiring significantly less torque to operate and reducing energy waste by approximately 30%. Secondly, equipping withering troughs with VFDs allows for dynamic air-flow control, matching the motor speed to the specific moisture removal needs of the tea at different stages of the process. This technology alone is estimated to save up to 40% of energy consumption in withering section. Thirdly, there is need to transition from outdated batch withering to continuous withering. This shift can achieve an EUI as low as 0.05Kwh/KgMT in withering section, representing a 60% saving compared to standard optimization techniques. Fourthly, strict maintenance procedures should be put in place. There is need to establish rigorous priority matrix for maintenance, focusing on critical areas such as motor re-winding, weekly checks on belt and tensions and regular inspection of switchgears to prevent energy losses of up to 20 %. There is need to leverage on AI and predictive maintenance tools for early failure detection, ensuring systems consistently operate at pick efficiency.

VI. RECOMMENDATION FOR FURTHER RESEARCH

In this study, current energy state map of tea manufacturing facility was created and analyzed. Future energy state map was then created, simulated and analyzed for improve performance. The study was limited to four critical sections in the tea manufacturing value chain. Therefore, the scope of the research should be expanded to include other none critical auxiliaries such as lighting systems, air conditioning, sorting and packaging sections. This will enhance model reliability subsequently improving its accuracy. The research utilized energy smart meters, energy data logger and tachometers as tools for data collection. To enhance data accuracy, future research should adopt the use of torque sensors in order to accurately capture motor mechanical power output. The present work was limited to creating future energy state map which was successfully done showing that energy intensity can be reduced to 0.437Kw/KgMT. However, future research should focus on utilizing the data from this research to develop digital monitoring platform for real time section energy consumption. This could be achieved by using sensors and digital analytics. By leveraging on enhanced visibility, corrective action could be taken in real time therefore achieving system efficiency. Furthermore, future research should focus on optimization of thermal energy consumption. Studies have shown that tea manufacturing require approximately 6Kwh/KgMT of thermal energy which is huge further proving the point that tea manufacturing is energy intensive. To fully address sustainability of tea manufacturing, a comprehensive study on thermal energy consumption should also be carried out in order to ring fenced the place of tea industry in future Kenyan economy.

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