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Performance Evaluation of Solar-Powered DC Milking Machine for Dairy Cattle

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ABSTRACT

This research practically evaluates the impact and performance of the solar-powered DC milking machine on dairy cattle. The milking machine was tested and evaluated on the Sokoto Gudali and Geurnsey cattle with respect to the milking time, milk yield, milking efficiency and energy efficiency. The environmental impact of the design was assessed using RETScreen software to ascertain the level of greenhouse gas emissions in comparison to conventional milking machine. The results indicated that both breeds of cattle takes approximately 8 – 15 minutes per day and 4 - 8minutes across morning and evening milking sessions. They produce 2.3 – 6.6litres of milk per day and 1.0 - 4.4litres of milk across the morning and evening milking session. Milking efficiency ranged from 0.26l/min - 0.62l/min while the energy efficiency was at the range of 0.15kJ/l - 0.36kJ/l. The environmental impact of the solar-powered DC milking machine showed to have a 93% significant reduction in gross annual greenhouse gas emissions.

Keywords: Milking Time; Milk Yield; Milking Efficiency; Energy Efficiency; Milking Machine

INTRODUCTION

The principle of machine milking is to extract milk from the cow by vacuum. The machines are designed to apply a constant vacuum to the end of the teat to extract the milk and transport it to an appropriate container, while also applying periodic external pressure to the entire teat to promote blood circulation. The milking machine is a rather an automatic machine installation for milking cows. It is vital to choose an appropriate milking machine practice and understand the impact of various milking techniques on dairy operations to sustain milk quality and udder health (Dohmen et al., 2010).

The dairy industry has experienced a steady increase in the implementation of automated technologies in recent years (Cogato *et al*., 2021). This fast rising implementation is due to some remarkable advantages such as reduced labour cost and milking consistency. As a result, it is of utmost importance to understand the interactions between cows and their immediate environment that influence behavior and movement through the AMS facility to accomplish system success (Jacobs *et al*., 2012; Siewert*et al*., 2019).

Efficiency is an essential factor in the design of milking machines, as it directly impacts the productivity of the farm. Efficient DC milking machine will aim to maximize milk extraction while minimizing energy consumption, operational costs, and labor requirements. Through the optimization of milking efficiency, dairy farmers can augment milk production, alleviate stress on animals, and enhance overall farm profitability. The utilization of sustainable energy sources, particularly solar, wind, and biomass, will not deplete their availability. The growing demand for clean energy can be met with the presence of abundant sunlight which serves as a constant energy reservior (Qazi et al., 2019).

A notable improvement in efficiency has made milking machines a crucial tool for contemporary dairy farms. In contrast to naturalist frameworks, modern advancements in the domain of food production demonstrate the potential to enhance food accessibility, reduce greenhouse gas emissions, and maintain animal welfare (Wesseler & Zilberman 2021).

The recent models of automatic milkers can vary the pulsation rate and vacuum level based on milk flow from each quarter. According to Siewert *et al*(2019), farmers with AMS have expressed that parity has an impact on AMS efficiency. Hence AMS has the potential to revolutionize the dairy sector by increasing the quantity of output with little or no man power, making it easier for dairy farmers to milk large herd of cows in a day. The economic feasibility of AMS would be highly improved if the milk extracted per automatic milking unit could be increased (Lightfoot and Mulvany, 2002; Jago *et al*., 2006), either through milking more cows or extracted more milk/cow per day.

Milking machine is mostly not a single unit, but rather an assembly of components designed to handle as many as hundred cows an hour as opposed to the use of hand milking which is quite stressful, strenuous and time consuming. Conventional hand milkers are prone to experience joint pain in knees, backbone and stiffness in shoulder, as well as overall weakness

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of the body after milking large herd of cattle in a day (Gadekar et al., 2017). Therefore it is mostly inefficient, energy intensive and poses significant health risks due to potential contamination during and after the milking procedure.

Several milking machines incorporate modern technology at a high level. However, the milking system chosen is not always suitable for all animals in pastoral system, since the physiological control mechanisms and oxytocin release in animals are specific and cannot be changed by humans. In order to achieve maximum milk extraction, the milking routine and technology must be adapted to the animal body structure and function (Kaskous, 2016).

Portable milking machines are designed such that they can be transported and moved from one location to another as opposed to the conventional AMS. The machine helps to provide an efficient and convenient way of milking animals in cases when the use of pipeline milking machines is not possible or when attending agricultural expedition, for small, medium or large herd. The utilization of mobile milking machines is fast rising due to their extended life span and relative low energy consumption (Revenko & Medvedskyi, 2010).

The farming business has seen an increase in profit since the introduction of the portable milking machine. According to Basarir (2002), farming activities requires the services of family members as every farmer wants to maximize profit, but at the same time tries to maintain land conservation for next generation legacy.

The use of portable milking machine has subsequently ease the milking process and improve the quality of life of dairy farmers. Other than the fact that it is easier to operate and maintain, this machine can be used anywhere at any time. A more suitable result will be achieved if individuals involved in the business have high motivation in running the business (Dobbs & Hamilton 2006).

The portable milking machine comes in different sizes and designs, though the principle of operation and features still remains unchanged, Pulsation in the cluster is created by a pneumatic pulsator fitted on the portable milker. This type of pulsator has been designed to meet simplicity, precision, sturdiness and reliability requirements. The pulsation rate can be adjusted using adjustment screw on the pulsator. Pulsation ratio can be selected by the user, its ranges from 40 - 60 pulse per minute. Adjusting the pulsation rate has a direct effect on milking efficiency, indicating that optimizing the pulsation rate can improve the overall performance of a portable milking machine (Singh *et al.,* 2024).

The vacuum pressure is set to the appropriate level for milking. Recommended vacuum level for milking a cow with a portable milker is within 48-50 kPa (kilopascal), the milk is then collected in a plastic or stainless steel bucket for further transportation. Portable milkers for cows come with one or two clusters depending on the design. The cluster type significantly affects milking characteristics, where different cluster types may show variations in milk flow rate and vacuum reserve. It has been observed that certain cluster types are more efficient in maintaining consistent flow rates and vacuum levels during milking operations, which could potentially lead to improved milking performance (Hillerton *et al.*, 2000).

As time progresses, it is predicted that the global market for portable milking machine will witness consistent growth, motivated by a combination of continuous technological advancements, increasing environmental awareness, and a growing demand for more streamlined operations. In order to take advantage of the evolving market opportunities, it is expected that industry participants will focus their efforts on product innovation, strategic collaborations, and expanding their presence in different geographical regions (Porter *et al*., 2011).

Report on portable milking machine market unveils numerous significant market strategies that can assist businesses in leveraging their position in the market and expanding their range of product. A significant proportion of dairy cattle farms in Indonesia are categorized as small-scaled enterprises, accounting for approximately 80% of the total. Additionally, a notable percentage, approximately 17%, falls under the mid-scaled category. These businesses exhibit a relatively low level of business efficiency. Nevertheless, there exists potential for improvement by expanding the scale of operations (Swastika, 2011).

It is an effective market report instrument for conquering certain business setbacks. This sort of innovative market research provides useful data in a timely manner. It also carries out research studies that utilize data analysis to offer valuable knowledge on various aspects of market expansion. The majority of the significant findings in this particular study are derived from comprehensive data collection methods involving primary and secondary sources. There is a high demand for dairy product in the market and this create an opportunity for operational management support such as the use of automatic milking machine (Ouweltjes & de Koning 2004).

The adoption of portable milking machines varied across different regions, and several factors played a significant role in determining the uptake of this technology. Factors such as farm size, infrastructure availability, access to veterinary services, and economic conditions were found to influence the adoption of portable milking machines in various geographic locations. Mobile milking allows the use of smaller or fragmented land parcels (Neal 2014).

MATERIALS AND METHOD

Materials for the Evaluation of Milking Time and Milk Yield of the Solar-Powered DC Milking Machine

The materials used for the evaluation of milking time and milk yield are:-

Calibrated Milk Bucket

A calibrated milk bucket was used to measure the amount of milk produced by each cow. It was vital for keeping track of milk production.

Maintenance and calibration of milking machines are essential tasks that dairy farmers must regularly perform to ensure the efficient and effective operation of the equipment and to maintain the health and well-being of their cows. Check and calibrate the milk bucket and vacuum level of the milking machine regularly using a vacuum gauge. The vacuum level should be set at the optimal range recommended by the equipment manufacturer to ensure proper milk extraction and minimize the risk of udder damage. Proper maintenance and operation of any milking system is a key aspect of successful milking (Mein 2012).

Stop Watch

A stop watch was used to accurately monitor the time taken to milk each cow using the milking machine. The essence of the stop watch was to adequately distinguish the cluster removal time from the actual milking time.

Early studies by Sagi (1978) & Rasmussen (1993) revealed that an increment in the cluster remover take-off milk flow threshold from 0.2 to 0.4 kg/min led to a decrease in the duration of the milking process without detrimentally impacting milk production.

Materials for Evaluation of Milking Efficiency and Energy Efficiency of the Solar-Powered DC Milking Machine

The materials used for the evaluation of the milking efficiency and energy efficiency are:-

Efficiency in the milking process is a key for the success of a dairy farm. By implementing proper management practices, utilizing modern milking equipment, and prioritizing cow health and comfort, farmers can optimize milk production, quality, and overall farm profitability. Several key factors such as Proper cow management, timely milking routines, Monitoring and data analysis and hygiene and cleanliness contribute to achieving a high level of efficiency in the milking process. Applying a maximum milking time determined by expected milk yield at an individual milking session, is one strategy to optimize parlor efficiency (Edwards *et al*., 2022).

Stop Watch

A stop watch was used to accurately monitor the milking time of each of the cows to evaluate its efficiency in respect to quantity of the milking extracted.

Recent scholarly research has provided evidence that the inclusion of a latency period between stimulation and cluster attachment does not enhance milk yield or cluster-on time when the udder fill exceeds 40% (Kaskous & Bruckmaier, 2011). Thus, if the time required for cluster attachment can be minimized through the implementation of pre-milking stimulation without the need for a latency period, there is a potential for improving milking efficiency (measured by the number of cows milked per operator per hour) without an increase in labor demands in certain dairy settings.

Energy Meter

An energy meter was used to measure the amount of energy consumed by the milking machine in order to evaluate its efficiency.

Dairy farms require a lot more energy now than they have in the past due to the increase in the number of dairy farms, as they use more automated equipment to milk larger herd of cattle, and they operate around the clock. Electric consumption is one of the most relevant and uncontrollable operational cost of AMS, ranging between 35 and 40% of their total annual operational costs. Efficient utilization of energy within the agricultural sector is a crucial prerequisite for the attainment of sustainable agriculture, this is primarily due to its ability to yield financial savings, safeguard non-renewable fossil resources, and mitigate air pollution (Pervanchon *et al*., 2002).

Methods

The performance evaluation and energy determination of the milking machine was carried out using the appropriate statistical tools, while RETScreen software was used to determine environmental impact of the design.

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Experimental Data Collection and Statistical Analysis

The milking was carried out on dairy farm in Kasarawa, Sokoto State Nigeria. The milking process began by gently washing the cow's udder and milk bucket with clean water to prevent contamination of milk. The teat cup was gently placed on the four teat of the cow's udder in an air tight manner to prevent air leakages during milking. The solar-power DC milking machine was then turned-on to enable suction of milk to the milk bucket. Morning milking was carried out at 7am while the evening was done by 4:30pm using a calibratedmilk bucket to measure the quantity of milk extracted and a stop watch to record the milking time for each cattle using the solar-powered DC milking machine. The energy consumed was recorded using an energy meter while energy efficiency was determined by dividing the quantity of milk extracted by the energy consumed milking each cow, similarly the milking efficiency was determined by dividing the quantity of milking extracted by the time taken to milk each cow. Plate 1 shows the solar-powered DC milking machine during milking session.

Plate 1: Solar-Powered Milking During Performance Evaluation

Evaluation of the Milking Time and Milk Yield of the Solar-Powered DC Milking Machine.

The milking time and milk yield of the solar-powered DC milking machine was evaluated using regression analysis to show the relationship between the two sets of variables. The results obtained from the evaluation was assessed to determine:-

The Average Morning and Evening Milking Time per Cow

The assessment showcased the time of the day with the longest and shortest milking time for each cow and was illustrated using a bar chart.

The Average Morning and Evening Milk Yield per Cow

A bar chart was used to illustrate the quantity of milk produced by each cow per day across morning and evening milking session.

Evaluation Milking Efficiency and Energy Efficiency of the Solar-Powered DC Milking Machine.

The milking efficiency and energy efficiency of the solar-powered DC milking machine was evaluated using a Two sample t-test. To obtain the milking efficiency, the total milk yield of each cow per-day was divided by the total milking time of each of the cow. However, in Automatic Milking Systems (AMS), the efficiency and productivity are highly influenced by the duration of milking and the overall time dedicated to milking in the robot throughout the day (Gygax *et al*., 2007).

$$\text{Milking Efficiency} = \frac{\text{Milk yield per day (l)}}{\text{Time (m)}}$$

The energy efficiency per liter of milk extracted using milking machine was obtained by dividing the litres of milk produced by total energy consumed (Sefeedpari *et.*, *al* 2020).

$$\text{Energy Efficiency} = \frac{\text{Milk yield (l)}}{\text{Energy consumed (kJ)}}$$

The results obtained from the evaluation was assessed to determine:-

The Energy Efficiency and Milking Efficiency per Cow

A line graph was used to illustrate the effect of milking efficiency on energy efficiency for each cow evaluated across the two milking session.

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Assessing the Environmental Impact of Using the Solar-Powered DC Milking Machine in Comparison to the Conventional Milking Machine Using Retscreen Software

A simulation was carried out using RETScreen software to determine the level of greenhouse gas emission of the design in comparison to the conventional milking machine. Abdulhameed et., al (2019) conducted a simulation using RETScreen software to determine the techno-economic and environmental sustainability of solar photovoltaic technology in Nigeria.

The Design Worksheet

The design worksheet in RETScreen Software was used to enter general information about the design such as capacity and type of suction pump, solar module, battery and charge controller.

Emission Analysis

The Emission Analysis worksheet was provided to facilitate the estimation of the greenhouse gas emission reduction (mitigation) potential for the proposed milking machine. The initial phase involved selecting the preferred type of analysis from the ribbon interface. The ribbon also contained global warming potential factors for greenhouse gases (GHG). For Level 1, this emission reduction analysis worksheet comprises three principal sections: Base Case Electricity System (Baseline), GHG Emission, and GHG Reduction Revenue. Conversely, for Levels 2 and 3, it encompasses five principal sections: Base Case Electricity System (Baseline), Base Case System GHG Summary (Baseline), Proposed Case System GHG Summary (Plan), GHG Emission Reduction Summary, and GHG Reduction Revenue. The sections titled Base Case Electricity System and Base Case System GHG Summary provided a comprehensive description of the emission profile associated with the baseline system.

The results obtained from the assessment was illustrated in form of a bar chart showcasing:-

The Base Case and Proposed Case of Greenhouse Gas Emission

The base case and proposed case of greenhouse gas emission was assessed to ascertain the level of greenhouse gas emission reduction of the milking machine prototype.

RESULTS AND DISCUSSION

Evaluation of the Milking Time and Milk Yield of the Solar-Powered DC Milking Machine

The milking time and milk yield for each cow was recorded and measured using a stopwatch and a calibrated milk bucket. Table 1 shows the breeds of cattle evaluated using the solar-powered DC milking machine.

Table 1: Breeds of Cattle Evaluated

Cattle	Breed
A	Sokoto Gudali
B	Sokoto Gudali
C	Guernsey
D	Guernsey
E	Sokoto Gudali

Table 1 showing the breeds of cattle evaluated

From Table 1, five cattle of two breeds were evaluated using the solar-powered DC milking machine, the Sokoto Gudali and the Guernsey cattle.

Sokoto Gudali

The Sokoto Gudali is an indigenous cattle breed of Sokoto State which can produce up to 3 litres of milk per milking session in first lactation year. The quantity of milk produced by this breed increases over time as they give birth to more offsprings. However the quantity may also decrease in some case due to a number of factors such as feeding, weather, mood and age of the cow as evaluated.

Guernsey Cattle

The Guernsey cattle on the other hand are breeds of dairy cattle that originated on the island of Guernsey. This breeds can produce 4-5lites of milk per milking session. However, this number is not specific as it may vary due to factors like feeding, weather mood and age of the cattle.

The total milking time and milk yield of the solar-powered DC milking machine was evaluated using a regression analysis as shown in Figure 1.

The regression equation is

Milking Time = 5.277 + 1.117 Milk Yield

S = 2.18744 R-Sq = 66.8% R-Sq(adj) = 55.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	28.8453	28.8453	6.03	0.091
Error	3	14.3547	4.7849		
Total	4	43.2000			

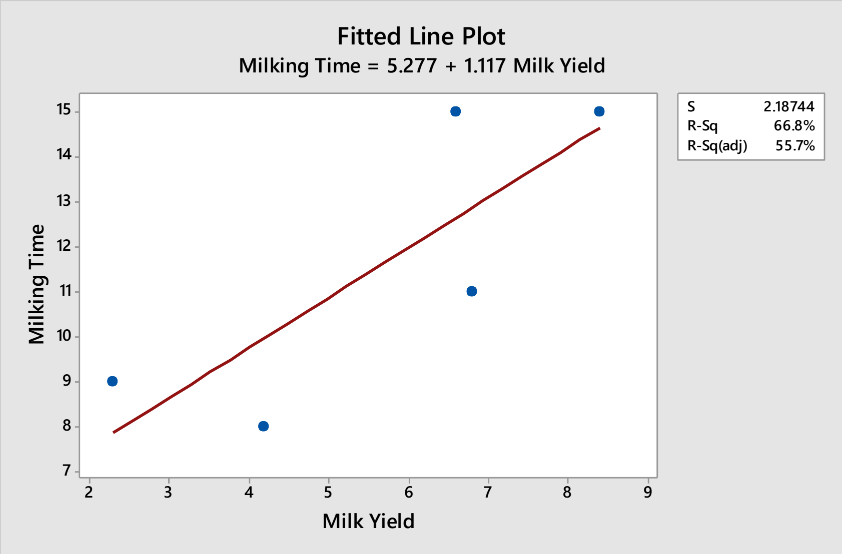

Figure 1: Fitted Line Plot of Milking Time Against Milk Yield

From the result in Figure 1, the P-value 0.091 is greater than the alpha value 0.05 which indicates that the result is not statistically significant. This further shows that the milking time has no significant effect on the overall milk yield per day.

Milking Time

The milking time of each cow per milking session (morning and evening) was further evaluated as shown in using Figure 2.

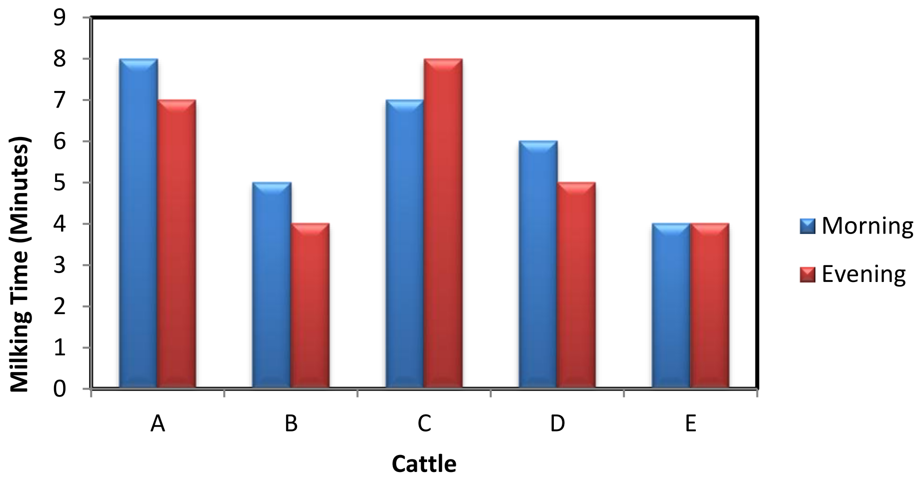

Figure 2: Morning and Evening Milking Time

From Figure 2, it is worthy of note that the morning milking time for cow A, B and D are longer than their evening milking time. However the morning milking time of cow C is seen to take longer in the evening than morning and that of cow E is seen to be at Equilibrium. The morning and evening milking time for cow A, B and D is observed to be normal due to the high quantity of milk produced by cattle in morning, which leads to longer milking time than evening. The deviation in cow C is due to liner slip during the evening milking process, thereby leading to longer milking time while that of cow E is due to lower battery current leading to reduced suction, hence equal morning and evening milking time.

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Milk Yield

Figure 3 shows the morning and evening milk yield of each cow to ascertain the session with highest and lowest output.

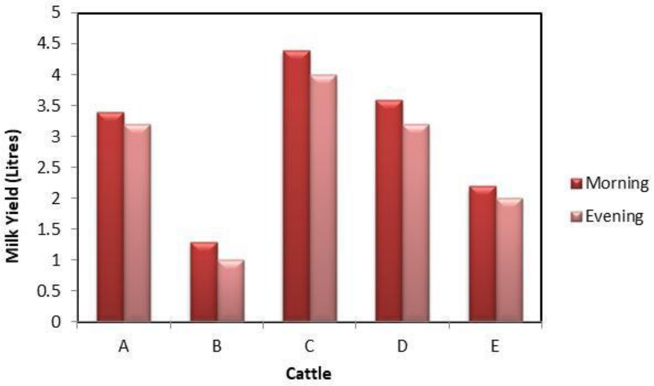

Figure 3: Morning and Evening Milk Yield

From Figure 3, it is observed that the average milk yield of each cow per morning session is higher than that of evening. The reason for the surge in morning yield is simply due to the time duration between evening to morning and that of morning to evening. Milking is carried out as early as 7am for morning milking and 4:30pm for evening milking. Hence the time duration between evening and morning is longer than between morning and evening, thereby leading to lower evening yield. Another reason is that the cattle are well fed and rested in the evening thereby enabling them produce more milk in the morning.

Evaluation of the Milking Efficiency and Energy Efficiency of the Solar-Powered DC Milking Machine

The milking efficiency and energy efficiency each cow per day was evaluated using a Two sample t-test as shown using a Boxplot in Figure 4.

Two-sample T for Milking Efficiency vs Energy Efficiency Null hypothesis (H0) - $\mu_1 = \mu_2$ All means are equal

Alternative hypothesis (H_1) - $\mu_1 \neq \mu_2$ At least one mean is different

	N	Mean	StDev	SE Mean
Milking Efficiency	5	0.482	0.140	0.063
Energy Efficiency	5	0.2820	0.0823	0.037

Difference = μ (Milking Efficiency) - μ (Energy Efficiency)

Estimate for difference: 0.2000

95% CI for difference: (0.0222, 0.3778)

T-Test of difference = 0 (vs ≠): T-Value = 2.75 P-Value = 0.033 DF = 6

The p-value is 0.033 which is less than the alpha value 0.05, suggesting a statistically significant effect between the variables. Hence we reject the null hypothesis in favor of the alternative hypothesis. Which means there is a relationship between the two variables being studied (at least one variable affects the other).

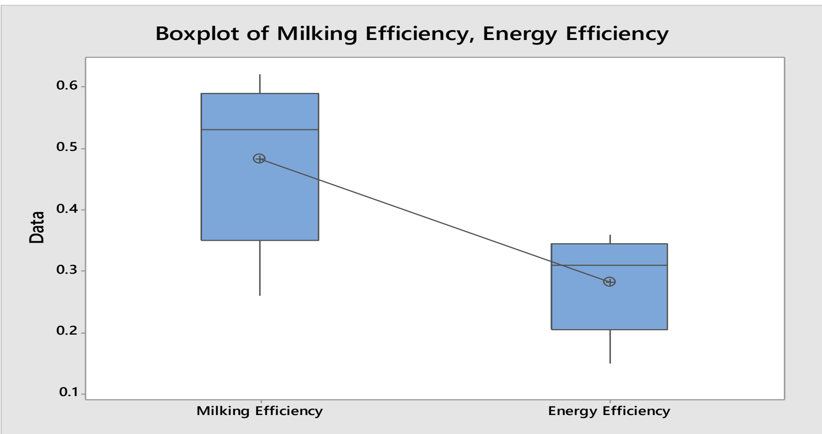

Figure 4: Boxplot of Milking Efficiency and Energy Efficiency

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It can be observed from the Boxplot in Figure 4 that there is a significant difference in efficiency when the milking efficiency is at 0.44l/min and energy efficiency at 0.26kJ/l.

Figure 5 illustrate the relationship between the milking efficiency and energy efficiency of the solar-powered DC milking machine.

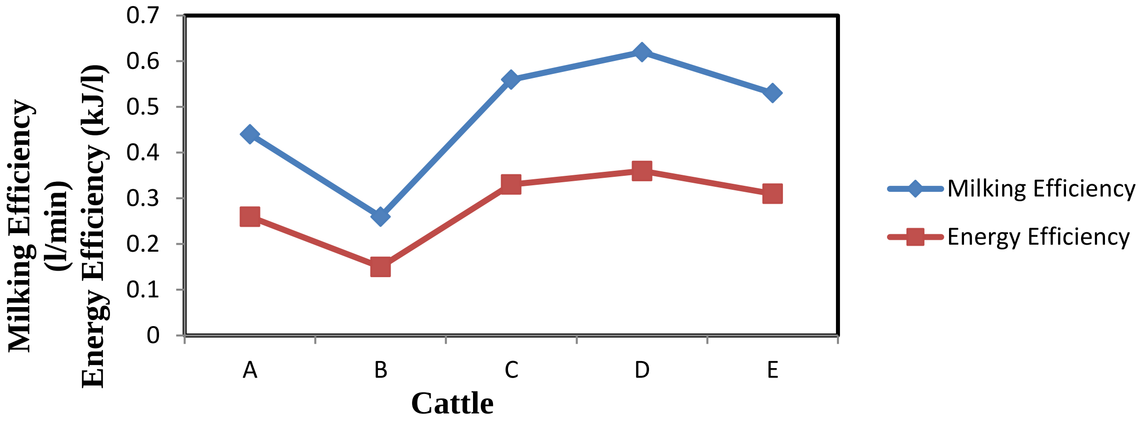

Figure 5: Milking Efficiency and Energy Efficiency

Figure 5 shows that the energy efficiency increases as the milking efficiency increases and vice versa. Hence they are parallel to one another.

The Impact of the Design on United Nation's Sustainable Development Goals

The solar-powered DC milking machine design will equip farmers with the proper machine required to boost productivity and increase income (SDG 1 - No Poverty). The components used in design of the milking machine was sourced locally and powered strictly by solar, hence making it more affordable and eco-friendly (SDG 7 – Affordable and Clean Energy**)**. The use of the design would promote decent work amongst dwellers in remote communities as most will engage more in dairy farming which will in turn boost economic growth (SDG 8 – Decent Work and Economic Growth). The design is an innovative one that would provide opportunity for industry to develop and produce in large scale (SDG 9 – Industry, Innovation and Infrastructure). Considering the fact that the design was made from locally available materials and powered by clean energy from solar module, the system would make our cities and communities more sustainable (SDG 11 – Sustainable Cities and Communities). Energy consumption was optimised with the use of the design, hence increase productivity as oppose to the use AC powered milking machine (SDG 12 – Responsible Consumption and Production). The milking machine was specifically designed to mitigate greenhouse gas emission and combat climate crisis (SDG 13 – Climate Crisis).

Assessment of the Environmental Impact of Using the Solar-Powered DC Milking Machine in Comparison to the Conventional Milking Machine Using RETScreen Software

The environmental impact of the solar-powered DC milking machine was assessed using RETScreen software to ascertain the level of greenhouse emission and environmental friendliness of the machine compared to conventional milking machine. The design parameters, location and climatic data were used in the evaluation.

The assessment of the level of greenhouse emission using the solar-powered DC milking machine compared to the conventional milking machine can be seen in Plate 1.

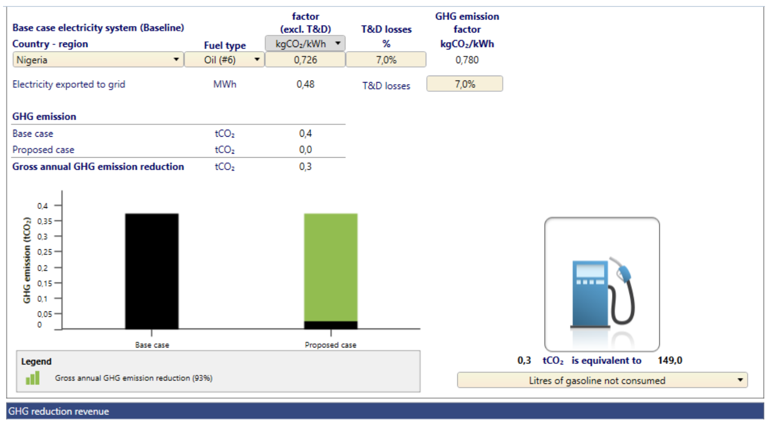

Plate 1: Assessment of GHG Emission Reduction

Plate 1 illustrates the level of greenhouse emission reduction using RETScreen software. For level 1, the base case electricity, greenhouse gas emission and greenhouse gas reduction revenue for the host location was imputed in the worksheet. It was observed that the greenhouse emission factor/electricity utilized annually was about 0.780 kilogram carbon dioxide/kilowatt hour (kgCO_2/kWh) using conventional source of energy. However in level 2 and 3, the base case electricity system (Baseline), base case system of greenhouse gas summary (Baseline), proposed case system greenhouse gas summary (Plan) and greenhouse gas emission reduction summary we evaluated. The greenhouse emission after transmission and distribution was evaluated to be 0.726 kilogram carbon dioxide/kilowatt hour (kgCO_2/kWh) while the electricity losses during transmission and distribution to grid was 7.0%. Base case of conventional greenhouse gas emission was computed to be 0.4 tonnes of carbon dioxide, while the proposed case was simulated to emit 0.0 tonnes of greenhouse gas. The gross annual greenhouse gas emission reduction using the solar-powered milking machine was assessed to be 93%.

CONCLUSION

From the result of the performance evaluation of the milking time and milk yield carried out, both breeds of cattle takes approximately 8 – 15 minutes per day and 4 - 8minutes across morning and evening milking sessions. They produce 2.3 – 6.6litres of milk per day and 1.0 - 4.4litres of milk across the morning and evening milking session.

The result of the milking efficiency and energy efficiency evaluation showed that the milking efficiency ranged from 0.26l/min - 0.62l/min milking the two breeds of cattle while the energy efficiency was at the range of 0.15kJ/l - 0.36kJ/l.

The environmental impact of the solar-powered DC milking machine was assessed compared to conventional milking machine using RETScreen software and was found to have 93% reduction in annual greenhouse gas emission.

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