Animate prime movers: an un-exploited resource towards achieving United Nations SDG 7-future research requirements

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ABSTRACT

Renewable energy is a prominent concept that encompasses various forms, such as solar photovoltaics, wind power, and geothermal energy. Although less familiar, animate energy resources, which include human beings and animals, may also be seen as being explored. While animal-based renewable energy generation may appear novel, different research articles, patents, and a couple of commercially available products have been developed. For the specific case of dairy farms, harnessing this resource can be coupled with appropriate exercise regimens for cows, which may lead to clean energy, animal welfare, and even potential benefits for human health. These efforts align with the sustainable development goals (SDG) of the United Nations, specifically SDG 3 and SDG 7. However, ethical concerns regarding the use of animals for energy production as well as the potential and clean nature of this resource need to be thoroughly investigated before it can be exploited on a larger scale. This research paper aims to identify deficiencies in the current relevant body of knowledge and to present requirements for future research efforts that may help tap into this resource. By exploring the potential of animate energy resources, we may contribute towards sustainable energy production while promoting animal welfare and human health.

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1. INTRODUCTION

Throughout history, humans have traditionally relied upon animals for a variety of purposes, such as transportation, food, clothing, and other necessities. Animals have been utilized as prime movers for milling and drawing water from wells. However, with the advent of the steam engine and subsequent advancements in science and technology, machinery has largely replaced animals in many areas. Yet, as history has demonstrated, there may again be a need to turn to the animal kingdom for support, given the current search for sustainable alternatives to replace fossil fuels. Despite the perception that animal power is an outdated form of technology, recent research suggests that animal draught power may have a viable role to play in modern society. Miara *et al.* [1] says that agriculture in developed countries is witnessing use of draught animal power– the paper is basically a review article mentioning various other articles that indicate use of draught animal power in developed countries. The paper mentions that reviews from both scientific literature as well as press, indicate a renewed interest for the case of animal traction. This traction has its benefits for energy as well as economy. It has also been mentioned that, although the reviews indicate the agro-ecological potential of animal traction, however, it is facing difficulty for gaining suitable acknowledgement. Research by Nunes *et al.* [2] mention a case of modern animal traction for supply chain of residual biomass–the article mentions that using modern animal traction may lead to sustainable development of local and regional projects. Research by Daum *et al.* [3] compares animal traction and tractors (two wheel and four wheel) for farm mechanization in the perspective of Africa. Moreover, "Draft animals: 100 answers for harnessing animal power" [4] and "Horse-powered farming for the 21st century: a complete guide to equipment, methods, and management for organic growers" [5] are a couple of relevant books. In sum, while animals have long been viewed as a traditional and somewhat antiquated means of power, evidence suggests that animal draught power may be a viable and sustainable alternative to conventional fossil fuels. In fact, Gantner *et al.* [6] refers to fodder as a biofuel, for the case of horses being used in agricultural work.

Different research papers point towards use of animals for generation of energy. Conference articles are dominant in number here, than journal artices; and this points towards a deficiency of detailed studies in this area. Research by Perrone *et al.* [7] mentions use of animal power to generate electricity for pumping water–the implementation of a patented invention has been mentioned, moreover, the article compares feasibility of using animal power versus photovoltaic power for rural areas. In the conclusion section, the authors mention that cost-effectiveness and portability was offered by animal powered approach. Research by Blažević *et al.* [8] mention an energy harvester for farm animals for internet of thing (IoT) applications–the work mentions presenting a proof-of-concept energy harvester for cows. Reference [9] is a paper from the Italy based "Water and energy from draught animal power" WEDAP center–the author mentions that traditional energies from remote villages may be envisaged to enter the market of Carbon credits. Reference [10] is a paper attempting to harness animal energy via a treadmill setup–although incomplete, the paper discusses an effort to build a prototype treadmill that could be used for a large animate prime mover to generate electric power. Final results retrieved via humans running on the setup have been mentioned in this paper. Research by Dastgeer *et al.* [11] discusses estimation of renewable power producible via an animal moving on a treadmill. Moreover, Jakhar *et al.* [12] mention a prototype setup where a camel was used to generated electricity. The authors mention that a camel can generate around 1 kW of power, for more than six hours in a single day. In their experimental setup, the camel moves around a circular path–this movement is converted into a more than 3,000 rpm rotation, which is required by the generator. The authors mention that their system has been designed such that it provides safety as well as comfort to the camel.

However, there appear to be so many issues with the concept of animals as prime movers. Firstly, they do not look 'fashionable' in the language of [13]–which is actually an article that advocates the notion of seeing human and animal power as renewable energy sources. The authors mention the view point that the technologies which are used for harnessing the human and animal based renewable energy, should be equally recognized as being inclusive in the family of renewable energies. In this context, certain research articles can be found which indicate utilizing human power for generation of electricity, examples are [14], [15]. Secondly, animal welfare is a valid concern that must be considered when considering any animal-powered machinery (APM) setup. Various aspects of animal welfare should be considered and ensured. If executed properly, an APM setup might even benefit the welfare of tethered cows, which lack adequate physical exercise and movement opportunities. Lastly, it is essential to note that animal-based energy generation setups may not produce power in the mega-watts range. Unlike a diesel engine, which can generate large amounts of CO^2, the power generation capabilities of a single animal are limited. For instance, a camel's capacity is only about 1 kW. This level will be even lower for dairy cows, as their primary concern is healthy exercise, not power generation. In sum, the APM idea may not be favored by the community for the reasons outlined above.

However, if one looks at the flip side of animals as prime movers, firstly, this is a renewable resource–it may also fit into definitions of green energy and/or sustainability. So, even if the power level is less as compared to fossil fuel based generation, still the plus point lies in its being renewable and potentially non-polluting to the environment. The current paper makes the argument, that, why shouldn't the feasibility of this resource be explored? If this renewable energy is available, and utilizable in a feasible and sustainable method, why should it not be used for the benefit of humanity? Secondly, we have scientific inventions for tapping this resource, such as "A system for generating electricity using nonconventional source" [16] mention use of horses that will move in a circular path to generate energy. The same inventor recently, patented a relevant invention [17]. The invention [18] again mentions generating clean energy by utilizing animal power, where the animals may be camels or horses. A five stage system has been mentioned, which includes compressed air stages. The invention [19] mentions a power generating setup employing livestock movement. Thirdly, when coupled with the idea of animal exercise–there are many a research article mentioning benefits of exercise for farm animals, e.g., Daigle *et al.* [20] mention at a point that moderate exercise "… has the potential to improve cattle welfare and feedlot productivity", Popescu *et al.* [21] compare two cases of tie-stall dairy cows, with and without exercise, and indicate positive effects of exercise on tethered cow welfare. Research by Shepley and

Vasseur [22] mention pasturing or provision of outdoor exercise yards as becoming common in best-practice recommendations; lastly, if exercise is established as a source of health for animals and power for humans–this resource is available in quite a good amount, in the thousands of animal farms around the world.

For the concept of coupling exercise and power generation; the ‘Bovine treadmill’ patent [23], clearly mentions that the device is for exercising large animals. As noted by the inventor, a veterinarian, exercise has been witnessed to have salutary effects on dairy cattle, like human beings. The invention suggests integrating a power generation setup with the treadmill, whereby the kinetic energy of the cow's walking motion can be harnessed to produce energy. While the patent provides an initial framework, further investigation is required to comprehend the intricacies of exercising dairy cows while simultaneously generating power. This includes determining an exercise session's optimal duration, intensity level, and frequency. The present research effort is essential for future investigators to initiate exploration and address the numerous unanswered questions. The subsequent section will elaborate on the novelty of this work.

The United Nations' sustainable development goals (SDGs) urge the adoption of renewable energy, with a particular emphasis on “Affordable and clean energy” SDG 7. A potential source of this renewable power can be found in the muscles of millions of domesticated and farm animals worldwide. Despite relevant patents and research publications, this resource remains largely untapped. A comprehensive study that can identify future research requirements and lead to this renewable resource's exploitation is imperative. This research article seeks to address this gap, particularly regarding dairy farms.

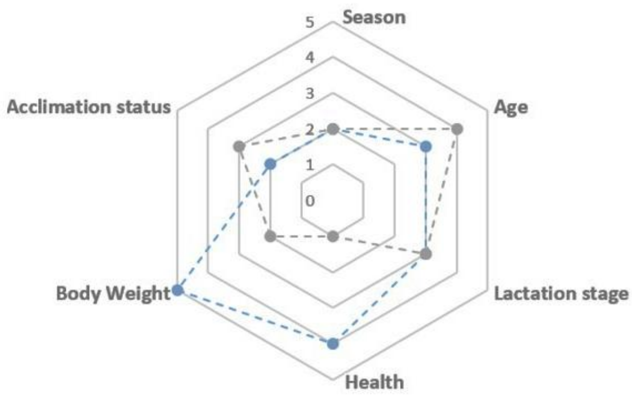
2. FUTURE RESEARCH DIRECTIONS

2.1. Determination of the potential of generatable power

It is imperative to provide quantitative answers to inquiries regarding the volume of energy/power that can be generated from manifold variations of a given resource. The scientific community can depict these variations as state variables of a multi-state space. For instance, Figure 1(a) presents a sample question that needs investigation. Figure 1(b) presents a diagram for dairy cows with two arbitrary states. The dimensions comprise the year's season, age of the exercising animal, lactation stage, health condition, body weight, and acclimation status to the exercise setup. At present, the radar figure only showcases sample states; however, it can be tailored to correspond to the area of the state, which can be linked to the amount of energy/power that can be produced. Table 1 provides sample values for the different dimensions, where arbitrary variables have been utilized for age, body weight, and health to convey the concept.

How much power/energy may be produced,	<u>Illustrative values</u>
from a dairy farm of n animals,	n = 100
which are all healthy m animals,	m = Holstein Friesian
in their lactation stage l,	l = early lactation
during the season s?	s = winter

(a)



(b)

Figure 1. Conceptualizing the exploration of the potential of generatable power; (a) sample question for future research and (b) state space diagram for dairy cows

Table 1. Sample values for variables of a single cow state

No.	Season	Age	Acclimation status	Body weight	Health (%)	Lactation stage
1	Spring	A	Novice	α	70	Early
2	Summer	B	Not fully acclimated	β	80	Mid
3	Autumn	C	Fully acclimated	γ	90	Late
4	Winter	D		δ	100	
5		E		ε		

Detailed research effort is required, to be able to collect data, so that the amount of generatable power/energy for any combination of the state variables, may be estimated for an average Holstein Friesian cow or a Buffalo. In the past research efforts, there are a few hints to this direction of work–references [24], [25] quote power generating capabilities for draught animals; however, dairy cows have not been mentioned, there is only one mention of Buffalo. Research by Niekerk and Hancke [26] mentions typical draught animal capabilities (while quoting from another reference) where the animals are cow, bull, horse, donkey, and mule. For an average cow (weight range 400–600 kg), the working speed has been mentioned to be 0.7 m/s and the power is 350 watts. Any further details such as the lactation stage of the animal, its age, time of the year have not been mentioned.

Moreover, it is noteworthy that while the area may be deemed a gap in research that necessitates further exploration, an even more conspicuous deficiency in the existing corpus of knowledge is the absence of a linkage between generatable power and the optimal workout for working farm animals. Consequently, to address this deficiency, future research endeavors should aim to determine the permissible level of power/energy generation that can be attained without exceeding the healthy exercise threshold for an animal. The aforementioned research work needs to be undertaken, while considering various state space conditions such as seasonal variations, body weight, and other relevant factors that may impact the animal's well-being. The proposed research direction emphasizes the need for a comprehensive approach that incorporates the latest advances in animal physiology, biomechanics, and energy systems.

2.2. How much workout is suitable and ethically allowable

The American Dairy Science Association® has published a student review paper [22], which highlights the need for additional research to examine the relationships between various methods of providing movement opportunities to dairy cows and the resulting effects on cow health and comfort. The suitability of such methods to the overall well-being of cows is of utmost importance and can significantly influence the decision-making process of dairy farm owners. A Northern Ireland farmer developed a treadmill that utilizes cows to generate power, claiming that if all the cattle in the world could be made to work on treadmills for eight hours a day, they could generate 6% of the world's total power [27]. However, the applicability of this workout to individual animals has not been discussed. As such, the gap in knowledge needs to be filled to determine whether energy generation alone is sufficient to incentivize dairy farm owners or whether power production must confer benefits to the cows. Research by Shepley and Vasseur [22] emphasizes that "Pasturing or provision of access to outdoor exercise yards is becoming more common in best-practice recommendations," indicating that the benefits of exercise for cows are well-established. However, the focus of this paper is to quantify the amount of exercise in terms of generatable power that is suitable for a dairy cow, given factors such as environment, stress level, and body condition. Consequently, the exploration of this area of research is warranted to advance our understanding of cow health and comfort and to inform best-practice recommendations for the dairy industry.

In a study conducted around 1982 by Blake *et al.* [28], the physical fitness of dairy cows subjected to different exercise regimens was evaluated. The authors noted that cows in confinement exhibited poor physical condition, however, maintaining physiological homeostasis during exercise was found to be an indication of physical fitness, and exercise could improve the health of the animals. The study examined various walking exercise regimens and found that neither too strenuous nor very light exercise benefited the cows. Instead, moderate exercise, in the form of a daily 9.68 km walk at a speed of 3.54 km/hr, proved to be effective in improving fitness. In the concluding remarks, the authors recommend moderate exercise during the dry period, for at least 8 weeks, with a satisfactory exercise regimen consisting of an 8 km walk at 4 km/hr, five or more days a week. The authors' findings suggest that moderate exercise can help improve the physical fitness of dairy cows, which may have significant implications for the dairy industry.

The health benefits of exercise are well-established; however, it is crucial to ensure that the workout is suitable for the individual's needs. The suitability of exercise may be associated with factors such as resistance to diseases, milk quality, reproductive health, and overall well-being. Therefore, it is essential to investigate the appropriate exercise limit for different scenarios and express it in terms of measurable biomarkers, such as heart rate, respiration rate, and blood pressure. Once the maximum values of these biomarkers have been determined for an animal, or an artificially intelligent agent has been trained to predict them, the animal's exercise can be carried out up to these levels. For instance, the work of Blake *et al.* [28] suggests that a daily walk of 9.68 km at a speed of 3.54 km/hr is suitable for cows. However, these values need to be expressed in terms of measurable biomarkers to be implementable for cows with different body condition scores. Moreover, finding and establishing appropriate biomarkers for disease detection in dairy cows is of significant interest. Similarly, investigating these biomarkers for healthy automated precision milking APM exercise is a future research direction. In summary, future studies should investigate the biomarkers of an animal's exercise to determine their maximum levels, ensuring that the exercise is appropriate for the animal while also remaining within ethical limits. It is also worth exploring how different biomarker levels of exercise can target the achievement and maintenance of various attributes of well-being.

2.3. Automating monitoring of an ongoing animal-powered machinery exercise

To automate an APM exercise in a dairy farm, what may be done is to have a machine learning setup, employing supervised learning techniques such as convolution neural network [29] or gaussian process regression [30], to train an agent with a dataset of animal state variables as inputs and upper limits of biomarkers (as determined in previous subsection) as outputs. Once trained, this agent may be deployed in a computer system where it can predict the upper biomarker limits for any animal in the farm which comes for the APM exercise–and an accompanying rule based system, outputs the exercise intensity level (power generation level) while taking the inputs of upper biomarker limits from the machine learning agent and the actual biomarker levels from the sensors used in the setup–Figure 2 conveys this notion. If a substantial amount of labeled training data is available and the exercise environment is not subject to changes, supervised learning can be a practical and straightforward approach. Alternatively, reinforcement learning offers the advantage of adaptability and the potential to optimize exercise protocols over time. Moreover, robustness of rule-based algorithm depends on the stability of exercise regime, need for interpretability and likelihood of rule changes. The future research directions may be summarized as, to investigate which supervised learning technique is most suitable for predicting upper thresholds of biomarker levels–or should reinforcement learning be used? Lastly, is rule-based algorithm sufficient for the final automation?

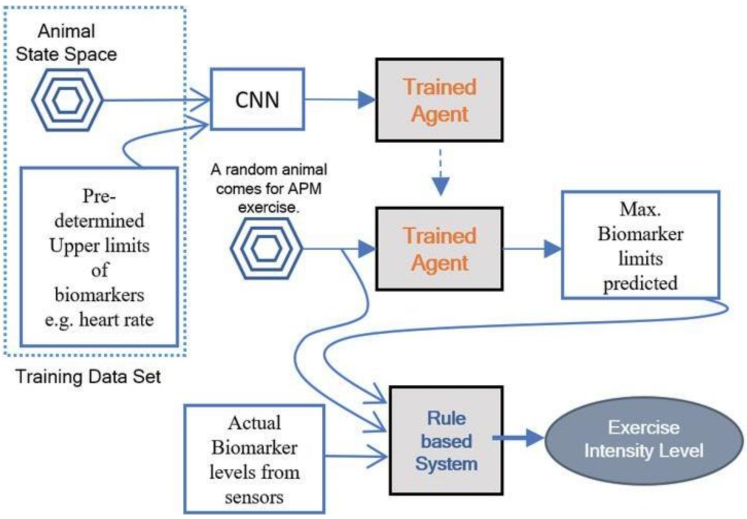


Figure 2. Automatic adjustment of exercise intensity level

2.4. Exploring brain computer interface for suitability of animal-powered machinery workout

The brain computer interface (BCI) represents a technological paradigm wherein direct communication between the brain and external devices, such as computers, is facilitated. In this framework, brain activity serves as the input to control these external devices. BCI systems can be categorized as either invasive or non-invasive, with one prevalent non-invasive approach relying on electroencephalography (EEG) to capture the brain's electrical signals generated by neurons. Notably, EEG offers a high temporal resolution, enabling real-time monitoring of brain activity. By placing electrodes on the scalp, EEG signals can be recorded. EEG has found utility in assessing stress and fatigue levels in humans [31], [32]. Moreover, recent investigation [33] have highlighted the applicability of EEG in detecting stress responses in goats, suggesting its potential extension to stress measurement in other animal species.

Expanding on this notion, EEG's capacity to gauge stress and fatigue levels could be leveraged in animals engaged in physical activities, such as treadmill exercises. Monitoring EEG signals during treadmill workouts could provide valuable insights into the stress and fatigue experienced by animals, thereby evaluating the efficacy and suitability of physical exercise regimes like APM workouts for animals. Such an approach may lead towards optimizing animal welfare and performance across various contexts.

2.5. Determining the suitable brain computer interface technique

Which APM technique should be used–treadmill or traditional draught work? Both techniques are present in literature. In relation to the treadmill-based workout–patents include "Bovine treadmill" [23] and "Animal Power Generator" [34]. Looking at research articles [15] is an effort for using human power via treadmill, while for the use of animals, Javed *et al.* [10] represents an incomplete effort. The in-availability of detailed treadmill-based power generation studies, for different cases of animal type/state, is apparently a gap in the current body of research. Efficiency of treadmill based APM setup for animals, is also a missing data apparently.

Regarding the use of traditional draught power, where the animal walks on a surface, the patents' side shows, "Livestock power generation system" [19] and "A system for generating electricity using nonconventional source" [16] as a couple of relevant patents. On the side of research articles, Chandrakar *et al.* [25] use a pair of bullocks to produce power for charging batteries, Perrone *et al.* [7] mention a setup which used a horse as the prime mover to produce around 400 watts, and the efficiency of this setup was determined to be around 70%. In summary, both techniques can be found in literature. However, the focus of this manuscript is to point towards the insufficiency of detailed empirical studies comparing the two power generation schemes. These studies should consider various factors such as efficiency, installation cost, space requirement, and other factors related to the prime mover, such as animal type, animal health, and acclimation status. The objective is to determine which technique is the superior option under varying scenarios.

2.6. Stress levels

Does the APM exercise induce any stress for the animals? Stress can have different implications for animals-for instance, in case of short term heat stress of dairy cows, Jo *et al.* [35] state that this stress has negative effects towards feed and water intake, heart rate, and milk characteristics. Similarly, chronic stress "is likely to deeply affect the emotional state, health, immunity, fertility and milk production of cows" [36]. Although, a routine APM workout is not likely to produce chronic stress, it may still induce short-time stress, especially, for un-acclimated animals, as the article [37] mentions, citing from another source, that, "Novelty is a very strong stressor of farm animals".

Contrarily, it is also to be noted that exercise has its own stress reducing feature as well. The article [38] (in the perspective of Korean adolescents), suggests that intense physical activity can have a positive impact for stress management. In relation to small animals, the review article [39] mentions that exercise reduced oxidative stress biomarkers, and Davidson and Beede [40] reports an overall improvement in physical fitness of (late-pregnant and non-pregnant) dairy cows with exercise training. However, it is important to conduct further research to identify the pros and cons of animal stress levels induced by exposure to various APM power generation exercise scenarios. Experts may create multiple scenarios based on their professional opinion to assess which setting leads to the lowest stress level for un-acclimated dairy cows. The options include treadmill versus traditional draught work, moderate to long duration exercise versus light intensity, and more. Hence, it is imperative to explore suitable options for the well-being of the animals.

2.7. Quantifying the benefits gained and sustainability attributes

How much is the cost savings, in terms of reduced annual medical expenses of a dairy farm which has installed an APM setup ([41] mention increased use of medicine for captive livestock, and also mention that exercise physiology research has shown benefits of rational exercise)? Is there any improvement in milk yield ([28] mentions such a case) after routine exposure to suitable APM exercise regimen–if yes, then how much? What is the quantity of any additional benefit gained e.g., improvement in milk quality due to reduction in medicine usage-Zachut *et al.* [42] mention that elevated use of medicine for dairy cattle, may have negative affect on human consumers. Can this resource be classified: sustainable/green? Is it totally clean? Or does the APM exercise lead to increased feed consumption which may lead to a burdening of manure management system? Questions like these also need research efforts for investigation. In general, a future investigation direction can be to investigate/quantify the potential benefits (other than energy) of APM setup–these may include, reduced medical expense in farms (economy), contribution to human health (society), and a cut-down of fossil-fuels (environment). Prove/disprove if the resources is green/sustainable.

For instance, to prove/disprove the green energy classification of APM power generation setup, firstly, description of green energy may be consulted from recent literature e.g., [43]–subsequently, various of positive green energy attributes, such as reduction in greenhouse gas emission, and negative attributes e.g., increase in manure, may be measured empirically in comparison with a traditional energy source, to be able to reach a conclusion.

3. CONCLUSION

Throughout centuries, animals have been a reliable source of support for humans. One such form of future support is the generation of electric power from animals, particularly from those found in cattle farms. This form of bioenergy, which relies on the muscles of animals, is an excellent way to achieve the United Nation's SGD 7, which focuses on affordable and clean energy. Additionally, this draught workout can provide healthy exercise for cattle. There are still gaps in the current body of knowledge that need exploration. For example, it is unclear what the suitable amount of work for a dairy cow would be. It is also unknown how this amount of work may differ from one animal to another or how it changes depending on weather conditions. These are important questions that require further research. This perspective paper explores the potential of harnessing farm cattle draught power to generate renewable electric energy. The paper identifies several gaps in the current body of knowledge and outlines the need for further research in this field. The study estimates that cows can generate up to 350 watts of power, but further research is necessary to determine the precise amount of power that dairy cows can generate. In summary, several areas require further investigation, and research in the APM domain has the potential to improve the welfare of farm animals while simultaneously reducing fossil fuel consumption. Such research could lead to significant benefits for the environment and contribute to the sustainability of the agricultural industry.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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