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Renewable Electric Power from the Equine Treadmill: An Evaluation of the Potential

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ABSTRACT

Horse power – the prime mover that has been there with humans for ages; chiefly used for transportation in the early days, and later, also used as an energy source leading to the conception of the term – horse power (hp). The current paper presents an interdisciplinary effort that brings forward an approach for evaluation of the potential of renewable power extractable from this prime mover once again. Specifically, the focus is towards extracting power from the equine treadmills (dry-type) whereby the incline of the machine is replaced by an equivalent (or pseudo-equivalent) energy generation mechanism leading to the coupling of renewable power with an equine workout. This approach comprises aerobic power (evaluated from oxygen uptake data) as well as anaerobic power (evaluated from plasma lactate data) – each of which is estimated from the difference values between equine running on a flat treadmill and when the mill is inclined. Furthermore, a literature review mentioning different inventions as well as some research efforts directed towards tapping somatic energy of animals is included in the manuscript. Also, a section dedicated towards assumptions/weak points helps judge the applicability of the presented work.

1. Introduction

For centuries, humans have benefitted from animals in one way or the other. Animals such as camels, cows and goats have provided us with milk as well as meat, hides (leather) have been used for a variety of purposes, and in the transportation department – they have been there, whether it was a draft work such as moving heavy loads by oxen carts or it was a high speed transit benefitting from the pace of Equus Caballus i.e. the horse. Despite living in close proximity for ages, the dawn of modern lifestyle has parted animals from their human beneficiaries, especially for the city dwellers who can obtain milk and meat from the market; besides getting access to a variety of honey, eggs and even leather and wool products in a superstore. As regards the transport, it has been taken up largely by fossil-fuel based automobiles. So, has this separation been for the good, or have we lost something that we shouldn't have – this may be deemed a debatable issue. Reference [1] mentions in its abstract that the positive effects of human-animal interaction have been researched by various studies and it has been shown that animal-assisted activities can be used to improve the physical and mental health of humans. The authors of [1] present a study concerning effect of equine-assisted activities (EAA) on prosocial behavior of adolescents and conclude that '… in this sense EAA has a protective effect on the behavior of adolescents'. Reference [2] identifies equine grazing, domestic biodiversity, land use, tourism and equine work as five 'green assets' of equines and mentions a case (with its certain conditions) which showed that for the same amount of carbon emissions, a donkey could prepare larger agricultural land area than a machine. The authors of [3] present a study of effects of horse riding upon children and deduce that riding a half-breed horse or a pony had a positive effect on causing the go- and no-go (self-control) reaction on children and it even improved solving of arithmetic problems.

Orienting towards the topic of the current paper, the horse in particular, has been serving humankind for ages. It offers the highest sprint speed (surpassing other rideable animals such as camels and steers) coupled with human-friendliness as well as ease of keeping. However, as the 20th century witnessed the spread of automotive industry, the horse can now be found in equestrian sports and leisure riding (exceptions may include draft work). One of the equipment used for equine exercise as well as research is the treadmill. Furthermore, some of the treadmills can have an incline function where the mill is tilted (w.r.t. ground) to increase the intensity of equine workout without reaching maximal speeds. The current paper makes the argument: why not keep the mill flat while extracting an equivalent amount of energy electrically, thus maintaining the exercise while generating clean renewable energy. To this end, the paper provides an approach for evaluating the amount of power that can be generated by an average horse.

The idea of energy generation from the horse via an equivalent (-to-incline) treadmill is unorthodox as well as interdisciplinary – involving Electrical Engineering (Power Engineering and Power

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Electronics) as well as Equine Science (may include bio-mechanics as well as Equitation Science). The subsequent literature review mentions various inventions and research papers directed towards generation of energy from animate prime-movers.

2. Literature Review

This literature review is neither intended to define the scope of various inventions/research efforts nor may it be considered as a compact summary encompassing all the inner details of the inventions/research efforts.

Energy capture via treadmills is a fascinating concept with a fair number of research efforts. A US patent is presented in [4] which mentions that the invention provides a system and method for electricity generation via using animals like horses. The invention is different from treadmills; over here, the animal moves on trolleys which in turn move on a track. An elaborate system of gears, springs and levers converts the biological energy into rotational energy for an electric generator. The inventor says that this device is superior to a treadmill which only uses a half of the force of movement. He further goes on to say that it is envisioned that a treadmill like free running environment may be developed without departing from the invention. Also, it has been mentioned that the specific intention for the device is for rural areas with limited or non-existent electricity generation.

An exercise machine is presented in the patent [5], for large animals such as dairy cows. The invention is a treadmill type device and includes hoof abrasion system as well as a treadmill cleaning or flushing system. The inventor argues that as exercise gives a lot of benefit to humans, in a similar way it can be beneficial to dairy cows. A frame supports an endless track, upon which the animal will walk. One embodiment of the device includes a power generation system, wherein the walking energy of cow powers an electric generator. Energy may be stored or fed to the grid.

Continuing the treadmills, the patent [6] presents a treadmill for humans which can generate electric power. According to the inventor, a manually operated treadmill that can generate power for itself or for other electrical equipment may be beneficial for various environmental and practical reasons. In an exemplary embodiment the kinetic energy (KE) of the treadmill which the user imparted to the running belt is converted to electrical power via the power generation system.

Furthermore, the patents [7–10] also mention inventions using animate prime movers for electricity generation. The patent [7] mentions a mechanical platform comprising five stages used to convert energy from animals such as camels and horses into electrical energy. The multiple stages include a rotating base, air compression mechanism, a steam device and a dynamo for electricity generation.

Movement of livestock for energy production has been used by [8]. The patent presents equiangular radial levers which will generate moment of force when driven by livestock. Eventually, KE will be converted to electrical energy. The patent [9] uses a treadmill for harnessing animal power while the animal is walking on the belt and its head is in the feed end. It also gives the idea of getting more work from a powerful animal and vice versa; via a computer system developed for this. The patent [10] harnesses equine power where horses move in a circular path driving a central shaft via gears which drives a synchronous generator.

Looking at research publications, Fuller and Aye [11] are of the view that human and animal somatic energy is a forgotten source of renewable power. The paper mentions that on a global scale, the energy (authors are not exactly focusing on electrical energy) contributed by humans and animals is estimated to be twice that of the wind power. In the authors' words, "the paper makes the case that human and animal power be seen as renewable sources of energy"; the authors further say that the techniques for using these energy sources should be deemed "as part of the 'renewables' family." Posing the question why human and animal powers are not included in well-known renewable energy forms, the authors answer that several explanations are possible; these include human/animal powered technologies not being very fashionable and lack of support from big companies. Despite the paper not being targeted towards generation of electrical energy and being largely discussing rural habitat – it has been mentioned that the relevance of such technologies for developed countries should not be overlooked.

The authors of reference [12] give the idea of using animal draft power as well as biogas for electricity generation for rural areas. Animals are attached to rods connected to a circular plate which is connected to a chain sprocket system which transmits power to an electrical generator via a gear box. Estimated energy output (without including electrical component losses) is 18kWh/day from twelve oxen.

Energy generation via human treadmills is presented in [13–15]. Both electrical energy (generated via permanent magnet DC machine) and mechanical energy (used by a special washing machine) have been exploited in [13]. The system is not grid connected and detailed measures for maintaining (nearly constant) treadmill speed have not been mentioned. An elaborate work presenting hardware setup for a grid connected treadmill is mentioned in [14], where an infra-red sensor senses user position on the treadmill; consequently a three-phase permanent magnet synchronous machine connected to the belt is operated as either a motor (if the user leads reference) or as a generator. The synchronous machine receives/supplies power from/to a DC bus via a three phase AC/DC converter which operates the machine via field-oriented control. The DC bus is connected to the grid via a single phase bi-directional converter operated via single phased d-q frame. In [15], the authors present another human treadmill where the generated energy may be used for charging a battery or for a low voltage CFL.

In short, this section has mentioned efforts of various authors and inventors who have worked towards the idea of harnessing the energy of animate prime movers. However, the specific idea of generating electric energy from flattening the inclined dry-type treadmill for an exercising horse is rather unorthodox and thus could not be covered in literature review – although, instances of treadmills where horses walk to generate mechanical power (e.g. for wood splitting) may be found from sources other than published research literature.

3. Work, Metabolic Cost & Horse Power

3.1. Work

Encyclopedia Britannica defines work, in physics, as "measure of energy transfer that occurs when an object is moved over a distance by an external force at least part of which is applied in the direction of the displacement." Work is the product of force and the displacement: hence, if the displacement is opposite to force, the work is negative. For example, in humans, if the triceps brachii is used for a fast accelerated extension of the fore-arm along the horizontal plane i.e. parallel to the ground surface – the muscle performs positive work, however, before reaching the straightening of the arm (i.e. the max extended position), the biceps brachii naturally exerts a decelerating force and slows down the arm – thus performing negative work. Another way to look at this is that the triceps accelerated the forearm, thus imparting KE; while the biceps decelerated the forearm thus extracting that kinetic energy. Consequently, the net work, performed by the body upon the forearm limb is zero (another way to comprehend net zero work is that the limb returns to same energy state KE = 0, Potential Energy (PE) = as before). However, internally both the muscles consumed metabolic energy (explained subsequently) of the body while applying their respective contractive forces.

3.2. Internal Work

Work performed upon the limbs w.r.t. the Center of Mass (COM) of the body may be regarded as internal work e.g. the protraction phase of an equine forelimb during a gallop, when the limb is moving forward (being protruded) may easily be comprehended as a case of internal work.

3.3. External Work

This is the work performed by the limbs to move (upward and/or forward) the COM of the body e.g. in the stance phase (hoof touching the ground) of an equine gallop, the propulsive part which accelerates the body, is performing external work.

As a summary, the stance phase includes external works – negative and then positive, when the COM is braking and then accelerating respectively, while the swing phase (hoof not touching ground) includes internal work. On a level locomotory activity such as walking, at a constant speed, for horses or humans, the *net* external work performed by the body is zero (energy expended against aerodynamic drag is not included in this). Alternative argument for the zero work concept is that the body is undergoing no *net* change in its KE or PE per stride. Reference [16] mentions this, that in level walking or running, the net work per stride is zero.

However, the body is still expending metabolic energy (discussed subsequently) which is being used up in

i. Internal work
ii. Within stride External work – this includes the decelerating and accelerating work per stride. Reference [17] gives graphs of within-stride KE variation for equine walk, trot and gallop.

3.4. Metabolic Cost

Metabolic cost for a physical activity refers to the energy expended by metabolic reactions within the body for performing that activity. For locomotion, the metabolic cost becomes Joules expended per meter of covered distance i.e. J/m; on per kg of body mass it is augmented to Jkg-1m-1. The portion of released energy which is converted to mechanical work decides the efficiency of the muscles; [18] quotes this efficiency to be in the range of 25 – 30% and mentions it to be a product of two efficiencies

- Phosphorylative coupling efficiency (around 60%)
- Efficiency of contractive coupling (around 49%)

For equine performance, [19] mentions that the energetic cost (expressed as kJ/min) is essentially linear with speed, with the condition that the animal can change gait freely. A relationship on per kg basis is provided as well, this relationship may be given as

$$Energy\ (kcal/min) = 0.0289 + 0.00074 * speed(m/min) \tag{1}$$

The author of [19] further mentions that Adenosine Triphosphate (ATP), the immediate source of energy in muscles, is quite limited (6mmol/kg of muscle mass) – it has to be replenished for muscular contractions lasting more than a second or two. The aerobic and anaerobic processes (utilizing and not utilizing oxygen respectively) are the pathways for the release of energy in the body leading to the replenishment of ATP for muscular contractions. The intensity of both the pathways can respectively be judged via

- Oxygen uptake - VO_2 (also symbolized as $\dot{V}O_2$), which is the volume of oxygen consumed given as ml.kg-1.min-1.
- Blood lactacte concentration mmol/L

3.5. Horse Power

How much power can a horse generate? 1horse-power i.e. 746 Watts? Actually, the authors of [20] say that one horse (600kg mass and assumption of 100 W/kg of muscle mass) could in theory give 24hp; it has been further mentioned that realistic estimate of peak performance is around 12 – 14.9hp. The term horse power was coined by James Watt when he was commercializing his steam engine. Watt observed that during a day's work, a horse would expend a power of 33,000 ft-lbf/min [20], equivalent to 745.7Nm/s. This unit came to be known as horse power. As this power value was intended to show a replacement potential of horses by steam engines, hence it is not an indicator of peak equine potential; rather a through-out-the-day power which a horse could deliver.

4. Treadmills

The first equine treadmill dates back to 1960 as mentioned in [21] and the initial studies were focused on metabolic variables. Treadmills were subsequently adopted in kinematic studies as well as for equine exercising. The incline function of the treadmills can increase the exercise intensity, consequently a maximal workout may be achieved at sub-maximal speeds. More recently, water treadmills have been introduced which can increase exercise intensity due to drag of water.

4.1. Scope of the current paper

The scope of the current paper is towards evaluating the potential of renewable electrical power generate-able via the equine dry type treadmill. If the treadmill is kept flat, and an adaptive/controllable energy generation unit is coupled with it that may be grid-tied or connected to a battery bank – the exercise/study intensity may be adjusted equivalent to the value that the inclined mill offered, thus producing clean renewable energy at the same time. The scope of the current paper is different from many citations quoted in literature review; over here, rather than being the primary objective, energy production may be regarded as a secondary objective, wherein the chief purpose may be the exercising of the horse.

4.2. Direct and Indirect Assessment Methods – why mgv_v is not used.

Reference [22] examines speed of racehorses on different gradients on an undulating racecourse. The authors say that the race horses reduce speeds on inclines and the speed detriment corresponds to trade-off between metabolic costs of height gain and horizontal galloping. The paper mentions that the power required to move up an incline may be expressed as

$$power = mgv_v \ where \ v_v = v_h . s \qquad (2)$$

m and g are the body mass and gravity, v_v and v_h are the vertical and horizontal components of velocity and s is the slope of the gradient. The paper calculates that moving up a 10% incline at 8m/s i.e. at $v_v = 0.8$m/s equates to 8W/kg.

In the current effort, an indirect assessment of the power generatable via equine treadmill is presented. This indirect approach uses ΔVO_2 and Δlactate values (between flat and incline) for the power assessment – details of the methodology are presented in the sections 5 and 6. A direct assessment of the power actually being expended on the vertical mill, via the use of (2) has not been performed (although there are research efforts which use this approach for the treadmills). We refrain from using it because we are of the view that this approach is not exactly applicable to treadmills where the center of mass (COM) may not move absolutely the same as its movement on an actual uphill incline. A subsequent kinematic study or a prototype demonstration may be able to verify or disprove the results of this paper – in light of such results, the currently presented approach may be reworked to look for a discrepancy and readjusted as per need.

For use of ΔVO_2, we present the case of [23] where an uphill/downhill (incline of ±8%) treadmill work (for humans) was simulated on a flat treadmill, via the use of a horizontal force applied to the waist of the runner (speed 2.5m/s). For the uphill case, despite the Pearson correlation coefficient given to be 0.42 and the authors regarding the VO2 correlation between the two methods (uphill simulation on flat treadmill and actual inclined treadmill) to be not significant; still, the mean VO_2-net (ml.kg-1.min-1) values for simulated incline and actual treadmill incline running were fairly close. These values were reported to be (Mean±SD) equal to 38.6±2.19 and 37.2±4.25 for simulated and actual treadmill incline respectively. An observation of the graphical results presented in the paper shows that, out of the eleven humans tested, three gave VO_2 results for the simulated method to be very close to the actual inclined treadmill, and the remaining eight were distributed so that six gave higher VO_2 for the simulated method while two gave otherwise. For the current paper, the fair proximity in the average VO_2-net values for simulated and actual treadmill incline as mentioned earlier, may be regarded as a basis for the provided approach of evaluating the equine renewable power potential from an average horse.

Moreover, it is worth mentioning that an alteration in the ground reaction forces (GRFs) is also expected as the treadmill is changed from inclined to horizontal while maintaining exercise intensity. We deem such an alteration to GRFs beyond the scope of the current paper. However, we do like to mention that the GRFs on an inclined treadmill are already not the same as those on a flat track apparently; the change from inclined to horizontal, might just be in-favor-of, or benign-to, the exercising equine.

5. Evaluation of The Potential: The Aerobic Contribution

5.1. Evaluating the generatable renewable power

We present an indirect metabolic approach for evaluation of the power expended on inclined treadmills at different slopes. The authors of [24] have examined effect of treadmill incline on VO_2 and other parameters for five horses. The VO_2 has been plotted against treadmill speed for different inclines (reproduced here in Figure 1). Attempting to describe their data mathematically, the authors say that for 2.5% and 0% (i.e. flat), the VO_2 vs. speed relationship could be best defined by second order polynomials while for 5%, 7.5% and 10%, the relationship was described via linear regression. Table 1 gives various coefficient values for their relationships.

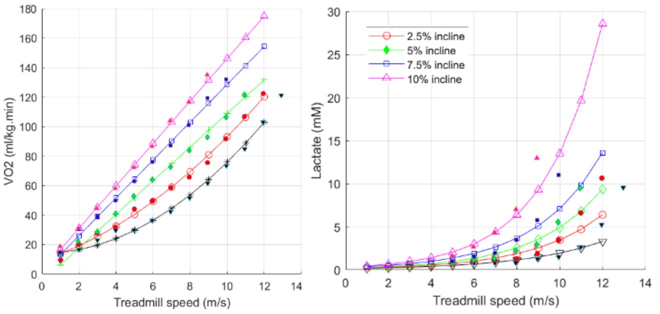
Table 1: Speed and incline relationship coefficients of [24]

Coefficients Incline	x^2	x^1	x^0
0%	0.61	0.10	13.89
2.5%	0.43	4.08	9.29
5%	-	11.40	-5.11
7.5%	-	12.82	0.43
10%	-	14.38	2.30

'x' represents the horizontal axis quantity of speed in m/s. The y-axis quantity is VO_2 in m,kg^{-1}min^{-1}. Linear regression coefficient values are means only - non-inclusive of ± SE

Fig 1. plots the VO_2 and lactate concentrations (after taking antilog of $\log_{10}$ values) obtained from provided relationships as well as those obtained from the provided graphs (from [24], Figure 1A for VO_2 and Figure 4A for lactate conc. – mean values acquired via) using a MATLAB based graph digitizer program [25]. Some of the points for lactate concentration (e.g. lactate mM at 9m/s for 10% incline) with large variation between graph based and regression equation based values have been approximated to their graph digitized values. The current work takes the data of [24] and calculates the differences of oxygen uptake ΔVO_2 between each incline and the flat e.g. for the 2.5% incline $\Delta VO_{2\text{-}2.5\%}$ may be obtained as

$$\Delta VO_{2-2.5\%} = VO_{2-2.5\%} - VO_{2-0\%} \qquad (3)$$



(a) (b)

Figure 1: (a) VO_2 and (b) Plasma lactate concentrations vs treadmill speed – empty symbols are for values obtained from relationships, filled symbols are for values acquired from graph

Subsequently, the joule equivalent of oxygen ($O_{2\text{-}J\text{-}eqv}$) is taken to be 21.1 J/ml O_2 [26]. The extra power expended (not exactly expended – rather, this is the power extractable at 0% incline to produce a similar/same energetic response) for vertical motion at 2.5% incline denoted by $p_{mech\text{-}aer\text{-}2.5\%}$ may be expressed as

$$p_{mech-aer-2.5\%} = CRS_{CF} * \Delta VO_{2-2.5\%} * O_{2-J-eqv} * m_{equ} * \eta_{mscl} * \left(1/_{60}\right) \qquad (4)$$

where η_{mscl} represents locomotor muscle efficiency, m_{equ} represents the equine mass, 1/60 converts from minutes to seconds and CRS_{CF} is the correction factor for Cardio-Respiratory system oxygen demand explained subsequently. Furthermore, (5) provides a look at (4) in terms of dimensions (units)

$$Watts\ (J.s^{-1}) = ml.kg^{-1}.min^{-1} * J.ml^{-1} * kg * min.s^{-1} \qquad (5)$$

Next we assume a value of 30% for η_{mscl} [17] and a 492 kg equine body mass (as in [24]). The factor CRS_{CF} is a rather crude approximation of the VO_2 used up by the heart and lungs. The web article [27] (although not exactly for the equine heart) provides values for the myocardial oxygen consumption (MVO_2) to be 8ml O_2 per minute per 100g, for the cardiac state of 'resting heart rate' while for the state of 'heavy exercise', the value is raised to 70ml O_2 per min. per 100g. Next we assume the lowest activity state of locomotion at 1m/s on the treadmill of 0% incline (i.e. flat mill) to be equivalent to the resting state for MVO_2. The corresponding VO_2 for this state equals to 8.8ml/kg.min (obtained via graph digitization). Furthermore, [28] presents mean heart weight of racing type (Thoroughbreds and Standardbreds) horses to be about 0.86% of bodyweight – hence, for the ongoing study mean heart mass is taken to be 0.86% of m_{equ} which equals about 4.2 kg. Consequently,

$$total\ MVO_2 = 4.2kg * \ 80ml.kg^{-1}.min^{-1} = 336\ ml.min^{-1} \qquad (6)$$

and the MVO_2 as a percentage of total VO_2 roughly equals

$$\frac{total\ MVO_2}{total\ VO_2} = \frac{336\ ml.min^{-1}}{8.8 * 492\ ml.min^{-1}} \approx\ 0.078 \rightarrow 7.8\% \qquad (7)$$

Performing similar calculations for the highest speed point (10m/s) for 7.5% treadmill slope (as it corresponds to the highest heart rate provided by [24]) and using the 'heavy exercise' cardiac state, total MVO_2 equals

$$total\ MVO_2 = 4.2kg * \ 700ml.kg^{-1}.min^{-1} = 2940\ ml.min^{-1} \qquad (8)$$

and

$$\frac{total\ MVO_2}{total\ VO_2} = \frac{2940\ ml.min^{-1}}{132.2 * 492\ ml.min^{-1}} \approx\ 0.045 \rightarrow 4.5\% \qquad (9)$$

subsequently, we approximate the total MVO_2 to be equal to 5% of the total MVO_2 being taken up for any given speed and slope. This is obviously a crude approximation, and a more detailed approach can involve use of multiple values for the *total MVO_2/total VO_2* ratio which can yield multiple values of CRS_{CF}.

Continuing towards the lungs, [29] mentions that the lung consumes 5% of whole body oxygen uptake – using this value as it is (although [29] is neither for equines nor for exercise) and combining it with the estimated 5% value of the total MVO_2, means that about 10% VO_2 is being consumed by the cardio-respiratory system for its own functionality – hence, 90% VO_2 is the value available to the rest of the body. The CRS_{CF} is then taken to be 90% (i.e. 0.9) thus showing that (only) 90% of the $\Delta VO_{2\text{-}2.5\%}$ in (4) is available for the evaluation of $p_{mech\text{-}aer\text{-}2.5\%}$.

Figure 2 shows plots of $p_{mech\text{-}aer\text{-}2.5\%}$ and the mechanical power values for other inclines. Also shown are the metabolic power values generated at different speeds and inclines. A relatively light exercise of 2.5% incline at 5m/s (3 – 6m/s has been regarded as most energy efficient speeds regardless of incline by [24]) is generating around 500 Watts of clean power – assuming a 30 minute exercise and an 80% efficiency of the power extraction and conversion system, 400W may be supplied to the grid for half an hour.

5.2. Sketching the metabolic power lines

Figure 2 also shows metabolic power $p_{met\text{-}aer}$ lines. These are sketched by looking for speed points of the same (chosen value of) metabolic power on curves of different inclines – this is achieved via a spline interpolation of speed vs. metabolic power (at different inclines) data - the metabolic power e.g $p_{met\text{-}aer\text{-}2.5\%}$ has been evaluated as

$$p_{met-aer-2.5\%} = VO_{2-2.5\%} * O_{2-J-eqv} * m_{equ} * (1/60) \qquad (10)$$

Subsequently, corresponding to the speed point acquired and the $p_{met\text{-}aer}$ value in consideration, $p_{mech\text{-}aer}$ points are obtained for each incline. Connecting these points constitutes the linear joints of the $p_{met\text{-}aer}$ lines. Lastly, for the selected metabolic powers a spline extrapolation is performed using the speed points and corresponding $p_{mech\text{-}aer}$ points towards the upper end of the figure.

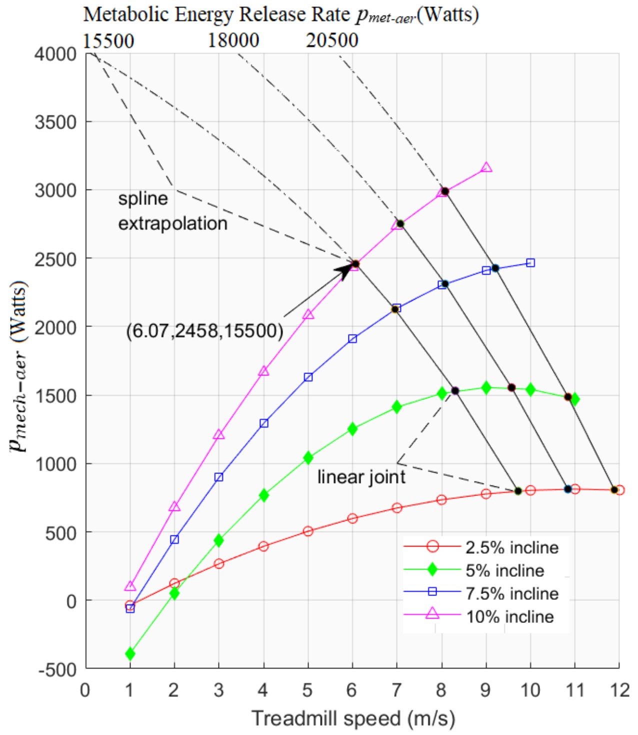


Figure 2: Power generation potential for various inclines. In general, the $p_{mech\text{-}aer}$ values beyond 3m/s may be deemed practical, while errors in speed points of 1 & 2m/s may be attributed to corresponding cluttered VO_2 data of Figure 1(a). The top horizontal axis shows metabolic power lines for different speeds and inclines. A single point (x_{bottom}, y, x_{top}) e.g. (6.07m/s, 2458W,15500W) is to be interpreted as release of 15500W metabolic energy where the horse is moving at 6.07m/s (on the incline of 10%) wherein the aerobic mechanical power generatable via flattening the mill is 2458W.

5.3. Power and Energy

For a discussion about energy, three points α, β and γ are taken from Figure 2; the coordinates are taken as (x_{bottom}, y, x_{top}) i.e. (speed, $p_{mech\text{-}aer}$, $p_{met\text{-}aer}$). These points are (approximately):

$\alpha \rightarrow$ (6.07m/s, 2458W,15500W) - 10 %incline
$\beta \rightarrow$ (8.08m/s, 2312W, 18000W) - 7.5%incline
$\gamma \rightarrow$ (8.08m/s, 2988W, 20500W) - 10 %incline

It may be seen that, while the operating point α can deliver mechanical power value of 2.46kW; the point β is delivering slightly lesser power of 2.31kW, while depleting metabolic energy at a higher rate of 18kW. Consequently, the potential of energy generation at α is higher than that of β. Furthermore, γ is showing even higher potential of delivering about 3 kW but the depletion rate of metabolic energy is also huge - a 20.5kW, hence a probable reduced time duration for maintaining a healthy workout at the point γ, may reduce its energy potential. A detailed analyses of energy generation potentials for different equine breeds, exercise schedules for various gaits, treadmill slopes and speeds incorporating the data of on-set of fatigue/maximum exhaustion (e.g. [30] mentions Times to Fatigue of 45 and 20.2 minutes for an Arab and a Thoroughbred horse exercised at 4.5m/s, 6% incline) is deemed beyond the scope of the current which is aimed at presenting methodology for the evaluation of power that may be generated.

5.4. Point of optimum (aerobic) mechanical power generation

Looking for the point of optimum power generation potential, Figure 3 plots treadmill speed (including and beyond 3m/s) versus treadmill slope (the four inclines) versus $p_{mech\text{-}aer} : p_{met\text{-}aer}$ ratio at the different points.

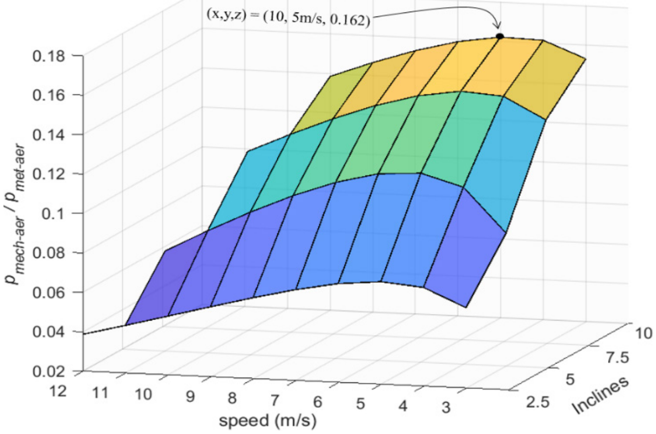


Figure 3: Treadmill speed vs. Treadmill Slope vs. $p_{mech\text{-}aer} : p_{met\text{-}aer}$ ratio. Speed points 1 and 2 m/s are ignored for reason mentioned in Figure2 caption.

The highest value of 0.162 for the $p_{mech\text{-}aer} : p_{met\text{-}aer}$ ratio was found to occur at the speed of 5m/s for the treadmill slope of 10%. With respect to the treadmill slope, Figure 3 shows a trend of increase in $p_{mech\text{-}aer} : p_{met\text{-}aer}$ ratio and w.r.t the speed, highest $p_{mech\text{-}aer} : p_{met\text{-}aer}$ ratio values are achieved around 5m/s. It may be noted that this is in line with the top values of economy of locomotion (ml.kg^{-1}.m^{-1}) occurring in range of 3 – 6 m/s as evaluated for the initial data (of the current study) by [24] - which further mentions high speed locomotion to be less efficient (for flat and 2.5% incline).

Lastly, towards the end of this section, it is worth mentioning that the methodology described here may be considered to be only an approach towards the evaluation of the potential. The values are not definitive – with variations arising from different factors such as equine body mass and precision in value of energy released per ml of O_2 etc. Reference [24] has itself mentioned that the regression coefficients for the speed and VO_2 relationship have range from 11.1 to 19.61 in different studies. It has been further mentioned that the variations in studies may be due to differences in methodology including different factors such as horse breed, bodyweight as well as treadmill acclimation.

6. The Anaerobic Contribution

This section provides an approach to assess the anaerobic (lactic) contribution to energy and power for equine exercise on inclined treadmill. Once again, the data of [24] has been used which has provided plasma lactate concentration graphs as well as linear regression log10 lactate concentration versus speed relationships. Mean values have been used excluding the standard deviations – the same was the case for aerobic approach. The difference in plasma lactate concentration between each incline and the flat treadmill have been evaluated. These differential lactate values represent the additional exertion expended due to the incline of the treadmill and are converted to corresponding delta (Δ i.e. difference) metabolic energetic approximations as expressed in (11) for the 2.5% incline. Differing from the approach of aerobic contribution where a portion of the VO2 was given to the cardiorespiratory system, over here, lactate value are assumed to be a result of the activity of exercising muscles only.

$$e_{met-\Delta-2.5\%} = \Delta_{lact-2.5\%} * lact_{p\to b} * lact_{O2-eqv} \\ * O_{2-J-eqv} * m_{equ} \tag{11}$$

where,

- $e_{met\text{-}\Delta\text{-}2.5\%}$ is the Δ metabolic energy for the anaerobic pathway for the 2.5% incline
- $\Delta_{lact\text{-}2.5\%}$ is the difference in lactate concentrations between the 2.5% incline and flat treadmill – units of Δ_{lact} are milli moles per litre (the units may be symbolized as mM)
- $lact_{p\to b}$ = 1.5^{-1} is a factor to represent a 1.5 times reduced concentration of blood lactate as compared to plasma lactate as mentioned by [31]
- $lact_{O2\text{-}eqv}$ is 3mlO$_2$/mmol lactate (per litre blood) – it is the oxygen equivalent of blood lactate as described in [26]
- $O_{2\text{-}J\text{-}eqv}$ is the Joule equivalent of O_2 equal to 21.1 J/ml O_2 as used by [26]; a slight variation of 20.92 J/ml O_2 has been used by [32]
- m_{equ} is the mean equine mass of 492 kg as in [24]

Subsequently, (12) shows calculation of the corresponding mechanical power generation $p_{mech\text{-}anaer}$ which is evaluated by taking difference of two consecutive energy points $\Delta e_{met\text{-}\Delta}$ and dividing this by the two minutes of interval length for lactate measurement as mentioned by [24] (which mentions blood sample collection during last 15s of each interval) – also, as for the case of aerobic power, the metabolic to mechanical conversion is achieved assuming η_{mscl} i.e. muscular mechanical efficiency of 30% as in case of aerobic power. Figure 4 presents the results of $p_{mech\text{-}anaer}$ for the different inclines and speed points.

$$p_{mec-anaer-2.5\%} = \Delta e_{met-\Delta} J/120s * \eta_{mscl} \tag{12}$$

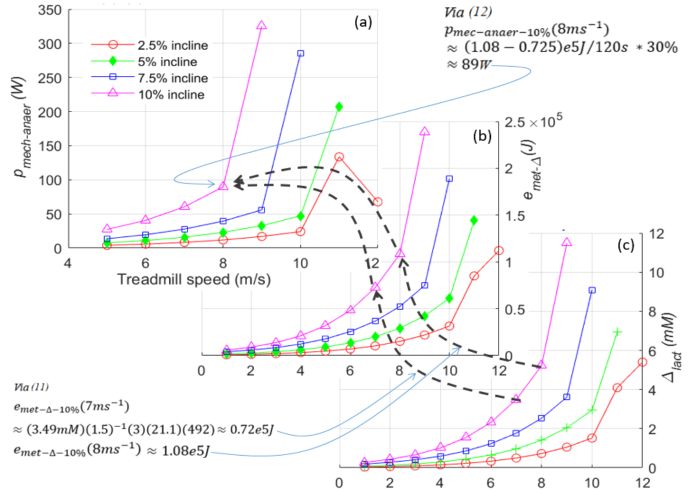


Figure 4: Anaerobic contribution composite figure. (a), (b) and (c) show anaerobic mechanical power, metabolic energy (y-axis in 10e5 Joule) and the differential lactate concentration values respectively. The horizontal axis shows treadmill speed for each subfigure. A single point of (a) e.g. (8m/s, 89W) for the 10% incline

indicates that, 89W of power generation potential is available corresponding to this point and metabolically, this power will be generated via anaerobic pathway.

Interestingly, Figure4 shows that for 12m/s at 2.5% slope, the power potential is actually reduced and this may be attributable to the fact that at this speed, the lactate threshold for the flat mill has also been crossed (as may be seen from Figure 1b) – consequently, the differential anaerobic energy is reduced and hence the power graph shows a dip. Furthermore, anaerobic alactic contributions could not be evaluated in this study because of in-availability of corresponding data in [24], however, these may be deemed minor - [32] mentions the alactic energy contributions to be around 0.1% for supramaximal exercises in their study.

7. Including the Drag

Aerodynamic drag becomes considerable as speed increases. [33] calculates this drag via $\frac{1}{2}C_D\rho Av^2/\textit{body-mass}$ (with $C_D = 0.9$, $\rho = 1.29$ kg/m^3, $A = 1$m^2, $v = 12$m/s and $mass = 550$kg) to be equal to 0.15 Jkg^{-1}m^{-1}. Converting this to power translates into 990 J/s i.e. about 1kW. It has been mentioned by [33] that, while the drag is often considered negligible, it is actually a larger proportion of the external mechanical work compared to what was considered before. So, a horse galloping on the track at 12m/s is expending about 1kW of external mechanical work for countering the aerodynamic drag forces. Consequently, as the same horse is exercising at 12m/s on a high speed treadmill, extracting 1kW of power can make the equine work-out closer (in terms of power consumed) to the over track exercise. Figure 5 plots variations in the mechanical power $p_{mech\text{-}drag}$, calculated as in (13), expended (in over-ground running) for overcoming the drag

$$p_{mech-drag} = \frac{1}{2}C_D\rho Av^3 \qquad (13)$$

at various speeds while including the effect of variation in air density ρ as it varies from 1.2 kg/m3 to 1.29 kg/m3.

The two data points selected in the figure show a pmech-drag difference of about 230Watts between the extremes of ρ for the speed of 18m/s. From the figure, around 3.4kW of power generation potential is available as the same workout of 18m/s in an atmosphere of ρ = 1.29 kg/m3 is being carried out on a high speed equine treadmill.

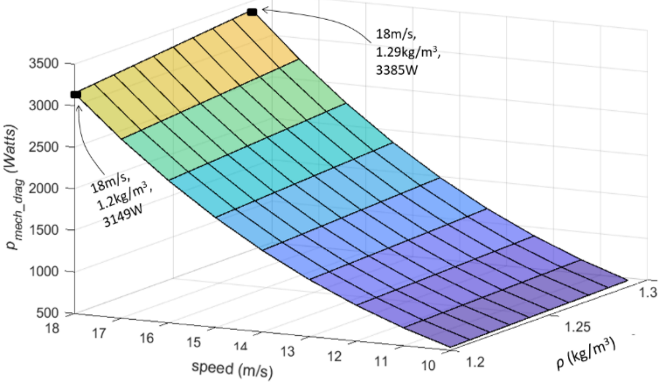


Figure 5: Treadmill speed vs. Air density (ρ) vs. $p_{mech\text{-}drag}$

Furthermore, [34] mentions a case where the exercise on flat treadmill provided a lower cardiac and blood lactate response as compared to exercise on ground at the same speeds. A treadmill incline of 3.5% was found to give heart rate closer to that of the track exercise (especially in the range of 9.1 – 10m/s). Again, if appropriate energy is being extracted from a treadmill, this might give a better replication of the over track exercise while generating renewable power at the same time.

8. Total Mechanical Power: Combining Aerobic and Anaerobic Portions

8.1. Total Generatable Power

Figure 6 presents a wholesome picture – curves for total generatable mechanical power $p_{mech\text{-}total}$ via combining the contribution from the aerobic and anaerobic mechanical powers have been sketched. Except for the last (or second last for 2.5% incline) speed points, the $p_{mech\text{-}total}$ lines are generally quite close to the pmech-aer lines, hence the anaerobic contribution is clearly far less than that of the aerobic part. Furthermore, the rise in $p_{mech\text{-}total}$ lines towards the last speed points may also be explained from Figure 4, which shows a significant rise in $p_{mech\text{-}anaer}$ for the last speed points (except for 2.5%). The dip in $p_{mech\text{-}anaer}$ for 2.5% incline is briefly explained in section 6.

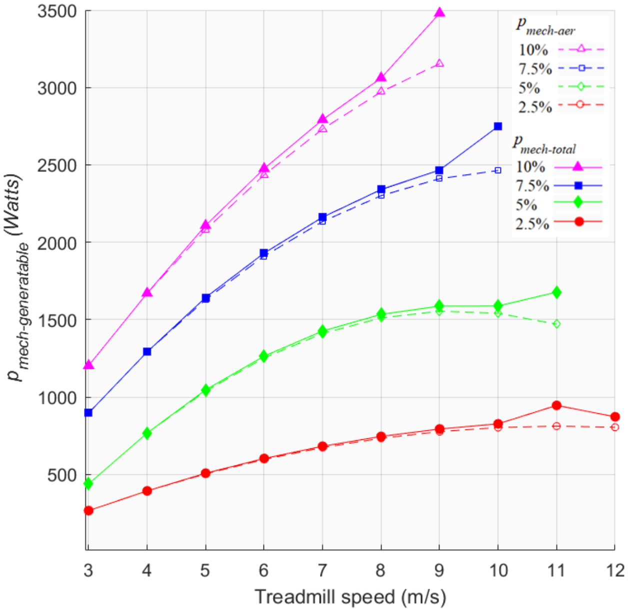


Figure 6: Total generatable power evaluated via combining aerobic and anaerobic portions. The speed points 1 and 2 m/s are ignored for reason mentioned in Figure2 caption.

8.2. Total Expended Power – Revisiting mgv$_v$ concept

Reference [35] summarizes various studies mentioning efficiency for vertical mechanical work for different species – in case of horses the efficiency falls in range of 35 – 40%. If this is true and if a 35% value may be taken for the η_{mscl} variable ([22] mentions use of 35% for vertical efficiency for horses), then the $p_{mech\text{-}total}$ curves, now renamed as $p'_{mech\text{-}total}$, are re-plotted in Figure 7 using the altered value for η_{mscl} (for both the aerobic and anaerobic contributions). Also, plotted are the mgv$_v$ lines for different slopes.

The results of Figure 7 showed an interesting behavior – except for the 7.5% incline (which presents an over-estimation scenario), the mgv$_v$ lines are generally close to the evaluated $p'_{mech\text{-}total}$ curves around the range of 4 - 6m/s (the region is shaded and may be named '*High Proximity Region' (HPR)*). Now if η_{mscl} is truly equal to 35%, the results may be interpreted as suggesting that in a certain speed range, the equine locomotion is involving movement of the whole body, quite the same as it would do on an actual incline – while at other speeds, the COM is moving lesser vertically compared to how it would have to move on an actual uphill incline.

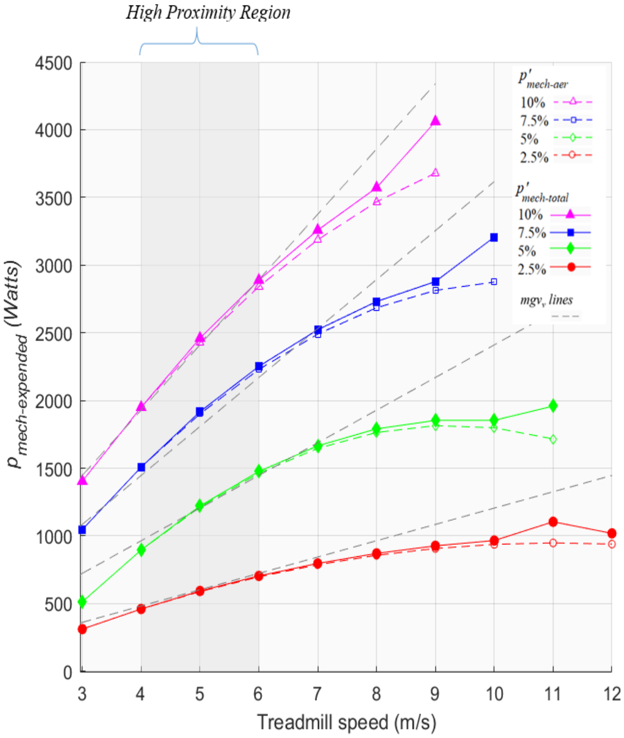


Figure 7: Total expended power evaluated via using 35% muscle efficiency. The speed points 1 and 2 m/s are ignored for reason mentioned in Figure2 caption.

9. The Electrical Power Generatable

The generatable mechanical power $p_{mech\text{-}total}$ is finally converted to electrical power which may be supplied to the grid. Different conversion schemes may be employed, however, for the sake of providing an approach for the evaluation of the potential, the current effort assumes a simple scheme. A DC generator is assumed to be coupled with the treadmill belt, thus converting $p_{mech\text{-}total}$ to p_{dc}. A fixed efficiency of 80% is taken for this conversion.

Next, a grid-tied DC/AC inverter is assumed to convert p_{dc} to AC power $p_{elect\text{-}ac}$ supply-able to distribution electrical power system. For this DC/AC conversion, the Fronius IG Plus 12 curve is selected from [36] ('Figure 4. Typical per unit efficiency curves for grid-connected solar inverters'), graph points are obtained via digitization (using 'grabit' [25]) and curve fitting is used which expresses the efficiency characteristic via (14)

$$Inverter\ Efficiency\ = ax^{b} + c \qquad (14)$$

where a = - 0.6217, b = -1.183, c = 96.98 and x represents the x-axis point of p_{dc} pu (the p_{dc} per unit is obtained via dividing any actual p_{dc} by 3000Watts which is taken as the rating of the inverter). Subsequently, p_{dc} is converted to $p_{elect\text{-}ac}$ according to the (14). Figure 8 presents the inverter efficiency characteristics (digitized points and the curve fitting approximation) as well as the $p_{elect\text{-}ac}$ lines.

10. Assumptions and Weak Points

The purpose of this section is to summarize some of the weak points/assumptions of the presented effort – this may lead to future improvements as well as better evaluation of the quality of results.

1. *Use of ΔVO_2 and $\Delta lactate$ values (section 4.2)*

A justification is provided in the section. Furthermore, due to this assumption, the work may not be applicable to every single individual horse, rather, it would be applicable to an average horse – in other words, if the approach of [23] (which is for humans and for ΔVO_2 only, and not for Δlactate) can be extended to this work (including Δlactate) , then the results should be applicable on the average to different equines with plus minus deviations individually.

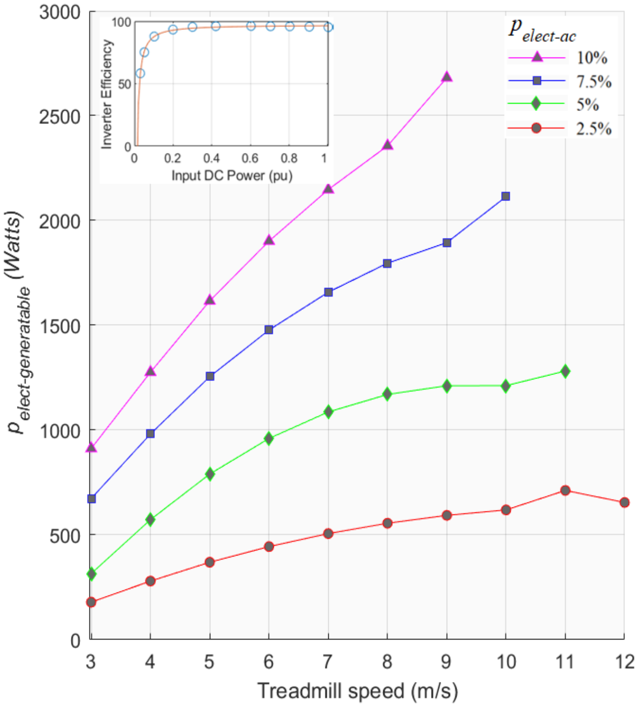


Figure 8: Total generatable (and grid deliverable) ac electrical power from the renewable exercising equine animate prime mover. Inset sub-figure presents inverter efficiency curve – circles show digitized graph points while the curve shows plot of the equation obtained via curve fitting.

2. *Variation in $O_{2\text{-}J\text{-}eqv}$ (sections 5.1 & 6)*

Depending upon respiratory exchange ratio, O2-J-eqv can vary from 19.61 to 21.1 [26]. The current study does not take any such variation into account - $O_{2\text{-}J\text{-}eqv}$ = 21.1 J/ml O_2.

3. *CRS_{CF} (section 5.1)*

The cardio-respiratory system correction factor is a crude approximation with various assumptions – derivational details are mentioned in the appropriate section.

4. *η_{mscl} (sections 5.1 & 6)*

The mechanical efficiency of muscles (for horizontal locomotion) is taken equal to 30%, also, any variation in this value has not been accounted.

5. *Using mean values only*

From the basic reference [24], which is the source of the treadmill VO_2 and lactacte data – only the mean values are taken and standard deviations have not been included.

6. *$lact_{O2\text{-}eqv}$ (section 6)*

As per our understanding, the current work is not explicitly involving any lactate clearance alongside lactate generation.

7. *Vertical η_{mscl} (section 8.2)*

A fixed value of 35% has been used.

8. *Efficiency of DC generator (section 9)*

A fixed value of 80% has been used. This is a far from true assumption, as the actual efficiency will vary with operating point. However, it may be said that the purpose of section 10 is mainly to convey the idea of $p_{mech\text{-}total}$ to $p_{elect\text{-}ac}$ conversion, so, for the DC/AC inverter, the efficiency variation with changing operating point has been used and then, to keep things simple, this variation was not used for the DC generator.

11. Contributions to Body of Knowledge

As per the understanding of the authors, the following points may be regarded as the contributions of the manuscript

- Bringing forward a novel concept of harvesting energy from an equine exercise treadmill – thus presenting a case of renewable energy generation from animate prime-movers, without compromising the original purpose i.e. exercise of the treadmill machine.
- Presenting an approach to quantify the generatable power from an exercising equine.

12. Conclusion

The paper has presented the idea of tapping renewable energy from the inclined treadmill for equine exercise. The somatic energy of the horse has long been used by humans – the current paper uses it for electricity generation, albeit maintaining exercise as the primary function of the treadmill workout. For determining the amount of the generatable power, a detailed approach has been presented which includes power of aerobic and anaerobic metabolism as well as the conversion into electrical power.

The paper does rely upon assumptions, but an effort has been made to clearly mention them. The (deemed) contributions to the body of knowledge have been mentioned as well. On the whole, the paper is an interdisciplinary effort presenting a novel concept as well as a subsequent quantitative methodology for estimation of the potential.

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