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Research Papers

# Perpetual motion electric truck, transporting cargo with zero fuel costs

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ABSTRACT

The transportation sector is going through a rapid transition to electric vehicles to minimize our reliance on fossil fuels and reduce $CO_2$ emissions. This is also happening in the cargo transport sector, with a rapid deployment of electric trucks. This paper proposes that the replacement of diesel trucks with electric trucks should first happen on routes where cargo is delivered from a location with a higher altitude to a location with a lower altitude. This way, the regenerative braking system of the truck can completely recharge the truck's battery. This paper investigates scenarios where electric trucks could operate indefinitely without grid electricity to charge their batteries. This concept was named perpetual motion electric truck (PMET). Results show that with an average road slope of 5 %, 60 km/h speed, the weight of the cargo should be at least 1.32 times the weight of the truck, PMET can be achieved. PMET is an interesting alternative to reduce electricity demand and increase the sustainability of the transport sector.

## 1. Introduction

In 2018 around 14 % of global emissions came from the transport sector [1]. Out of the transport emissions, 25 % comes from heavy trucks [2]. Strategies to reduce emissions from heavy trucks are expected with the transition to electric trucks [3–8] and the use of hydrogen [9–11]. Fig. 1 (a) presents the global heavy-duty sales outlook from 2020 to 2040 by BloombergNEF [11]. Regenerative braking systems in electric trucks can reduce the energy consumption of diesel trucks by 32–54 % in an urban setting due to the constant breaking [12–14]. In mountainous regions, this figure should be higher than in urban settings, as the truck requires a lot of energy to drive up the mountain and recharges the battery while driving down the mountain. This figure reduces to 5–34 % in a highway setting [12]. Regenerative braking is a mature technology with motor and generator efficiency higher than 90 %, as shown in Fig. 1 (b). This electric motor model is based on a 20 kW permanent magnet synchronous machine. The electric power map determines how much power is extracted from or supplied to the battery.

There are cases where cargo transportation does not require plugging into the grid or fuel, and the battery is recharged with gravity through the regenerative braking. Researchers have estimated the amount of energy recovered with off-road mining dump trucks to be as high as 65 % [17]. For example, The Infinity Train, under development in Australia, will store energy from moving iron ore down a mountain so that the train does not require energy for the return trip [18]. A limestone mine in Switzerland has dump trucks that transport rocks to a cement factory 8 km from the mine [19–21]. The minerals are transported down a mountain recharging the truck's battery. In some cases, dump trucks can generate a positive energy balance of 200 kWh daily [22]. Other studies on mining dump truck's regenerative breaking can

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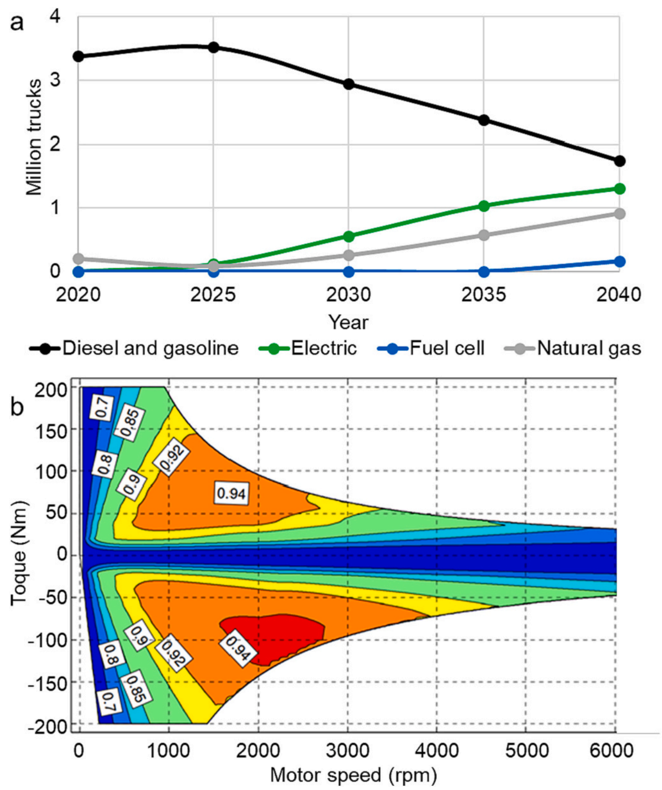


**Fig. 1.** (a) Global heavy-duty sales outlook [15], (b) efficiency map of the electric motor, including inverter efficiency [16].

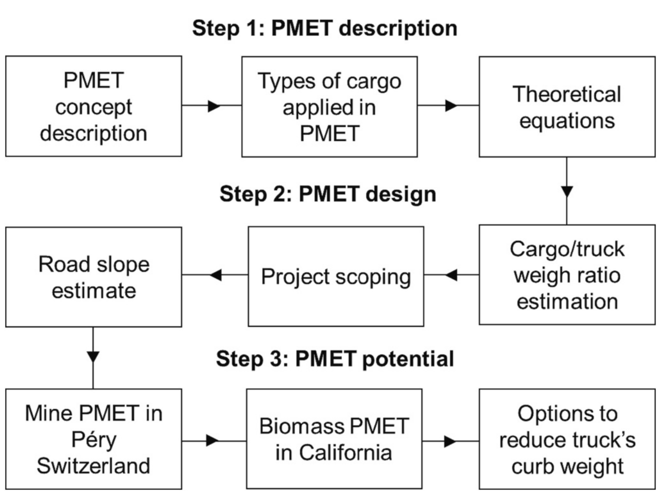


**Fig. 2.** The methodological framework for PMET analysis.

also be seen in [23–25]. Depending on the road slope, electric trucks can even provide hydropower, by transporting water down the mountains [26].

The paper's main contribution is to investigate the conditions under which an electric truck can transport cargo from the top to the bottom of a mountain without connecting to the grid. This transport strategy was named perpetual motion electric truck (PMET). A perpetual motion machine is a theoretical device that operates indefinitely without requiring an external energy source to sustain its movement indefinitely. This differs from the proposed system, as additional potential energy is added to the truck at the top of the mountain. The name was coined to spur the imagination and interest of the readers of the paper. The main motivation for this research is to reduce fuel or electricity use for cargo transportation in mountainous regions. The main research objective of this paper is to calculate the minimum road slope required for perpetual motion electric truck to be achieved. The paper is divided into five sections. Section 2 presents the perpetual motion electric truck (PMET) concept and describes the methodology applied to estimate the technology's efficiency. Section 3 presents the results of this study. Section 4 discusses the technology, and Section 5 concludes the paper.

## 2. Methodology

Fig. 2 depicts the methodology applied in this work to evaluate the perpetual motion electric truck concept. Each stage of the research framework is described in detail in the following subsections. The first step is "PMET description", where the concept is described, different types of PMET are presented, and the theoretical equations applied are explained. The second stage consists of the "PMET design", where the cargo/truck weight ratio is estimated, and the approach to scope potential projects and road slope estimate is described. The third stage describes the "PMET potential" presenting two case studies, one a real-life example in a limestone mine in Switzerland, and the other a proposal using biomass in California. It also explores different options to reduce the truck's curb weight to increase the potential for PMET.

### 2.1. *Perpetual motion electric truck (PMET)*

Perpetual motion electric truck consists of delivering cargo from a location at a high altitude to a location at a lower altitude without the need to recharge the truck's battery, as shown in Fig. 3. This is possible because the weight of the truck moving down the mountain is higher than that of the truck moving up the mountain. This allows the regenerative braking system to charge the battery of the full truck moving down the mountain more than the energy consumed to drive up the mountain with an empty truck. The empty truck should reach its final destination with its battery fully charged, and ready to return. Apart from not needing to charge the battery of the trucks, PMET also removes the impact of charging electric trucks in the grid [27].

Fig. 3 presents three different scenarios where PMET can be implemented. Fig. 3 (a) presents an example where wood logs, biomass, biofuels, or commodities are produced in mountainous regions, where the climate is appropriate, and transported down the mountain for process heat, electricity generation, hydrogen production, civil construction, and other products or export. Fig. 3 (b) presents an example of manure or municipal waste being transported down the mountain to produce biogas, biomethane, composting, hydrogen, or biorefinery products. Fig. 3 (c) presents an example where mineral resources are extracted and transported down the mountain for further processing or export.

Table 1 shows the electric dump truck used in this paper, which is based on [28]. The costs and possibilities for PMET are estimated in this article using today's electric truck prices. It should be noted that these expenses are projected to fall in the future as energy storage technology advances. Electric trucks typically have a driving range of 300 to 500 km what implies large capacity batteries. The truck's lifetime is assumed to be limited to the truck's mileage, which is 1,600,000 km. This results in a lifetime of seven years if it operates at a speed of 40 km/h. Assuming that the truck is expected to operate for seven years, the battery's lifetime is presumed to be the same as the truck's lifetime.

The force analysis when the electric truck is running is shown in Fig. 4. When the electric truck goes down the hill, the gravity component of the truck and the cargo along the slope drags the truck downward, and the resistance at this time includes the friction force from the ground and the air resistance. Assuming that the electric truck is in uniform linear motion on the slope, according to the primary mechanic's theory, we have the following:

Where $G_S$ is the gravity component along the slope, $G_N$ is the gravity component on the vertical slope, $f_R$ is the ground friction resistance; $f_A$ is

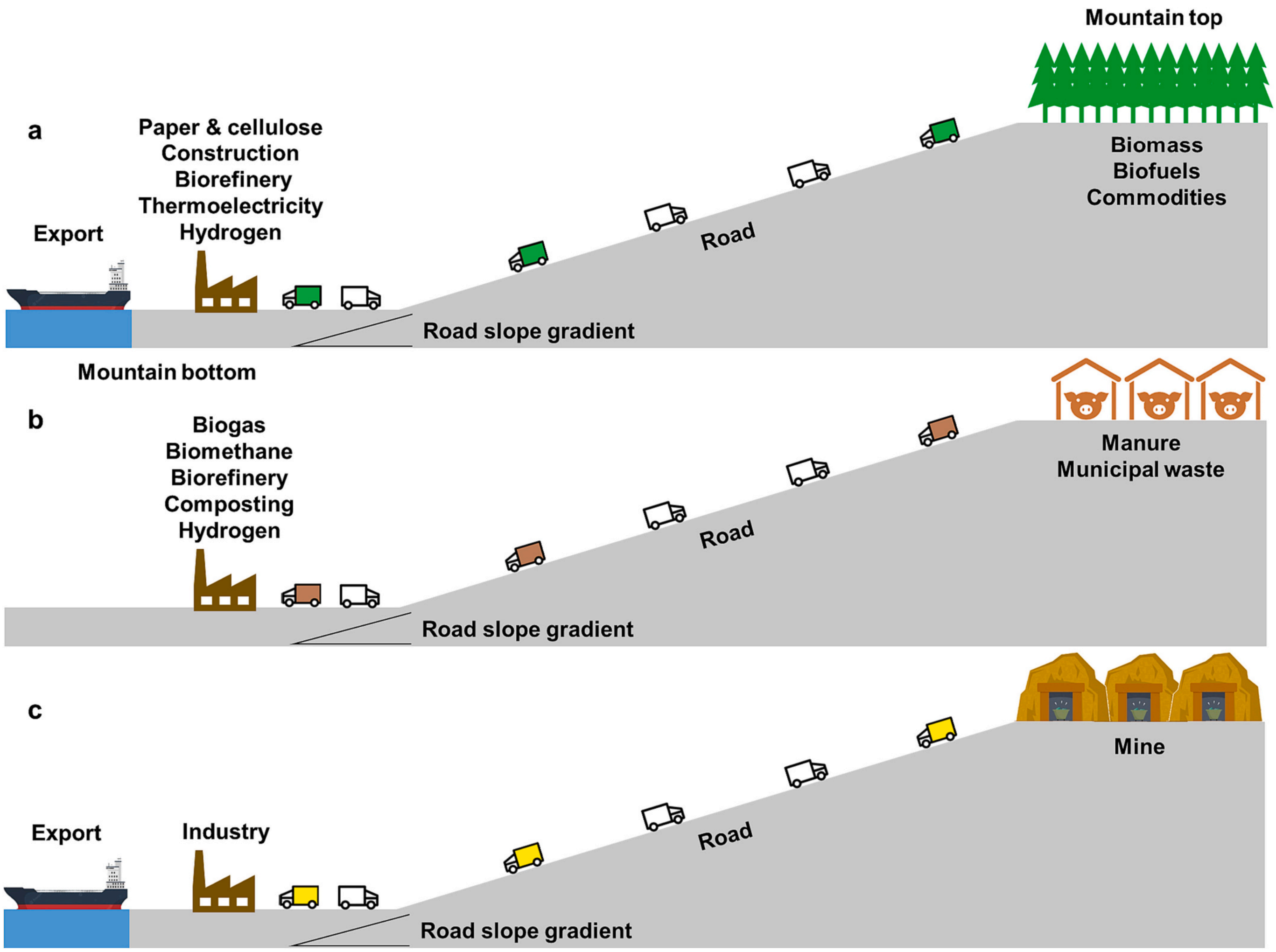


**Fig. 3.** Perpetual motion electric truck (PMET) system description, using (a) biomass, (b) waste, and (c) mineral resources.

**Table 1**
Description of the electric truck applied in the paper [28].

| Item | Description |
|---|---|
| Truck and battery cost (USD) | 300,000 |
| Dimensions (m) | L 9.175 × W 3.400 × H 3.930 |
| Maximum speed (km/h) | 40 |
| Total traction mass (kg) | 90,000 |
| Curb weight (kg) | 30,000 |
| Curb weight – reduced battery (kg) | 25,000 |
| Sand/water capacity (kg) | 65,000 |
| Drive Wheel | 6 × 4 |
| Maximum grade ability | 40 % |
| Drive motor rated power (kW) | 250 |

the air resistance of the truck. $f_{em}$ is the electromagnetic resistance generated by the regenerative braking equipment (motor), which force generates electrical energy through electromagnetic coupling; μ is the rolling resistance coefficient between the tires and road, assumed to be 0.008, $C_D$ is the drag coefficient, assumed to be 0.36 [29], ρ is the air density, assumed to be 1.275 kg/m$^3$, $A$ is the frontal area of the truck (in m$^2$), $V$ is the velocity of the truck (in m/s). $\theta$ is the angle between the slope and the horizontal plane, $g$ is gravity's acceleration, which is 9.81 m/s$^2$, $m_T$ is the mass of the truck, $m_C$ is the mass of the cargo, *down* refers to the direction of the truck, down the mountain, and *up* refers to the direction of the truck, up the mountain.

When the truck goes up the hill, the component of gravity, friction, and air resistance that the truck is subjected to has become the resistance, and at this time, the truck needs to rely on the traction force F provided by the battery-driven motor to go up the hill. Eqs. (6)–(10) each quantity and Eqs. (1)–(5) each quantity corresponds to, not to repeat.

$$F = G_S^{up} + f_R^{up} + f_A^{up} \tag{6}$$

$$G_S^{up} = m_T g sin\theta \tag{7}$$

$$G_N^{up} = m_T g cos\theta \tag{8}$$

$$f_R^{up} = \mu G_N^{up} \tag{9}$$

$$f_A^{up} = 0.5 C_D \rho A V_{up}^2 \tag{10}$$

The analysis of energy flow during PMET operation is shown in Fig. 5. When the truck is going down the hill, the gravitational potential energy of the truck and the cargo is converted into electrical energy stored in the battery through regenerative braking equipment. According to the conservation of energy in the process of going downhill, we get,

$$E_{PT} + E_{PC} = E_{Bat} + L_r + L_A + L_T + L_B + L_R \tag{11}$$

where $E_{PT}$ is the gravitational potential energy of the truck; $E_{PC}$ is the gravitational potential energy of the cargo; $E_{Bat}$ is the electrical energy stored in the battery after regenerative braking generation; $L_r$ is the loss

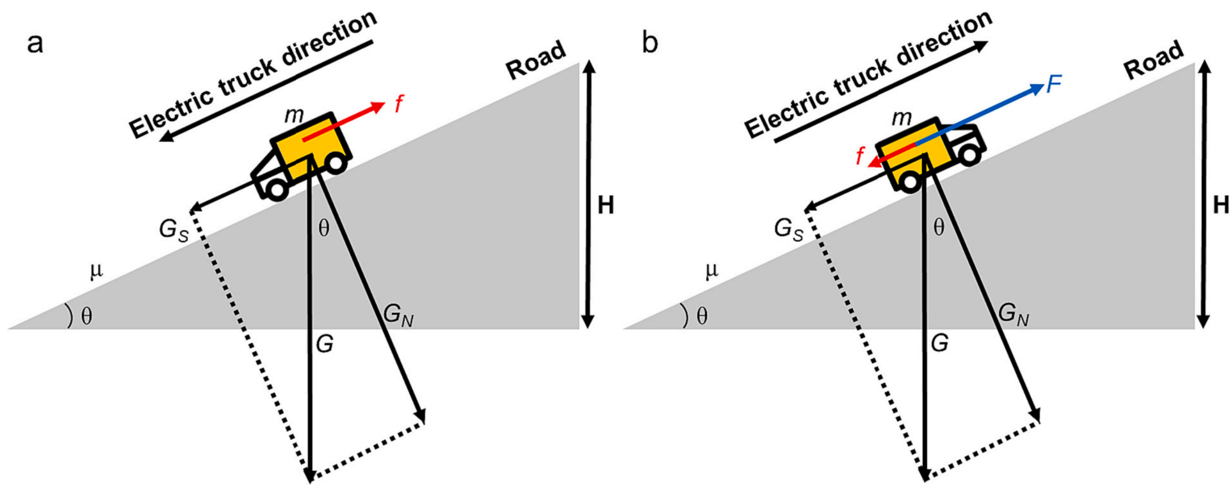


**Fig. 4.** Schematic diagram of the force analysis during the operation of the electric truck (a) moving down the mountain and (b) up the mountain.

$$G_S^{down} = f_R^{down} + f_A^{down} + f_{em} \tag{1}$$

$$G_S^{down} = (m_T + m_C)gsin\theta \tag{2}$$

$$G_N^{down} = (m_T + m_C)gcos\theta \tag{3}$$

$$f_R^{down} = \mu G_N^{down} \tag{4}$$

$$f_A^{down} = 0.5C_D\rho AV_{down}^2 \tag{5}$$

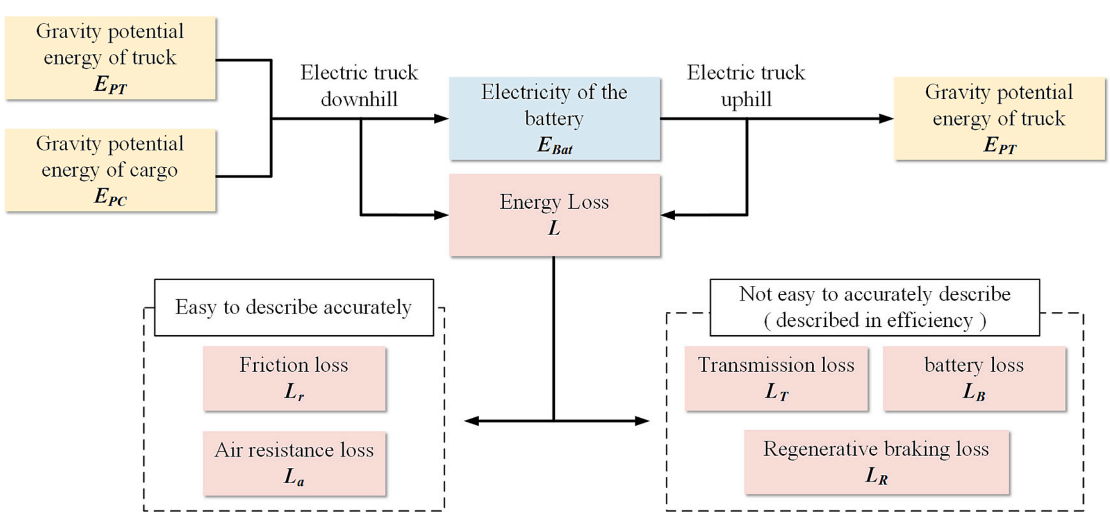


**Fig. 5.** Energy flows diagram during PMET operation.

caused by ground friction; $L_a$ is the loss of air resistance; $L_T$ is the loss of transmission equipment; $L_B$ is the inherent loss of the battery; $L_R$ is the loss of regenerative braking equipment (motor).

When the truck goes up the hill, the battery releases electrical energy and drives the motor to drive the truck up the hill, thus converting the electrical energy in the battery into the gravitational potential energy of the truck. According to the conservation of energy in the process of going up the hill, we can get:

$$E_{Bat} = E_{PT} + L_r + L_a + L_T + L_B + L_R \tag{12}$$

Whether going up or down a hill, the truck has energy losses. For the two processes of uphill and downhill, all the losses are the same except the losses caused by air resistance (because the speed of uphill and downhill may not be the same) and the losses caused by ground friction (the total weight of the truck is different in uphill and downhill). The loss caused by ground friction and air resistance in the process of going up and down the hill can be expressed as:

$$L_r^{down} = f_R^{down} D \tag{13}$$

$$L_r^{up} = f_R^{up} D \tag{14}$$

$$L_a^{down} = f_A^{down} D \tag{15}$$

$$L_a^{up} = f_A^{up} D \tag{16}$$

where $D$ is the slope length. Transmission loss, inherent battery loss, and

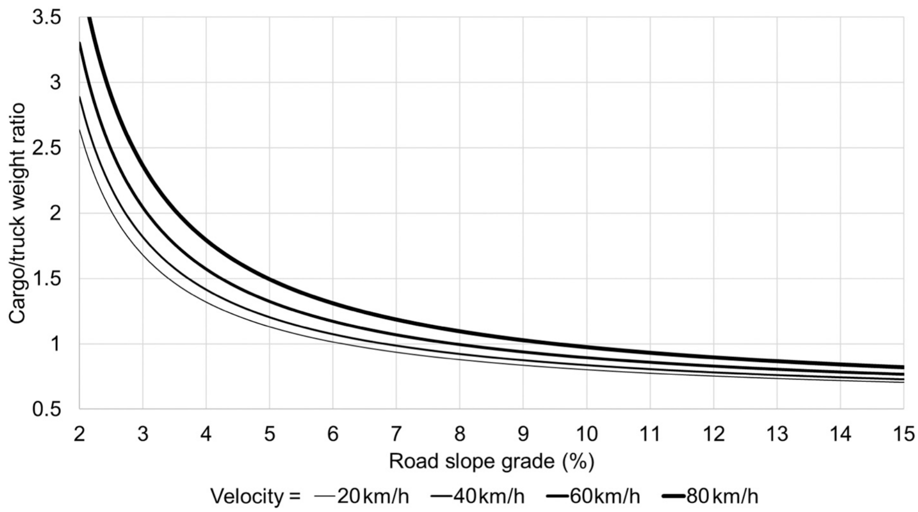


**Fig. 6.** Cargo weight required to achieve perpetual motion in the electric truck at different road slopes and driving velocities.

regenerative braking equipment (motor) loss are difficult to describe precisely. According to other literature data, this paper uses energy conversion efficiency $e_T$, $e_B$, $e_R$ to describe these three losses. Combined with the force analysis, the energy conservation of the whole process of going downhill and going uphill (the realization condition of PMET) can be obtained:

$$\left(G_S^{down} - f_R^{down} - f_A^{down}\right)De = \frac{\left(G_S^{up} + f_R^{up} + f_A^{up}\right)D}{e} \tag{17}$$

$$e = e_T e_B e_R \tag{18}$$

The slope is defined as:

$$s = tan\theta \tag{18}$$

Combining Eqs. (1)–(10), (13)–(16) and (18) to simplify Eq. (17) gives:

$$\frac{m_C}{m_T} = \frac{1}{s-\mu}\left(\frac{s+\mu}{e^2} + \frac{\sqrt{s^2+1}}{2gm_T}\left(\frac{C_D\rho AV_{up}^2}{e^2} + C_D\rho AV_{down}^2\right)\right) - 1 \tag{19}$$

The road slope estimation applied in the case studies is described as follows. Firstly, the altitude profile was extracted from Google Earth [30]. To remove noise from the curve, the moving average of the altitude profile was produced and utilized.

## 3. Results

Fig. 6 shows how the most significant factors influence PMET systems. These are the road slope gradient, the average velocity of electric trucks, and the cargo/truck weight ratio. The horizontal distance between the lower and top storage locations is directly affected by the grade of the road. According to Eq. (7), a 5 % road slope gradient, for example, consists of driving 20 km horizontally to move 1 km vertically. Federal roads in the United States often have a 10 % slope restriction. Because of the associated air drag, the truck's speed affects the system's efficiency. A truck at 60 km/h and a road slope of 4 % grade (25 km horizontally and 1 km vertically) requires the cargo to be at least 1.56 times heavier than the empty truck allowing the perpetual motion to take place.

### 3.1. Mine perpetual motion electric truck in Péry Switzerland

This case study is an actual project in Péry, Switzerland. It consists of an electric dump truck named eDumper (Fig. 7 (a)), used to transport limestone from a mine on a mountain near the cement factory (Fig. 7 (c)). The slope from the cement factory to the top of the mountain and from the top of the mountain to the bottom of the mine is 7.8 % and 7.1 %, respectively (Fig. 7 (d)). The overall slope from the cement factory to the bottom of the mine is 4.4 %. Assuming that the eDumper drives at 40 km/h and Eq. (1 to 3), the cargo/truck weight ratio should be 1.31. According to (Fig. 7 (b)) and [31], when the eDumper drives up empty (58 tons), it uses the stored power from its batteries for the electric drive. The eDumper is loaded with 65 tons of rock on the top of the hill. Energy is converted when braking the loaded 123 tons eDumper moving down the mountain gains energy instead of releasing it in the form of heat via brake discs. This results in a cargo/truck weight ratio of 1.12. This means that this paper slightly underestimates the potential for PMET. Table 2 further details the mine PMET in Péry, Switzerland. More details on mine PMET is presented in [31,32].

### 3.2. Biomass perpetual motion electric truck in California, USA

The California highlands have a significant potential for biomass plantation, as shown in Fig. 8 (a). This potential is located at a high altitude, as shown in the topography map in (Fig. 8 b), and close to the mountain bottom where wood and biomass are processed to produce paper, cellulose, construction material, furniture, heat, electricity, or other woody material. This makes California an ideal location for biomass PMET. Maps of existing biomass power plants and sawmills can be seen in [33–36]. A good example of biomass PMET is presented in Fig. 8 (c), where biomass is collected along the road in black with a total distance of 31.5 km and transported down the mountain to a cogeneration, heat, and power plant described in Table 3. Fig. 8 (d) presents the road slope grade of 3.2 %. Assuming a 60 km/h speed up and down the mountain, the cargo/truck weight ratio equal to 1.92 results in biomass PMET. A cargo/truck weight ratio larger than 1.92 results in excess electricity that can be used to supply the grid with electricity.

Sierra Pacific Industries converts “wood waste” into electricity for homes and businesses via eight cutting-edge cogeneration facilities in California and Washington [35]. These facilities generate over 150 MW of electricity when combined. It is enough energy to power 150,000 houses. Part of the energy generated is utilized to power the mill where it is created. Surplus electricity is sold to local utilities and energy service providers, reducing the country's reliance on fossil fuels. Forest wood waste is also used in the cogeneration process. In regions where trees are excessively thick and provide a fire risk, unmerchantable wood (small trees and branches) is deliberately removed and processed to enhance the remaining stand of timber.

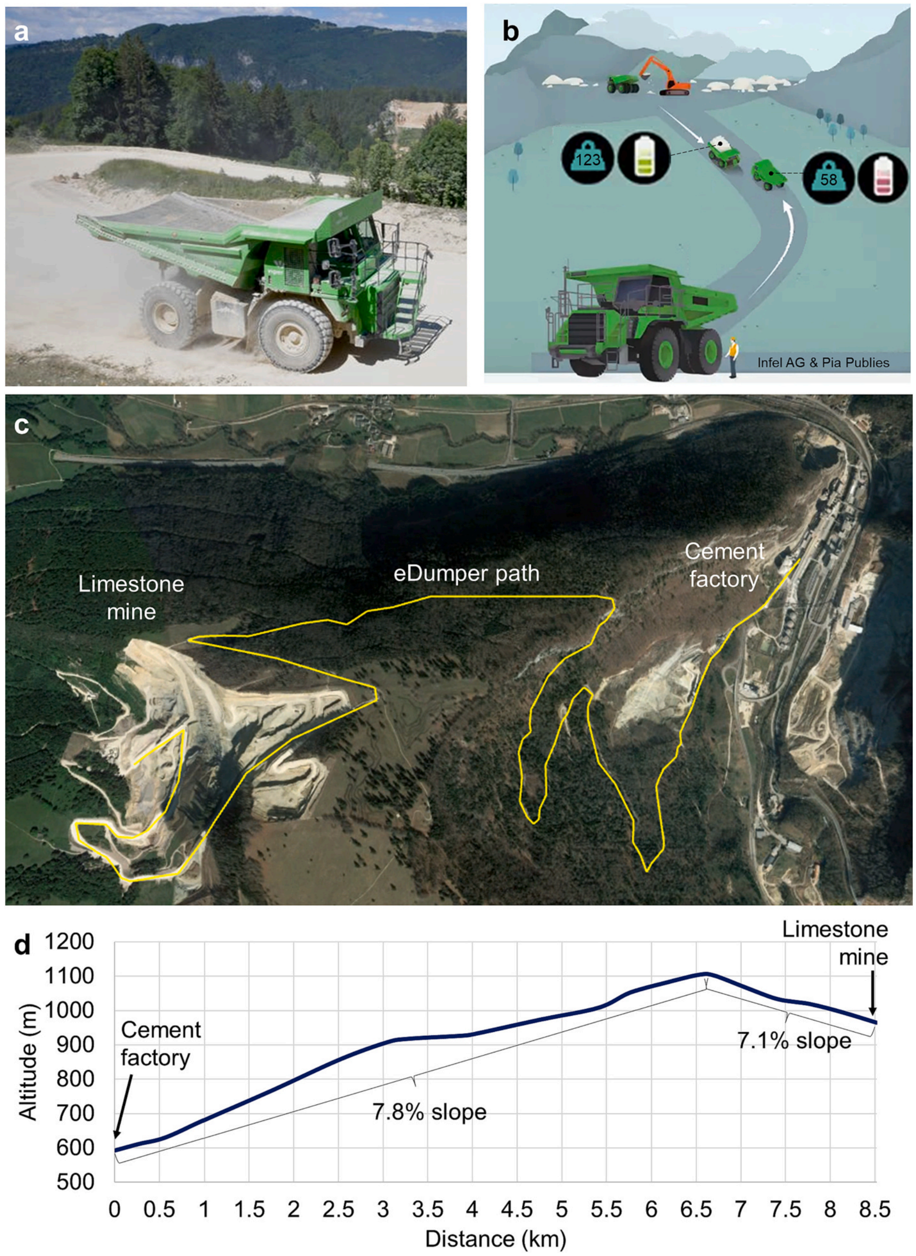


**Fig. 7.** (a) Electric dump truck used in Swiss mine (eDumper), (b) operation description of the eDumped, [31] (c) real case of PMET system between a limestone mine and a cement factory.

**Table 2**
Details of the mine perpetual motion electric truck in Péry, Switzerland [31,32].

| Item | Description |
|---|---|
| Company name | Ciments Vigier SA |
| City | Péry, Switzerland |
| Factory latitude | N 47.1846 |
| Factory longitude | E 7.2489 |
| Dump truck | Komatsu 605–7 HD |
| Fuel | Fully electric |
| Battery capacity | 600 kWh |
| Motor | 634 kW synchronous / 200 kW asynchronous motor (auxiliary units) |
| Maximum slope grade fully loaded | 14 % |
| Top speed | 40 km/h |
| Other details | Possibility of returning excess energy to the grid |

## 4. Discussion

As presented in the paper, PMET can be achieved when the average road gradient is 5 %, the electric truck speed is 60 km/h, and the cargo weight is 1.32 times that of the electric truck. This is the ideal cargo weight for the truck to deliver indefinitely without recharging. If the cargo weight moving down the mountain is greater than 1.32 times that of the electric truck, the battery will accumulate more electricity than it consumes. In this case, the extra electricity stored in the battery could be sold to the grid. If the cargo weight moving down the mountain is less than 1.32 times that of the electric truck, the battery will consume more electricity than it regenerates. In this case, the truck will have to be connected to an electric charger to compensate for the energy losses in the system. Future work will perform sensitivity analyses to investigate the amount of electricity produced or required by changing the road's slope, the truck's velocity, and the weight ratio.

Most countries require heavy governmental subsidies to install

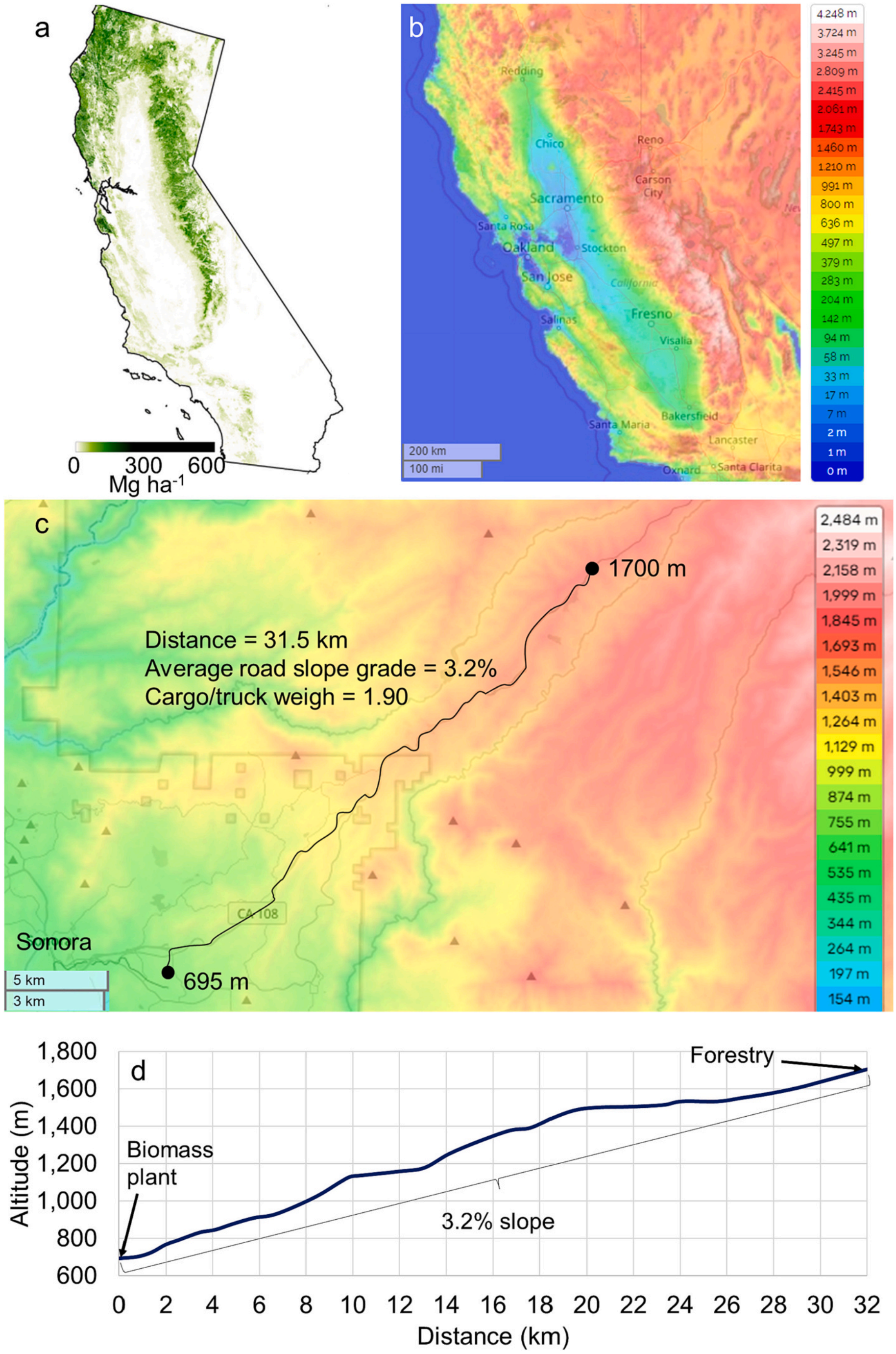


**Fig. 8.** (a) Biomass growth potential in California [37], (b) topography of California [38], (c) biomass PMET case study, (d) road slope grade.

**Table 3**
Details of the biomass perpetual motion electric truck in California [33,35].

| Item | Description |
|---|---|
| Company name | Sierra Pacific |
| City | Sonora, CA, USA |
| Powerplant latitude | N 37.9723 |
| Powerplant longitude | W 120.3200 |
| Power capacity | 10.9 MW |
| Energy services | Electricity and heat |
| Fuel type | Bark, sawdust, and other low-grade byproducts of the sawmill manufacturing process are the primary fuel |
| Direct employees | 12 |

electric charges and upgrade the electricity grid to transition to electric cars and trucks [39]. This is a particularly challenging "chicken and egg problem". Without electric trucks, the demand for electric chargers is low. Without electric chargers, it is difficult to drive electric cars. Another important advantage of PMET is that the trucks would not require expensive electric charging infrastructure, allowing the implementation of electric trucks before the construction of electric charges and upgrading the electricity grid.

One strategy to increase the chances of reaching permanent motion with electric trucks, is to reduce the truck's curb weight. We propose four strategies to reduce the curb weight of the electric truck: (i) Reduced battery weight [40,41]: the electric truck battery's energy storage capacity should be a little higher than the amount of energy required to

**Table 4**
Electric truck weight reduction with different materials [44].

| Lightweight material | Mass reduction % |
|---|---|
| Carbon fiber composites | 30–70 |
| Magnesium | 50–70 |
| Aluminum and aluminum matrix composites | 30–60 |
| Titanium | 40–55 |
| Glass fiber composites | 25–35 |
| Advanced high-strength steel | 15–25 |
| High-strength steel | 10–28 |

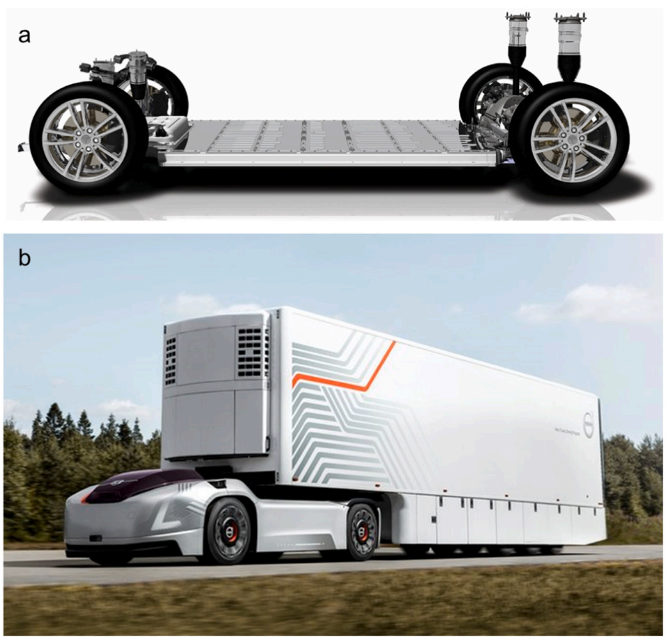


**Fig. 9.** (a) Tesla model S composite material battery [45], (b) Volvo Vera autonomous electric truck [46].

drive up the mountain in the PMET system to minimize the weight of the truck's battery pack. (ii) Using lightweight materials: use aluminum and carbon fiber instead of steel in the truck's structure. Table 4 presents the weight reduction of using aluminum, and carbon fiber. (iii) Composite structural batteries: using composite structural batteries [42,43] (Fig. 9 (a)). (iv) Autopilot: if the truck operated autonomously, it is also possible to reduce the truck's weight by removing the driver's cabin, as shown in Fig. 9 (b). Strategies 1 and 3 also allow for more space to be loaded and more cargo to be transported. This not only reduces the weight of the truck, but also increases the weight of the cargo, which increases the cargo/truck weight ratio even more.

Perpetual motion electric truck can be combined with Electric Truck Hydropower (ETH) [26] to reduce energy consumption for cargo transportation when the truck drives up the mountain with relatively light cargo and drives down the mountain filled with water. In these cases, the truck can fill with water at the top of the mountain and drive down the mountain filled with water (Fig. 10 (a)). PMET can be reached with a graph like Fig. 6. However, instead of cargo/truck weight ratio the Y axis would be (water-cargo)/(cargo+truck) weight ratio. If PMET is to be implemented, the truck capacity will not be fully utilized. If the truck capacity is to be fully utilized, PMET cannot be implemented and can only be combined with ETH to reduce power consumption. If some cargo is transported on the way down, the truck could be partially filled with water to increase the truck's weight and enhance the battery recharge in the descent trip Fig. 10 (b). This also applies with anything that needs to be transported from a high place to a low place (not necessarily water). Alternatively, it could be used for long-term energy storage [47–55].

## 5. Conclusions

Perpetual motion electric truck is a novel method of conserving energy by transporting cargo down a mountain and charging the truck's battery with its regenerative brake system. PMET uses a renewable braking system to convert the gravitational energy storage released as the cargo descends the mountain into electrical energy to store in the battery and uses that energy to re-deliver the empty truck up the mountain. Thus, PMET achieves perpetual motion of the truck by making full use of the gravitational potential energy of the cargo when descending the hill in the delivery downhill scenario. We assume a renewable braking efficiency of 90 % for the electric truck motor, a mechanical transmission efficiency of 90 %, and a battery cycle efficiency of 90 %. Under this assumption, PMET can be achieved when the average road gradient is 5 %, the electric truck speed is 60 km/h, and the cargo weight is 1.32 times that of the electric truck. The study shows that the average slope, cargo-to-truck weight ratio, and operating speed affect the PMET realization. The greater the average slope, the greater the cargo-to-truck weight ratio, and the lower the operating speed, the easier PMET can be realized. PMET can be applied in cases where products like biomass, biofuels, commodities, manure, municipal waste,

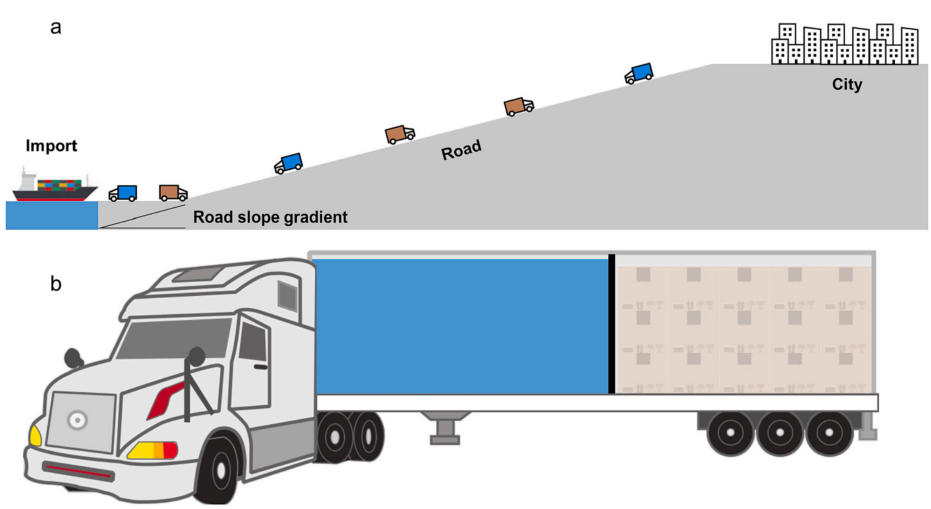


**Fig. 10.** Perpetual motion electric truck integration with Electric Truck Hydropower (a) drive up the mountain with relatively light cargo and down the mountain filled with water or (b) transport cargo and water down the mountain.

and natural resources can be produced on the top of a mountain to be consumed, processed, or exported on the bottom. PMET should be widely considered during the transition from diesel and gasoline to electric trucks, particularly due to the significant amount of electricity recovered by transporting the cargo down the mountain and the lack of investment required for the charging infrastructure.

## CRediT authorship contribution statement

Conceptualization, J.H.; Methodology, A.N., W.T.; Software, E.P.; Validation, B.Z.; Formal analysis, J.J.; Investigation, B.D.; Resources, W. F.; Data Curation, D.P.; Writing - Original Draft, J.H.; Writing - Review & Editing, W.T.; Visualization, M.F.; Supervision, Y.W.; Project administration, Y.W.; Funding acquisition A.N. All authors have read and agreed to the published version of the manuscript.

## Declaration of competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

In other words, there is no conflict of interest involved in this publication.

## Data availability

Data will be made available on request.

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