Can We Go All-Electric?

[1]

Word Count: 2975

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Brief Historical Background

The automobile industry has come a long way since its first appearance in the early years of the 19^{th} century. Three decades after the invention of the first steam-powered carriage by Richard Trevithick [2], the first DC electric motor was used on locomotives. Non-rechargeable batteries initially used were soon replaced by rechargeable ones. Despite the introduction of the first internal combustion engine in 1885 by Karl Benz [3], electric vehicles continued to dominate the market. On the stroke of the 20^{th} century, of the 4200 vehicles sold in the US, 38% were electric, with internal combustion engines accounting for a mere 22% [4]. A chain of major events in the next couple of decades proved critical to the devastating drop in electric transportation, with the internal combustion engine overwhelmingly dominating the industry ever since.

The first of the three major contributors was the limited range capability of the electric battery. With ever-improving road infrastructure, it was obvious that the battery's range was inadequate to satisfy the rising demand for long-distance transportation. The second contributor was the introduction of Model T, the first mass-produced vehicle, by Henry Ford in 1908 [5]. The inability of battery manufacturers to replicate Ford's model of cost-efficient production lines dealt a severe blow to electric transportation, rendering electric vehicles a product for the wealthier portion of society. Third, to cap it all off, the invention of the electric starter motor and its use in internal combustion vehicles eradicated the requirement for manual power to start up the engine.

Since the introduction of Ford's Model T, the petroleum industry's importance had been gradually increasing, ultimately overtaking coal as the world's primary energy source by mid-20^{th} century [6]. The then seemingly abundant supply of oil and its low price ensured that the internal combustion engine was a much more commercially viable product than the electric vehicle engine. Thus, inevitably, the latter was of little use at that time.

The ensuing decades saw the world's dependence on fossil fuels sky-rocket in order to produce the vast amount of energy required to meet the booming demand of the developing world.

Increasing global population coincided with an overall increase in GDP. Consequently, people's demand for travel increased, adding to the burden of providing energy for the transportation sector. The apparent lack of alternatives to provide this energy resulted in the automotive industry relying heavily on fossil fuels, with petroleum-derived fuels accounting for 92% of the global transportation energy requirements [7].

The world's insatiable appetite for fuel to produce the energy needed for the booming demand resulted in unsustainably high levels of resource depletion.

There is little, if any, doubt that our environment is seriously harmed by the emission of greenhouse gases into the atmosphere. As Figure 1 shows, global greenhouse emissions have experienced a steady increase over the past two decades. As the emission of these gases is directly related to the combustion of fossil fuels, society is faced with a great challenge to switch to 'cleaner' alternatives. Contributing, as it is, to 27% of the world's total fossil fuel consumption [9], the transportation sector plays a major role in this huge issue.

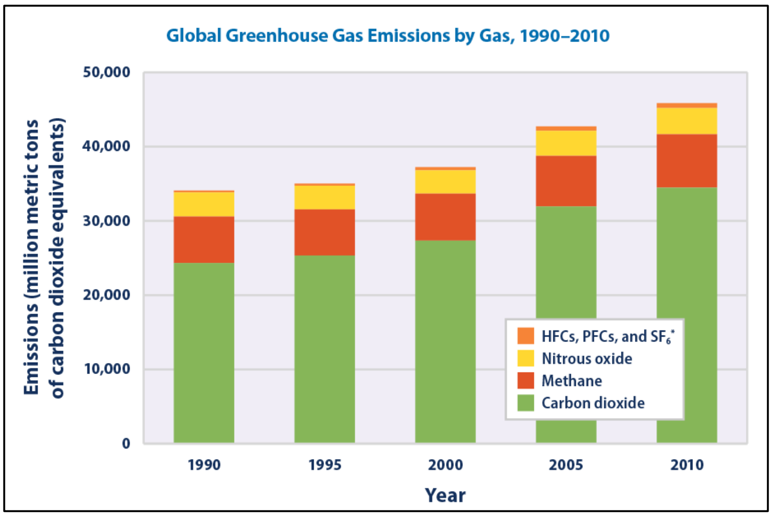

Figure 1: Global greenhouse emissions [8].

Car manufacturers have gradually begun to respond to this problem, facing increasing pressure from stricter government regulations. By 1970, the first hybrid cars entered the market. Since then, significant progress has been made in the field of electric vehicles. Major car manufacturers are committed to improving current technology in this area, devoting much of their expertise in resolving the remaining issues still inhibiting all-electric vehicle transportation.

The role of Physics

As with all means of transportation, electric cars involve several principles of physics. The charge stored in the battery, the electric motor used to spin the wheels and the regenerative braking system, are examples where characteristic physics principles are utilised to produce an electric vehicle. The main physics principles in an electric car, including key issues which require further improvement in order to render a transition to all-electric transportation feasible in the foreseeable future, are discussed in this article.

What is Wrong with Internal Combustion Vehicles?

Internal combustion engines have dominated the automotive industry for over a century. Why is it now important to re-consider their continued dominance?

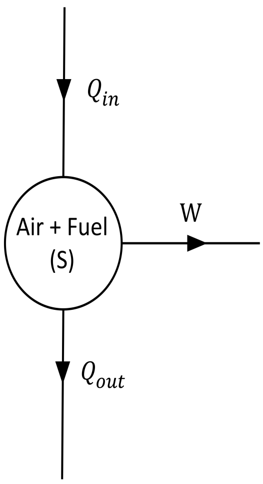

Figure 2: Schematic of a Heat Engine

As already mentioned, most of our energy production comes from the burning of fossil fuels. The basic concept of such combustion is to produce heat, which is then converted to other forms of energy. For the purpose of operating a vehicle, this energy must be converted to mechanical energy. This is the very definition of the heat engine: converting heat into work. The internal combustion engine uses air and fuel as the substance (S) upon which it does work during the cyclic process. Using the First Law of Thermodynamics, the work done by the engine is $W = Q_{in} - Q_{out}$, as $\Delta U = 0$ by definition of a cyclic process. A schematic diagram is shown in Figure 2. For a two-reservoir engine, $Q_{in} = Q_H$ and $Q_{out} = Q_C$ [10].

The idealised process by which an internal combustion gasoline engine operates is called the Otto Cycle. Figure 3 shows the PV diagram during this cycle. At (c), a mixture of gasoline-air enters the cylinder and is compressed adiabatically up to (d), where it is ignited and heat Q_H is added to the system along (d)→(a). The substance undergoes adiabatic expansion up to (b), and is then cooled to its initial temperature at (c). As the substance is returned to its initial state at the end, the process is a cyclic one. Its invention by Nikolaus Otto [11] revolutionised engine science and indeed the automotive industry. The cylinder's vertical motion in the Otto Cycle is used to spin the wheel axles which move the vehicle. Behold the internal combustion vehicle!

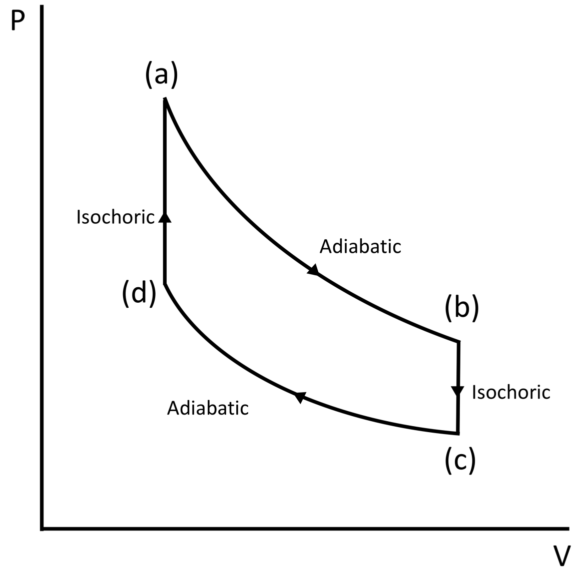

Figure 3: Otto Cycle PV Diagram

So what's bad about it?
Despite the limitation in its efficiency, highlighted by Carnot's theorem, the main setback is the waste product. During the cooldown process, the unwanted gas leaves the engine and is emitted in the atmosphere. We have already discussed the seriously harmful impact of these emissions. The aim of switching to cleaner alternatives is to eliminate this unwanted part of the process.

In contrast, an electric vehicle spins its axle using chemical energy stored in its battery without any emissions in the atmosphere.

Electric Battery

Since the invention of the first battery by Alessandro Volta in 1800 [12], the battery has become an integral part of our everyday lives. Without it, mobile phones, laptops and nearly all portable electronic devices would not have been possible, at least in the way we know them today.

A battery consists of three main parts: an anode and a cathode at each end and an electrolyte in-between. The anode and cathode are made of materials that donate and accept electrons respectively. This property is characterised by a material's standard electrode potential. Hence, as a result of various chemical reactions occurring within the battery, electrons accumulate on the anode causing a potential difference between it and the cathode. The electrolyte in-between, usually a liquid containing free ions, stops the electrons from flowing directly through it towards the anode, thus contributing to the accumulation of opposite charge on the battery's two ends. Connecting the two ends via a wire allows the electrons to flow through it to complete the circuit. The anode loses electrons and gains cations (positively charged ions), through a process called oxidation. This process carries on until there is no more material left to keep the chemical reactions repeating.

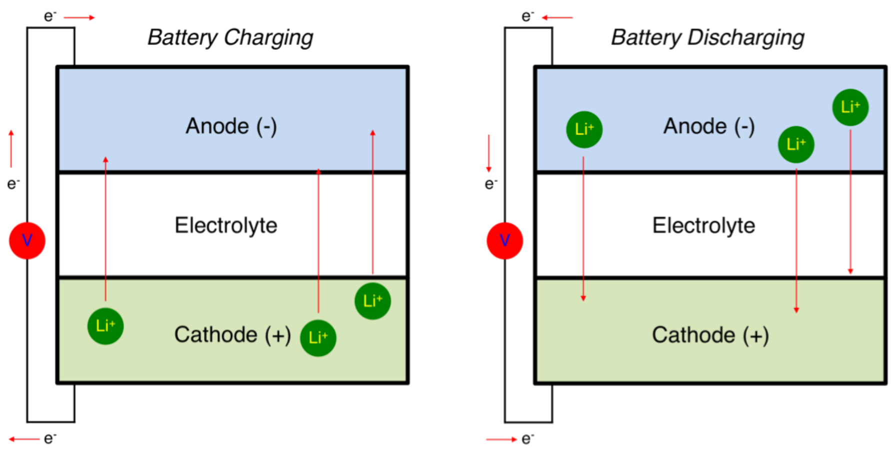

Figure 4: Schematic of a Li-ion battery during charging (left) and discharging (right) [13].

In 1865 Gaston Planté solved the problem of disposable batteries by recharging through a process that requires an external source of energy being applied to the battery, thus reversing the direction of electron flow and restoring the charge [14]. Battery charging and discharging is shown diagrammatically in the two schematics in Figure 4.

The most common type of battery used today on electric vehicles, and indeed on most electronic devices, is the lithium-ion (Li-ion) battery, first introduced into the commercial market by Sony in 1991 [15]. Its relatively low-cost materials and lightweight structure make it suitable for use in electronic devices. A typical Li-ion battery is made out of a number of cells. This number varies widely from device to device, ranging from three or four included in a typical laptop battery to several thousands in a Tesla Model S [16].

There are many factors to consider when it comes to choosing the most suitable battery for electric cars. As always, safety comes first. With all the ongoing research about transportation safety, the battery poses a challenge to overcome. During the past few years, many incidents have taken place highlighting the need to improve the safety of the batteries. Next in importance is for the battery to have sound values of specific energy and specific power, which determine the driving range and acceleration [17]. Li-ion batteries are particularly popular due to their significantly greater driving range of 220 miles compared to the modest 80 and 120 miles that its lead-acid and nickel-metal hybrid counterparts currently respectively offer [18]. Other critical factors include the life cycle of the battery, its performance under extreme temperature conditions and, as always of course, the cost of production.

Electric Motor

Few inventions have had such a profound effect on our daily lives as the electric motor has. Combining the theories formulated by Ampère and Faraday, Prussian Moritz Jacobi produced the first electric motor in 1834 [19]. Since then, the electric motor has taken gigantic leaps in shaping the way we live with its broad range of applications. Needless to say, electric cars altogether would not have been possible without it.

In simple terms, an electric motor is a device that uses electric current (I) to rotate an axle, thus converting electrical into kinetic energy. A current-carrying wire of length l consists of moving charges, each feeling the Lorentz force, given by $\mathbf{F} = \mathrm{I}\hat{\mathbf{n}}\times\mathbf{B}l$, $\hat{\mathbf{n}}$ being the unit vector in the current direction. In a loop of wire, as $\oint_c \mathrm{d}l = 0$ the net force vanishes and we consider the torque, given by $\mathbf{\Gamma} = \boldsymbol{\mu}\times\mathbf{B}$, where $\boldsymbol{\mu}$ is the magnetic dipole moment. In a DC motor, this torque is always restoring. Using commutators, the sign of the current reverses each time the loop traverses, thus allowing causing a rotating motion rather than always restoring it towards equilibrium [20]. A single loop is usually replaced by several ones to make the rotating motion more uniform.

When comparing the electric motor's performance with the internal combustion engine, numbers talk by themselves. It is well-known that Teslas reach 60mph faster than any other vehicle in the world, with the Model S P90D achieving it in a mind-blogging 2.8s [21]. There are various reasons behind this, with the main one being that the transfer of electrons from a battery to an electric motor (via a wire) is much faster than the transfer of fuel from the tank to the piston, which involves a chain of other steps in-between.

In the internal combustion vehicle, as the speed increases, torque increases too. However, beyond a particular speed it is much harder to force air into the piston, causing the torque to drop, as illustrated in Figure 5 (left) below. In contrast, the electric motor provides maximum torque once current is provided. At very high speeds, due to back-EMF being induced, the torque provided gradually decays, as shown by Figure 5 (right).

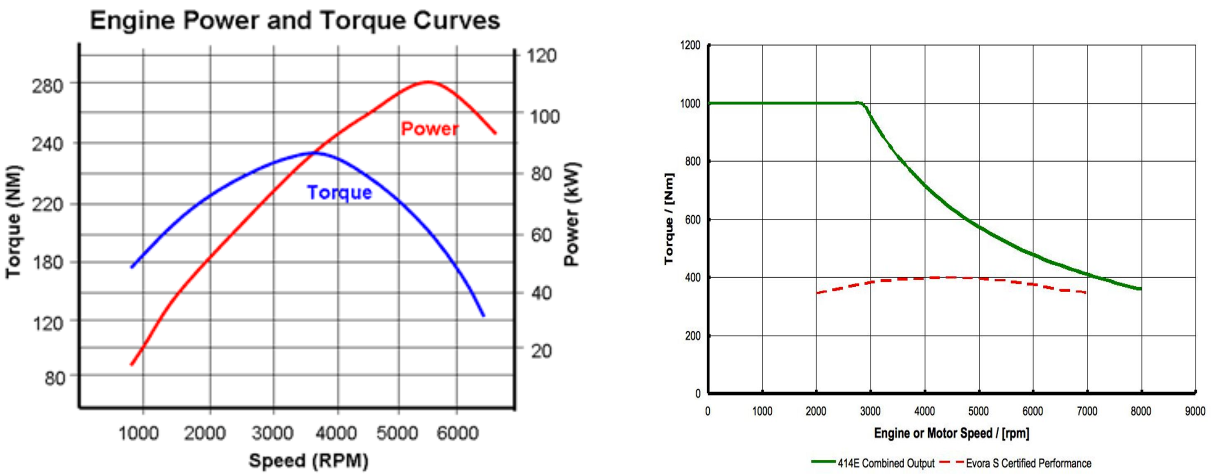

Figure 5: Torque vs Power curves for Internal Combustion Engines (left) and Electric Motors (right) [22].

Regenerative Braking

Over the past decade, the driving range achieved by electric vehicles has been extended as a consequence of regenerative breaking, often referred to as regen braking. This involves recuperating a portion of the kinetic energy by charging the battery, rather than converting it into heat 'wasted' in the atmosphere.

Conventional braking mechanisms involve two braking pads, usually positioned on either side of the wheel and being pressed on it when the brakes are applied, forcing the kinetic energy to be converted into heat energy through friction. This heat energy is then dissipated into the atmosphere.

Through regenerative braking, when the driver applies the brake, the direction of the rotating motor that spins the axle reverses. As it is located in the magnetic field between two magnets, the motor essentially acts like a generator instead. Rotating in the opposite direction to the wheels, the motor gradually slows the vehicle down. While doing so, due to the time-varying magnetic flux, an emf $\varepsilon = -\frac{\mathrm{d}\Phi_B}{\mathrm{d}t}$ is induced into the coils of the motor, which is then transferred to a controller which transforms the electric energy into chemical energy stored in the vehicle's high-voltage battery [23].

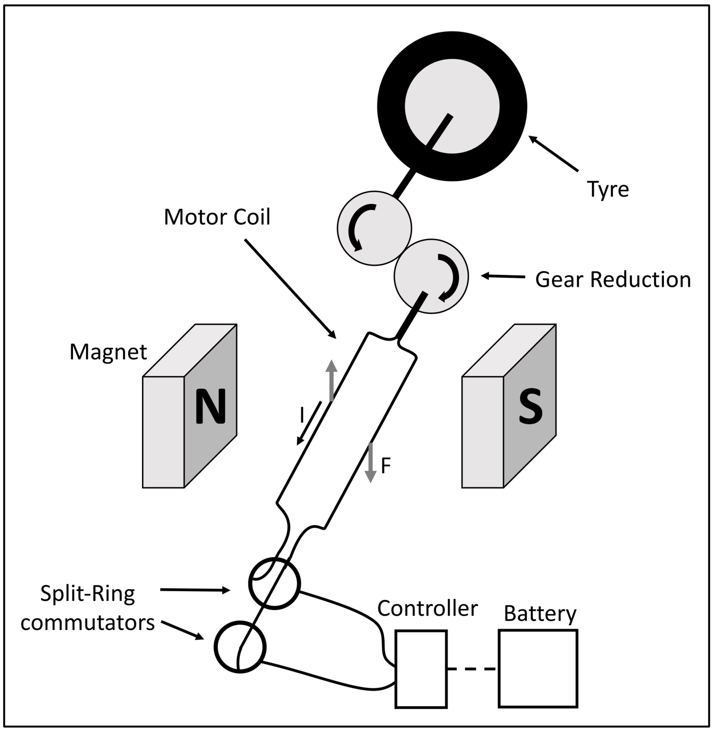

Figure 6: Simplified schematic of AC Motor used in Regenerative Braking

Figure 6 shows a simplified schematic of how the AC motor works during regen braking. During normal driving, the battery is powering the motor which rotates to spin the wheel forward. When the driver steps on the brake, current is induced inside the rotor in the magnetic field, causing a retarding force (F) to decelerate the vehicle. At the same time, the induced current (I) passes through the controller which transfers it to be stored in the battery.

Regen braking improves the vehicle's driving range and operates as an additional braking system, albeit it is only really effective for the latter within a particular speed range. Another limitation is that regen braking cannot be used to completely immobilise the vehicle, as the electric motor can no longer supply sufficient torque due to the low kinetic energy of the car [24]. Thus, all electric cars combine both conventional friction brakes with regen systems to secure optimisation of the vehicle's brakes.

Electronic Control Unit (ECU)

In terms of the mechanics of the vehicle's propulsion, that's about it. We should also mention the function of the Electronic Control Unit (ECU). Commonly referred to as the brain of the car, the purpose of the ECU is to receive an array of information from sensors (input) and perform certain actions (output). It uses these to adjust the settings of the vehicle, thus optimising performance. Common inputs include accelerator position and wheel speed, while some outputs include fuel injection and turbo boost, to name but a few. The ECU has revolutionised the automobile industry, enhancing automation and improving performance.

So what's next?

Of the world's total registered vehicle population, which exceeds 1 billion [25], only two million are electric. This says a lot about how far we still are from regarding the electric vehicle as a replacement of its internal combustion counterpart. However, with the pace of today's research as well as the recent trends which indicate a gradual shift towards this technology, electric vehicles seem to indeed have the capacity to play a far more important role in the future development of the automotive industry.

The electric motor is already performing at extremely high levels, much more efficiently than its internal combustion counterpart. The main challenge now is to further improve the performance of the battery. Hence, it is no surprise that most of the current research is in this area, striving for a safer battery with higher electric charge and lower cost.

Primary focus is given on the safety of the battery, which is one of the reasons that all breakthroughs are considered with caution. A safer battery requires developing further a non-flammable electrolyte [26]. Developing a suitable battery also means one with a high energy density. This is the main reason for Li-ion's dominance of the battery market, with a share of 63% [27]. As Figure 7 shows, Li-ion has a significantly higher energy density than its main alternatives.

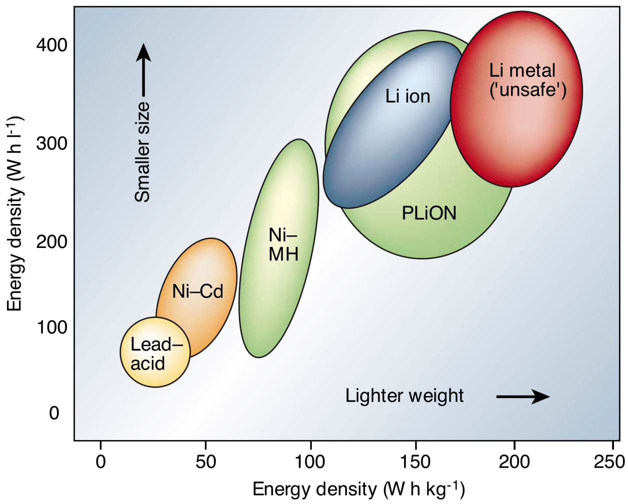

Figure 7: Plot of different battery types and their energy density [27].

Over the next decade, there is hope that solid-state chemists will succeed in developing further the Li-ion battery, with the aid of advancements in cell engineering. This will allow the electric vehicle's driving range to increase, making it a closer match to that offered by the tank of a fuel engine.

<u>Conclusion</u>

With global population projected to increase from 7.6 billion to 10 billion in the next 50 years, the number of vehicles is predicted to increase from 1 billion to 2.5 billion [28]. Year by year, the effects of global warming are becoming more noticeable. The global average temperature has increased by approximately 0.6°C over the past century [29], endangering the fate of species inhabiting our planet and causing extreme weather phenomena. Being a major contributor to greenhouse emissions, the automotive industry is faced with a colossal challenge to change to cleaner methods of transportation. With today's technology, the most promising solution seems to be a switch to electric vehicles.

With increasingly stricter government regulations with respect to emissions, with progress in Li-ion battery research gathering pace and its cost dropping significantly, electric cars seem destined to replace internal combustion vehicles soon. Already, the world's leading car manufacturers are committed to adopting electric technology in the very near future.

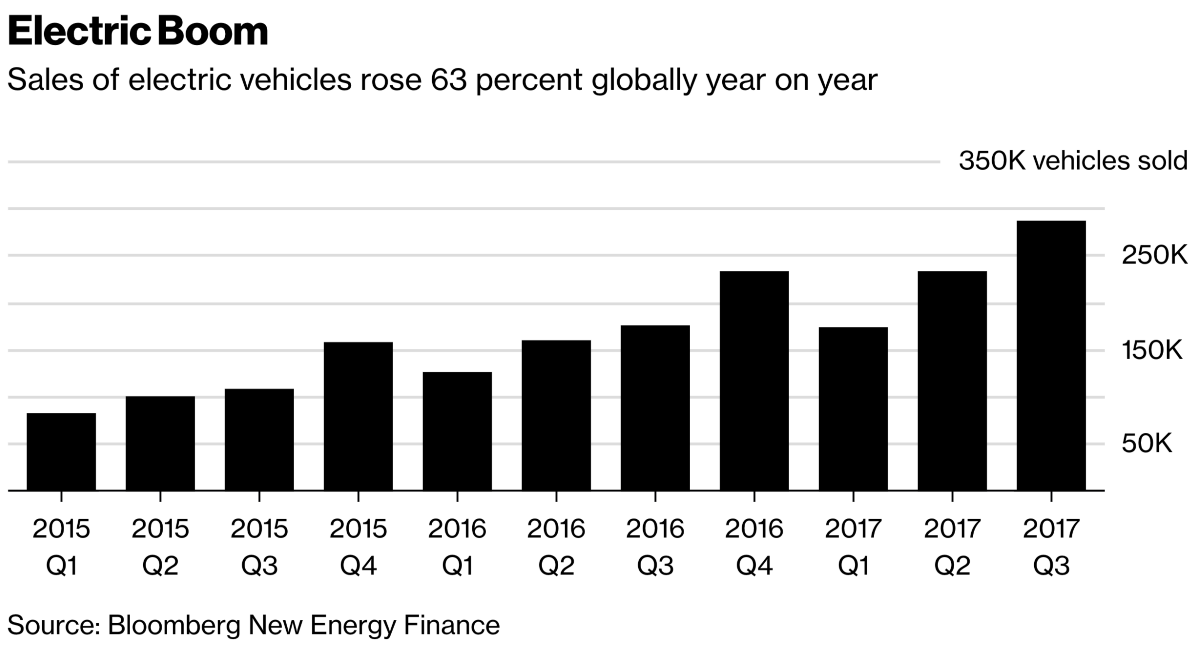

Figure 8: Volume of sales per month for 2015-17 [30].

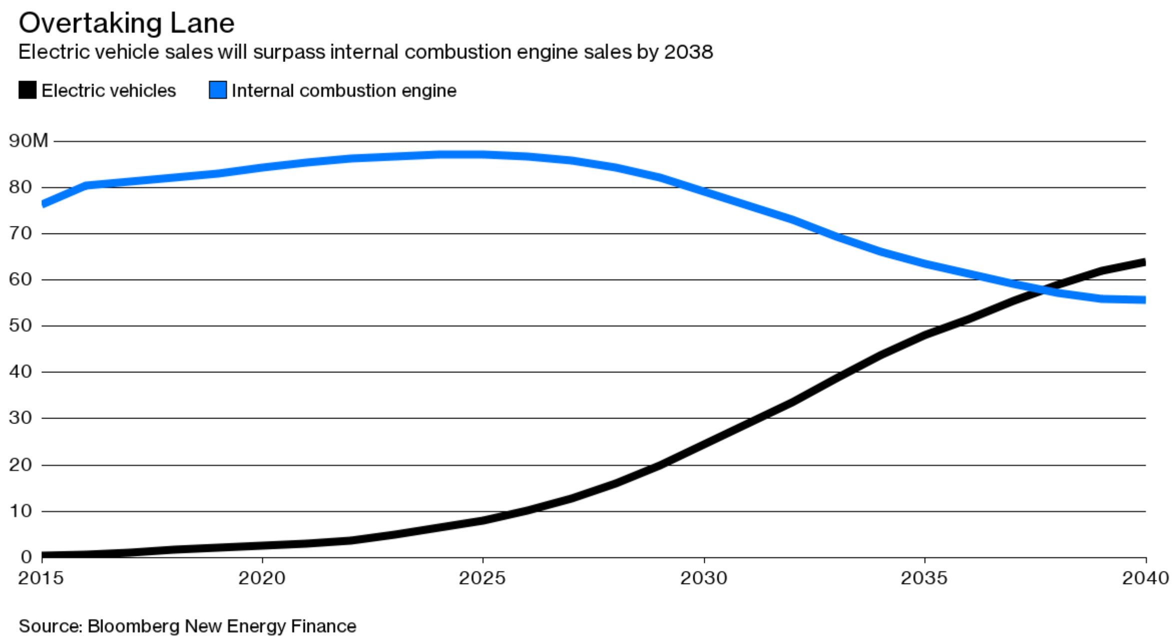

Figure 9: Forecast of Electric Vehicle and Internal Combustion Sales for 2015-2040 [31].

So, having discussed the physics principles behind the operation of an electric vehicle and bearing in mind today's technology, are we already in the electric car revolution? As shown in Figure 8, total sales of plug-in vehicles recorded a significant increase over the last two years. Additionally, figure 9 shows that electric vehicles are predicted to surpass internal combustion ones by 2038.

With total sales already on the increase and with the forecast future trend following a similar, if not faster-growing, pace, we are already very much into the electric vehicle era.

It should come as no surprise if we indeed soon go all-electric.

Acknowledgements

I thank my Group C Tutor for Year 2 Professional Skills, Dr Brindley, for providing me with thoughtful feedback on my initial brainstorming. Same goes for our tutorial assistant, Mr David Stansby. Dr Tymms for offering the official feedback to my article plan, attached further on. Professors McCall and Tymms for delivering lectures and notes with the most relevant material to the topic. Ms Ann Brew for her comments and suggestions regarding the referencing. Finally, my parents for providing me with the mental support and reminding me to keep focussed during the Christmas break in my country, Cyprus!

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SCIENTIFIC ARTICLE PLAN

Main aim

The article's main aim will be to discuss the physics principles behind the operation of electric cars. After reading the article, the reader should have a general understanding of how theory is put into practice and leads to the operation of an electric car. The reader should gain awareness on how popular this transportation means is, as well as getting an insight on what the main challenges are for the future, which in a way coincides with current areas of research regarding this field.

Title

Although not yet finalised, something in the lines of: "*Can we go all-electric?*" It doesn't say much about what the article will go on to discuss but a catchy title is probably more fitting for an article. The informal style is likely to engage more people as well.

Structure

The order is not yet finalised but the main categories and sub-categories are likely to be:

1. Introduction
    a. What the article is about and what it will discuss
    b. Brief historical background and "timeline" of electric cars
    c. Why it is important for us today?
    d. Intro to how physics contributes to its operation

   } May include basic diagrams (statistics, trends)
2. Physics of the car
    a. Difference between electric vehicle and internal combustion engine vehicle
    b. Electric battery principles
    c. Electric motor principles
    d. Braking system principles

   } Bulk of Science/Physics in this section, including diagrams
3. Future
    a. Challenges faced: Why is it not yet the most popular option?
    b. What must be improved: Areas of current and ongoing research
4. Conclusion
    a. Is it a viable option - What does the data suggest?
    b. Prediction for the future

   } Present personal opinion on whether a conversion is possible
5. Acknowledgements
    a. Anyone who contributed to the composition of the article in any way
6. Bibliography
    a. References of the sources used } e.g.: articles, books, reports, journals

Relevant Research / Data

Some basic numerical statistics are likely to be needed; these can be extracted from annual reports of companies (e.g. car manufacturers) and official government figures. Scientific knowledge for Section 2 is likely to be needed from physics books and Lecture courses of Year 1 and 2 (up to now). Areas of current research and interest are most likely to be found in more recent (online) journals. Some interesting books found that contain some information that will be helpful:

- Electric and Plug-In Hybrid Vehicles - (ISBN: 978331918638)
- Electric Vehicles: technology, policy and commercial development - (ISBN: 9781849714150)
- Environmental Physics: Sustainable energy and climate change - (ISBN: 9780470666753)

Challenges and where to focus

The notation used will be kept as close as possible to the one familiar with Imperial College students. Special care needs to be taken to stay focused on the actual physics principles, which is the main aim of the article, rather than to diverge into complicated engineering and other disciplines.

Feedback

A very decent topic which should be very easy to research with the major challenge to find a proper focus and write an article which is self-contained. The plan is pretty good in this regard but I feel you may struggle to contain it all within 3,000 words and may need to cut down some content. I wonder whether the comparison with the internal combustion engine need be included at all?
Try and incorporate some peer-reviewed journal research alongside the books.

Vijay Tymms, December 2017

Feedback Response

I believe that the article's main aim to describe the physics behind the main principles of operation of an electric vehicle was achieved. Namely, the physics of the electric battery, the electric motor, the braking system and a brief mention to the ECU were the topics covered.

In terms of physics explanation and theory, more emphasis was given on the thermodynamics involved in the internal combustion engine cycle and the electric motor. The ECU involves more complicated computing and electronics software that would have been trickier to discuss in the article.

Despite the suggestion to try to avoid the part on the internal combustion engine, a part was included in the article to help the reader understand what is wrong with the internal combustion engine and why we seek cleaner alternatives.

Peer-reviewed journals were indeed used and referenced throughout the article, as well as the books mentioned in the original plan.