



A Figure of Merit for the Assessment of Electrification in Transport and Vehicle Applications

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Abstract. The purpose of this study is to give an overview of the feasibility of electrification in different domains of vehicles for transportation and construction at a vehicle level. To achieve this an analytical framework for estimating the requirement domain in which a technology combination can be used in a system. Looking at key properties of technologies such as specific energy and power. This results in the definition of a figure of merit in the relationship between performance and cost. In this paper it is used on electric aircraft technologies, i.e., battery electric and hydrogen fuel cell aircraft, on heavy road vehicles and on work machines.

Keywords: Technology assessment · specific energy · critical technology · cost-benefit factor

1 Introduction

A technological system that emits no or very little carbon dioxide is referred to as “carbon-neutral” (CO₂ neutral). Indeed, climate change pressures have made it mandatory that an energy-efficient design be entirely based on renewable energy [1, 2]. This is precisely the challenge that designers have faced when attempting to improve the energy efficiency of vehicle systems [3, 4], and to include them is a system of renewable energy. What technologies should be included in the system? How should they be assessed? Because it is perceived as complex and uncertain, this integration is extremely difficult. This is one of the aspects that necessitates efforts at innovation and experimentation in order to reduce risks and increase companies’ comfort in the transition process. In this paper the focus is on electrification as a part of a chain needed to implement a society based on fossil free energy, even though it is realized that electrification by itself do not necessarily solve the climate problem unless the source energy is fossil free.

A formal method to estimate the feasibility of a technology for an application area was introduced in [12]. One of the initial premises was that first is necessary to determine the specific set of requirements for the technology. Second, it’s critical to understand what kind of system the new technology could be useful for. After examining these questions,

we proposed a structure for mapping the valid region of requirements that would identify the applications in which a new technology system could be used. Simultaneously, this model should indicate which regions the design would be viable in. Characteristics such as the design parameters associated with key technological capability, application, market segment, and sustainable transition values are highlighted in this process.

It should be noted that electrification is investigated here at a vehicle perspective with respect to the feasibility with the premise that fossil fuel technologies are not viable options or are at least penalized at a level corresponding to their environmental impact. Otherwise, it is hard to compete even at the present fuel prices, since even small differences in cost effectiveness can be decisive. Furthermore, issues related to infrastructure is largely the beyond the scope of this paper.

2 Comparison CO2 Producers in Sweden

To put the applications described here in perspective, the case of Sweden is used since it is an example of a highly industrialized nation. In Table 1 can be noted that flying both national and international, is at about the same levels as cars. Also, this is about the same as the emissions from steel production in Sweden. Work machines, although less, is still about a third of that of road cars, while heavy road transport is at about half that of road cars.

Table 1. Comparison of CO2 producers in Sweden (2019).

CO2 producer	Possible sustainable solution
Swede's flying 2019 approx. 10 million tonnes CO2	Hydrogen (burn or fuel cell)/SAF
Swede's car use 2019 approx. 10 million tonnes CO2	Battery
Heavy road transport 5 million tonnes CO2	Battery/hydrogen fuel cell
Work machines 3.5 million tonnes CO2	Battery/hydrogen fuel cell
Ships to and from Sweden, 8 million tonnes of CO2	Hydrogen (burn or fuel cell)/SAF
SSAB's direct CO2 emissions of 9.8 million tonnes of CO2	Hydrogen

3 Specific Energy and Specific Power

The specific energy and specific energy of the energy and power sources are of critical importance to understand the feasibility of a technology for a certain application. In Table 2 the specific energy of various types of energy storage is shown. It is clear that electric batteries suffer from a huge disadvantage when it comes to specific energy. It is also evident that high pressure hydrogen storage has only about an order of magnitude higher energy density than batteries and falls in a category between diesel and batteries, even though hydrogen has a specific energy almost three times higher than diesel. However, energy density can also be an issue and here hydrogen is at an advantage with a energy density just about a third of that of kerosene (Fig. 1).

Table 2. Specific energy of various types of energy storage.

Type of energy storage	Specific energy [Wh/kg]	Energy density [kW/l]
Diesel (about the same as petrol and kerosene)	12 600	10.7
Battery (Tesla, pack level)	170	0.450
Hydrogen (liquid)	33 000	2.79
Hydrogen high pressure storage (700 bar)	1700–3300	1.5

Table 3. Specific power of various sources of power. (Compilation of data from manufacturers).

Power source	Specific Power [kW/kg]	Efficiency
Truck diesel	0.7	0.4
Petrol engine (with turbo)	1–8	0.25
Turbo shaft engine	6–10	0.5
Electric motor	1–3 (10 peak)	0.95
Fuel cell (incl. syst)	0.5–2	0.5–0.7
Battery	0.4 (2 peak), (2–10C)	0.96
1932 Pratt & Whitney	1.2	0.2



Fig. 1. The effect of specific. The Gee Bee racer from 1932 (left) with a piston engine with 1.2 kW/kg, where the engine is about half of the empty weight of the aircraft, and the Saab 340 (right) with turbo shaft engines with about 8 kW/kg. Both have a comparable top speed of 476 km/h and 502 km/h respectively.

4 Cost Benefit Factor

In Krus and Pereira [12] a framework for technology driven design was introduced. A key concept is the identification of the degree of criticality a technology possess. Three regions were define; critical, technology sensitive and technology comfort zone. If the technology is in the critical region, it is unlikely to be used unless there are no other alternative. It usually means that a technology needs to be developed further in order to be viable. This has very much been the case for e.g., batteries for electric cars, where

we have seen dramatic improvement both in performance and, for that application even more important, in cost. As a measure of the degree of criticality, the *cost benefit* factor was introduced and used as a figure of merit. It represents how much it cost to increase a performance attribute in relative terms. I.e., if a performance attribute is to be increased one percent, how many percent will the cost of the whole system increase. This can be expressed as:

$$\kappa_i = k_{0p} k_{0c}^{-1} \left(\frac{x_i}{p} \frac{\partial p}{\partial x_i} \right) \left(\frac{x_i}{c} \frac{\partial c}{\partial x_i} \right)^{-1} \quad (1)$$

Here p is a performance attribute, c is the cost of the system (or in this case, vehicle) and x_i is a design parameter, e.g., the size of a component. k_{0p} is the normalized sensitivity of performance with respect to the design parameter, and k_{0c} is the normalized sensitivity of cost with respect to the design parameter. A definition used is that a system is technology critical if:

$$\kappa = \max \kappa_i < 1 \quad (2)$$

The *technology comfort zone* is the region where it is easy to select parameters, i.e., the region where the requirements can be met with a comfortable margin. In this region, it is not necessary to particularly optimize the product for performance. Instead, to get a competitive product, other aspects need to be emphasized. In the technology comfort zone, the performance is, more or less, directly proportional to the design parameters. Here, this is defined when the cost benefit factor is more than half an order of magnitude larger than the critical, i.e., $\kappa > 3$. In the region in-between we say that the system is *technology sensitive*.

The assumption made here is that changing the size of a component to change its performance, does not involve any development of the technology as such. For instance, increasing the size of a battery to gain capacity does not imply that the technology is more advanced. However, if the energy density, which is the amount of energy that can be stored in a battery of a given size, can be boosted, this requires an improvement of the technology as such.

5 Applications

The applications chosen for this study were trucks, work machines, and aircraft. These are all areas where massive efforts are being made for electrification. Cars was left out since we already see a massive penetration in some markets already, clearly showing the technical and economic feasibility of electrification. Furthermore, it was also studied in [12].

5.1 Electric Trucks

Long-haul trucks have a rather well-defined work profile. A driver can work for a maximum of 4.5 h and is required to have a 45 min break before the next drive. To have some margin and have a 30 min recharge time means that a charge rate of 2C is required,

which is reasonable for the battery technology. However, the problem is the rate of power needed at the charging station, considering that there will be many trucks recharging at the same time. Therefore, hydrogen storage and fuel cells could be an attractive solution at least as a complement. There are already some battery electric trucks on the market, so it will be interesting to see how the charging infrastructure will be developed.

For a typical 40-ton truck in EU the energy consumption is roughly about 1.4 kWh/km [14]. At a speed of 90 km/h this means that during 4.5 h of driving 567 kWh is consumed. The part of the truck that is not payload and battery is assumed to be 13 tons leaving 27 tons for payload. To have some reserves and to not fully deplete the battery, it needs, however, to be larger than that. I.e., only 80% of the capacity should be used. With 710 kWh this means that a battery of about 4170 kg is needed. This is 10.45% of the total weight.

The range can be expressed as:

$$R = \frac{E_b}{F_r} = \frac{m_0 \phi \zeta_b}{F_r} \quad (3)$$

The normalized sensitivity to performance from the design variable is then

$$k_{0,p} = \frac{x_i}{p} \frac{\partial p}{\partial x_i} = \frac{\phi}{R} \frac{\partial R}{\partial \phi} = \frac{\phi}{\frac{m_0 \phi \zeta_b}{F_r}} \frac{m_0 \zeta_b}{F_r} = 1 \quad (4)$$

Here ϕ is the battery fraction and ζ_b is the specific energy of the battery. The cost per kg payload, is here simply expressed as the total mass of the vehicle divided with the payload mass. A more elaborate cost model could of course be used, but as first approximation this is used here.

$$c = \frac{m_0}{m_{pay}} \quad (5)$$

The payload can be written as:

$$m_{pay} = m_0(1 - \phi - \beta) \quad (6)$$

where β is the fraction of the total weight excluding payload and batteries. Hence:

$$c = \frac{1}{1 - \phi - \beta} \quad (7)$$

The sensitivity with respect to ϕ is then:

$$k_{0,c} = \frac{x_i}{c} \frac{\partial c}{\partial \phi} = \frac{\phi}{c} \frac{\partial(1/(1 - \phi - \beta))}{\partial \phi} = \frac{\phi}{1 - \phi - \beta} \quad (8)$$

This finally yields.

$$\kappa = \frac{k_{0,p}}{k_{0,c}} = \frac{1 - \phi - \beta}{\phi} \quad (9)$$

In this example $\beta = 13/40 = 0.32$ and $\phi = \frac{4170}{40000} = 0.1045$. This finally yields:

$$\kappa = 5.46 \quad (10)$$

This is clearly in the technology comfort zone for batteries i.e., to increase the range 1% only would cost less than 0.2% more (in overall weight). This means that it is plausible to use, even though the load capacity is slightly reduced.

However, to charge the battery 567 kWh in 30 min requires a power of 1.134 MW. As a comparison the state-of-the-art chargers e.g., Tesla Supercharger, can charge 250 kW. In addition, the resting areas for trucks holds a large number of trucks, that all needs to be charged with this power, which means new high-capacity electric infrastructure is needed. An alternative here would therefore be hydrogen and fuel cells. However, it must be considered that using hydrogen as an energy carrier will be several times more expensive than using electricity directly. It should also be noted that we can see autonomous trucks in a couple of years that do not need any rest, other than for recharging the batteries. This means that the requirements will change dramatically.

5.2 Electric Work Machines

Work machines such as excavators and backhoe loaders are comparable to trucks in many ways. The energy consumption of an excavator varies a lot depending on the application but about 10 l diesel/h could be realistic as a typical value of a machine of 15 ton. With a diesel engine efficiency of 30% this means that 1 l diesel corresponds to 3.2 kWh of electric energy. This means that 32 kWh is used per hour. With an 8-h workday and using only 80% of the capacity means that a battery of 320 kWh is needed with a specific energy of 170 Wh/kg for the battery pack, this will result in a battery back of 1900 kg. This is probably an increase in weight of not much more than 1000 kg since the diesel powertrain is replaced. A work machine in general does not have the same kind of weight budget as a truck do with a regulated maximum weight, although there might be limits due to the handling and logistics of the machine. The conclusion is that with the present state of technology a work machine is within the comfort zone for electrification at the vehicle level.

5.3 Electric Aircraft

There is a strong push for electrification of aircraft, no doubt inspired by the success in the automotive sector. However, aircraft are very different in that performance is so dependent of weight.

In [4], it is also argued that electric propulsion is becoming increasingly interesting for larger aircraft. In [6], hybrid propulsion system and pure electric propulsion systems are studied as options for future aircraft. A critical performance parameter for aircraft applications is range. Both references deal with performance calculations including range, but here the simple approach in [5] is used. There are many technical issues to be resolved in order to have electric propulsion in commercial aircraft but perhaps the most critical performance parameter for the aircraft applications is the range. For a battery-powered aircraft, this can be calculated from first principles as:

$$R = \frac{\zeta_b}{g} \eta \left(\frac{L}{D} \right) \frac{m_b}{m_0} \quad (11)$$

This is very similar to the Breguet range equation except that in the case of fuel, the weight of fuel gradually diminishes during flight. Here ζ_b is the specific energy of the battery in J/kg. The takeoff weight (mass) m_0 is: $m_0 = m_e + m_b + m_{pay}$. Where m_{pay} is the payload m_b the battery weight and m_e is the rest of the mass. (L/D) is the aerodynamic efficiency, lift over drag at cruise and η is the propulsive efficiency. Note that the term ζ_b/g represents the altitude to which the battery could be lifted if all its energy was converted to potential energy. Introducing:

$$m_b = \phi m_0 \quad (12)$$

Furthermore, introducing the structure weight (empty weight with battery excluded):

$$m_s = \beta m_0 \quad (13)$$

The takeoff weight can be written as:

$$m_0 = m_s + m_b + m_{pay} \quad (14)$$

The payload can be written as:

$$m_{pay} = (1 - \phi - \beta)m_0 \quad (15)$$

Using the battery fraction ϕ as the design variable the range can be written as:

$$R = \eta \frac{k_b}{g} \left(\frac{L}{D} \right) \phi \quad (16)$$

The cost (per kg of transported goods) is considered proportional to the takeoff weight divided by the payload. Again, a more elaborate model could be used but this is not to be as a first approximation. Hence:

$$c = m_0/m_{pay} = 1/(1 - \phi - \beta) \quad (17)$$

the normalized sensitivity to range (performance) with respect of the design variable ϕ is:

$$k_{0,p} = \frac{x_i}{p} \frac{\partial p}{\partial x_i} = \frac{\phi}{R} \frac{\partial R}{\partial \phi} = \frac{\phi}{\eta \frac{k_b}{g} \left(\frac{L}{D} \right) \phi} \eta \frac{k_b}{g} \left(\frac{L}{D} \right) = 1 \quad (18)$$

The normalized sensitivity to cost is in the same way:

$$k_{0,c} = \frac{x_i}{c} \frac{\partial c}{\partial x_i} = \frac{\phi}{c} \frac{\partial c}{\partial \phi} \frac{\partial c}{\partial x_i} = \frac{\phi}{1/(1 - \phi - \beta)} \frac{\partial(1/(1 - \phi - \beta))}{\partial \phi} = \frac{\phi}{1 - \phi - \beta} \quad (19)$$

Hence

$$\kappa = \frac{k_{0,p}}{k_{0,c}} = \frac{1 - \phi - \beta}{\phi} \quad (20)$$

Solving ϕ for range, κ can be expressed as a function of range, R .

$$R = \frac{\phi\eta(1 - \beta)k_b(L/D)}{(\phi + 1)g} \quad (21)$$

Here the following data are used. $\beta = 0.4$, $(L/D) = 20$, $\eta = 0.9$ and $g = 9.82$ [m/s²]. The battery specific energy k_{eb} is here assumed to evolve over time with an increase of 5% every year. According to (Misra, 2018) a more optimistic view on the development of power density driven by the need in aerospace, could be expected. However, this is very difficult to predict but looking at historical data it is not an unreasonable assumption to use 5% per year. As a starting point a value of 200 Wh/kg (720 kJ) at pack level is assumed in 2022.

$$k_b = 720000 \times 1.05^{y-2022} \quad (22)$$

As can be seen, if the battery weight is increased beyond a certain point the design will leave the comfort zone and at some point, it turns into a critical technology. In order to investigate the criticality of the technology, typical values representative of some of the best aircraft in operation are used in the equation. Using these values means that other technologies are also kept within their comfort zone. Here $\zeta_b = 200$ Wh/kg at pack level for 2022 is assumed, (corresponding li-ion technology batteries of Tesla), the propulsive effectiveness, $\eta = 0.9$, the aerodynamic efficiency, $(L/D) = 20$. An increase in (L/D) would directly affect the range, but it would also mean leaving the technology comfort zone of aerodynamic design, since (L/D) of already 19 already represents very good commercial aircraft. The structural fraction $\beta = 0.4$. Even though all of these values can be improved they can only be so incrementally and are already represents highly optimized technologies.

The plot in Fig. 2 shows the normalized sensitivity. It should also be noted that the range is the maximum range without any reserve, that would be necessary for operation. Another performance that is of interest is the cruise speed. The cruise speed is highly dependent on engine power, but power also drives weight which in turn increases drag. Therefore, the specific power of the power plant can become critical. Looking at Table 3 it is clear that a combination of fuel cells and electric motors that is needed to convert hydrogen into propulsive power has a specific power that is not more than a piston engine, which severely limits the achievable cruise speed to of the pre-gas turbine era.

It is clear from the Fig. 2 that battery electric aircraft for the foreseeable future is practical only for very short missions. Electric fuel-cell aircraft powered by high pressure hydrogen can have a more practical range and could be used for short and medium range. For longer range hydrogen in cryogenic tanks could be used and burn the hydrogen directly in gas turbines instead to achieve a higher specific power for higher performance. For long range, the low volumetric density of hydrogen starts to become a problem and some other sustainable aviation fuel is needed. This shows that from the applications that have been investigated, aviation is by far the most difficult to electrify.

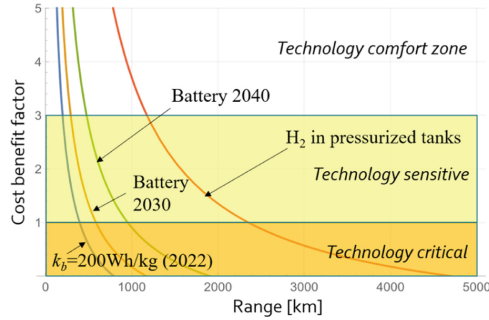


Fig. 2. The cost benefit factor as a function of theoretical range of electric aircraft, with batteries at (today) 2022 and forecasted values for 2030 and 2040 and for hydrogen in pressurized tanks.

6 Conclusions

In this paper an analytical method to assess feasibility of electrification, based on cost-benefit factor as a figure of merit, is described. It is used on a range of applications that have considerable CO₂-foot prints. There is already a very quick penetration of electric cars in the market, especially in Europe e.g., in February 2022 60% of all new cars sold in Sweden were either battery electric or plug-in-hybrids. This is increasing the expectations to other types of applications to follow suit. However, the potential and difficulties can be quite different. While ground based application can be more or less readily be electrified with available battery technology, at least looking at the vehicle platform itself, it is quite different for aviation. Here, anything but very short rang, only accounting for an insignificant share of transportation can be powered by batteries. Electric aircraft powered by hydrogen through fuel cells, can be used for regional flight, but for long-haul, where most CO₂ emissions come from, there is no electric technology in sight to make it feasible as a replacement. Here some other form of sustainable aviation fuel is required.

Acknowledgements. This paper has partly been sponsored by the Swedish Brazilian Research and Innovation Centre, CISB.

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