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Economic and Environmental Impact of Military Electrical Vehicle Conversion and Solar Electricity Production

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Abstract. Military vehicles carry out defence and training functions; however, they also participate extensively in military operations apart from war, such as supporting citizens in emergency situations. Nonetheless, they continue to contribute to pollution, and carbon emissions in Chile have doubled in recent years. Thus, this study seeks a partial solution to this problem, extending the useful life of an archetypal military vehicle, i.e. AIL Storm internal combustion engine vehicle (ICEV), 4.0L gasoline, through its conversion into an electric vehicle (EV) using lithium-ion batteries. AIL Storm ICE emissions are compared with an equivalent EV conversion prototype, analysing the CO_2 emissions of the EV charged from the Chilean electricity grid or from a solar photovoltaic charging station, taking advantage of the high levels of solar radiation in Chile. This studied model obtains a travel cost of 0.04USD/km in the "electric grid charge mode" and 0.02USD/km in the "Solar power station charge mode", affecting the environment with 155kg_{CO2} emissions per year of use. In the future, technologies to manufacture or assemble lithium batteries must be developed in the Chilean market. Given the availability of this mineral in Chile, this step would reduce costs and make electric mobility more attractive and affordable.

1. Introduction

Energy, in the form of mechanical power, is essential in vehicle mobility. Transport largely use internal combustion engines (ICE) based on fossil fuels (gasoline, diesel oil, natural gas) to generate the required mechanical power. The main inconvenient of ICE is the emission into the atmosphere of harmful products, such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2) and particulate matter (PM), as direct residual products of the combustion of fossil fuels.

After three consecutive years of stable global emissions [1, 2], CO_2 emissions grew by 1.6% in 2017 to 36.2Gt (billion tons), and are expected to grow a further 2.7% in 2018 to a record 37.1 ± 2Gt CO_2 [3].

Fossil fuel burning and cement production are responsible for about 90% of all CO_2 emissions from human activities [4]. Considering the environmental impact of ICE vehicles and the risk their emissions represent to the human health, there is a need for sustainable implementations to mitigate the negative impacts. Besides the role governments should play to spur, support and regulate such a transition, engineering sciences need to propose practical and viable solutions to reduce emissions from transport, through energy efficiency and clean energy production.

Ground tactical vehicles employed by armed forces (AF) around the globe generally use conventional ICE as power transmission system. This type of vehicle must fulfill a series of conditions, including reliability and autonomy, easy operation and maintenance, all-terrain transport and load capacity, as well as communication and orientation capabilities through various embedded tactical equipment. The ICE is usually employed in this type of vehicle, but in order to reduce the dependence on one particular resource, AF are concerned about widening the possibilities of alternative fuels. Their motivations is based on the strategic sense of keeping the mobility of their combat vehicles. For instance, records have shown that efforts were made during World War II to create synthetic fuels such as the hydrogenation of coal [5], or the US army evaluated the use of biodiesel for tactical vehicles [6].

There are other advantages in moving toward electric transmission for military vehicles. First, fossil fuels can account for up to 80% of the loads in convoys, bringing costs and risks. Moreover, according to the US Marine Corps [7], the cost of transporting petrol to some forward bases in Afghanistan can be 400 times the price of the fuel itself. Therefore, significant energy savings can be done, if EV were utilized. Secondly, AF are also interested in military EV because of the claim that the technology can offer lower-cost power sources, greater performance and stealth during operations [8]. Finally, electric transmission is gaining interest with the rising concerns towards the urgency of reducing vehicles exhaust pollutant emissions and mitigating negative environmental effects [9]. The environmental problem facing the transport sector include the needs for reducing exhaust emissions of pollutants. Electric motors and rechargeable batteries represent an attractive alternative for the motorization transport vehicles, as no exhaust pollutant are emitted from EV.

This study considers the replacement of the ICE powertrain by a combination of an electric motor and batteries, as an option to extend the useful life of these vehicles. The present work investigate the environmental and economic viability of the conversion of an archetypal ICE vehicle into an EV prototype. The analysis includes the evaluation of CO_2 emissions when the EV is charged from the Chilean electricity grid as well as when charged from a solar photovoltaic charging station.

2. Methodology

2.1. Archetype vehicle description

Among the large variety of military vehicles, the AIL Storm M240 is chosen as a representative vehicle for the purpose of the study, because such a vehicle has been in use since 1995, and considering its expected useful life of 25 years, the entire fleet from this generation will soon need to be retired from service. Instead of replacing them in the near future by other similar ICE vehicles, the study presents an option to extend the useful life of these vehicles and proposes to evaluate economically and environmentally its motorization conversion replacing used ICE by electrical motors with batteries for electricity storage.

For the purpose of the study, the AIL Storm M240 is supposed to be used for the on- and off-road transport of troops in the north of Chile, on a distance range of 120 to 150km per day or 2,250km per month. The AIL Storm M240 is a 4 wheel-drive multi-function vehicle, which include a conventional front engine design, a 77L gasoline tank and space for cargo or passengers (see Figure 1). It is conventionally powered by a gasoline engine (Otto cycle) of 4.0litres and 6 in-line cylinders developing 174 horse power at 4,700 revolution per minute. The average fuel consumptions of the ICE powered Storm M240 are presented in Table 1.

Table 1. AIL Storm M240 gasoline fuel consumption

Use	Average consumption (L per 100 km)
Urban	15.73
Road	13.88
Off-road	17.00

Figure 1. AIL Storm M240 model

The vehicle under study is mostly used in the desert climate in the north of Chile. This area presents daily thermal oscillations up to 35°C, low rainfall, and some of the highest solar DNI (direct normal irradiance) rates and clear sky indexes in the world.

For the present study, the parameter established for the minimum autonomy of 150km for the archetype vehicle, so it is necessary to store enough energy in the batteries to provide the necessary to travel that distance, considering a 40% in highway or city and the remaining 60% off road, under normal conditions, with a load of 500kg, equivalent to 4 soldiers with their equipment.

2.2. ICE to EV conversion

To transform the ICE to EV, fulfilling the previously established parameters, it will be necessary to carry out several steps: like the selection of the vehicle, its components and the way of charging the battery system.

2.2.1. Electric motor.

The selection of a motor for electric mobility and transformation of an ICV to an EV is one of the most important phases, since this choice determine the final performance of the converted EV. In this sense, 72volt DC motors is chosen because of similar torques characteristics with ICE. In this regard, an engine that has been tested in multiple conversions is the Warp 11HV, which has a double-ended axle, and allow the propulsion of the vehicle, as well as the operation of accessories, such as the hydraulic steering and the power brakes. The characteristics of this engine are the ones that are detailed in Table 2.

Table 2. Electric motor characteristics

Model	Warp 11-HV DC Motor
Retail cost	3,190USD
Motor type	Direct Current (DC)
Max voltage input	280V
Rated torque	235Nm at 72V and 597A (1442rpm)
Rated power	4kW at 72V and 597A (1442rpm).
Max Efficiency	88%

2.2.2. Electricity storage in batteries.

Currently, autonomy and distance range is the biggest constraint facing the EV sector. EV directly depend on the energy storage system. Li-Ion battery technology brings many benefits, so they were originally used for portable electronic equipment and lighting, but with the emergence of environmental trends linked to renewable energies, it has been developed for other purposes because of its ability to maintain capacity better than lead-acid batteries when delivering high currents, even at low temperatures [10].

It is necessary to evaluate the environmental impact at the end of the chain of production, transportation and use of lithium batteries. Considering Li-Ion batteries are manufactured in China, with transportation CO_2 emissions of 0.025gCO_2/kg.km for maritime transport and 0.105gCO_2/kg.km for the ground transport [11], it is estimated that CO_2 emissions are of 522,5gCO_2/kg considering a route of 18,800km from Shanghai in China through the Pacific Ocean to the central zone of Chile, and 500km of terrestrial route.

2.3. Fuel cost comparison

This section introduces a fuel cost comparison between the conventional ICE AIL Storm M240 and its equivalent conversion to EV. The comparison is not straightforward, since the price unit of gasoline is USD/litre, while the price unit of the electricity is USD/kWh. To allow the comparison, there is a need to calculate the cost of fuel spent to run on the same distance.

2.3.1. ICE vehicle.

ICE have generally an overall efficiency comprised between 15% and 19%, since a significant part of energy produced by ICE is lost through heat dissipation, during the vehicle stand-by, and through the drive line because of the aerodynamic drag [12]. Moreover, the ICE efficiency decreases while aging [13]. An ICE efficiency of 13% is considered in the study for the gasoline Storm M240. It is assumed that 1 litre of gasoline costs 1.2USD in Chile and provides 9.63 kWh of energy. The amount of kWh available at the end of the chain and the price of this energy are calculated as follows:

$$P_{full} = T_{cap} * P_l \quad (1)$$

Where P_{full} is the price to fill up the tank (USD), $T_{cap}$is the tank capacity (litres) and Pl is the price per litre of gasoline, in USD (national data). Thus, the price to fill up the tank is USD 92.4, and the energy supplied by the full tank is found using Equation 2:

$$E_{use\,full} = T_{cap} * E_l * \eta_{engine} \quad (2)$$

Where E_{useful} is the energy provided at end of chain, E_l is the energy provided from 1 litre of gasoline and η_{engine} the engine efficiency. The energy generated at the end of chain is 96.4kWh, and the price/km is calculated assuming the average distance range with a full tank of gasoline in 10% urban areas (6.36km/litre), 30% on road (7.2km/litre) and 60 % off road (5.88km/litre), is 487.14km. The price per km is then calculated as follows:

$$P_{km} = \frac{P_{full}}{D_{range}} \quad (3)$$

Where P_{km} is the price per km (USD) and D_{range} is the distance range (km). Thus, the gasoline cost of operating an ICV is 0.19USD/km (excluding maintenance costs).

2.3.2. EV conversion.

The two options available to charge an EV electric battery are grid power and a solar-powered charging station. The battery pack of a fully charged electric vehicle contains about 18kWh, which requires

36kWh to be supplied from the grid [14]. Furthermore, the efficiency between the battery and the transmission axle is about 70%, which leads to Equation 4:

$$\boldsymbol{E_u = \eta * E_b} \quad \textbf{(4)}$$

Where E_u is the energy use required to run the car, E_b is the energy in the battery, and η is the battery efficiency. The energy use to run the car is 12.6kWh.

2.3.3. On-grid charging.
For the first option, the electricity cost from the grid, administrated by the company ENEL [15], is considered USD0.159 per kWh, meaning that:

$$\boldsymbol{C_{ev} = C_{kWh} * E_g} \quad \textbf{(5)}$$

Where Cg_{ev} is the cost to fill up the battery from the grid (USD), Cg_{kWh} is the cost of kWh from the grid and E_g is the energy from the grid. In total then, it costs 0.04USD/km to run the EV in urban areas (10%), on road (30%) and off road (60%).

2.3.4. Solar charging.
Due to the strong development of the solar photovoltaic technology in the last decade, its cost have been reduced significantly. In the study, the cost to produce one kWh of solar PV electricity is estimated to be 0.1USD/kWh [16]. To calculate the cost for charging the EV battery from a solar station, we use the following Equation (6):

$$\boldsymbol{Cs_{ev} = Cs_{kWh} * E_s} \quad \textbf{(6)}$$

Where Cs_{ev} is the cost (USD) to fully charge the battery from the solar charging station, Cs_{kWh} is the cost to produce 1 kWh from the solar charging station and E_s is the amount of energy required to fill the battery. Considering the same distance of 150km for a vehicle in an urban area, road and off road, this means that it costs 0.02USD/km to run the EV on solar power.

2.4. Environmental comparison
We analyse the environmental benefits for vehicles in different experimental models. A traditional gasoline vehicle (ICE) and an EV, comparing CO_2 emissions when electric vehicles are fully charged with solar energy or on the grid.

2.4.1. ICE vehicle.
The CO_2 emitted by gasoline is assumed to be 2.38kg/l [17]; therefore, to make a comparison with respect to the emissions of the electric engine, we evaluate the emissions to run 150km, as the expected range of use of the vehicle.

$$\boldsymbol{E_{co2} = E_c * L_{km}} \quad \textbf{(7)}$$

Where E_{co2} is the CO_2 emissions (kg), E_c is the emission factor per litre of gasoline (kg/lt) and L_{km} is the Litres of gasoline required to run 150km (lt). Thus, a conventional combustion engine emits 56.92kg_{CO2} per 150km.

2.4.2. EV conversion – On-grid charging.
First, the study consists of determining CO_2 emissions when the battery is charged from the electric grid. In the study, we assume a CO_2 emissions factor of 0.42kgCO_2/kWh for electricity from the grid [18, 19].

$$Eg_{co2} = E_c * L_{km} \quad (8)$$

Where Eg_{co2} is the CO_2 emissions from electric grid (kg), E_c is the electric grid emissions per kWh (kg/kWh), L_{km} is the amount of kWh to recharge a battery to last 150km (kWh). Thus, emissions from an EV fully charged from the national grid amount to 15.1kg_{CO2} per 150km.

2.4.3. EV conversion – Solar charging.
Secondly, we estimate emissions when the battery is charged from the solar charging station. According to Chen et al. [14], the CO_2 emissions factor for the electricity produced by solar PV charging station is assumed to be 0.05kg_{CO2}/kWh.

$$Es_{co2} = Es_c * Ls_{km} \quad (9)$$

Where Es_{co2} is the CO_2 emissions from solar charging station, Es_c is the solar charging station emissions per kWh (kg_{CO2}/kWh), and Ls_{km} is the amount of kWh required to recharge a battery for 150km trip (kWh). Thus, the emissions from an EV fully charged with solar energy amounts to 1.8kg_{CO2} per 150km.

3. Results

Table 6 shows a summary of cost per km and CO2 emissions for each technology. It is observed that the cost per kilometre of EV AIL Storm is cheaper than ICV AIL Storm; therefore, from the economic and environmental point of view, it is convenient to use an EV versus a conventional ICE vehicle. Considering the results presented in Table 3, the cheapest solution is the EV AIL Storm charged by a solar power station. Likewise, this technology is the one that generates less CO_2 emissions.

Table 3. Cost per km and CO2 emissions per technology.

Technology	Cost per km (USD/km)	CO_2 emissions (kg/km)
ICV AIL Storm	0.19	0.380
EV AIL Storm (electric grid charge)	0.04	0.096
EV AIL Storm (Solar power station charge)	0.02	0.012

The use of AIL Storm prototype is in different places, either on or off road, so a fixed battery recharging station would not be suitable, that is why one or more deployable stations would be appropriate. These deployable stations would be made up of vehicles that have solar panels and charge controllers, along with battery replacement packages, this is made possible by a greater availability of the prototype AIL Storm or its fleet.

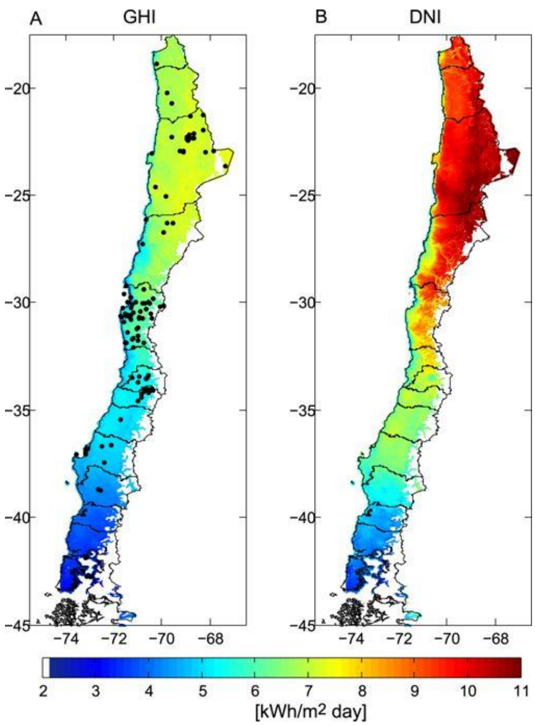

Figure 2. Solar radiation - Chile, orange and red indicate the highest amount of solar radiation during the day [20]

The viability of a deployable solar charging station depends on weather conditions and the availability of solar radiation. Given that the planned use of the AIL Storm prototype is in the northern zone of Chile, the recharging of its battery system will depend on solar radiation in that area. Figure 2 shows that in the employment area of the vehicle, between Arica and Copiapo, the direct normal irradiance (DNI) can reach levels between 9 and 11kWh/m^2 during the day [20]. Such a solar radiation availability in the area can benefit greatly to the studied EV, in terms of running costs and environmental impacts.

4. Conclusion

Globally, emissions of CO_2 have suffered a progressive increase, directly affected by the use of fossil fuels associated with human activities, mainly transport and heating. In this sense, the generation of CO_2 also involves the armed forces, since they mostly use vehicles that internal combustion (ICE), which have an extensive life and a variety of uses, not necessarily linked to military training. With the purpose of contributing to the decontamination and along with it, extending the useful life of some military vehicles, the present study reveals the improvements that can be implemented in an archetypal military vehicle, the AIL Storm M240, evaluating two different configurations of electric mobility (EV), considering the use of lithium batteries, which can be recharged through the electricity grid or through a solar PV plant.

On the other hand, a dominant factor was the environmental and economic impact of the use of lithium batteries for the electric mobility of the archetypal vehicle. Such a configuration obtained a running cost of 0.04USD/km in the “electric grid charge mode” and 0.02USD/km in the “solar power station charge mode”, while the running cost of the conventional ICE vehicle is more than four times the cost of running the EV charged from the grid and seven times the cost of the EV charged from the solar station. Regarding environmental impacts, the conventional ICE vehicle emits 853.4kg$_{CO2}$/month (assuming it runs for 2,250km/month), while the EV charged from the electricity grid would emit

216kg_{CO2}/month, and the EV charged from the solar station would have corresponding CO_2 emissions of only 27kg_{CO2}/month.

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