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Biofuels for an off-board hybrid solution avoiding the overloading of the electricity grid producing power for a more sustainable mobility

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First, Europe and then the rest of the world will undergo the transition to electric mobility in the coming decades. This shift will lead to a significant increase in power demand to charge all new electric vehicles. Therefore, power transmission and distribution management could become the most challenging problem to solve in the near future, worldwide. High costs and related emissions could nullify the benefits of electric mobility, making it less cost-effective. A potential solution to meet decarbonization goals is to employ generators fueled by biofuels, providing energy to charging stations in remote and/or extra-urban areas. The environmental advantages of biofuels and the existing fuel distribution infrastructures could offset the higher power generation costs using biofuels. In this work, an economic and environmental analysis is performed to compare three sustainable mobility scenarios: full electric, endothermic using biofuels, and the off-board hybrid. The results, obtained from the well-to-wheel analysis and cost assessment, show that the full electric scenario is the best from an environmental point of view, while the biofuel-based off-board hybrid can be a viable solution for a more sustainable energy transition. In particular, the CO2 equivalent emissions related to full electric mobility were found to be 6.5 kgCO2eq/100km, while the utilization of biofuels in internal combustion engines would guarantee a cost of 27.0 €/100km.

* 1. Introduction

By signing the Green Deal in 2019, the EU's constituent countries committed to making it carbon-neutral by 2050. To achieve this goal, member states are expected to reduce net greenhouse gas emissions by 55% compared to 1990 levels by 2030, and will continue to progressively reduce emissions by 2050 (*Clean and sustainable mobility*, 2021). As the leading cause of European greenhouse gas emissions, the transport sector must undergo a transformation that will require a 90% reduction in emissions by the expected date. According to the above, the European Commission has established that all new cars and vans (producing about 15% of total EU CO2 emissions) must be zero-emission by 2035. However, Europe will need of increasing of about 540 TWhe per year. By using only renewable sources (wind and solar power mainly) and nuclear energy to maintain or reduce carbon emissions (Blumberg et al., 2022). Further, an upgrading of the power grids will be needed to keep up with the growing renewable power production and the energy demand for electric charging stations (Khalid et al., 2019). Nevertheless, in many EU countries it is not so easy to quickly install new renewable plants and nuclear energy is limited or banned for safety reasons. This is the case of Italy, which currently consumes more than it produces and is therefore forced to acquire energy from other countries. For these countries the transition to a full electric car fleet could be very complicated, without significant expenses (Falfari and Bianchi, 2023). Moreover, this electricity should be transported by means of a not yet suitable and technologically underdeveloped electrical network. The novel sustainable technologies could be compared by evaluation of their overall life cycle, considering the production, use and recycling of materials (Tolomeo et al., 2020). In this regard, the batteries of electric vehicles and the accumulators, necessary for the proper functioning of the distribution network, are another element to be aware of. In fact, electric current storage systems are expensive, due to the rare materials of which they are composed, and their production and disposal are polluting and complex to manage. Despite their benefits, biofuel-powered endothermic motor vehicles face significant challenges, such as biomass supply for fuel production and urban air pollution. The primary issues are related to first-generation green diesel derived from dedicated crops. Although second-generation biofuels made from vegetable or animal waste are more environmentally friendly and have a lower impact, their availability remains limited (Caporusso et al., 2022). Local biofuel production by bioresources can be an opportunity also to valorize the potential green hydrogen availability due to the growing of the variable renewable energy sources (Giuliano et al., 2024). In addition to the aforementioned problems, it must be clear that, although the net CO2 emissions of biofuels are zero and the emissions of pollutants lower than those of fossil fuels, locally there would still be air pollution caused by fine dust emissions, which would be better avoided, especially in densely populated urban areas (McCaffery et al., 2022). In this work, an off-board hybrid scenario was also studied by comparing it with two other sustainable mobility strategies: 100% full electric cars and 100% liquid biofuel powered cars. This hybrid alternative is useful to take an integrated view of the technologies that allows to adopt the best solutions based on the cases. In urban contexts with a good charging infrastructure, electric vehicles could be the best choice. On the contrary, in rural or remote areas, the use of generators powered by liquid biofuels to charge electric cars could be a more economical and sustainable solution. Furthermore, this study aims to be the starting point for the creation of a decision-making tool aimed at implementing the most sustainable solution both from an economic and environmental point of view among different technologies in different situations. For this purpose, the well-to-wheel analysis will be used to allow a more immediate comparison for the different scenario.

* 1. Scenarios description

Three scenarios were analyzed from an energy, environmental and economic point of view. Below is a description of the scenarios considered.

* + 1. Full electric scenario

The full electric scenario contemplates a 100% electric car fleet, powered by the national grid. In this scenario, the following steps relating to the powertrain and energy distribution are considered:

1. the electric current is produced and fed into the distribution grid;
2. it reaches the column and recharges the vehicle's battery;
3. the energy is transmitted to the vehicle and reaches the wheels.
	* 1. Scenario full ICE bio

Green diesel is a drop-in biofuel that can replace conventional diesel entirely (up to 100%). It is primarily derived from vegetable oils, animal fats, or used oils. The production process involves chemical hydrogenation, during which the triglycerides in the oils are converted into hydrocarbons and propane. The benefits of green diesel include its ability to reduce greenhouse gas emissions compared to fossil fuels. This is because the carbon cycle is neutral: the CO2 released during combustion is the same CO2 that was absorbed by the plants used to produce the vegetable oil. Additionally, green diesel reduces particulate emissions and has an extremely low sulfur content, helping to mitigate air pollution and the phenomenon of acid rain. Beyond air quality benefits, green diesel contributes to the circular economy by transforming waste products, such as used oils, into valuable resources, thereby avoiding the need for disposal. Another significant advantage of green diesel is its compatibility with existing diesel engines, which do not require modifications, making it a viable and immediate solution to reducing fossil fuel use. The full ICE bio scenario is a scenario in which the entire car fleet is characterised by an endothermic engine powered by green diesel. According to this scenario, the energy conversion steps are:

1. the green diesel is produced in the biorefinery and transported by tankers to the service stations;
2. the car is refuelled at the service station;
3. the energy of the tank's green diesel is transferred to the wheels.
	* 1. Scenario off-board hybrid

The off-board hybrid system for charging electric vehicles uses a generator set powered by green diesel to supply electricity to charging stations. This approach combines the benefits of the green diesel supply chain with the advantages of a fully electric car fleet. Additionally, using a fixed-point internal combustion engine allows for the implementation of a CO2 capture system and achieves higher efficiency than cars equipped with internal combustion engines (ICE). In this scenario, the entire car fleet is 100% electric, but the vehicle batteries are recharged through charging columns that are not connected to the distribution network. Instead, they are powered by electrical generators operating in 'island' mode.

In particular, the first steps of energy conversion are common to the full ICE bio scenario, while the latter are common to the full electric scenario. Therefore, the energy conversion steps in this scenario are as follows:

1. the green diesel is produced in a biorefinery, transported from the production plant to the service stations and stored in a tank (as in the full ICE bio scenario);
2. the green diesel is taken from the tank and sent to the generator that transforms the thermal energy produced by the green diesel into electrical current then sorted to the charging stations;
3. the column recharges the vehicle battery, which transmits energy to the wheels (as in the full electric scenario).
	1. Methodology

The analysis conducted in this paper includes some simplifying assumptions. Specifically, the developed model is based on the Italian car fleet, considering factors like average distances and types of vehicles. The energy required for the wheels to travel 100 kilometres is based on the characteristics of the most sold vehicles on the Italian market, without accounting for differences between internal combustion and electric vehicles, such as weight or energy recovery during braking. For the analysis, 40 million cars travelling 11,000 km per year were considered. For the environmental impact assessment, only the equivalent CO2 emitted in the various conversion steps was considered. The cost analysis examines the gross costs of energy, fuels, infrastructure, components, and vehicles. The calculation tool in this study is based on the well-to-wheel analysis, which quantifies the impact of fuels and transport vehicles on energy use and greenhouse gas emissions. As more traction systems and alternative fuels are utilized, it's necessary to evaluate emissions and energy consumption from the primary source to final use. This provides a clearer understanding of the effects of specific technologies not just locally but starting from the source itself. The analysis investigates greenhouse gas emissions and energy efficiency, and a well-to-wheel analysis can be divided into two steps: the well-to-tank analysis, which considers how energy reaches the vehicle's tank, and the tank-to-wheel analysis, which focuses on the vehicle itself. For the energy analysis, the energy required for a vehicle's wheels to travel one hundred kilometres was calculated using an equation that considers the vehicle's frontal area, mass, and aerodynamic and rolling friction coefficients:

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| $$E\_{w}=\frac{A\_{f}∙c\_{d}∙1,9∙10^{4}+m\_{v}∙c\_{r}∙8,4∙10^{2}+m\_{v}∙10}{3600}$$ | (1) |

Then, using equations based on the efficiency chain principle, the various energies at different steps were obtained, up to the energy that the power plant must produce (equation 2):

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| $$E\_{cen}=\frac{E\_{w}}{η\_{p}∙η\_{r}∙η\_{g}∙η\_{d}}$$ | (2) |

For the environmental analysis, the results of the energy analysis and the emission factors for each energy conversion step were used to calculate the total equivalent CO2 emitted to travel 100 kilometres:

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| --- | --- |
| $$CO\_{2e,tot}=CO\_{2e,whe}+CO\_{2e,gen}+CO\_{2e,dist}+CO\_{2e,pri}-CO\_{2e,abs}$$ | (3) |

Finally, the cost analysis takes into account the different expenses necessary:

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| $$C\_{tot/100km}=C\_{veh/100km}+C\_{fuel/100km}+C\_{col/100km}+C\_{gen/100km}+C\_{net/100km}+C\_{sto/100km}$$ | (4) |

Values from the literature (Table 1) were used to obtain the comparison values. Specifically, the emission factor from biofuel combustion was necessary for the internal combustion engine (ICE) and off-board hybrid scenarios, while this value is zero for electric vehicles (EVs). For calculating emissions at the primary source, the emission factor used for electricity production was derived from the national energy mix. This value is crucial for the fully electric scenario, as it represents the only source of emissions from the primary source to the wheel. In cases where energy is derived from biomass to produce green diesel, the emission factor used is based on fuel combustion. In the scenarios using biofuels (ICE and Hybrid), the Carbon Sequestration Rate (CSR) is the parameter that calculates the amount of CO2 absorbed from the atmosphere per unit of biofuel used. This parameter is vital for the environmental analysis of green diesel usage, making it sustainable in terms of emissions. Lastly, the values adopted for the cost analysis of electric and endothermic vehicles were based on the prices of the best-selling cars in segment C. The cost of electricity at the charging station included a surcharge on the average PUN of 2024. Starting from the Rapid-50 charging station, the purchase price and power of the charging station were selected from the catalogue. To calculate the cost of the generator, commercial data from the supplier were used, considering the power of the generator and the energy at the refueling station to calculate its efficiency.

Table 1: Literature parameters used into the present work

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| --- | --- | --- |
| Parameter | Value | Source |
| *Af cd* | 0.7 m2 | (Guzzella and Sciarretta, 2007) |
| *mv* | 1,500 kg | (Guzzella and Sciarretta, 2007) |
| *cr* | 0.013 | (Guzzella and Sciarretta, 2007) |
| *ηp* | 70 % (EV)25 % (ICE) | (Genovese et al., 2015) |
| *ηr* | 90 % (EV)100 % (ICE) | (Genovese et al., 2015) |
| *ηg* | 50 % (Hybrid) | (Motore Perkins, 2024) |
| *ηd* | 94 % (EV)100 % (ICE & Hybrid) | (Gómez-Camacho and Ruggeri, 2019) |
| *CO2e,pri* | 309 kgCO2e/MWhe (EV)2.7 kgCO2e/kgdiesel (ICE & Hybrid) | (Caputo, 2024) |
| *CSR* | 3.6 kgCO2e/kgdiesel | (Galanopoulos et al., 2020) |
| *Cv* | 41,001 €35,529 € | (UNRAE, 2022) |
| *Cfuel* | 160 €/MWhe (EV)2.0 €/L (ICE & Hybrid) | (Giuliano et al., 2024) |
| *Ccol* | 25,410 € | (Modello INGEREV®, 2024) |
| *Cgen* | 47,022 € | (Motore Perkins, 2024) |
| *Cret* | 10,700,000,000 € | (Viganò et al., 2021) |
| *Csto* | 212.9 €/kWh | (Ralon et al., 2017) |

* 1. Results

Among the results obtained, one of the main data that emerges is the marked difference between the full electric scenario and the other two. In particular, the energy requirement from the power plants per 100 km is equal to 21.0 kWhe/100km, this value is less than half compared to the other two cases: 49.6 and 52.0 kWhe/100km for the ICE bio and off-board hybrid, respectively. This discrepancy is due to the fact that the electric motor is much more efficient than the endothermic one and to the absence of energy transformations from the battery to the production plant in the full electric scenario. However, the energy balances were stopped at the production plant, without considering the primary source. If the primary source had also been considered, the total annual energy required would have been similar for the three cases, given that the production yields of electricity are not particularly high (especially if production from renewable sources is considered). The environmental analysis returns a similar behavior, the case with the lowest environmental impact, in terms of greenhouse gas emissions, is the full electric scenario, followed by the full ICE bio case and the off-board hybrid case (Table 2). The result of 6.5 kgCO2/100km is due to the absence of emissions along the entire path of the electrical energy, except for its production. This value can only improve if the energy mix for the production of electrical energy, decreasing the share of energy produced from fossil fuels, becomes increasingly sustainable. Considering the off-board hybrid scenario, however, it is evident that the environmental impact is greater than in the full ICE bio case, despite the use of electric vehicles. This is attributable to chemical energy contained in the generator tank is greater than that contained in the tank of the vehicle with an internal combustion engine. The two solutions both use green diesel, so they have the same emission factors and, therefore, the favorable result for the full ICE case depends only on the energy in the tank. Clearly, these results could vary significantly if the regenerative braking of electric vehicles or the use of CO2 capture systems for the generator were considered, solutions that are not applicable to internal combustion vehicles.

 Table 2: Environmental assessment results for the scenarios considered

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| --- | --- | --- | --- |
| Scenario | Full electric(kgCO2eq/100km) | Off-board hybrid(kgCO2eq/100km) | Full ICE bio(kgCO2eq/100km) |
| *CO2e,whe* | / | / | +10.1 |
| *CO2e,gen* | / | +10.6 | / |
| *CO2e,dist* | / | +0.2 | +0.2 |
| *CO2e,pri* | +6.5 | +11.5 | +11.0 |
| *CO2e,ads* | / | -15.3 | -14.6 |
| *CO2e,tot* | +6.5 | +7.0 | +6.7 |

Table 3: Economic assessment results for the scenarios considered

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Full electric(€/100km) | Off-board hybrid(€/100km) | Full ICE bio(€/100km) |
| *Cveh/100km* | 19.1 | 19.1 | 16.6 |
| *Ccol/100km* | 0.1 | 0.1 | / |
| *Cnet/100km* | 0.1 | / | / |
| *Csto/100km* | 18.4 | / | / |
| *Cfuel/100km* | 3.4 | 10.9 | 10.4 |
| *Cgen/100km* | / | 0.1 | / |
| *Ctot/100km* | 41.1 | 30.3 | 27.0 |

Table 3 shows the costs associated with a traveled distance of 100 kilometers. As expected, results highlighted that the use of electric vehicles is associated with higher costs. The largest costs were for the batteries. The items that stand out and strongly influence the total costs are the cost of the vehicle, higher for electric vehicles due to the large battery pack, and that of the accumulators for the electrical network. The aim to replace fossil fuels with renewable energy, although positive from an environmental point of view, involves huge costs, not so much for adapting the network, but for the accumulators needed to guarantee energy in every period of the year. These batteries, characterized by large capacities, imply high costs to make up for the intermittency of renewable sources. The obtained values highlighted the full electric mobility scenario, alternative solutions are to be developed for energy storage and rely on diversified energy sources, not only renewables. This will allow for more constant production of energy and a consequent reduction in investment costs for grid storage batteries.

* 1. Conclusions

This study evaluated three different sustainable mobility scenarios based on environmental impact and costs. Specifically, it compared an off-board hybrid scenario powered by biofuels with two more traditional scenarios: a fully electric one and a 100% internal combustion engine scenario powered by biofuels. The results indicate that electric mobility offers advantages in terms of energy efficiency and emissions, but involves significant costs and requires changes to existing infrastructure. Given the high costs of grid batteries, it is clear that there is a need to diversify energy sources and develop alternative storage systems. The off-board hybrid scenario emerged as a viable transition solution to reduce investment costs and local vehicle emissions, despite some efficiency limitations that resulted in higher global emissions compared to the full ICE biofuel scenario. One way to address this issue could be to improve efficiency in the generator-to-charging station process. With advancements in electric mobility technologies, from powertrains to charging stations, and lower energy consumption at the wheels, the off-board hybrid solution could become more sustainable than using endothermic vehicles.

Nomenclature

Af – vehicle’s frontal area, m2

cd – aerodynamic friction coefficient, -

cr – rolling friction coefficient, -

mv – vehicle’s mass, kg

CO2e,tot – total emissions, kgCO2e/100km

CO2e,whe – vehicle emissions, kgCO2e/100km

CO2e,gen – generator emissions, kgCO2e/100km

CO2e,dist – distribution emissions, kgCO2e/100km

CO2e,pri – production plant emissions, kgCO2e/100km

CO2e,abs – absorbed emissions, kgCO2e/100km

Ctot/100km – total costs, €/100km

Cveh/100km – vehicle cost, €/100km

Cfuel/100km – fuel cost, €/100km

Ccol/100km – charging station cost, €/100km

Cgen/100km – generator cost, €/100km

Cnet/100km – grid adaptation cost, €/100km

Csto/100km – storage cost, €/100km

CSR – Carbon Sequestration Rate, kgCO2e/kgdiesel

Ew – energy to the vehicle’s wheels, kWh/100km

Ecen – energy to the production plant, kwh/100km

ηp – powertrain efficiency, -

ηr – refueling efficiency, -

ηg – generator efficiency, -

ηd – distribution efficiency, -

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