Converting a Conventional Car into a Hybrid Solar Vehicle: a LCA Approach

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Abstract:
The growth of world energy consumption and the increase of passenger vehicles areis setting new challenges to environmental protection. Large diffusion of electric vehicles and hybrid electric vehicles seems to be the most feasible solution. However, the need of fast charging infrastructure, the still low penetration of renewable electricity production and the massive reconversion of fleets limit the feasibility of this solution.
A life-cycle assessment study of several mobility options is presented in the paper. The analyses, performed by the use of the GREET model software, show that a suitable solution to reduction of total energy consumption and greenhouse gases emissions in the short to medium term could be the conversion of conventional vehicles into hybrid solar vehicles, as in the system developed at the University of Salerno.

Keywords: Hybrid Electric Vehicles, Life-Cycle Assessment, Automotive, Greenhouse Gases, Energy Consumption, Solar Vehicles

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1. INTRODUCTION

The economic growth, with particular emphasis on Organization for Economic Cooperation and Development nonmembers (non-OECD) regions, would cause a world energy consumption increase by 28% between 2015 and 2040. World gross domestic product (GDP) would increase by 3.0% per year from 2015 to 2040, while the price of North Sea Brent crude oil would reach 109 \$/barrel. These forecasts are valid for a Reference case determined on the views of economic and demographic trends for OECD regions. High and Low scenario have been addressed as-well. In these two scenarios, GPD would increase, respectively, by 3.3%/year and 2.7%/year. Analogously, oil price would reach 43 \$/barrel in the Low Oil Price scenario, and 226 \$/barrel in the High Oil Price one (EIA (2017)).

Although the exploitation of renewable energy sources will increase, fossil fuels are expected to continue to meet a large part of world's energy demand. Petroleum and other liquid fuels are expected to have a large share of world energy even if their usage would decrease from 33% in 2015 to 31% in 2040. It is also forecasted that liquid consumption will increase in industrial and transportation sector, and decline in electric power generation. The transportation sector remains the largest consumer of refined petroleum and other liquids growing from 54% in 2015 to 56% in 2040 (EIA (2017)).

In the decade 2005 to 2015 the worldwide number of vehicles has sensibly increased. Passengers cars and commercial vehicles increased from 892,028 in 2005 to 1,282,270 in 2015. The largest growth rate is represented by Asia/Oceania/Middle East area that signed a +141% (International Organization of Motor Vehicle Manufactures (2015)).

Internal Combustion Engines Vehicles (ICEVs) are frequently criticized and new regulations to control the environmental impact of vehicles (e.g., Directive 2017/1347 of 13 July 2017) set new challenges to the automotive sector. Furthermore, the so called "dieselgate" affair opened the Pandora's box which led to the approval of a new, stricter emission standard Euro 7 in the EU in late 2018 (Sinay et al. (2018)).

The best opportunity to reduce pollutants and Green House Gases (GHGs) emissions (Nemry et al. (2009)) and the relative effect on population health (Hawkins et al. (2012)) is given by the penetration of Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs) in the passengers cars' market. The benefits of HEVs and EVs in the operating phase are evident, but their impact from production phase and energy supply (well-to-wheel) can be even worst than conventional ICEVs (Helmers et al. (2017)). In fact, if, and only if, the charging electricity for EVs and Plug-in HEVs (PHEVs) has very low CO_2 and GHGs emissions, they can reach their full potential in mitigating global warming (Girardi et al. (2015)).

Penetration of EVs and PHEVs in everyday life has several aspects. Their deployment and their need of fast and diffuse recharging clash with the present infrastructure and topology of the grid (Marra et al. (2017)). In addition, large penetration of the EVs and PHEVs can have great impact on to the power grid, particularly in the case with poor coordination of charging times (Gong et al. (2012)).

In this study the Life Cycle Assessment (LCA) method is used to evaluate the total energy usage and environmental impact when a driver continues to use a conventional ICEV, fueled with gasoline or diesel, after a certain period of time or chooses to demolish and replace it with an EV or a HEV. The option of hybridizing the ICEV into a hybrid solar electric vehicle by the installation of the so called "HySolarKit" is evaluated as well.

HySolarKit is a kit developed by University of Salerno that allows to hybridize a conventional vehicle to a Through the Road (TTR) parallel hybrid. The hybridization is obtained by the integration of motors in rear wheels, the installation of an additional battery, of flexible photovoltaic panels on the vehicle body and an additional management unit using data from On-Board Diagnostic (OBD) port. In particular, the electrification of rear wheels with two wheel motors of 7 kW has been realized, converting the original FIAT Grande Punto in a TTR HEV with a Degree of Hybridization (DoH) of about 16% (Mild Hybridization) (Rizzo et al. (2018); Guzzella and Sciarretta (2013)).

The benefits, apart reduction of fuel consumption and emissions as detailed in next chapters, are enhanced performance, acceleration and vehicle control due to two additional electric motors, possibility of electric driving and access to Low Emission Zones. The results of large survey on potential users have also shown a good inclination to adopt such innovation (de Luca et al. (2015)).

The project, awarded with the "Seal of Excellence" by Horizon 2020, has been financed by the European program LIFE (LIFE-SAVE, Solar Aided Vehicle Electrification), with a participation of four Italian industrial partners (eProInn, Landi Renzo, Mecaprom and Solbian). The goal is to bring to industrialization (TRL=9) 4/5 prototypes of cars, and to foster a joint-venture between the partners to go to the market. Further details are available in the web site www.life-save.eu.

Argonne National Laboratory (U.S. Department of Energy) has a recognized leadership in performing LCA analyses. Its work led to the development of a tool, called GREET (Greenhouses gases, Regulated Emissions, and Energy use in Transportation) model, specific for the automotive sector. This software provides a comprehensive, lifecycle based approach to compare energy use and emissions of conventional (ICEVs) and advanced vehicle technologies (HEVs, PHEVs and EVs). The tool, whose latest update was in 2017, is developed in Microsoft Excel. It was used in this study but some modifications - such as fuel mix for electricity generation and fuel economy of vehicles - to the model were needed to adapt it to the Italian energy and vehicles market.

2. STATE-OF-THE-ART OF LCA IN AUTOMOTIVE

Among the LCA literature, it is possible to notice that only few studies considered the traditional vehicles conversion into HEV or EV. By these studies it emerged that the conversion of a traditional vehicle allows to save CO_2 emissions, also taking into account the production of electric supply, electric motors and batteries (Helmers et al. (2017)). Every study, however, is based on simulation, made up by generic LCA softwares, using a definite mileage and specifying the drive cycle used (Bauer et al. (2015); Castro et al. (2003); Samaras and Meisterling (2008); Bartolozzi et al. (2013)); for the data evaluation are considered the CO_2 and GHGs emissions and the energy consumption in every phase of vehicle life.

Each study agrees on the fact that the use phase is the most critical one for emissions and energy consumption of traditional vehicles because of the large use of fossil fuels, while for the electric ones the energy supply phase is the most critical phase. One of the most frequent topic in vehicle LCA studies is how to reduce fuel consumption during the vehicle use, making the vehicle lighter using alternative material like plastic reinforced material or aluminum instead of steel (Suzuki and Takahashi (2005); Kim and Wallington (2013); Lewis et al. (2014)).

Another topic is the comparison of a vehicle line up to evaluate how the performance raised during the years (Danilecki et al. (2017)). Other studies, instead, focused on the environmental performance of vehicles, considering various energy sources for the electric production (Hawkins et al. (2012); Girardi et al. (2015)); some studies have shown that if the electricity is generated using coal fired plant, the emissions of traditional PHEVs or EVs vehicle are higher than the emission or traditional ICEVs vehicle, while using the German average mix for electricity supply, as in (Helms et al. (2010)) the emissions are quite similar to each other (Rangaraju et al. (2015)). This underlines that for the advent of electric mobility is necessary to increase the production of electricity by renewable source (Nordelöf et al. (2014)). In any case, the electric vehicle is the best option for urban mobility because it has no emission during the vehicle use; this could contribute to refine the air quality of urban place. Moreover, electric motors have a better energy conversion than internal combustion engine, particularly at low loads occurring in urban driving (Althaus (2012)).

Large attention is placed in the end of life of vehicle, because about 75% of end-of-life vehicles materials, mainly metals, are recyclable in the European Union (Kanari et al. (2003); Nicolli et al. (2012); Lashlem et al. (2013)). The rest of the vehicle is considered waste and generally goes to landfills. Many studies focused on the environmental impact of batteries used for vehicle energy storage, and on the technologies used for recycling or reusing them. Applying the LCA study to these, in fact, results that batteries have a small incidence in energy consumption or emission compared with the total vehicle life (Matheys et al. (2009); Ramoni and Zhang (2013); Zackrisson et al. (2010)).

3. THE GREET MODEL

The GREET model tool, as mentioned, has been developed by Argonne National Laboratory to determine greenhouse gases and regulated emissions in addition to the energy use in transportation. The tool consists of two separated Excel files: the first one focuses on the fuel-cycle and calculates energy consumption and emissions during the production, transport and usage phases of fuels; the second file, instead, focuses on the vehicle-cycle and determines energy consumption and emissions during the life of a vehicle, including manufacturing, disposal and recycle/reuse of vehicles' components.

The fuel-cycle model contains aggregate data on the following processes per each fuel type:

- Production, transport and storage of the primary energy source;
- Production, transport, storage and supply of fuel;
- Usage of fuel, taking into account combustion and other chemical reactions.

Analogously, the vehicle-cycle model contains the aggregate data on:

- Extraction, recycle and processing of raw materials;
- Manufacturing and assembly of vehicle's components;
- Disposal and recycle of the vehicle.

The two Excel files interact with each other to determine the total energy consumption and emissions in a vehicle life-cycle, as shown in Figure 1.

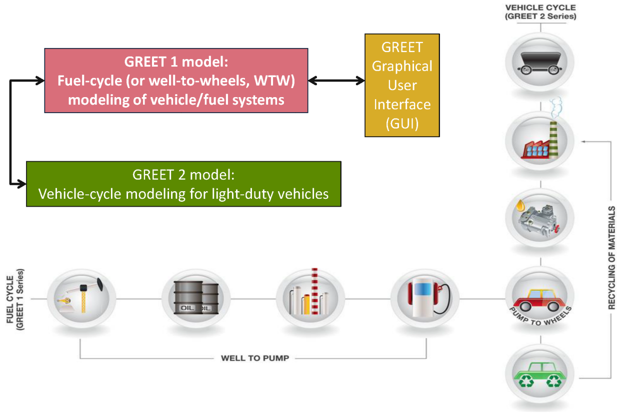

Fig. 1. GREET model

Outputs of the GREET model can be grouped into three main categories:

- Well-to-Pump (WTP), comprehending the production and distribution phase of fuels;
- Vehicle Cycle, which includes all the operation of manufacturing and disposal of the vehicle;
- Vehicle Operation, which consists of vehicle use and maintenance phase.

3.1 Tool assumptions

In GREET a vehicle is considered as aggregate of several components, due to the large number of variables to take into account. Those components are included in the tool's *systems*.

The mass of vehicles varies significantly according to their type. Total mass is shown in Table 1. Table 2 shows the battery and fluids mass per vehicle typology, while Table 3 summarizes the components composition of ICEVs, HEVs and EVs expressed as percentage of the total (excluding batteries, fluids and fuel). Each material is associated with energy consumption and CO_2 and GHGs emissions.

Particular attention was given by the development team on the vehicle maintenance throughout its life cycle. In fact, substitution of batteries (both standard starting battery and storage battery for EVs and HEVs), tires and fluids (refrigerant, brake, engine oil, etc) are considered. Brake pads, spark plugs, air filters and wiper blades are aggregated with other components that are not substituted during the life of the vehicle due to their minimal contribution to the total energy consumption and emission.

Table 1. Total Vehicles Weight

ICEV	HEV	PHEV	EV
1286 kg	1320 kg	1739 kg	1482 kg

Table 2. Battery and fluids weights of ICEVs, HEVs, PHEVs and EVs

SYSTEM	ICEV	HEV	PHEV	EV
Battery - Lead-Acid	16 kg	10 kg	10 kg	10 kg
Battery - Li-Ion	0 kg	0 kg	144 kg	202 kg
Battery - Ni-MH	0 kg	40.4 kg	0 kg	0 kg
Engine oil	3.9 kg	3.9 kg	3.9 kg	0 kg
Brake fluid	0.9 kg	0.9 kg	0.9 kg	0.9 kg
Trasmission fluid	11 kg	0.8 kg	0.8 kg	0.8 kg
Powertrain coolant	10 kg	10 kg	10 kg	7 kg
Windshield fluid	2.7 kg	2.7 kg	2.7 kg	2.7 kg
Adhesives	13.6 kg	13.6 kg	13.6 kg	13.6 kg

Table 3. Composition of ICEVs, HEVs, PHEVs and EVs (excluding batteries, fluids and fuel)

SYSTEM	ICEV	HEV	PHEV	EV
Body System (including BIW, interior, exterior, and glass)	46.1%	41.9%	38.2%	47.5%
Powertrain System	24.7%	22.5%	23.9%	4.8%
Transmission System	5.3%	5.0%	4.7%	5.7%
Chassis (w/o battery)	23.9%	24.5%	24.9%	28.9%
Traction Motor	0.0%	2.1%	3.2%	7.2%
Generator	0.0%	2.1%	3.2%	0.0%
Electronic control	0.0%	1.8%	1.8%	5.9%

HEVs battery size is set equal to 23 kW, while for PHEVs and EVs the battery size is expressed in energy and it is equal, respectively, to 15 kWh and 27 kWh. Nickel-Metal Hydrate (Ni-MH) battery is assumed for HEVs, whilst EVs and PHEVs are equipped with Lithium-Ion (Li-Ion) batteries. The software expects that Ni-MH and Li-Ion should be substituted after traveling 250,000 km. This value agrees with the range of 150,000 to 300,000 km in literature (Duvall et al. (2004)).

Vehicle tires are changed every 65,000 km, while fluids are substituted depending on its typology:

- lubricant oil is changed every 6,500 km;
- power steering oil is not changed. HEVs and EVs are equipped with an electrified power steering system;
- brake fluid is changed every 65,000 km;
- transmission oil is substituted once during the life of the vehicle.

Analogously, each fuel and electricity generation is carefully analyzed, taking into account every phase of extraction, refinery and transportation (for fuels) and the fuel mix used for generation (for electricity generation).

3.2 Modifications to the GREET model

As mentioned, the fuel mix for electricity production was substituted with the Italian one. Table 4 reports the Italian fuel mix in 2016 which includes the electricity imported by other European countries (such as, electricity from nuclear).

Table 4. Italian fuel mix

Source	**Value**
Renewables	38.4%
Natural Gas	37.6%
Carbon	15.9%
Nuclear	3.9%
Biomass	3.2%
Petrol	1.0%

The fuel economy of conventional cars has been changed to 5.5 liters per 100 km according to the European average (Pavlovic et al. (2018)). Diesel vehicle fuel economy is automatically calculated by the tool itself by dividing the gasoline fuel economy by a factor equal to 1.21.

3.3 Integration of HySolarKit

In order to integrate HySolarKit into the GREET model, the main components of the kit have been individually analyzed (photovoltaic panels, batteries and electric motors). The impact of the components' material is derived by the tool itself. In detail, photovotaic panels made in monocrystalline silicon with a mass equal to 1.7 kg have been considered. Lithium-ion batteries with 4 kWh capacity is assumed, while for the electric motors it has been assumed that they have the same impact, during the construction phase, of the electric motors of HEVs and EVs.

Fuel consumption savings (and corresponding emission reductions) are due to two concurrent mechanisms:

- mild hybridization, allowing partial recovery of the energy during braking and downhills and an increase of the mean engine efficiency, due to cooperation with the electric propulsion; this benefit would depend on type of driving, and is maximum in urban driving;
- photovoltaics, providing a free partial recharge of the battery along all the day (including parking time); thanks to this contribution, the vehicle can operate in charge depleting mode, rather than in charge sustaining, as for pure hybrids. The daily harvested energy depends on location, season and weather conditions, while the relative weight of this contribution depends on the daily energy spent for traction, function of driving type and time; its relative contribution is maximum for typical urban use (about one hour per day driving).

An analysis of fuel consumption reduction for different driving cycles, component sizing and driving habits has been performed using a longitudinal dynamic model (Marano et al. (2013); Rizzo et al. (2014)). The effects of different vehicle configurations (i.e. Drive by Wire vs direct pedal actuation) on driveability and on energy management have been studied by Dynamic Programming (Rizzo et al. (2018)), and specific aspects related to regenerative braking actuation have been analysed (Grandone et al. (2016)). The results show that for typical urban use (i.e. FUDS cycle, about 1 h driving per day), the savings due to combined effects of hybridization and solar recharge can be of the order of 20% in sunny days. Therefore, regarding the fuel consumption of the vehicle equipped with the HySolarKit two separate conditions have been considered:

- best case: the use of the kit allows a 20% reduction of fuel consumption;
- standard case: the use of the kit allows a 10% reduction of fuel consumption.

In the use period of the kit there is no need to refurbish the photovoltaic modules installed on the vehicle, while the batteries are substituted as in the HEVs and EVs cases.

4. DESCRIPTION OF SIMULATIONS

This study is divided into two temporal periods, one following the other. In the first period, lasting 10 years, the purchase and use of a conventional passenger vehicle is considered. This vehicle travels 50 km per day, thus a total of 182,500 km, of which 70% traveled on urban cycle. In the second period, having the same length of the first one and drive-cycle, three different scenarios have been analyzed:

1. the driver keeps using the conventional vehicle;
2. the driver purchases a new alternative vehicle (HEV, PHEV or EV);
3. the driver converts his vehicle with HySolarKit.

In both time periods, the life-cycle of vehicles is accounted in terms of :

- Total Energy: the total energy used for the manufacture, disposal, use and maintenance (kJ/km);
- GHGs: GHGs emissions (g/km);

5. RESULTS

5.1 First time period

The results of the analysis relating to the first hypothetical scenario are explained in this section.

Figure 2 shows the total energy consumption for production (including disposal) and use of both gasoline and diesel cycle. As expected, the diesel-fueled vehicle shows lower consumption in Vehicle Operation phase since the diesel vehicle's fuel economy is better than the gasoline one. The lower consumption in the Well to Pump phase is due to the fact that diesel fuel is less refined than gasoline. These aspects lead to a reduction of 461 kJ/km (17.6%) in case of use of a diesel vehicle.

The same behavior is found when GHGs emission are evaluated. Figure 3 shows a reduction of 23 g/km (12.6%) of GHGs.

Both figures show that the most critical phase of life of a vehicle in the selected scenario is its use, while vehicle cycle and fuel cycle affect to a lesser extent. In fact, the vehicle operation phase represents about the 65% of the overall total energy consumption for both vehicles and about the 70% of CO_2 and GHGs emissions.

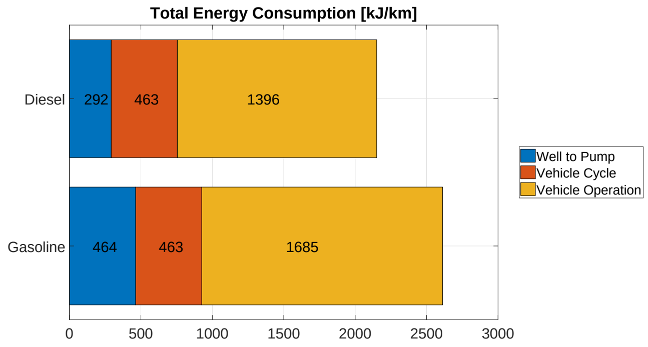

Fig. 2. First period: Total Energy Consumption

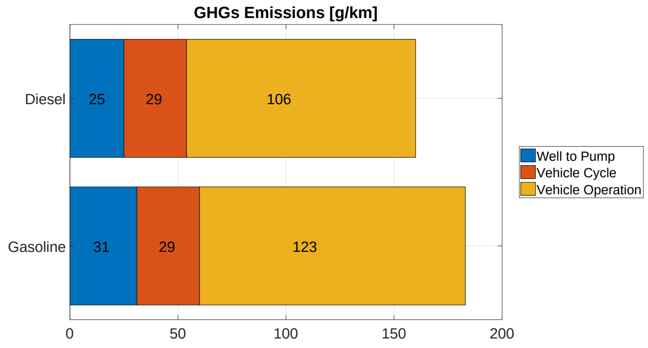

Fig. 3. First period: GHGs Emissions

5.2 *Second time period*

In the second time period, the mobility options for the driver are analyzed. The following figures summarize the results. Before commenting them, it has to be specified that for the case in which the driver keeps using its vehicle the LCA analysis does not include the vehicle cycle phase since it has already been considered in the previous time period.

The analysis of the total energy consumption highlights some results that could not be expected. If on one hand it was expected to find a lower energy consumption from EVs, HEVs and PHEVs on the vehicle operation side, on the other a total energy consumption higher or comparable with the one of the use of the same diesel or gasoline engine was not predictable. As shown in Figure 4 the vehicle cycle and well-to-pump phase play a critical role in the total energy consumption for EVs, PHEVs and EVs. Moreover, the PHEV has the greatest total energy consumption. In this case, the well-to-pump phase assumes a great importance because it includes the fuel mix for the generation of the electricity that is supplied to the vehicle during charging.

Figure 4 also shows that the conversion of the vehicle by the installation of the HySolarKit allows, both in the standard and in the best case, the vehicle to have a lower total energy consumption than PHEVs and HEVs. This is due to the fact that the vehicle cycle phase only includes the manufacturing of the kit components, thus resulting in much lower energy consumption than those of new PHEVs and HEVs. In particular, a diesel vehicle converted with HySolarKit has a lower total energy consumption that a full electric vehicle in the examined scenario.

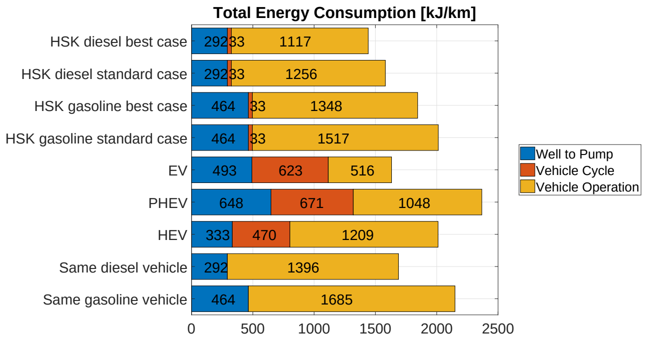

Fig. 4. Second period: Total Energy Consumption

The analysis of GHGs emission confirms some of the results from the total energy consumption. Also in this case, the substitution of the diesel vehicle with a PHEV or a HEV is not convenient. Only the disposal of the gasoline ICEV allow a small reduction (about 10%). For the PHEV the well-to-pump has a considerable share of the overall GHGs emission which depends on the fuel mix for electricity generation. Conversely, even if the HEV has the lowest well-to-pump dependency, the vehicle operation phase assumes the greatest contribution to GHGs emissions.

Results corroborate what has been found in the total energy consumption analysis. A vehicle converted with HySolarKit has lower GHGs emission than HEVs and PHEVs three times out of four. In particular, hybridized diesel ICEVs have the lowest GHGs emissions, outdone only by EVs which are characterized of not having vehicle operation emission since there is no fuel burned.

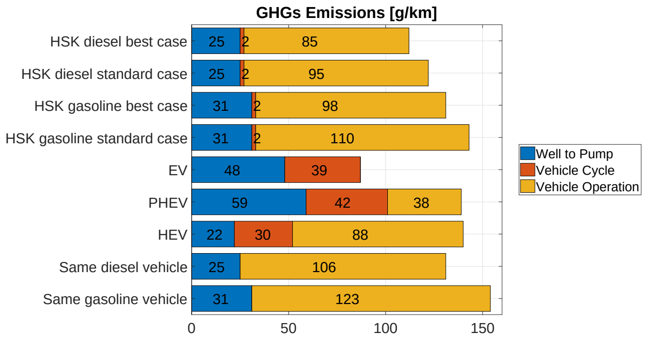

Fig. 5. Second period: GHGs Emissions

6. CONCLUSIONS

The paper presents the application of LCA for the evaluation of total energy consumption and GHGs emissions when a driver is in front to several mobility options. The analysis includes the option of converting a conventional car into a solar hybrid vehicle with HySolarKit which allows fuel economy improvement up to 20%.

A wide literature analysis on LCA applied to the automotive sector has been performed. This showed that only few studies focused on the conversion of vehicles, while the majority of them focused on the reduction of energy consumption and GHGs emissions by operating on manufacturing materials and traction options.

The LCA analysis of this study has been performed by the use of the GREET model tool developed by Argonne National Laboratory. The life-cycle analysis included gasoline and diesel ICEVs, HEVs, PHEVs, EVs and converted ICEVs with HySolarKit. Two separated time periods have been analyzed. In the first one, lasting 10 year, a driver uses its conventional vehicle on a 70% urban drive cycle. In the second time period, with same time length and drive cycle, the substitution of the vehicle with an alternative vehicle (HEV, PHEV and EV) or the conversion with HySolarKit has been confronted.

Results of the first time period prove that the conventional diesel ICEVs have lower total energy consumption and GHGs emission due to the fact that diesel fuel is less refined that gasoline and that the diesel ICEV is more efficient than a gasoline one.

The second time period analysis showed that the hybridization of the vehicle with HySolarKit entails a lower total energy consumption that HEVs and PHEVs because of, mainly, the lower contribution of the manufacturing of the kit in respect of the manufacturing of a new vehicle. In addition, diesel ICEVs converted with HySolarKit have the lowest total energy consumption in the examined scenario.

In terms of GHGs emissions, only the full electric option allows the best reduction. Also in this case, the conversion of ICEVs with HySolarKit leads to lower GHGs emission than PHEVs and HEVs three times out of four.

In conclusion, results showed that that electric mobility (PHEVs and EVs) options have a strong dependency on the fuel mix for electricity generation. Only if it is characterized of a large share of renewable energy, it is possible to sensibly reduce total energy consumption and GHGs emissions. In addition, the installation of HySolarKit gives better results than the purchase of a brand-new HEV and even compete with EVs in terms of total energy consumption.

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