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A prototype car converted to solar hybrid: project advances and road tests. ⋆

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Abstract: A project for upgrading conventional cars to hybrid electric vehicles is presented. The project is carried out by four Italian partners within a EU project financed by the LIFE programme. Hybridisation to a through the road parallel hybrid structure is obtained by integration of wheel motors in rear wheels, the addition of an additional battery, of flexible photovoltaic panels and a Vehicle Management Unit. The technical aspects related to vehicle conversion and the results of test bench and road tests on first prototypes are presented and discussed, as well as the perspectives related to the industrialization of such system.

Keywords: Sustainable mobility, Photovoltaics, Vehicle conversion, Electrification, Hybridized vehicles, Solar assisted vehicles

1. INTRODUCTION

The increasing world energy consumption and the growth of passenger vehicles are setting new challenges to environmental protection. In fact, the transportation sector accounted for the 28.9% of world energy consumption in 2019, and that share has been almost constant for over two decades. Since the scenarios to 2030 and beyond do not predict a reduction of the overall share of the transportation sector energy use, the recourse to Electric Vehicles (EVs) and to Hybrid Electric Vehicles (HEVs) seems to be the most feasible solution to match the goal of containing the global temperature with +1.5 C from pre-industrial era (International Energy Agency, 2021).

However, the need of fast charging infrastructure, the still low penetration of renewable electricity production and the need of massive reconversion of fleets limit the feasibility of these solutions, at least in a short-medium term perspective. Electricity production from renewable energy sources and nuclear represents an overall share of 38% worldwide and in the Stated Policy Scenario (STEPS) it is expected this share to increase to 68% (International Energy Agency, 2021) in 2050. Moreover, a massive and premature dismissal of millions of vehicles often still in good conditions is a non-sustainable option if the problem is properly analyzed in a life-cycle perspective (Rizzo and Tiano, 2020).

In such a context, the vehicle reuse after their ecological reconversion is a more sustainable solution, compliant with the principles of circular economy. A project for upgrading conventional cars to hybrid electric vehicles is presented by the authors. The technical aspects related to vehicle conversion and the results of test bench and road tests on first prototypes are presented and discussed, as well as the perspectives related to the industrialization of such system, able to accelerate the transition toward a more sustainable mobility.

2. LIFE-SAVE PROJECT

The project of converting existing vehicles into solar hybrid cars was developed and patented at first by professors and researchers of the University of Salerno. The project, initially named HySolarKit, is now carried out within a EU project financed by the *LIFE programme* (LIFE-SAVE, Solar Aided Vehicle Electrification) by four Italian partners: Mecaprom (project leader), eProInn (University of Salerno spin-off company), Solbian and Landi Renzo (LIFE-SAVE, 2022). Hybridization to a Through-the-Road (TTR) parallel hybrid structure (Rizzo et al., 2020) is obtained by integration of wheel motors in rear wheels, the addition of an additional battery, of flexible photovoltaic panels and

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a Vehicle Management Unit (VMU) (Rizzo et al., 2018). The installation of the additional battery is mandatory to supply energy to the electric powertrain. The achieved mild-hybridization is schematized in Figure 1.

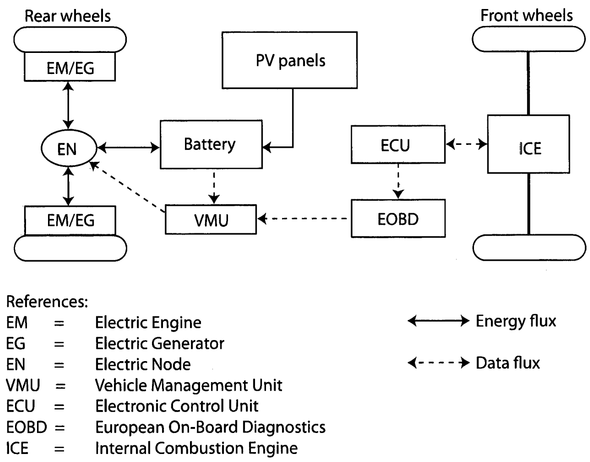

Fig. 1. Block diagram of a vehicle converted into a TTR hybrid (Rizzo et al., 2011)

The conversion kit can be installed on front-wheel cars and does not require the OEM's clearance. In fact, the data necessary for the control of the electric powertrain are obtained from the OBD port of the vehicle through which it is possible to reconstruct its the operating conditions (D'Agostino et al., 2014).

The vehicle converted to a solar hybrid will be able to operate in three operating modes: i) purely thermal mode, ii) hybrid mode in both charge sustaining and charge depleting, and iii) purely electric mode.

2.1 The Prototypes

The first prototype A first prototype was developed at the University of Salerno. A kit for solar hybridization of front-driven cars has been developed and installed on a FIAT Grande Punto Diesel 1.3 l (see Figure 2). This prototype was equipped with market-available 7 kW In-Wheel Motors (IWMs) in the rear wheels without mechanical brake, LiFeYPO4 technology battery, laboratory-made battery management system, flexible photovoltaic panels and a control system installed on a laptop using data from the On-Board Diagnostic (OBD) port.

A significant research activity was carried out via both numerical modeling and experimental tests.

The potential and estimates of fuel consumption reduction of a hybrid vehicle have been the subject of several studies (Onori et al., 2016). Many researchers also focused on TTR hybrid vehicles (Galvagno et al., 2013; Sabri et al., 2016, 2018; Chen et al., 2019; Wang et al., 2019; Sabri et al., 2021). The application of *Dynamic Programming* was evaluated in order to be able to determine a performance benchmark of the converted vehicle (Pisanti et al., 2014). The limitations of this algorithm for real-time implementation on the vehicle led to an investigation into other energy management methodologies. Among many,

Fig. 2. The prototype of FIAT Grande Punto converted into solar hybrid

the study focused on the application of *Pontryagin's Minimum Principle* (PMP) and on the *Equivalent Consumption Minimization Strategy* (ECMS) (Tiano, 2020). The simulation of the application of these two methodologies, which concretely converge in a single control technique, has shown results that demonstrate the effectiveness of vehicle conversion for reducing fuel consumption (Tiano et al., 2021).

Specific studies have been focused on regenerative braking, with specific application to the case of cars converted into Through-the-road (TTR) hybrid vehicles. The optimization of regenerative braking by means of braking force modulation has been analysed, and optimal modulation strategies have been proposed and simulated (Rizzo et al., 2021). An algorithm based on Model Predictive Control (MPC) has been also studied and its benefits assessed via simulation (Mariani et al., 2022).

Studies and models aimed at estimating temperature effects for photovoltaic panels installed on a car under real meteorological conditions have been also carried out (Tiano et al., 2020). The direct use of solar energy on hybrid vehicles is undoubtedly a niche topic but has found, over the years, a fair diffusion in various groups of researchers (Conti et al., 2018; Mohan et al., 2018; Bai and Liu, 2021).

The second prototype The first prototype has allowed to verify the possibility to drive the car in hybrid mode, and to control the electrical powertrain deriving the information on the vehicle operation via the OBD port. However, according to the scale of Technology Readiness Level (TRL) adopted by EU (Héder, 2017), its technology level was considered about 5 (Technology validated in relevant environment). In order to progress to the industrialization, a project aimed at the development of prototypes ready for the market (TRL=8/9) has been started within the EU project LIFE-SAVE (Solar Aided Vehicle Electrification). During the LIFE-SAVE project, a new prototype of a solar hybrid vehicle was created using a VolksWagen Polo (see Figure 3).

The power system architecture of the new prototype has been updated as depicted in Figure 4.

Fig. 3. The second prototype on VW Polo with solar panels on the roof

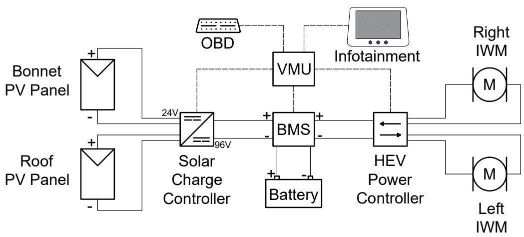

Fig. 4. Simplified schematic of the hybridized vehicle power system (Tiano, 2020)

For the preparation of the second prototype, the project involved the design and construction of new IWMs with a power of 10 kW each and with an integrated disc brake, shown in Figure 5, as well as an automotive standard power and control electronics, shown in Figure 6, installed in the spare wheel housing. Specifications of the new IWMs are reported in Table 1.

Table 1. Specifications of the new IWMs

Parameter	Value/description
Motor type	PMSM
Surface mounting	External
DC link voltage	96 V
Pole numbers	28
Nominal current	65 A
Nominal torque	95.9 Nm
Nominal frequency	175 Hz
Nominal speed	750 rpm
EMF constant	0.291 V/Hz 0.080 V/rad
Constant power operating area	750-1000 rpm
Stator phase current	0.11 Ω
Stator phase inductance	600 μH

In addition, the LIFE-SAVE partner Solbian has developed an Maximum Power Point Tracker (MPPT) equipped charge controller specific for the automotive use of a photovoltaic panel as well as a proprietary technique to build flexible double-curved panels so that they can be suitable for installation on the vehicle body.

Finally, a new traction battery conforming to automotive standards was identified and equipped on the prototype. The battery capacity, equal to 10 kWh, allows an easier

Fig. 5. Mecaprom designed In-Wheel Motors (IWMs) in the VW Polo Prototype

Fig. 6. Particulars of electronics in the VW Polo Prototype (Work in progress)

and long-lasting use of the charge depleting mode in hybrid as well as in electric mode of the vehicle. More specifically, the prototype is equipped with a traction battery made by Eco-Volta model eTB96-100-10 battery. Its specifications are available in (Eco-Volta, 2022).

All the components of the kit are integrated in a CAN communication protocol.

3. EXPERIMENTAL TESTS

A series of tests have been carried out on vehicle test bench on the VW Polo prototype, in order to study the performance of the electrical powertrain and of IWMs.

3.1 Test bench test

Some data measured on vehicle test bench are presented in Figures 7 to 10. An acceleration test has been performed, up to a speed of about 60 km/h. The measured values of mechanical torque and power, of current in the two wheel motors are presented in the graphs. The comparison between electrical power in input and mechanical power in output allows to estimate the wheel efficiency, ranging around 75% and 90%.

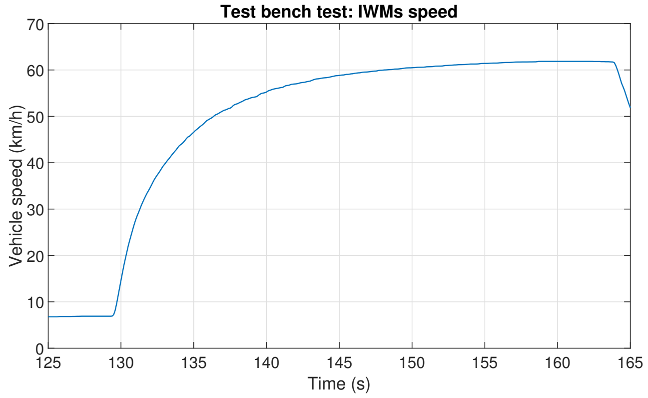

Fig. 7. Results on vehicle test bench: IWMs speed

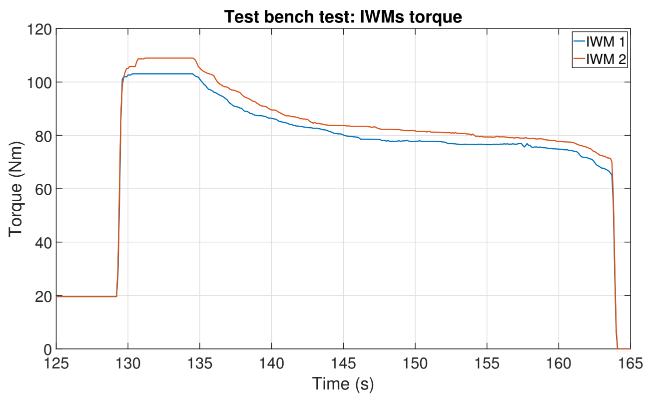

Fig. 8. Results on vehicle test bench: IWMs torque

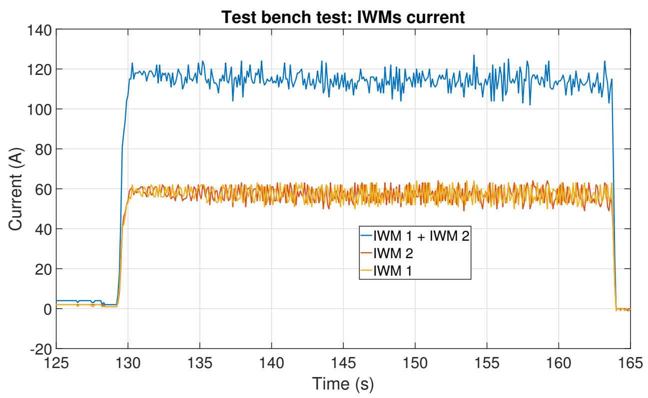

Fig. 9. Results on vehicle test bench: IWMs current

3.2 Road test

Table 2 describes the road tests performed with the prototype, near the Mecaprom premises in Biella, Italy. On each test, data were acquired via CAN Analyzer and processed by a Matlab code. The table shows the key figures of each test. In the following, some data referring to test #1 (in Hybrid mode) and test #2 (Electric mode) are presented and discussed.

Fig. 10. Results on vehicle test bench: IWMs efficiency

Electric mode test Figures 11 to 14 present a set of data measured during a test of the vehicle in Full Electric Mode. The test, on a flat road, have confirmed the capability of the vehicle to run up to 60 km/h (see Figure 11) without the contribution of the thermal engine. The efficiency of IWMs has been assessed to range around 80% for most of the operation time (see Figure 14).

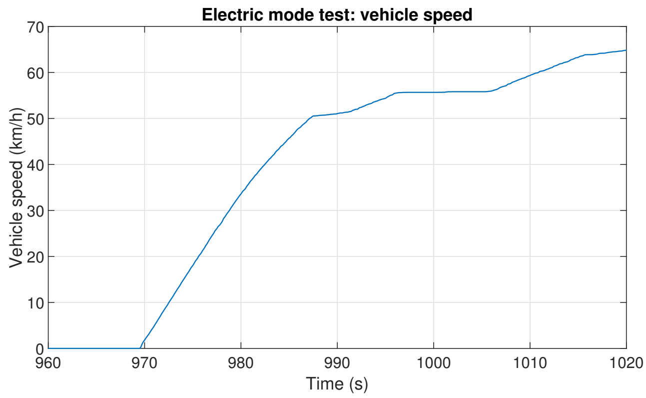

Fig. 11. Results on electric mode test: vehicle speed

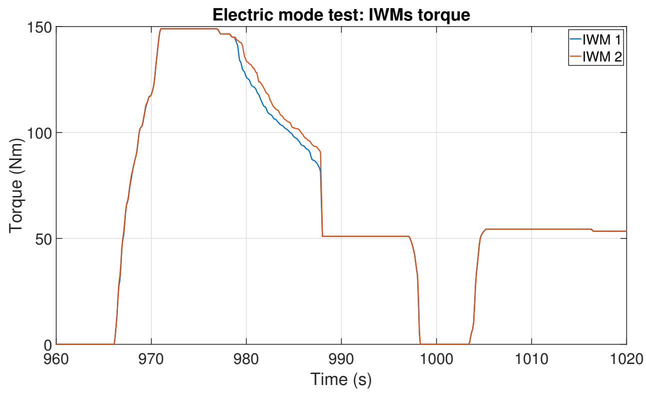

Fig. 12. Results on electric mode test: IWMs torque

Table 3 summarizes the elements measured during the test in electric mode. It shows a consumption of 173 Wh/km which, with a 10 kWh battery, translates into a range of 58 km at a constant speed of 65 km/h.

Since the continuous charging power of the battery is about 4.9 kW, the quickest recharging time is about 2 hours. As for the charging costs, these depend on the electricity price charged by the supplier, obviously.

Table 2. Road test on the VW Polo near Mecaprom premises in Biella, Italy

Case	**Length** (km)	**Duration** (s)	**Electric mode** (s)	**Hybrid mode** (s)	**Engine mode** (s)	**SOC from**	**SOC to**
1	49.3	3 239	310	1 604	613	54.7	44.1
2	1.6	478	128	0	0	83.4	80.6
3	46.7	4 703	3884	1 469	53	80.3	72.8

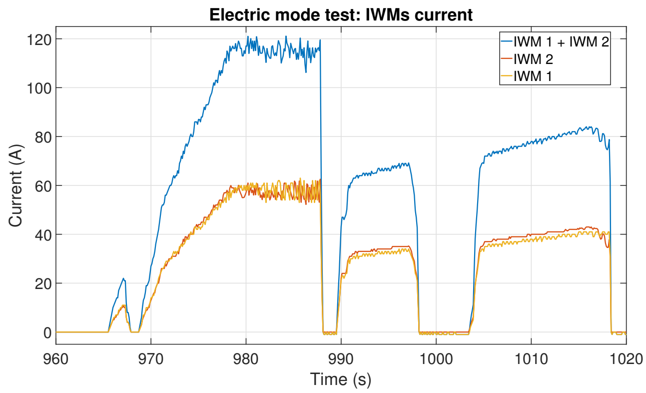

Fig. 13. Results on electric mode test: IWMs current

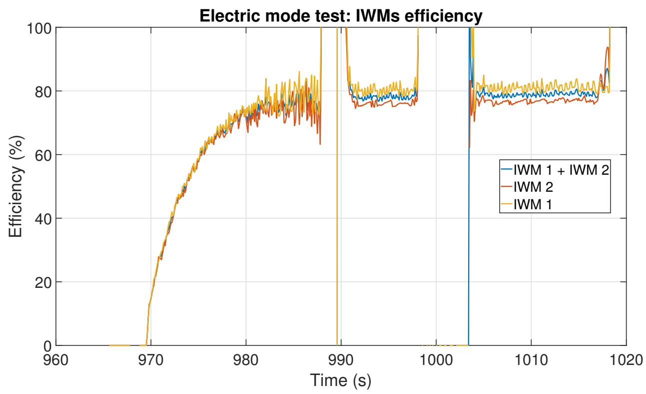

Fig. 14. Results on electric mode test: IWMs efficiency

Currently, the Single National Price as of May 2022 in Italy is equal to 0.23 €/kWh. Consequently, a full recharge of the battery, considering the gross energy, would have a cost equal to 2.22 €. This cost considered the energy component only, consequently the costs relating to energy transport costs, system charges, taxes and VAT must be added.

Table 3. Summary of eletric mode test

Parameter	**Value**
Velocity	65 km/h
Mechanical power	9 kW
IWM efficiency	0.8
Electric power	11.25 kW
Energy consumption	173.08 Wh/km

Hybrid mode test Finally, Figures 15 to 17 present a set of data measured during a test of the vehicle in Hybrid Mode, lasting for about 23 minutes. Vehicle speed has been extended from zero to about 100 km/h (see Figure 15), with engine speed ranging up to 3 500 rpm (see Figure 16). The graph of battery SOC evidences that during the test the vehicle operates both in recharging mode and in discharging mode (see Figure 17).

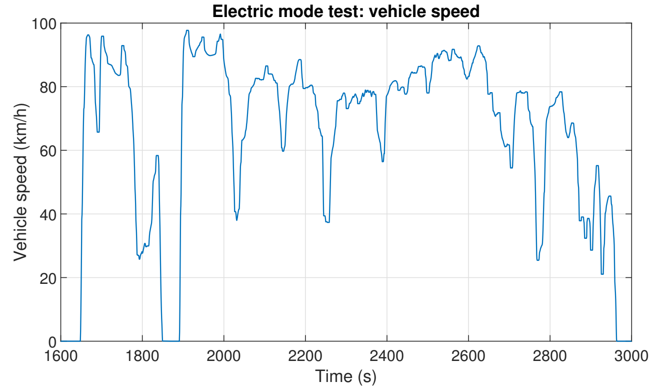

Fig. 15. Results on hybrid mode test: vehicle speed

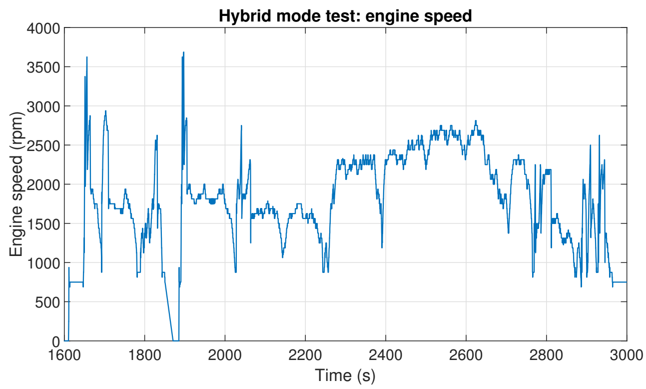

Fig. 16. Results on hybrid mode test: engine speed

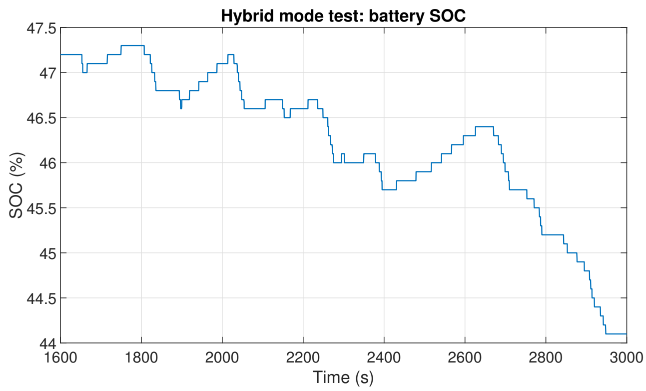

Fig. 17. Results on hybrid mode test: battery SOC

3.3 CAN irregularities

It has to be noticed that some graphs are affected by significant noise. This is particularly evident, for instance, for the graph of wheel efficiency Figures 10 and 14. This is primarily due to the presence of noise in the measured data: in fact, as reported in literature (Di Natale et al., 2012; Solano-Araque et al., 2019), CAN characteristics may lead to signal distortions and uncertainties. In case of wheel efficiency, its value is computed starting from voltage, current, torque and speed, and the combination of the noise if each signal may be magnified in the resulting value.

4. CONCLUSION

A system to convert conventional vehicles into solar hybrid may represent a valuable option toward fleet electrification, compliant with circular economy principles. A novel prototype at TRL=8/9 is now approaching its full development. The tests performed on vehicle test bench have confirmed the good performance of wheel motors integrated with braking system, while first road tests have confirmed the possibility to operate the vehicle also in Full Electric mode during urban driving. Further tests are in course to analyze and optimize the operation in hybrid mode, to overcome some problems emerged during the tests (noise reduction) and to ensure a full operation in electric mode, as for brake booster and power steering.

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