Comparison of Modern Powertrains Using an Energy Model Based on Well-to-Miles Analysis

Published Version:
Comparison of Modern Powertrains Using an Energy Model Based on Well-to-Miles Analysis / Falfari, Stefania ; Mariani, Valerio ; Bianchi, Gian Marco ; Cazzoli, Giulio. - In: SAE TECHNICAL PAPER. - ISSN 0148-7191. - ELETTRONICO. - 2023-24-0005:(2023), pp. 2023-24-0005.1-2023-24-0005.20. [10.4271/2023-24-0005]

Availability:
This version is available at: https://hdl.handle.net/11585/962720 since: 2024-02-27

Published:
DOI: http://doi.org/10.4271/2023-24-0005

Falfari, S., Mariani, V., Bianchi, G.M., and Cazzoli, G., "Comparison of Modern Powertrains Using an Energy Model Based on Well-to-Miles Analysis," SAE Technical Paper 2023-24-0005, 2023.

The final published version is available online at:

https://doi.org/10.4271/2023-24-0005

Comparison of Modern Powertrains Using an Energy Model Based on Well-to-Miles Analysis

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)
Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

The need to reduce carbon dioxide emissions from motor vehicles pushes the European Union towards drastic choices on future mobility. Despite this, the engines of the "future" have not yet been defined: the choice of engine type will undoubtedly depend on the type of application (journey length, availability of recharging/refueling facilities), practical availability of alternative fuels, and electricity to recharge the batteries. The electrification of vehicles (passenger and transportation cars) may be unsuitable for several aspects: the gravimetric energy density could be too low if the vehicle has to be lightweight, must achieve a high degree of autonomy, or needs a very short refueling time. To compare the sustainability of various partially or fully electric propulsion systems equipped with thermal engines powered by alternative fuels (e-fuels, hydrogen, green methane, etc.) or powered by fuel cells, it is necessary to consider the entire life cycle of the vehicle, including the production stage of the "propellant". This methodology, the well-known Well-to-Miles analysis, is the basis of the energy model presented in this work and developed with Matlab code. The energy model is able to consider the overall energy cost required by a vehicle to complete a specific journey starting from the production of the fuel that powers it (electricity included). The model is validated by comparison with reported carbon dioxide emissions and fuel consumption data for two modern cars, one powered by a petrol engine, the other plug-in. Finally, a comparison between the declared data and the simulation results for a fuel cell vehicle and a pure battery vehicle is reported. The model is a valuable tool for energy assessment (consumption, emissions) of various propulsion units suitable for making a specific trip.

Introduction

Modern society makes extensive use of road mobility for the transport of goods and people. Worldwide road vehicles are responsible for 11.9 % of GHG emissions, or 73.5 % of the emissions of the entire transport sub-sector [1] (which is responsible of 16.2 % of GHG emissions, data for the year 2022). It is also true that the production of electricity accounts for 37 % of GHG emissions. It makes little sense to think of forced electrification, at least of passenger vehicles, if the electricity production phase is not first decarbonized. The European Commission has recently changed the limits for CO_2 emissions from car and van exhausts (together responsible for 15% of CO_2 emissions, the main greenhouse gas): in particular, it increased its CO_2 emission reduction targets for 2030 and set a new 100% target for 2035 [2]. All new cars or vans sold in the EU from 2035 must be zero emission vehicles (in this sense, only hydrogen could be used in internal combustion engines): the European Commission has also specified that these zero emissions refer to vehicle exhaust, but there is the possibility that the use of synthetic fuels (also called sustainable fuels) in modern internal combustion engines will be accepted.

Overview of E-fuels, Synthetic fuels and Biofuels

The traditional energy sources make the energy supply more predictable than the renewable energy resources, which have to overcome the challenge of their intermittency (there are periods where no energy can be harvested), i.e., they depend on the weather conditions. This makes them unsuitable as the unique source of energy. Also considering the mean restart time of traditional energy production systems (a steam thermal power plant takes about 24 hours), it is not possible to program a sudden switch-on of these traditional systems to deal with unexpected "holes" in energy production from renewable sources. Thus, the idea could be to make both plants work together and to use in a different way any surplus of energy deriving from renewable sources.

Synthetic fuels are fuels not derived from petroleum but specially created with hydrogen (produced in various ways, more or less sustainable, such as methanation and electrolysis for example) and carbon (for example from the capture of CO_2). Synthetic fuels generated using electricity produced from renewable sources and carbon from carbon capture procedure are called "e-fuels". They are the only fuels that the EU could accept as fuel for modern internal combustion engines because the CO_2 balance is zero by capturing it from the air and combining it with green hydrogen (i.e., hydrogen produced from electrolysis using renewable electricity sources). Thus, synthetic fuels produced with renewable surplus electricity depict an interesting solution for the decarbonization of mobility and those transportation applications which are not suited for electrification. Green hydrogen is counted among the e-fuels: all might be thought as chemical energy carriers.

Biofuels are fuels derived from living materials using renewable energy, so they could be thought as chemical energy carriers too. However, biofuels have important shortcomings, first the fact that the production of ethanol creates a net energy loss and increases food prices.

All these fuels must have a formulation that allows them to be used in internal combustion engines already in production, without modifications.

Present work

At a research level the authors of the present work deem it necessary to carry out energy analyzes also including synthetic fuels, whose CO_2 balance can be zero in the overall cycle from production to vehicle emissions. In fact, it is necessary to consider that the entire road transport cannot become electric for various reasons:

1. Need for an increase in the electricity produced (see Falfari et al. [3]) and the creation of a capillary infrastructure capable of bringing the necessary power to every part of Europe. In [3], the authors found that, in 2050, the surplus of electricity to be produced compared to the current production in Italy (year 2021) will be equal to +27.6 %. Furthermore, the demand for electricity availability is concentrated in specific time slots for both domestic and industrial uses (including the need to recharge electric vehicles). Therefore, in specific areas of the country with a high population density, this percentage, in relation to availability, could increase significantly, while it would decrease in less populous areas.
The request of electricity would increase if two extreme scenarios were considered [3]: (i) it would become +40.0 % in an extreme scenario in which the entire private car fleet consisted of pure electric vehicles only; (ii) it would become +100.6 % if the entire car fleet consisted of fuel cell vehicles powered exclusively by green hydrogen.
2. Not all vehicles are suitable for purely electric traction: in the case of long journeys or vehicles that require to be particularly light in terms of weight-to-power ratio or with very short recharging times, purely electric traction is not suitable.

As far as the authors know, no forecast to date provides for a complete transition of road transport to the electric propulsion system. In [3], the authors proposed a methodology to predict the number of future vehicles in Italy and the different types of propulsors that will power them. They found that, in the time frame 2030-2050, there will be a reduction of ICEVs (Internal Combustion Engine Vehicle) with a progressive increase of PHEVs (Plug-In Hybrid Electric Vehicle), BEVs (Battery Electric Vehicle) and FCEVs (Fuel Cell Electric Vehicle). HEVs (Hybrid Electric Vehicle) will be a major transition point until 2040 and will then be gradually replaced by PHEVs, BEVs and FCVs. The authors of the present work believe that the type of vehicle (and therefore its traction system) should be chosen according to the "primary typical journey" of the vehicle, i.e., the prevailing characteristics of use. It is, therefore, necessary to compare the energy performance (consumption, efficiency) of different modern powertrains on different types of travel to choose the optimal one (depending, as mentioned, on its primary use).

In this work, some modern powertrains have been compared, starting from the more classic gasoline-powered ones (which represent the reference case): ICEV, HEV, PHEV, FCEV, BEV. For FCEV, the only fuel considered is green hydrogen. For HEV, PHEV, and ICEV, the fuel could be hydrogen or e-fuel (synthetic fuel in general). The model is an energy model based on the Well-to-Miles (WtM) analysis and was developed with Matlab code: to compare the energy cost of each powertrain, it is necessary to consider the life of vehicle from “cradle to grave”, including production, transport, and storage processes of the fuel or electricity. The model is based on the work by Guzzella et al. [4] and by Hänggi et al. [5]. Guzzella et al. [4] presented the WtM analysis, considering the different steps from the primary energy source (necessary for fuel production, transportation, and storage) to the final energy necessary at wheels for performing a given driving profile (altitude included). Hänggi et al. [5] derived a WtM analysis for five synthetic fuels: hydrogen, methane, methanol, dimethyl-ether (DME) and Fischer–Tropsch Diesel. They started with renewable electricity, water and carbon dioxide captured and computed the fuel production process (including fuel storage and distribution) based on a literature study and their own research data plus data from available technologies. For the Tank-to-Miles (TtM) analysis, the authors used the Willans approach. Finally, they combined the powertrain model with the dynamic vehicle chassis model by Guzzella et al. [4] to simulate a WLTP class 3b cycle for deriving the mean fuel energy demand per kilometer. They found, comparing the energy consumption of the five fuels, that fuel cell vehicles have the most significant advantage over vehicles powered with methane, methanol or DME. They did not consider BEVs in the analysis because they focused on synthetic fuels.

The novelty of the model presented in this work lies in its integration with other sub-models for the computation of:

1. Charging efficiency of battery vehicles (BEVs, PHEVs), always considering a global approach from the electricity production phase to the electricity stored in the battery [6]. In [6] the authors proposed a physical-based statistical method for evaluating the effective electric energy consumption of a BEV (including brake regeneration efficiency), using the relationship between the driving cycle and vehicle parameters.
2. State of Charge (SoC), which can be varied to prefigure different energy scenarios. The State of Charge is a parameter that expresses the ratio between the capacity available in the battery and the nominal capacity as a percentage. There are several models to evaluate the SoC estimation: the Coulomb method has been chosen (counted among the conventional methods), as in [7-10]. Both Coulomb Counting Method (CC) and Enhanced Coulomb Counting Method (ECC) have been implemented in the present energy model.
3. For BEVs and FCEVs, the power required to cool and heat the passenger compartment, as in [11, 12]. The power of the auxiliaries is assumed to be constant and is an input to the energy model. To this power is added the power required for heating and cooling the passenger compartment, which requires the external temperature as input data.

In addition, the authors added in the work gasoline as a reference fuel. The model was validated by comparing the main results with available data for four cars on the market: one is powered by a gasoline engine, one is a plug-in vehicle, one is a fuel cell vehicle and the last one is a pure battery vehicle. The model has proven to be a valid tool for energy assessment of various propulsion units suitable for making a specific journey. Finally, an overall energy comparison was performed between the four vehicles.

Paper Structure

The manuscript is organized into two macro-sections, which are in turn divided into sub-sections:

1. Description of the energy model:
    a. Wheel-to-Miles (WhtM) analysis, which calculates the required mechanical power to the wheels based on the chosen test cycle;

b. Tank-to-Wheels analysis: computes the conversion of the chemical power stored in the tank into the required mechanical power.
    i. Modeling of conventional ICE;
    ii. Modeling of the hybrid powertrain (HEV and PHEV):
        - Control scheme for hybrid vehicles: regenerative braking and SoC computation.
    iii. Modeling of the pure electric powertrain (BEV) and fuel cell powertrain (FCEV).

c. Well-to-Miles analysis: it computes the electric energy necessary to produce, store and transport some synthetic fuels. In this paragraph, for BEVs and PHEVs, was added the evaluation of the actual electric energy consumption of a BEV or a PHEV, thus the electricity that must be produced to meet the mechanical power required at the wheels (which is greater than what is actually loaded into the battery).

2. Validation of the energy model: the model is validated by comparison with reported carbon dioxide emissions and fuel consumption data for two modern cars:
    a. BMW 318i, fueled by gasoline only.
    b. BMW X5 45e, which is a plug-in vehicle fueled by gasoline.

    And consumption data only for:
    c. HYUNDAI NEXO 2021;
    d. MERCEDES-AMG EQE 295 series.
3. Energy comparison between the four vehicles to state which is the most convenient to travel the WLTP cycle (which is the reference cycle in the analysis).

The four vehicles were chosen first of all because all the data necessary for the model was found for them. In particular, the gasoline-only car and the plug-in one come from the same company (BMW) so as to compare two vehicles with the same alleged "combustion" technology. The BMW X5 45e represents the typical plug-in vehicle, which is usually a SUV due to the need for space to house the electrical components. The Hyundai Nexo is the only FC vehicle available on the market, except for the Toyota Mirai. The MERCEDES-AMG EQE 295 represents a high-segment vehicle. The purpose of the comparison is to demonstrate: 1. vehicle by vehicle if the model captures the average consumption and emissions of the vehicle in the WLTP cycle of reference; 2. check that the results obtained with the model are in line not only with what is declared for each vehicle but make sense in comparison with other types of powertrain. The comparison between vehicles in the same segment is ongoing and will be published later.

Finally, the conclusions are reported.

Energy Model

The model, which was developed in Matlab code, calculates the power demand needed to fulfill a specific mission profile for a given vehicle. Based on the specific mission profile (which also includes the type of trip, i.e. speed and slopes of the road) and the type of vehicle, the energy model calculates the power to the wheels to meet this profile (P_{wheels}), including the power of the auxiliaries to cool or heat ($P_{heat,cool}$) the passenger compartment.

From the computed power to the wheels, the model calculates:

1. The mechanical energy needed to fulfill the specific mission profile.
2. The chemical energy to be stored in the tank or the electrical energy to be charged in the battery (TtW analysis). In the case of vehicles also or only equipped with an electric motor, it calculates the energy recoverable during regenerative braking and considers the actual SoC.
3. The amount of fuel needed.
4. In the case of BEVs, the gross electrical energy that must be made available from the electricity grid to charge the vehicle battery to fulfill the specific mission profile.

SoC, power required to heat and cool the cabin, and regenerative braking power calculations are new compared to energy models in [4, 5].

The model inputs are:

1. Vehicle characteristics: mass m_{car}, type of fuel, front surface A_f, rolling c_r and aerodynamic drag coefficient c_d;
2. Engine and transmission data: final drive gear F_{drive}, rated power P_{max} and corresponding speed $\omega_e(Pmax)$, rated torque T_{max} and corresponding speed $\omega_e(Tmax)$, engine displacement V_d, piston stroke S, driveline efficiency $\eta_{driveline}$;
3. Electric motor and battery data: initial SoC, SoC maximum (SoC_{MAX}) and minimum (SoC_{MIN}), rated power of the electric motor $P_{ElectricMotor}$, efficiency of electric motor $\eta_{ElectricMotor}$ and battery η_{batt}, charger efficiency $\eta_{charger}$ and electric vehicle supply equipment efficiency η_{EVSE};
4. External temperature T;
5. Auxiliary power $P_{aux,const}$, supposed to be constant;
6. Tire data (width W, aspect ratio AR, wheels diameter D);

The meaning and unit of measurement of the physical quantities reported in the following equations can be consulted at the end of the manuscript.

WhtM analysis

From the specific mission profile considered (the WLTP cycle, the NEDC cycle or a constant speed cycle) it is possible to determine the speed, power and torque required at the wheels. The basic equations derived from [4, 5] are reported below.

The wheel power P_{wheels}, which is the mechanical power to the wheels required by the chosen driving cycle, is dependent on:

1. Specific characteristics of the vehicle: rolling friction P_{roll_fric}, aerodynamic drag P_{aerod_drag} and vehicle mass m_{car}.
2. Power of gravity load P_{grav} linked to the slope $\alpha(t)$ of the route traveled during the driving cycle.
3. Power of auxiliaries. The auxiliary power $P_{aux,const}$ is assumed to be constant and is an input to the energy model: it usually varies between 200 and 700 W. To this power is added the power required for cooling [11] and heating [12] $P_{heat,cool}$ the passenger compartment, which requires the outside temperature T as input data.

$$P_{wheels}(t)=\frac{\left[P_{roll_{frict}}(t)+P_{aerod_{drag}}(t)+P_{veh_{accel}}(t)+P_{grav}(t)\right]}{1000}+P_{aux} \quad (1)$$

$$P_{roll_{fric}}(t) = m_{car} \cdot g \cdot c_r \cdot v(t) \quad (2)$$

The term *v(t)* stands for the speed profile of the chosen driving cycle.

$$P_{aerod_{drag}}(t) = 0.5 \cdot \rho_{air} \cdot A_f \cdot c_d \cdot v(t)^3 \quad (3)$$

$$P_{veh_{accel}}(t) = m_{car} \cdot \frac{dv(t)}{dt} \cdot v(t) \quad (4)$$

$$P_{grav}(t) = m_{car} \cdot g \cdot \sin(\alpha(t)) \cdot v(t) \quad (5)$$

$$P_{aux} = P_{heat,cool} + P_{aux,const} \quad (6)$$

$$\begin{cases} P_{heat,cool} = \frac{-6}{35} \cdot T + \frac{24}{7} & -15\,°C < T < 20\,°C \\ P_{heat,cool} = \frac{1}{4} \cdot T - 6 & 24\,°C < T \le 44\,°C \\ P_{heat,cool} = 0 & 20\,°C \le T \le 24\,°C \end{cases} \quad (7)$$

It is assumed that the external temperature *T* of the ambient is constant and equal to the operating temperature of the battery.

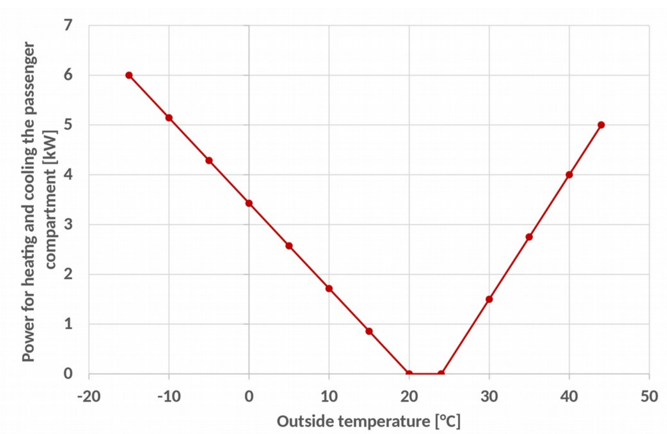

Figure 1. Outside temperature and power curve for heating and cooling the passenger compartment.

The thermal power is assumed to be zero for operating temperatures between 20°C and 24°C (comfort temperature). The dependence with the temperature is assumed to be linear, with a maximum of 6 kW for T=-15°C in the heating phase and a maximum of 5 kW for T=44°C in the cooling phase. The power curve for heating and cooling the cabin is shown in Figure 1 versus outside temperature.

It is worth mentioning that vehicles equipped by a different powertrain and/or with a different mission profile (autonomy), do not have the same weight (thus the same mass m_{car}). The energy cost is a function of the weight of the vehicle, as it depends on the mass of the vehicle itself, which in turn is related to the amount of fuel (necessary to fulfill the specific mission profile) in the tank, the size of the tank, the volumes, etc. The program uses an iterative procedure to calculate the effective mass of the vehicle (the choice of adopting it is optional):

1. The first simulation, for a fixed autonomy range, is launched with a first attempt mass value (inserted as input data);
2. The output results provide the weight of the vehicle;
3. New simulation is run with the insertion of the new weight of the vehicle computed in the previous step;
4. Verification of equivalence between the input weight and the output weight.

The procedure is repeated iteratively until the condition at point 4 is satisfied. Once convergence is reached, obtaining the energy cost for a vehicle with the chosen autonomy range is possible. This part of the model relating to the iterative calculation of the mass is new compared to energy models in [4, 5].

From Eq. (1) the mean energy demand per kilometer $E_{wheels,norm}$ can be computed:

$$E_{wheels,norm}(t) = \frac{\int P_{wheels}(t)\,dt}{\int v(t)\,dt} \cdot 10^3 \quad (8)$$

TtW analysis

The TtW analysis computes the conversion of the chemical power in the tank to mechanical power at vehicle wheels. It depends on vehicle and fuel characteristics. The equations used to model the different powertrains are based on the Willans approach but extended to negative range of power to model the regenerative braking phase in electrified powertrains. The Tank-to-Wheel efficiency is reported in Eq. (9).

$$\eta_{TtW} = \begin{cases} \frac{P_{wheels}(t)}{P_{chem}(t)} & if\ P_{wheels}(t) \ge 0 \\ max\left(0, \frac{P_{chem}(t)}{P_{wheels}(t)}\right) & if\ P_{wheels}(t) < 0 \end{cases} \quad (9)$$

In the following subparagraphs, the chemical energy to be stored in the tank or the electric energy to be stored in the battery are calculated based on the adopted powertrain.

Modeling of the conventional powertrain (ICE)

The model used to describe the operation of the combustion engine, in ICE, HEV and PHEV powertrains, is that of Willans [13]. It consists in calculating the average pressures that occur during an engine cycle in order to have simple equations for calculating the average mass flow rate of the fuel used, therefore consumption, emissions, and engine efficiency. The mean pressures considered in the model are mean effective pressure *pme*, mean absolute pressure *pma* and mean frictional pressure $p_{m,loss}$.

Before introducing the calculation of the various average pressures, it was necessary to model the vehicle gearbox, in such a way as to obtain the output of the engine speed during the entire driving cycle, expressed in rpm, as required by the model of Willans.

In fact, once the speed profile *v(t)* of the driving cycle considered is known, it is possible to obtain the relative rotation speed of the engine, through the Eq. (10):

$$RPM(t)=\frac{v(t)\cdot 30\cdot Gear(t)\cdot F_{drive}}{3.6\cdot \pi \cdot r_w} \quad (10)$$

The wheel radius r_w is calculated once the tire input data is known: width (*W*), aspect ratio (*AR*) and diameter *D*.

$$r_W=\frac{1}{2\cdot 1000}\cdot\left(D\cdot 25.4+2\cdot\frac{W\cdot AR}{100}\right) \quad (11)$$

In Figure 2 is plotted an example of the engaged gear and of the computed engine speed *RPM(t)*.

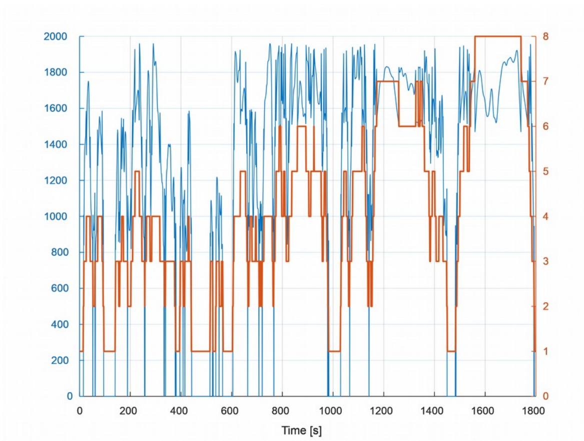

Figure 2. Example of the engaged gear and of the computed engine speed RPM(t) – BMW 318i (fueled by gasoline).

To select the optimal gear to engage while driving, it was decided to adopt an approach based on the same control strategy as a control unit in a real vehicle, i.e., to associate a specific gear to each speed capable of optimizing consumption and able to satisfy the torque demand such that the pre-set speed profile is satisfied.

The user enters maximum torque and power as initial data, together with the corresponding angular speeds. From these data it is possible to calculate the torque and power curves by defining a range of variation of the angular speed of the engine $\omega_e(t)$, from a minimum (idle) to a maximum.

Once the angular speed of the engine *RPM(t)* is known, it is possible to continue calculating the torque requested by the engine T_{req} (which depends on the instantaneous power P_{wheels} required from the wheels to complete the chosen cycle at the engine speed RPM). If the wheels power P_{wheels} is positive (the vehicle is in driving mode), the requested torque is calculated, otherwise (the vehicle is in deceleration or braking mode) the requested torque is assumed to be minimum and equal to 15 Nm.

$$\begin{cases} if\ P_{wheels}(t)>0 \rightarrow T_{req}(t)=\dfrac{9548.8\cdot P_{wheels}(t)}{RPM(t)} \\ else\ T_{req}(t)=15\,N\cdot m \end{cases} \quad (12)$$

It is now possible to calculate the average pressures necessary for the completion of the Willans model.

The mean effective pressure *pme* represents the mechanically available effective pressure:

$$pme(t)=T_{req}(t)\cdot\frac{4\pi}{V_d} \quad (13)$$

The mean absolute pressure *pma* characterizes the mean pressure that would be available if all chemical energy were transformed into mechanical energy:

$$pma(t)=\frac{pme(t)+p_{m,loss}(t)}{e_o(t)} \quad (14)$$

The mean friction pressure $p_{m,loss}$ represents all mechanical friction and pumping losses in the engine. The overall idea of the Willans model is to approximate the mean effective pressure and the mean frictional load losses with quadratic functions of the engine speed or the piston speed:

$$V_{pist}(t)=S\cdot RPM(t)\cdot\frac{1}{30} \quad (15)$$

Through the piston speed V_{pist} it is possible to calculate the efficiency coefficient e_0 and $p_{m\,loss}$:

$$\begin{cases} e_0(t)=e_{00}+e_{01}\cdot V_{pist}(t)+e_{02}\cdot V_{pist}^2(t) \\ p_{m,loss}(t)=p_{m,loss0}+p_{m,loss1}\cdot V_{pist}(t)+p_{m,loss2}\cdot V_{pist}^2(t) \end{cases} \quad (16)$$

Values of parameters e_{00}, e_{01}, e_{02}, $p_{m,loss0}$, $p_{m,loss1}$ and $p_{m,loss2}$ are reported in Table 1 [14].

Table 1. Values of the parameters of the Willans model [14]

Parameter	Value	Unit of measurement
e_{00}	0.3528	[-]
e_{01}	0.0108	[s/m]
e_{02}	$-4.4487\cdot 10^{-4}$	[s^2/m^2]
$p_{m,loss0}$	$1.3\cdot 10^5$	[Pa]
$p_{m,loss1}$	-351.3	[Pa · s/m]
$p_{m,loss2}$	822.5	[Pa · s^2/m^2]

Now it is possible to calculate the average fuel flow rate expressed in kg/s through the injectors:

$$\dot{m}_f(t)=\frac{1}{e_0}\cdot\frac{\omega_e(t)\cdot V_d}{4\pi\cdot LHV}\cdot\left(pme(t)+p_{m,loss}(t)\right) \tag{17}$$

The engine efficiency is:

$$\eta_{eng}=\frac{pme(t)}{pma(t)} \tag{18}$$

Once the fuel flow rate is known, the fuel consumption of the vehicle follows, expressed in kilograms:

$$m_{fuel}=\int_0^t \dot{m}_f\cdot dt \tag{19}$$

Known the density of the fuel ρ_{fuel} [kg/m^3], the consumption can be expressed in liters:

$$l_{fuel}=\frac{m_{fuel}\cdot 1000}{\rho_{fuel}} \tag{20}$$

Then dividing the liters required by the length of the driving cycle considered and doing the reciprocal gives the value in km/l. Once the consumption is known, the emissions produced by the vehicle also follow, starting from the calculation of the specific emissions of carbon dioxide q_{CO2}:

$$q_{CO2}=\frac{c_f}{h_f}\cdot\frac{M_{CO2}}{M_m} \tag{21}$$

Finally, the chemical energy is calculated, expressed in kWh, obtainable from the quantity of fuel used and stored in the tank to complete the specific cycle:

$$E_{chem_{ICE}}=\frac{m_{fuel}\cdot LHV}{3.6} \tag{22}$$

And the chemical power expressed in kW:

$$P_{chem}(t)=\frac{d}{dt}\left(E_{chem_{ICE}}.3600\right) \tag{23}$$

The total kilograms of carbon dioxide emitted are therefore:

$$m_{CO2}=q_{CO2}\cdot E_{chem_{ICE}} \tag{24}$$

Modeling of the hybrid powertrain (HEV and PHEV)

In this paragraph, reference is made interchangeably to HEVs or PHEVs.

The model for the description of the thermal engine is analogous to the model just described for conventional powertrains equipped with a thermal engine only. The only difference lies in the torque delivered by the engine.

In particular, two hypotheses were considered for hybrid powertrain: 1.The ICE can only work at full load conditions in the hybrid powertrain; 2 The ICE maximum efficiency operating point is found at full load. Therefore, the power delivered does not depend on the power required from the wheels (function only of the speed of the engine and its intrinsic characteristics): if the power supplied by the internal combustion engine exceeds that required from the wheels, the excess power is used to recharge the battery. The latter hypothesis is dictated by the fact that it is not possible to predict the manufacturer's strategy for each car in terms of the percentage of use of the thermal and electric powertrain (it must also be said that the management strategy could change according to some choices that the pilot of the vehicle can make during the trip). This seemed to the authors the most sensible option: other options of power management will be considered in subsequent developments of the model. Then the power supplied will be described by the relationship:

$$P_{engine}(t)=T_{engine}(t)\cdot\omega_e(t) \tag{25}$$

Now the T_{engine}, which is the torque delivered by the engine at its point of maximum efficiency, must be calculated. The torque delivered by the engine depends on the characteristics of the engine itself, which is different for each car and manufacturer. It is not possible to obtain the torque-power curves for every vehicle of interest. An alternative method was therefore used to approximate these values, as reported in [14].

$$T_{engine}(t)=a\cdot\omega_e^2(t)+b\cdot\omega_e(t)+c \tag{26}$$

Where T_{engine} is the maximum torque that can be delivered by the engine as a function of its velocity ω_e. *a*, *b* and *c* are non-dimensional parameters:

$$\begin{cases} a=\dfrac{T_{max}-T_{max}(P_{max})}{\omega_e(T_{max})^2-\omega_e(P_{max})^2-2\cdot\omega_e(T_{max})\cdot[\omega_e(T_{max})-\omega_e(P_{max})} \\ b=-2\cdot\omega_e(T_{max})\cdot a \\ c=T_{max}(P_{max})-a\cdot\omega_e(P_{max})^2-b\cdot\omega_e(P_{max}) \end{cases} \tag{27}$$

Control scheme for hybrid vehicles

In this sub-paragraph is presented the optimal energy control strategy developed in the present energy model and partially deduced from [15]. Based on the power request to the wheels, the control system must manage the ratio between thermal power and electric power:

therefore, instant-by-instant knowledge of the battery's state of charge (SoC) is essential. In fact, HEVs and/or PHEVs are equipped by an endothermic engine which can come into operation when the battery is close to discharge (low SoC values) or when the required power is insufficient. For hybrids, therefore, two further input parameters are defined:

a) The rated power $P_{ElectricMotor}$ that can be delivered by the electric motor, which is an input of the model and is related to the maximum power of the battery via the battery efficiency η_{batt}:

$$P_{batt_{MAX}} = \frac{P_{ElectricMotor}}{\eta_{batt}} \tag{28}$$

$P_{battMAX}$ is the maximum power that the battery can handle and which cannot be exceeded. It limits both the delivery of power by the battery and the recharging of the battery in the regenerative phase.

b) The minimum value of the State of Charge SoC_{MIN} below which the electric motor is deactivated. This is to avoid reaching too high Depth of Discharge (DOD) values which could irreversibly damage the battery.

The control scheme is based on the SoC value at time t. In the driving phase (P_{wheels} (t) ≥ 0):

1. If the SoC(t) is less than the SoC_{MIN} value, the required power is exclusively supplied by the endothermic engine. In this case, the internal combustion engine works at the fixed point of maximum efficiency: if the power supplied exceeds that required, the difference in power recharges the battery.
2. If the SoC(t) is greater than the minimum limit value, the analysis moves to the required power:
   a. If the latter is lower than the limit value that can be supplied by the battery, it is supplied entirely by the electric motor.
   b. If, on the contrary, the electric motor fails to cover the power requirement, the battery delivers the maximum possible power (without going below the value of SoC_{MIN} to preserve the battery) and the rest is supplied by the internal combustion engine.
3. If the SoC(t) is greater than the SoC_{MAX} but the battery power is not sufficient to cover the entire power demand from the wheels, the required power is supplied by both the endothermic engine and the electric motor. Also in this case the internal combustion engine could work at the fixed point of maximum efficiency: any excess power is dissipated in the form of heat because the battery is fully charged.

On the other hand, during braking/deceleration (P_{wheels} (t) < 0):

1. If the instantaneous SoC(t) is lower than the maximum value set as SOC_{MAX}, the negative power to the wheels is used to recharge the battery (regenerative braking), otherwise it is dissipated as heat by the braking system. See the sub-section on regenerative braking for more details.
2. Battery rechargeable power is limited by battery power ($P_{battMAX}$). If the power available for recharging exceeds that of the battery, the excess is dissipated as heat.

Regenerative breaking

Regenerative braking (which also includes simple deceleration of the vehicle) is the phase in which the power to the wheels is negative, i.e., the vehicle "returns" energy rather than requesting it. Figure 3 shows the diagram for the electrical part of the powertrain that equips electric cars or cars also equipped with an electric motor and a battery.

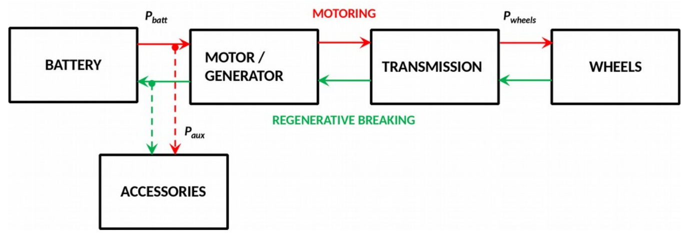

Figure 3. Diagram of the electrical part of the power unit equipped with at least the electric motor.

The battery power P_{batt} in Figure 3 can be outgoing or incoming depending on whether the vehicle is in the driving or braking phase. In the first case the power flows from the battery to the wheels and is assumed to be positive. During braking (or deceleration) the power flows from the wheels to the battery and is assumed to be negative.

$$\begin{cases} P_{batt}(t) = \dfrac{P_{wheels}(t)}{\eta_{driveline} \cdot \eta_{ElectricMotor}} \; if \; P_{wheels}(t) \geq 0 \\ P_{batt}(t) = P_{wheels}(t) \cdot \eta_{driveline} \cdot \eta_{ElectricMotor} \cdot \eta_{rb}(t) \\ \quad if \; P_{wheels}(t) < 0 \end{cases} \tag{29}$$

Where η_{rb} is the regenerative breaking efficiency. The regenerative braking system is the braking energy recovery system that allows the electric motor to operate as a generator to recover part of the negative power to the wheels otherwise lost. The braking recovery efficiency is defined as in [7]:

$$\eta_{rb}(t) = \frac{E_{recoverable}(t)}{E_{available}(t)} \tag{30}$$

Where $E_{recoverable}$ is the part of the energy recovered during braking and $E_{available}$ is the maximum energy recoverable during braking:

$$E_{available}(t) = \int_0^t P_{wheels}(t) \cdot dt \; if \; P_{wheels}(t) < 0 \tag{31}$$

Through the least squares method, an empirical relationship between the vehicle deceleration module *a(t)* at instant t and the efficiency of the regenerative brake is obtained for each instant t of the speed cycle [12, 14]:

$$\eta_{rb}(t) = \left[e^{\frac{0.0411}{|a(t)|}} \right]^{-1} \; if \; P_{wheels}(t) < 0 \tag{32}$$

From Eq. (32) the regenerative braking efficiency η_{rb} is calculated: from Eq. (30) the recoverable energy $E_{recoverable}(t)$ is derived, converted into power, and added to the power of the battery during the braking mode.

Finally, it is possible to calculate the total energy consumed by the battery considering the recovery efficiency under braking, as follows [7]:

$$EC=\frac{1}{3600}\cdot\left[\int_0^t P_{batt}(t)\cdot dt\right] \tag{33}$$

The parameters introduced represent the starting point for the classic Coulomb method, aimed at calculating the battery SoC.

State of Charge evaluation

The calculation of the SoC is necessary for vehicles equipped with electric engine, in order to be able to calculate the instantaneous state of charge of the battery and therefore the active propulsion system. In electric vehicles, the calculation of the instantaneous SoC allows the control of the state of charge of the battery. The SoC expresses, as a percentage, the ratio between the available capacity in the battery $Q_{available}$ and its nominal capacity Q_0:

$$SoC=\frac{Q_{available}}{Q_0} \tag{34}$$

In this work only the classical Coulomb method for the estimation of the SoC [8] for BEVs, HEVs and PHEVs is presented. Once the input or output power from the battery has been defined, for each instant of time of the cycle it is possible to update the SoC:

$$SoC(t)=SoC(t-1)-\frac{P_{batt}(t)}{Q_0}\cdot\Delta t\cdot 100 \tag{35}$$

Where $SoC(t)$, $SoC(t-1)$ are expressed as a percentage, $P_{batt}(t)$ is expressed in kW, Q_0 in kWh, Δt in hours. The estimate of the SoC for each instant t of the cycle requires the knowledge of the initial state of charge SoC_0. The measurement of the initial state of charge is difficult to achieve, as it is not a direct measurement, and depends on the State of Health of the battery at the time of measurement. In this work the knowledge of the initial SoC is assumed a priori (model input) and the aging and self-discharge processes, as well as the temperature effect, are neglected.

The calculation of the chemical power $P_{chem}(t)$ useful for defining the TtW efficiency is done as for the ICEVs if the thermal engine is active (Eq. (23)), otherwise as for the BEVs (see next paragraph, Eq. (36)).

Modeling of the pure electric powertrain (BEV) or fuel cell powertrain (FCEV)

A Tank-to-Wheels approach was adopted to model the propulsion units without internal combustion engines, starting from the energy required of the wheels per kilometer $E_{wheels,norm}$ (Eq. (8)). The chemical energy that needs to be stored in the tank in the form of fuel (hydrogen in this case) or the electric energy in the battery is calculated starting from the power required at the wheels.

$$P_{chem}(t)=\begin{cases} c_{1,pos}\cdot P_{wheels}(t)+c_{0,pos} & if\ P_{wheels}(t)\geq 0 \\ c_{1,neg}\cdot P_{wheels}(t)+c_{0,neg} & if\ P_{wheels}(t)<0 \end{cases} \tag{36}$$

Coefficients $c_{1,pos}$, $c_{0,pos}$, $c_{1,neg}$ and $c_{0,neg}$ are set to value reported in [5]. The term $P_{chem}(t)$ is then used in the expression of TtW efficiency (Eq. (9)).

Once the value of the SoC has been estimated for each instant of time, following the classic Coulomb method as for hybrid vehicles, it is possible to calculate the input and output power from the battery from Eq. (29).

WtT analysis

Finally, following the WtT approach, in the model it is possible to calculate the electrical energy necessary to produce some synthetic fuels: methane, methanol, Dimethyl ether and hydrogen. This can be useful because the European Union is opening a window to the use of synthetic fuels in internal combustion engines or when it is necessary to calculate the energy expenditure to produce green hydrogen to be used in a FCEV. In addition, the authors added in the work gasoline as a reference fuel (supposed to be a synthetic fuel too): in the present WtM analysis, the same production process of DME was considered for simplicity but this part of the model will be improved in the next future. The authors in [5] report the amount of electricity necessary for the production (electrolysis), transport and storage of some synthetic fuels. Starting from these values and calculating with the model presented above the chemical energy required to travel a kilometer with a specific propulsion unit, it is possible to calculate the electrical energy required for the production of synthetic fuels.

Table 2. Percentage losses of production, transport and storage of synthetic fuels per kilometer [5] in relation to the total electricity required.

Fuel	Percentage losses of electrical energy for production, transport and storage of synthetic fuels
Hydrogen	47%
Methane	54%
Methanol	56%
Dimethyl ether (DME)	54%

In particular, Table 2 shows the percentage losses of production, transport and storage as the type of synthetic fuel varies [5]. The required electricity for the synthetic fuel production, transport and storage is calculated by dividing the required chemical energy in the vehicle's tank per kilometer by one's complement of the percentage losses.

In the WtM analysis for BEVs and for PHEVs (for the electrical part only) it makes sense to compute the total electrical energy that must be supplied to the grid socket to charge the battery (E_{grid}). In [6] the authors proposed a physical-based statistical method for evaluating the effective electric energy consumption of a BEV (including brake regeneration efficiency), using the relationship between the driving cycle and vehicle parameters.

Charging efficiency of BEVs and PHEVs

The energy consumption of EVs is obtained from standardized driving cycles (NEDC, WLTP, etc.) or simulations, which however are insufficient because they do not consider multiple factors such as traffic, infrastructure, topography and the way guide. Thus, getting real data is one of the biggest challenges in analyzing EVs. The objective of this part of the program is to calculate the actual electricity consumption of a BEV (or a PHEV), i.e., the amount of alternating current electricity required by the grid to charge the battery and thus satisfy the power demand to the wheels. The methodology adopted was found in [6].

The model employed starts from the energy flows in the BEVs, which can be summarized in the following equation [6]:

$$E_{grid}(t) - E_{charg}^{loss}(t) = E_{batt}^{loss}(t) + E_{ElectricMotor}^{loss}(t) + E_{transmission}^{loss}(t \quad (37)$$

Where:

E_{grid} is the total electricity consumption from the grid.

E_{charg}^{loss} is the electricity lost during charging.

E_{batt}^{loss} is the electricity lost by the battery.

$E_{ElectricMotor}^{loss}$ is the electricity lost by the electric motor.

$E_{transmission}^{loss}$ is the electricity lost by the transmission.

E_{brake}^{loss} is the electricity lost during the braking phase.

E_{load}^{loss} is the load, which is equal to E_{wheels} in the present paper:

$$E_{wheels}(t) = \frac{1}{1000} \cdot \left(\int_0^t P_{wheels}(t) \cdot dt \right) \quad (38)$$

Eq. (37) can be converted if each energy loss term (E^{loss}) is written as the product of the available energy (E_{in}) by the complement to one of the relative efficiency ($1-\eta$). Therefore, Eq. (37) becomes:

$$E_{brk}(t) + E_{load}^{loss}(t) = \left(E_{grid}(t) \cdot \eta_{g2b} + E_{brk}(t) \cdot \eta_{rb}(t) \cdot \eta_{transmissi} \quad (39)$$

Where $\eta_{transmission}$ does not coincide with $\eta_{driveline}$ because electric vehicle transmissions ($\eta_{transmission}$) can be more efficient than traditional vehicle transmissions ($\eta_{driveline}$).

The braking energy is:

$$E_{brk}(t) = max\left(\left(E_{dec}(t) - \int_0^t F_{load}(t) \cdot v(t) \cdot dt \right), 0 \right) \quad (40)$$

Braking energy includes deceleration energy E_{dec} and load losses F_{load}.

$$E_{dec}(t) = max\left(\frac{1}{2} \cdot m_{car} \cdot \left(v(t)^2 - v(t+1)^2 \right), 0 \right) \quad (41)$$

In accordance with what is reported in the article [16], the load loss F_{load} can be traced with a good approximation to a two-term semi-quadratic equation, as reported here, neglecting the linear term because it is linked only to the effect of the wind.

$$F_{load}(t) = A + C \cdot v(t)^2 \quad (42)$$

The coefficients A and C were set constant and equal to the mean value of the results in [16]:

A= 22.19 kg

C = 0.0609 kg/(m/s)^2 (43)

The efficiencies of the electrical part of the vehicle are summarized in a single term:

$$\eta_{pow} = \eta_{transmission} \cdot \eta_{ElectricMotor} \cdot \eta_{batt} \quad (44)$$

The grid to battery efficiency η_{g2b} can be evaluated from [17]:

$$\eta_{g2b} = \eta_{charger} \cdot \eta_{EVSE} \quad (45)$$

Where $\eta_{charger}$ and η_{EVSE} are inputs of the model. Their typical values are respectively 0.90 and 0.98, therefore η_{g2b} value is 0.882. The term $\eta_{charger}$ represents the charger efficiency: although chargers can operate at peak efficiencies of 92-95% [17], most available chargers have much lower efficiencies.

The efficiency η_{EVSE} considers that domestic sockets cannot be used directly but must be completed by the Electric Vehicle Supply Equipment (EVSE). The losses that occur through this system are about 1-2% of the energy transmission capacity [17].

Finally, it is possible to get the expression of the total electricity consumption from the grid:

$$E_{grid}(t) = \frac{\frac{E_{wheels}(t)}{\eta_{pow}} + \left(\frac{1}{\eta_{pow}} - \eta_{rb}(t) \cdot \eta_{pow} \right) \cdot \left| E_{brk}(t) \right|}{\eta_{g2b}} \quad (46)$$

Energy Model Validation

The energy model has been validated by comparison with reported carbon dioxide emissions and fuel/electricity consumption data for four modern cars:

1. BMW 318i, fueled by gasoline only.
2. BMW X5 45e, which is a plug-in vehicle fueled by gasoline.
3. HYUNDAI NEXO 2021.
4. MERCEDES-BENZ AMG EQE 295 series.

The vehicles do not belong to the same segment. The choice of the car manufacturers was dictated by the fact that the declared technical data are very exhaustive in relation to the inputs of the model.

All technical data was taken from [18].

The iterative computation of the mass of the vehicle was not switched on in these cases because it would have sense only for vehicles of the same segment.

Inputs of the energy model for the cars

This paragraph shows the input parameters for the modelled cars:

1. BMW 318i, fueled by gasoline only.
2. BMW X5 45e, which is a plug-in vehicle fueled by gasoline.
3. HYUNDAI NEXO, fueled by hydrogen (fuel cell vehicle).
4. MERCEDES-BENZ EQE 295 series, which is a pure battery vehicle.

Table 3 shows the input values. The chosen cycle was the WLTP. The external temperature was fixed at 15°C and the auxiliary power to 200 W for all cars. The SoC_{MAX} value has been set to 80% to preserve the battery.

Table 3. Inputs of the energy model

Parameter	BMW 318i	BMW X5 45e	HYUNDAI NEXO	MERCEDES EQUE
Vehicle front surface [m^2]	2.22	2.9	2.52	2.46
Drag coefficient [-]	0.24	0.32	0.32	0.239
Rolling coefficient [-]	0.013			
Mass of vehicle [kg]	1575	2135	2340	2880
Final drive gear [-]	2.813	3.636	-	-
Rated power [kW]	115	290	-	-
RPM at rated power [rpm]	4500	5000	-	-
Rated torque [Nm]	250	450	-	-
RPM at rated torque [Nm]	1300	1500	-	-
Driveline efficiency [-]	0.92			
Displacement [cm^3]	1998	2998	-	-
Stroke [mm]	94.6		-	-
Tire characteristics	205/60 R16	265/50 R19	225/60 R17	255/50 R19
H_2 pressure in the tank [bar]	-	-	700	-
Mass of H_2 per unit mass of the tank [%]	-	-	5.7	-
Starting SoC [%]	-	80 / 25	80	80
SoC max [%]	-	80	80	80
SoC min [%]	-	25	25	25
Rated power of electric motor [kW]	-	83	120	180
Electric Motor efficiency [-]	-	0.85		
Battery efficiency [-]	-	0.90		
Charger efficiency [-]	-	0.90	-	0.90
EVSE efficiency [-]	-	0.98	-	0.98
Battery capacity [kWh]	-	24	1.56	89

Model results and discussion

Table 4 shows the CO_2 emission values and consumption data compared between the declared data (based on WLTP cycle) and the result of the simulations for the cars. The results of the BMW 318i are almost identical to the declared data, however for the BMW X5 45e the CO_2 emission data and the fuel consumption are overestimated in the simulation results compared to the declared data. The difficulty in modeling a hybrid or plug-in vehicle lies in the fact that it is not possible to predict the manufacturer's strategy for each car in terms of the percentage of use of the thermal and electric powertrain. The authors thus made the hypothesis of always making the internal combustion engine work, if it is on, at the point of maximum efficiency: any excess power recharges the battery.

The simulation results for HYUNDAI NEXO are close to the declared data, while for MERCEDES EQE there is an error of about 25%. The latter is attributable to the Willans model (Eq. (36)), which should be reviewed in the light of the most modern electric cars. There is also to say that the model underlies many hypotheses: the numerical results are not always superimposable but, in any case, they maintain a trend of validity extended to all powertrains. For a more accurate modeling it would be necessary to go into more detail about the definition of each single car, but the generality and usability of the model would be lost.

Table 4. Comparison between declared data and simulation results

WLTP cycle	CO_2 emissions [g/km]		Fuel consumption per 100 km		Energy consumption [kWh/100 km]	
	Declared	Sim	*Declared*	Sim	*Declared*	Sim
BMW 318i	*148.0*	146.9	*6.5 l*	6.3 l	-	-
BMW X5 45e	*27.0*	35.6	*1.20 l*	1.5 l	-	-
HYUNDAI NEXO	-	-	*0.95 kg_{H2}*	0.94 kg_{H2}	-	-
MERCEDES EQUE	-	-	-	-	*15.9*	20.0

Regarding plug-in vehicles, it is necessary to understand how fuel consumption and CO_2 emissions calculations are performed. The method is standardized by the WLTP test according to the ECE R101 standard and requires the vehicle to undergo two tests: the first with the battery charged ($SoC_{MAX} = 80\%$) and the second with the battery completely discharged ($SoC_{MIN}=25\%$). The first test, with a charged battery, requires the vehicle to undergo the normal WLTP driving cycle of 23.26 km, this until the powertrain control turns on the endothermic engine and goes into battery recharging mode: from this moment on, emissions and consumption will be measured, and it is ascertained the autonomy of the car in *e-drive mode*. Generally, modern PHEV cars are able to complete the entire driving cycle with electric propulsion alone, thanks to the large batteries: in this case the test will be repeated several times until the intervention of the combustion engine. For the second test, with the battery discharged, the vehicle is expected to travel the driving cycle in Charge Sustaining control mode, i.e., maintaining the State of Charge level constant, therefore the internal combustion engine will be on during the entire test. Once all the data is known, the emission levels and fuel consumption to be declared will be provided by the following equation:

$$M(t)=\frac{M1(t)\cdot D_e+M2(t)\cdot D_{av}}{D_e+D_{av}} \quad (47)$$

Where *M1* and *M2* are the mass of emissions or fuel consumption during the first (SoC set to SoC_{MAX}) and second WLTP test for PHEVs ((SoC set to SoC_{MIN}), respectively. Generally, *M1* value is null for modern PHEV vehicles. D_{av} is a constant value set to 25 km and D_e is the vehicle autonomy in E-drive mode (90 km for BMW X5 45e).

BMW 318i: simulation results

Below are some graphs relating to the simulation of the car with traditional powertrain.

Figure 4 shows the chemical power stored in the tank, i.e., the available power, and the mechanical power requested at the wheels. The available power is always greater than the mechanical requested power. Where the mechanical requested power is negative (vehicle is braking but regeneration is not possible with an ICEV), the engine torque is minimum (set to 15 Nm), as in Figure 5. The engine speed of BMW 318i was shown in Figure 2, together with the engaged gear.

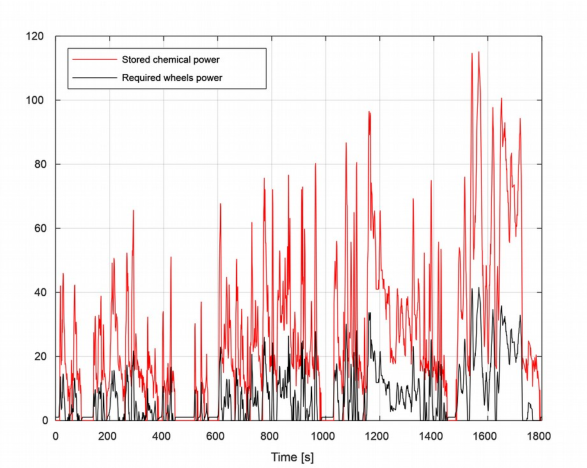

Figure 4. Power stored in the tank (available power) and power required at wheels.

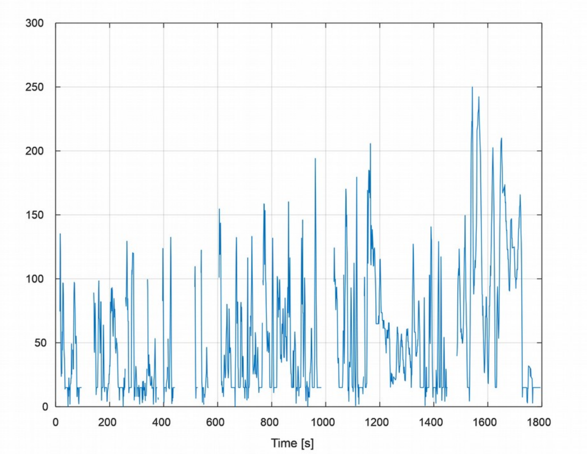

Figure 5. Engine torque.

Figure 6 shows the TtW efficiency trend for the chosen ICE vehicle during the WLTP cycle. The efficiency is equal to zero when the vehicle is braking ($P_{wheels}(t) < 0$), as no energy is supplied to the wheels. During the acceleration phase, on the other hand, the efficiency grows rapidly with the requested power, to then settle on an almost constant value equal to about 0.35.

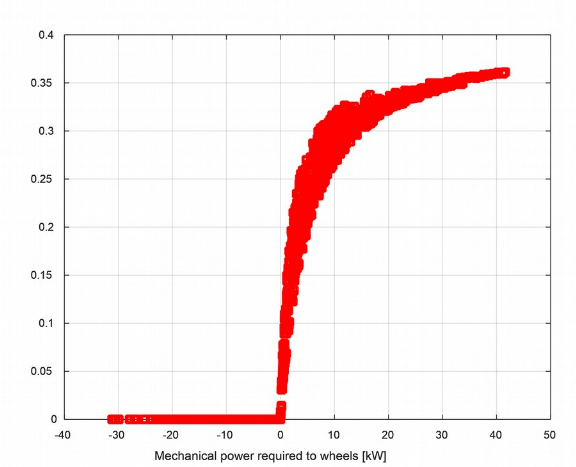

Figure 6. Tank-to-Wheel efficiency trend.

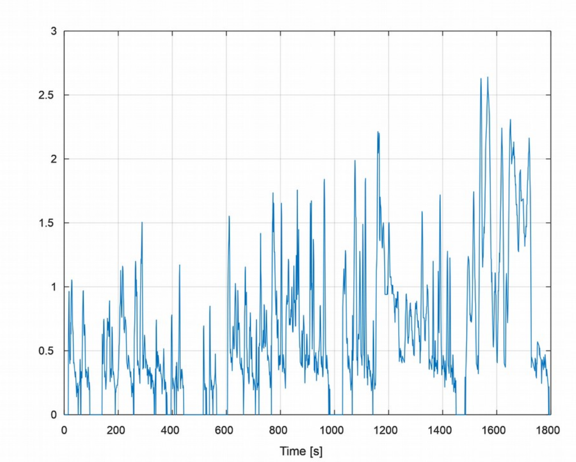

Figure 7. Mass flow rate of gasoline.

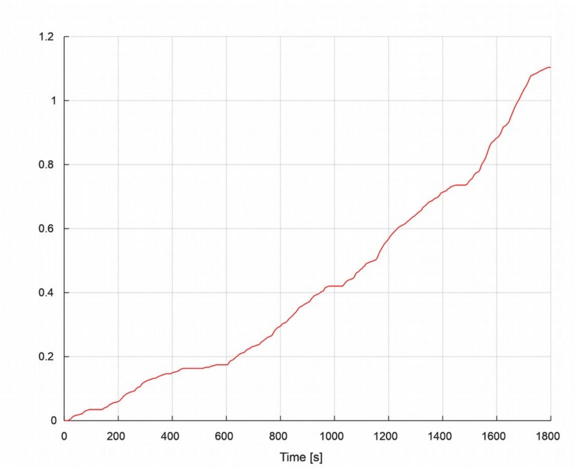

Figure 8. Total mass of gasoline (corresponding to 1.4716 liters of gasoline).

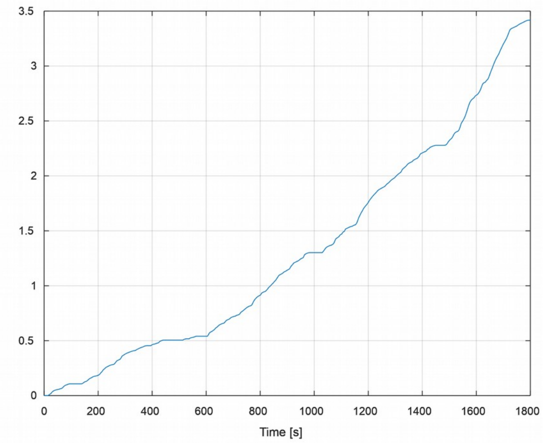

Figure 9. Mass of carbon dioxide emitted during the WLTP cycle.

Figure 7 shows the mass flow rate of the gasoline necessary to complete the cycle and Figure 8 the total mass of gasoline necessary to run the WLTP cycle. Figure 9 plots the mass of carbon dioxide emitted during the WLTP cycle by the thermal engine.

BMW X5 45e: simulation results compared to those of the BMW 318i

Below are some graphs relating to the simulation of the plug-in car. The case analyzed is the one having initial SoC set to 25% because is more interesting than the one with fully charged battery and is used for computing the actual fuel consumption and carbon dioxide emissions over the WLTP cycle (Eq. (47)). In this case, the control strategy implemented by the vehicle is represented by the Charge Sustaining, i.e. the strategy that allows to maintain the SoC of the battery constant, as shown in Figure 10, in order to operate the combustion engine at a more efficient fixed point, to meet the power demand from the wheels and recharge the battery to power the electric motor. To fully understand this control, it is interesting to compare the power required to the wheels to complete the cycle and the power made available by the internal combustion engine, as shown in Figure 11.

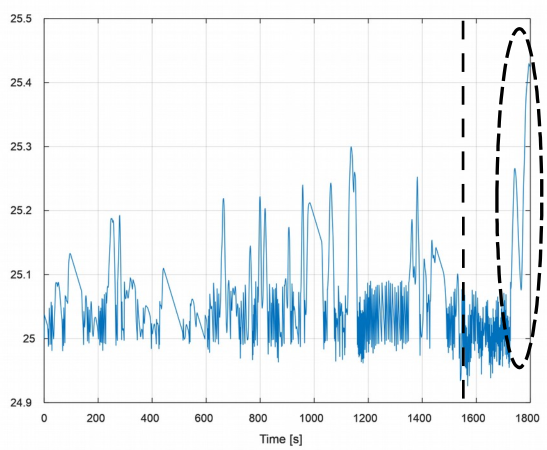

Figure 10. SoC trend - initial SoC 25%.

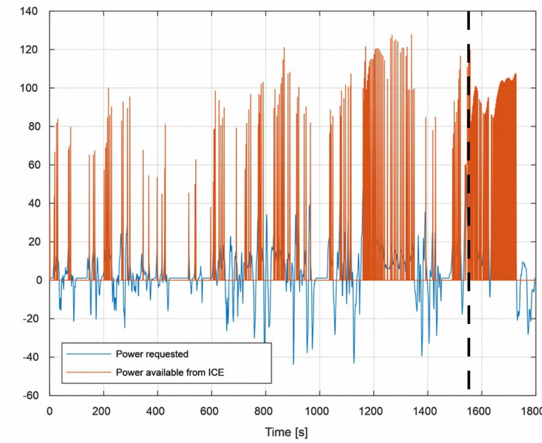

Figure 11. Mechanical power requested at wheels and power available from ICE - initial SoC 25%.

There is a significant difference between the powers and this difference can be used to recharge the batteries, so that the electric motor can start and work in support of the conventional one. In this control, the internal combustion engine can operate at a point of higher efficiency, a behavior that would not be possible in a purely combustion powertrain. It follows, therefore, that in every instant in which the ICE intervenes, it produces the maximum available torque as shown in Figure 12, while in the other points the torque demand is satisfied by the electric motor (the engine torque is null). From Figures 10 and 11 it is to note that, where the power requested to wheels is negative, i.e., during regenerative braking phase, the SoC increases (it is clearly visible towards the end of the cycle, in Figure 10, where it is highlighted by a black circle).

Figure 13 shows the mass flow rate of the gasoline: it is non-zero only when the ICE is switched on.

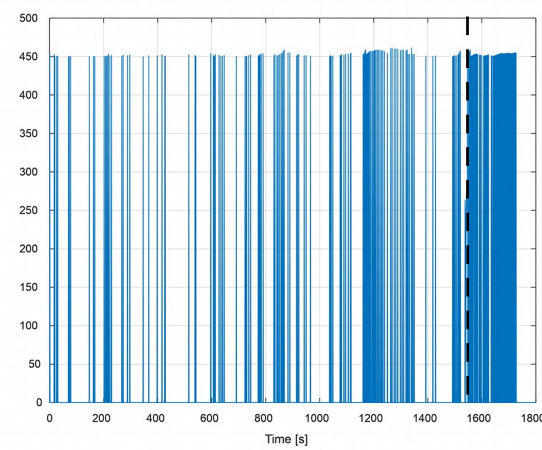

Figure 12. Torque delivered by the thermal engine - initial SoC 25%.

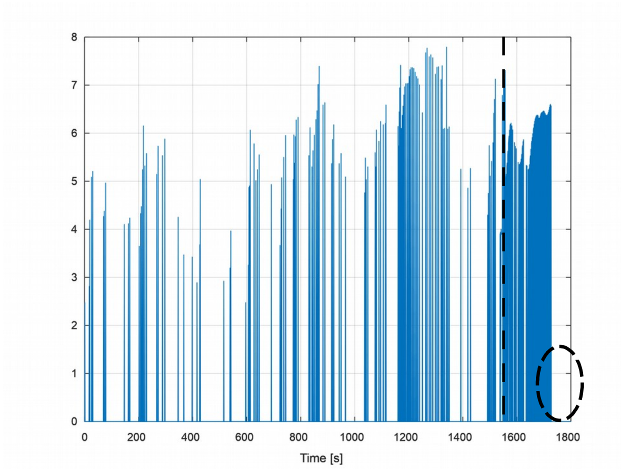

Figure 13. Fuel mass flow rate trend - initial SoC 25%.

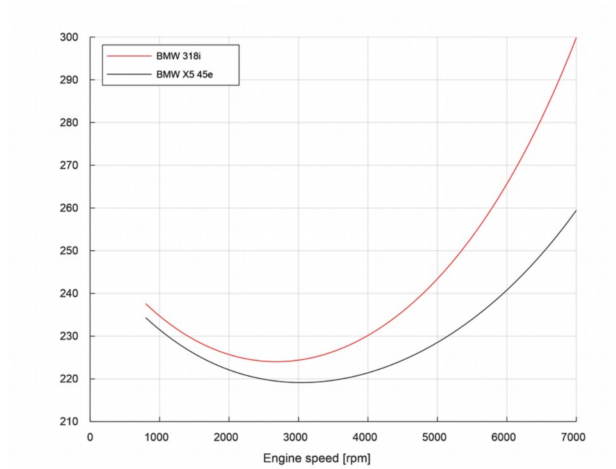

Figure 15. BSFC trend - initial SoC 25% for PHEV.

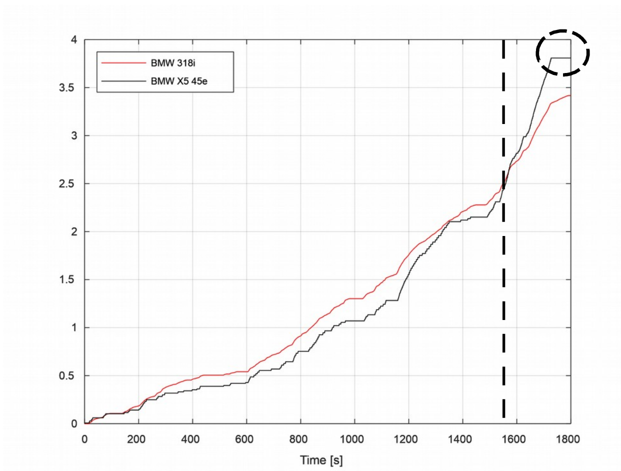

Figure 14. Mass of carbon dioxide emitted during the WLTP cycle by the ICE - initial SoC 25% for PHEV.

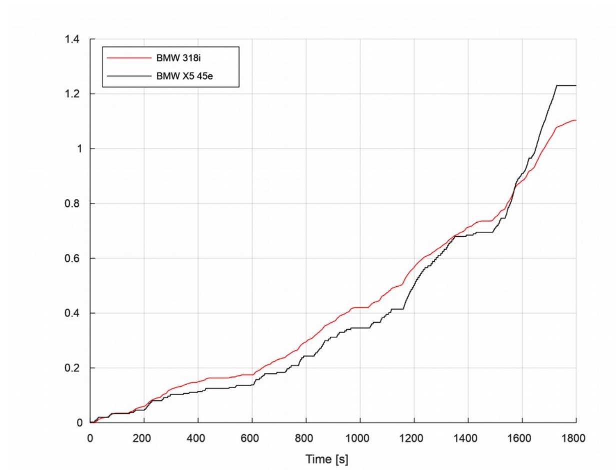

Figure 16. Total mass of gasoline necessary to fulfill the WLTP cycle.

Figure 14 shows the mass of carbon dioxide emitted during the WLTP cycle by the thermal engine alone (in the label BMW X5 45e) compared to the result of the conventional vehicle (thermal only propulsion) previously simulated (in the label BMW 318i). It can be seen how the CO_2 emissions, and therefore consumption, are lower for the plug-in version up to just before 1600 s in the WLTP cycle (point marked by a black vertical line with dotted lines): after this time, there is a power request (Figure 11), the SoC is at least 25% (Figure 10), therefore the battery cannot help with traction and the internal combustion engine must supply all the energy necessary to move the vehicle. The stretch of constant horizontal line, marked by a black circle with dashed line in Figure 14, is due to the fact that the CO_2 emissions are calculated with an integral, therefore the last calculated value is conserved over time. Furthermore, the strategy adopted of having the engine, when turned on, always work at the point of maximum efficiency (recharging the battery) also leads to an increase in CO2 emissions for PHEV. Overall, the specific consumption BSFC is lower for the plug-in vehicle (Figure 15). Figure 16 shows the total mass of gasoline for both BMW 318i and BMW X5 45e: it follows the trend of carbon dioxide emissions in Figure 14.

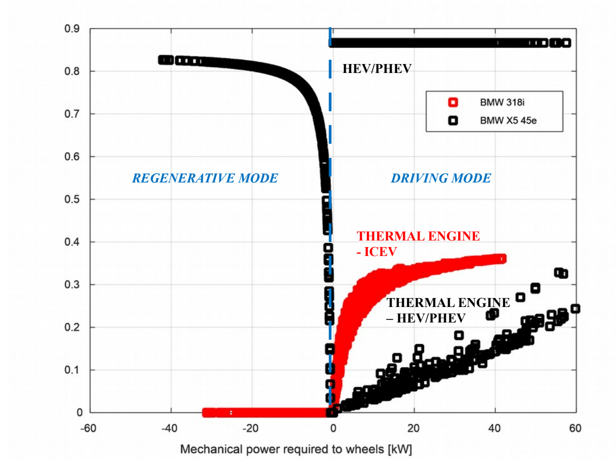

Figure 17. Tank-to-Wheel efficiency trend - initial SoC 25% for PHEV.

Figure 17 shows the trend of the TtW efficiency towards the mechanical power required from the wheels. When the mechanical power is negative, the vehicle is in "REGENERATIVE MODE", i.e., there is recovery of energy towards the battery because the vehicle is decelerating or braking. When the power is greater than zero, the vehicle is in "DRIVING MODE", i.e., it needs power to move. The two "MODES" are separated in Figure 17 by a blue dotted line located at zero mechanical power required to wheels. For a negative power demand to the wheels in Figure 17 ("REGENERATIVE MODE"), the TtW efficiency increases since the power is recovered through regenerative braking. This energy recovery is a great advantage for this type of powertrain compared to the conventional one (BMW 318i), which shows a null TtW efficiency (no regenerative braking allowable). During the driving phase ("DRIVING MODE"), the TtW efficiency of the traditional engine (318i) is shown in red. The efficiency of the BME X5 plug-in is visible in black: the efficiency varies depending on whether the thermal engine or the electric motor is working (efficiency above 85%). This result shown in Figure 17 confirms that the plug-in vehicle is worthwhile because the battery helps propel the vehicle. Therefore, the specific consumption of the plug-in vehicle (BMW X5) is lower overall (Figure 15). However, the TtW efficiency trend for the BMW X5 might seem strange. In fact, Eq. (36) replaces Eq. (9) when the electric motor is running.

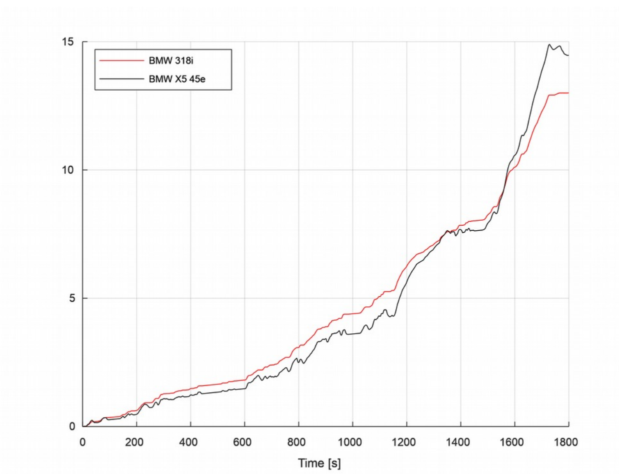

Figure 18. Required energy at wheels - initial SoC 25% for PHEV.

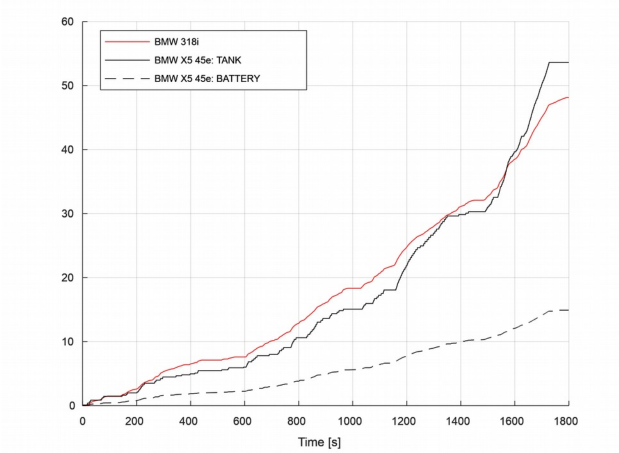

Figure 19. Chemical energy in the tank and / or stored in the battery (including the regenerative energy from braking) necessary to fulfill the WLTP cycle - initial SoC 25% for PHEV.

Figure 18 shows the energy required at the wheels for the two vehicles. The BMW X5 plug-in vehicle has a higher demand than the traditional vehicle because it weighs more (it has more equipment to be a hybrid vehicle) and has a larger frontal surface (lower aerodynamic performance).

Figure 19 shows the chemical energy in the tank and / or stored in the battery (including the regenerative energy from braking for PHEV) necessary to fulfill the WLTP cycle: the energy stored in the battery was computed by Eq. (33). Overall, the PHEV has a lower specific consumption (Figure 15) but uses a share of electric energy which in part comes from regenerative braking.

HYUNDAI NEXO: simulation results

This paragraph shows the simulation results for the HYUNDAI NEXO FUEL CELL 2021, fueled by hydrogen. It is equipped with 1 gears and automatic transmission CVT. The main inputs of the energy model are visible in Table 4.

In Figure 20 the TtW efficiency trend is shown: the regenerative efficiency is very important for this type of car because the battery capacity is very limited (1.56 kWh). In this case, Eq. (36) was used for the calculation of the chemical power.

The absolute value of the TtW efficiency is greater than the one typical of a conventional thermal engine (about 35% but even less). Figure 21 shows the chemical power stored in the tank, i.e., the available power, and the mechanical power requested at the wheels.

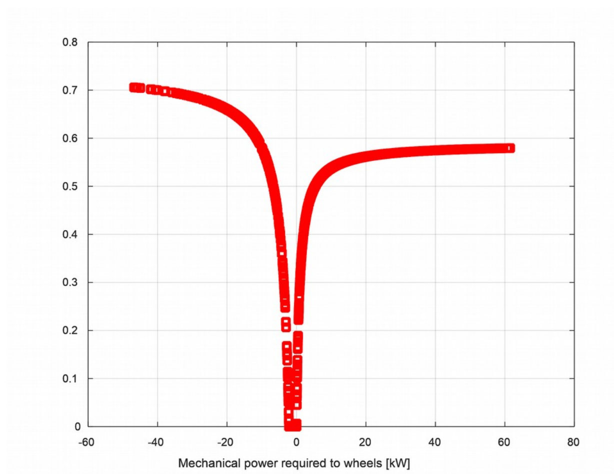

Figure 20. Tank-to-Wheel efficiency trend.

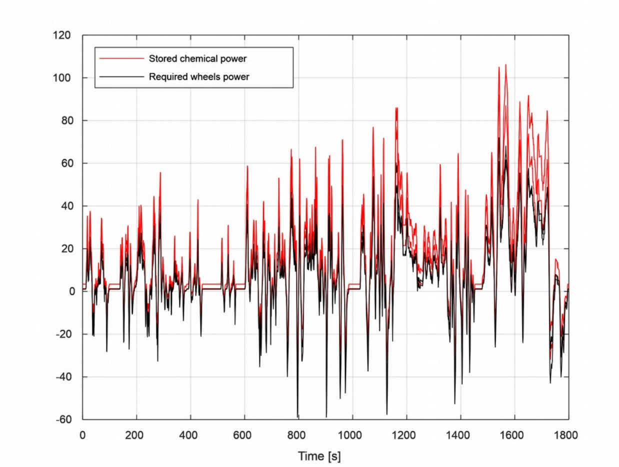

Figure 21. Chemical power stored in the tank (available power) and power required at wheels.

MERCEDES-BENZ AMG EQE 295 series

This paragraph shows the simulation results for the MERCEDES-AMG EQE 295 series (2022): it's a pure battery vehicle. It is equipped with 1 gears and automatic transmission. The main inputs of the energy model are visible in Table 4.

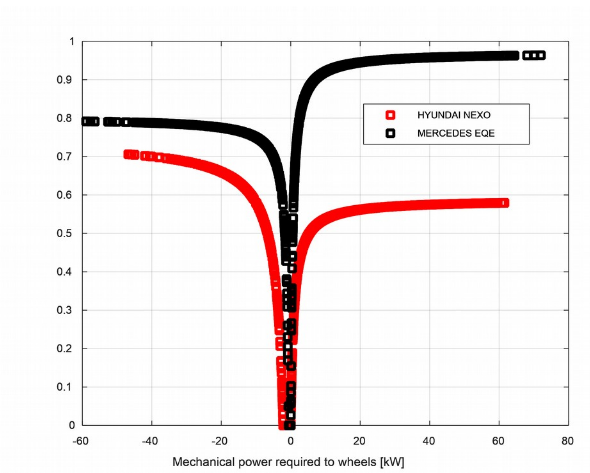

Figure 22. Tank-to-Wheel efficiency trend.

Figure 22 shows the TtW efficiency trend compared to that of the HYUNDAI NEXO. It can be seen that the efficiency of the electric vehicle is always decidedly higher even compared to a fuel cell vehicle. The too high TtW efficiency value (0.95) of the BEV during the driving phase is attributable, as the significant difference between the declared consumption and the simulated consumption (25% excess error in Table 4) to the Willans' model for BEVs, which presents critical issues that require a revision, as already mentioned. Figure 23 shows the power stored in the battery and the mechanical power requested at the wheels. In Figure 24 the SoC trend is visible: starting from 80% (initial SoC), the SoC of battery decreases during the cycle but very slowly because of the high battery capacity. Finally Figure 25 plots the comparison between the mechanical energy required at the wheels and the consequent electrical energy that must be supplied by the grid: the electricity of the grid (Eq. (46)) represents the actual energy cost of the BEV.

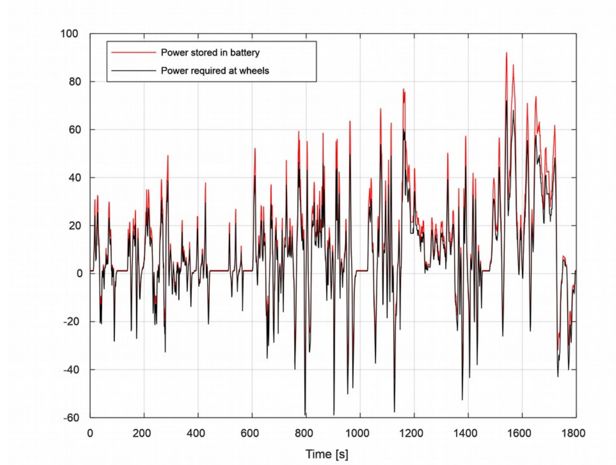

Figure 23. Battery power and power required at wheels.

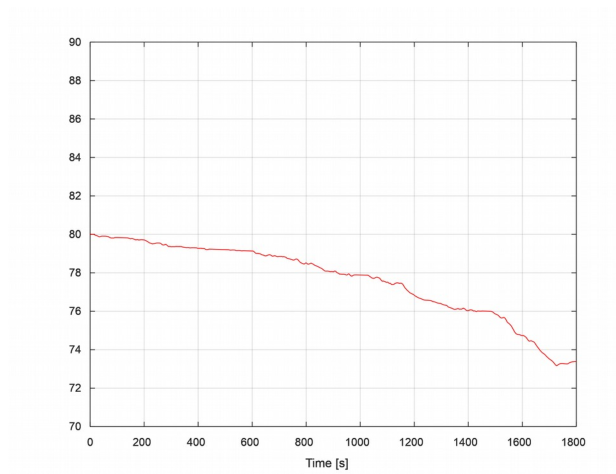

Figure 24. State of Charge trend.

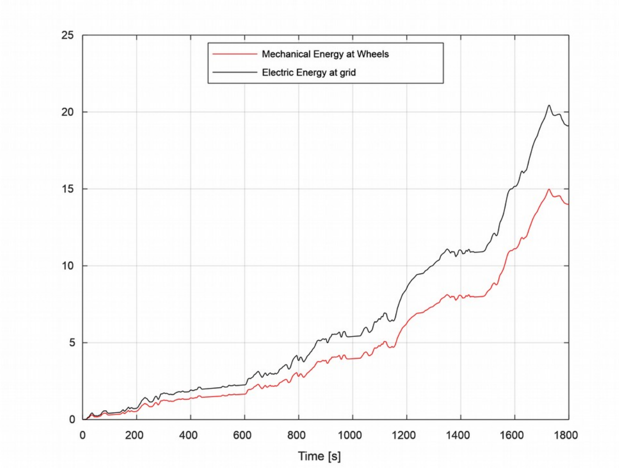

Figure 25. Comparison between the mechanical energy required at the wheels and the consequent electrical energy that must be supplied by the grid.

Comparison of the energy consumption of the four vehicles to travel the WLTP cycle

Finally, in this paragraph, were compared the mechanical energy required by the wheels for the four vehicles (Figure 26) and the effective energy expended to complete the WLTP cycle (Figure 27). It is clear that the vehicles do not belong to the same segment, but this comparison helps to verify that the model, despite the strong assumptions and limitations of the Willans model (for BEV modeling), is able to predict a global trend which is in line with what can be expected, i.e., BEVs are the cheapest vehicles in terms of energy costs.

In Figure 26, the BMW 318i (traditional vehicle) does not differ much in the demand for mechanical energy on the wheels compared to other vehicles The other vehicles have a comparable energy demand. It should be remembered that the mechanical energy required from the wheels is independent of the initial SoC for HEV/PHEV or FCEV or BEV.

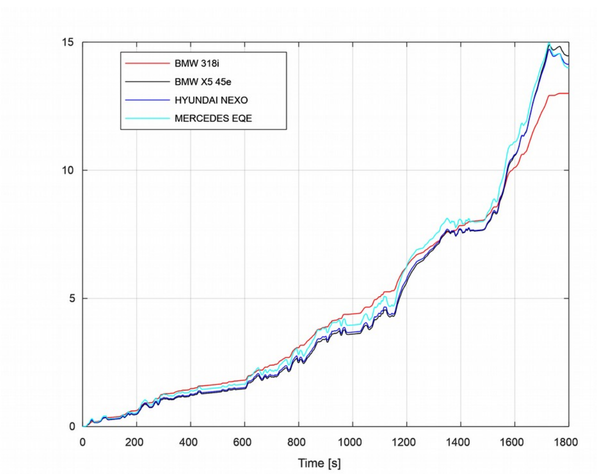

Figure 26. Energy required at wheels.

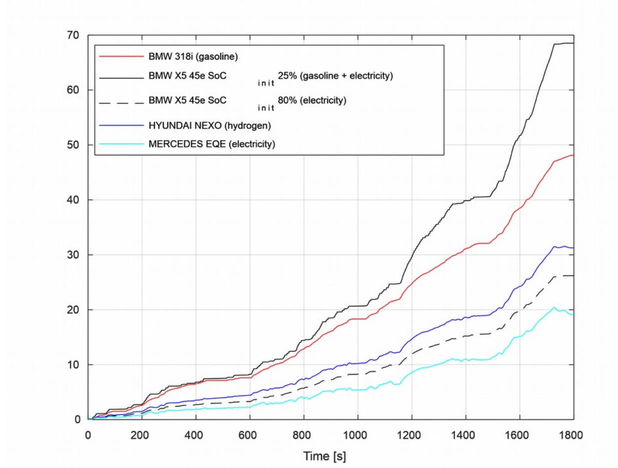

Figure 27. Effective energy expended to complete the WLTP cycle.

In Figure 27, the actual energy consumption (to satisfy the energy demand to the wheels of Figure 26) is least for the BEV vehicle (MERCEDES EQE) and maximum for the PHEV (BMW X5). In the BEV, the electricity needed by the grid to recharge the vehicle has been calculated so that it can travel the WLTP cycle. In the ICEV vehicle (BMW 318i) the chemical energy stored in the tank is considered. In the PHEV (BMW X5) the chemical energy in the tank is added to the electric energy of the battery: remember that the case outlined is the one with the initial SoC set to 25% to reproduce the switch-on of the thermal engine during the WLTP cycle. Therefore, the PHEV vehicle consumes less fuel, with the same mission profile, than a traditional ICEV. However, the overall energy expenditure is higher: electricity (partly from charging and partly from regenerative braking) must also be included in the total energy consumption. For a more complete comparison, the case of the PHEV with an initial SoC equal to 80% has been reported in dotted black line (same initial SoC of BEV and FCEV, as in Table 3): in this case the energy cost is just higher than the BEV. This is to say that the PHEV (like the HEV) has an energy rating strongly dependent on the initial SoC. To align with the real test case (with internal combustion engine running), the case with initial SoC at 25% was analyzed for the BMW X5, as previously explained. The BMW X5 vehicle (like all modern PHEVs) can carry out an entire WLTP cycle without power on the internal combustion engine (whose case is shown here in the dotted black line). The initial limit of the battery SoC to run the WLTP cycle in electric mode only is 55%. In fact, with SoC_{init} set to 50%, the SoC drops to 25% at the end of the WLTP cycle (Figure 28 in red line) while it remains above 25% for the initial SoC set to 55% (Figure 28 in black line). Then the thermal engine starts (as shown by the non-zero torque in the red line in Figure 29).

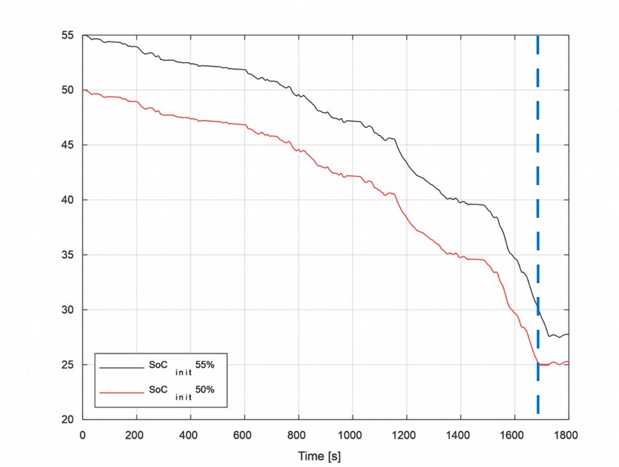

Figure 28. SoC trend – BMW X5.

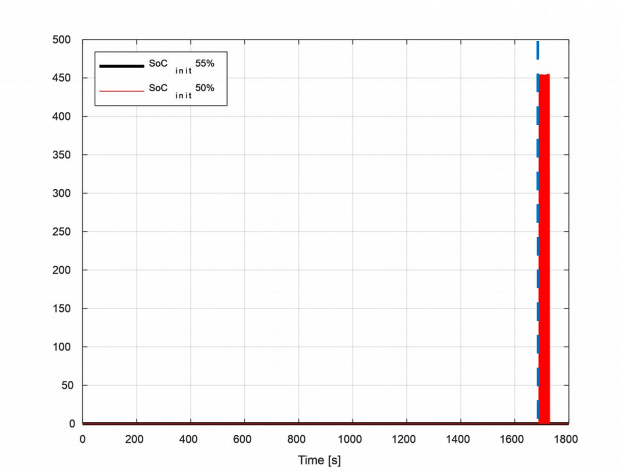

Figure 29. Thermal engine torque trend – BMW X5.

Finally, in Figure 27 the FCEV (HYUNDAI NEXO) has a higher chemical energy consumption (hydrogen) than the BEV but lower than the ICEV (as already highlighted in [4] in comparison with vehicles powered by thermal engines but fed by many fuels). Therefore, the maximum absolute efficiency in terms of energy, defined as the ratio between the mechanical energy at the wheels (Figure 26) and the energy expended (either chemical, electrical or both, shown in Figure 27) is of the BEVs, while the least is from the ICEV, which has an efficiency very close to PHEVs only if its initial SoC is set to 25%.

Assuming to synthetically produce gasoline (assimilated to DME in this work) or hydrogen (Table 2, WtT analysis), a quantity of electricity equal to:

1. 104.4 MJ for the BMW 318i;
2. 117.0 MJ for the BMW X5 with initial SoC set to 25% (BMW X5 45e 25% in the x-axis label);
3. 59.0 MJ for HUYNDAI NEXO

would be spent on the production of the mass of fuel necessary to complete the WLTP cycle. Conversely, the electricity from the grid required for the MERCEDE EQE to run through the WLTP cycle is only 19.1 MJ (as Figure 22). For the BMW X5 with initial SoC set to 80%, 0.0 MJ of electricity would be spent because the thermal engine is always turned-off during the WLTP cycle. Instead, the electrical energy required to complete the WLTP cycle in electric-only mode would be equal to 26.2 MJ (BMW X5 45e 80% E-MODE in the x-axis label).

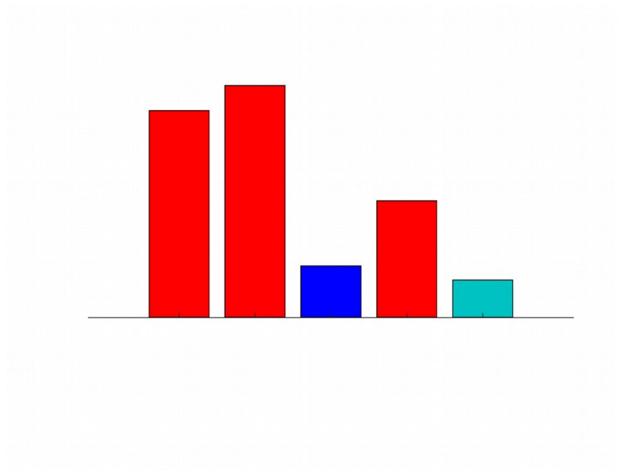

Figure 30. Final electricity costs for the production of the synthetic fuels (compared to electricity needed by the MERCEDS EQE).

All these electricity costs are reported in Figure 30. From the point of view of the electric cost alone and considering the electric cost of the production of synthetic fuels, the most energy-efficient vehicle between the four vehicles under consideration is the BEV, as one would expect.

Conclusions

In the present research work an energy model has been presented that is able to calculate the total cost of the energy required by a vehicle to make a specific journey starting from the production of the synthetic fuel that powers it (electricity included) or including the recharging efficiency from the grid. The followed methodology is based on the Well-to-Miles analysis. By the energy model is possible to compare the sustainability of various fully or partially electric propulsion systems equipped with thermal engines powered by alternative fuels (e-fuels, hydrogen, green methane, etc.) or powered by fuel cells.

The model was validated by comparing the carbon dioxide emissions (if applicable) and fuel consumption data of four modern cars: one powered by a traditional gasoline engine, another plug-in, one powered by fuel cells and the latest pure electric. The BEV shows the greatest discrepancy between declared and simulated energy consumptions: the Willans model needs to be revised, also in consideration of the too high value of the TtW efficiency (close to 95%).

The model showed that the most energy-effective vehicle between the four vehicles in analysis, for a given mission profile, is the BEV, followed by the PHEV with SoC_{init} set to 80% and then FCEV. The least convenient is the ICEV because it has the highest fuel consumption of all.

Therefore, the model is a useful tool for the energy evaluation of different powertrains in terms of consumption and therefore emissions. The model underlies many hypotheses: the numerical results are close to the actual ones. The model demonstrates to maintain a trend of validity extended to all powertrains. For a very accurate modeling it would be necessary to go into more detail about the definition of each single car, but the generality of the model would be lost. Therefore, the model is a valuable tool for energy assessment (consumption, emissions) of various propulsion units suitable for making a specific trip.

References

1. Climate Watch – Available online: https://www.wri.org/initiatives/climate-watch (accessed on 14th September 2022)
2. Available online – Fit for 55 - https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition (Accessed on February 23rd, 2023)
3. Falfari, S. Bianchi, G.M., Concerns on Full Electric Mobility and Future Electricity Demand in Italy. Energies 2023, 16, 1704. https://doi.org/10.3390/en16041704
4. Guzzella L. e Sciarretta A., "Vehicle Propulsion Systems - Introduction to Modeling and Optimization", Springer, Third edition - Available online: https://ftp.idu.ac.id/wp-content/uploads/ebook/tdg/ADVANCED%20ENGINE%20TECHNOLOGY%20AND%20PERFORMANCE/epdf.pub_vehicle-propulsion-systems-introduction-to-modelin-3.pdf (Accessed on June 24th 2022).
5. Hänggi, S., Elbert, P., Bütler, T., Cabalzar, U., Teske, S., Bach, C., Onder, C., 2019. "A review of synthetic fuels for passenger vehicles". Energy Reports 5, 555–569. https://doi.org/10.1016/j.egyr.2019.04.007
6. Xinmei Yuan, Chuanpu Zhang, Guokai Hong, Xueqi Huang, Lili Li, "Method for evaluating the real-world driving energy consumptions of electric vehicles", Energy, Volume 141, 2017, Pages 1955-1968, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2017.11.134.
7. C. Fiori, K. Ahn e H. A. Rakha, "Power-based electric vehicle energy consumption model: Model development and validation", Applied Energy, vol. 168, pp. 257-258, 2016. http://dx.doi.org/10.1016/j.apenergy.2016.01.097
8. C. Fiori, A. Kyoungho e H. A. Rakha, "Microscopic series plug-in hybrid electric vehicle energy consumption model: Model development and validation", Transportation Research, vol. 63, n. Part D, pp. 175-185, 2018. https://doi.org/10.1016/j.trd.2018.04.022
9. J. Xie, J. Ma e K. Bai, "Enhanced Coulomb Counting Method for State-of-Charge Estimation of Lithium-ion Batteries based on Peukert's Law and Coulombic Efficiency" Journal of Power Electronics, vol. 18, n. 3, pp. 910-922, 2018. https://doi.org/10.6113/JPE.2018.18.3.910
10. I. Sagaama, A. Kchiche, W. Trojet e F. Kamoun, "Evaluation of the Energy Consumption Model Performance for Electric Vehicles in SUMO", Conference: 2019 IEEE/ACM 23rd International Symposium on Distributed Simulation and Real Time Applications (DS-RT), 2019. DOI: 10.1109/DSRT47707.2019.8958704
11. B. Mebarki, B. Draoui, B. Allaou, L. Rahmani e E. Benachour, "Impact of the Air-Conditioning System on the Power Consumption of an Electric Vehicle Powered by Lithium-Ion Battery", Hindawi Publishing Corporation, vol. 2013, 2013. http://dx.doi.org/10.1155/2013/935784
12. P. Iora e L. Tribioli, "Effect of Ambient Temperature on Electric Vehicles' Energy Consumption and Range: Model Definition and Sensitivity Analysis Based on Nissan Leaf Data", World Electric Vehicle Journal, vol. 10, n. 2, 2019. DOI:10.3390/wevj10010002
13. Sorrentino, M., Mauramati, F., Arsie, I., Cricchio, A. et al., "Application of Willans Line Method for Internal Combustion Engines Scalability towards the Design and Optimization of Eco-Innovation Solutions," SAE Technical Paper 2015-24-2397, 2015, https://doi.org/10.4271/2015-24-2397.
14. Martin Hedon, "Modeling and Simulation of a Hybrid Powertrain", Degree project in vehicle engineering, second cycle, 30 credits Stockholm, Sweden 2018. PDF available online: https://www.diva-portal.org/smash/get/diva2:1249494/FULLTEXT01.pdf (Accessed on 24th November 2022).
15. Crain_washington_0250O_13550; Hybrid Vehicle Supervisory Controller Development Process to Minimize Emissions and Fuel Consumption in EcoCAR 2. PDF available online: https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/27117/Crain_washington_0250O_13550.pdf?isAllowed=y&sequence=1 (Accessed on 24th November 2022).
16. Yasin, T., "The Analytical Basis of Automobile Coastdown Testing," SAE Technical Paper 780334, 1978, https://doi.org/10.4271/780334
17. Sten Karlsson, Duncan Kushnir (2013), "How energy efficient is electrified transport?" 2013, pages 45-59 – Available online: https://publications.lib.chalmers.se/records/fulltext/179113/local_179113.pdf (Accessed on 23rd November 2022)
18. Automobile Catalog – Available online: https://www.automobile-catalog.com/#gsc.tab=0 (Accessed on March 31st 2023)

Contact Information

For more information, please contact Prof. Stefania Falfari stefania.falfari@unibo.it.

Definitions/Abbreviations

BEV	Battery Electric Vehicle
CC	Coulomb Counting Method
CVT	Continuously Variable Transmission
DOD	Depth of Discharge
DME	Dimethyl ether
ECC	Enhanced Coulomb Counting Method

FCEV Fuel Cell Electric Vehicle

HEV Hybrid Electric Vehicle

ICEV Internal Combustion Engine Vehicle

PHEV Plug-In Hybrid Electric Vehicle

SoC State of Charge

WtM Well-to-Miles

WtT Well-to-Tank

WhtM Wheels-to-Miles

TtM Tank-to-Miles

TtW Tank-to-Wheels

Nomenclature

$a(t)$ vehicle acceleration/deceleration [m/s^2]

A Coefficient of load losses = 22.19 kg

A_f Frontal area of the car [m^2]

AR Tire aspect ratio [%]

c_d Aerodynamic drag coefficient [-]

c_f Specific carbon content in the fuel [kg_C/kg_{fuel}]

c_r Rolling friction coefficient [-]

$c_{1,pos}$, $c_{0,pos}$ Coefficient based on Willans approach

$c_{1,neg}$, $c_{0,neg}$ Coefficient based on Willans approach

C Coefficient of load losses = 0.0609 kg/(m/s)^2

d Distance [km]

D Wheels diameter [mm]

D_{av} Constant value = 25 km

D_e Autonomy in E-drive mode [km]

$E_{available}$ Max energy recoverable during braking [kWh]

EC Energy consumed by the battery [kWh]

E_{batt}^{loss} Electricity lost by the battery [J]

E_{brk} Braking energy [J]

E_{brake}^{loss} Electricity lost during the braking phase [J]

E_{charg}^{loss} Electricity lost during charging [J]

E_{chem_ICE} Chemical energy stored in the tank [kWh]

E_{dec} Deceleration energy [J]

$E_{ElectricMotor}^{loss}$ Electricity lost by the electric motor [J]

E_{grid} Total electricity consumption from the grid [J]

E_{load}^{loss} Load, equal to E_{wheels} in the present paper [J]

$E_{recoverable}$ Energy recovered during braking [kWh]

$E_{transmission}^{loss}$ Electricity lost by the transmission [J]

$E_{wheels,norm}$ Mean energy demand per kilometer [kJ/km]

E_{wheels} Mean energy demand [J]

F_{drive} Final transmission ratio (drive gear) [-]

F_{load} Load losses [N]

g Gravitational acceleration [m/s^2]

Gear(t) Transmission ratio of the gear engaged

h_f Specific energy content in the fuel [kWh/kg_{fuel}]

kg_{H2} Kilograms of hydrogen [kg]

m_{fuel} Fuel consumption of the vehicle [kg]

m_{CO2} Mass of carbon dioxide emitted by the thermal engine during the test cycle [kg]

LHV Lower Heating Value [MJ/kg]

m_{car} Car mass [kg]

M1 Mass of emissions [g/km] or fuel consumption [l/100km] during the first WLTP test for PHEVs (SoC set to SoC_{MAX}). Generally this value is null for modern PHEV vehicles.

M2 Mass of emissions [g/km] or fuel consumption [l/100km] during the second WLTP test for PHEVs (SoC set to SoC_{MIN}).

M_{CO2} Molecular weight of carbon dioxide [kg/kmol]

M_m Molecular weight of carbon [kg/kmol]

$\acute{m}_f$ Mean fuel flow rate [kg/s]

P_{aerod_drag} Power lost due to aerodynamic drag [W]

P_{aux}	Total power of the auxiliaries [kW]
$P_{aux,const}$	Constant power of the auxiliaries only [kW]
P_{batt}	Battery power [W]
$P_{battMAX}$	Maximum battery power [W]
P_{chem}	Chemical power [kW]
$P_{ElectricMotor}$	Rated power of the electric motor [W]
P_{engine}	Power supplied by the engine [W]
P_{grav}	Power of gravity load [W]
$P_{heat,cool}$	Power for heating and cooling the passenger compartment [kW]
P_{max}	Maximum power deliverable by the engine [W]
pme	Mean effective pressure [Pa]
pma	Mean absolute pressure [Pa]
$p_{m,loss}$	Mean frictional pressure [Pa]
P_{roll_fric}	Rolling friction power [W]
P_{veh_accel}	Power needed for vehicle acceleration [W]
P_{wheels}	mechanical power to the wheels required by the chosen driving cycle [kW]
q_{CO2}	Specific emissions of carbon dioxide [kg/kWh]
Q_0	Nominal battery capacity [kWh]
r_w	Vehicle wheel radius [m]
RPM	Engine velocity [rpm] defined by the Willans model
S	Piston stroke [m]
t	Time [s]
ΔT	temporal amplitude between the instants of time t and (t-1) [h]
T	Outside ambient temperature [°C]
T_{engine}	Torque delivered by the engine at its point of maximum efficiency [Nm]
T_{max}	Maximum torque deliverable by the engine [Nm]
$T_{max}(P_{max})$	Maximum torque that can be delivered by the internal combustion engine at the speed corresponding to the maximum power [Nm]
T_{req}	Engine torque requested by the engine [Nm]
v(t)	Vehicle speed profile [m/s]
V_d	Engine displacement [m^3]
V_{pist}	Piston velocity [m/s]
W	Tire width [mm]

Greek letters

$\alpha(t)$	*S*lope of the route [rad]
η_{batt}	Battery efficiency [-]
$\eta_{charger}$	Charger efficiency [-]
$\eta_{driveline}$	Driveline efficiency (classical vehicle) [-]
η_{eng}	Engine efficiency [-]
$\eta_{ElectricMotor}$	Electric Motor efficiency [-]
η_{EVSE}	Electric Vehicle Supply Equipment [-]
η_{g2b}	"Grid to Battery" efficiency [-]
η_{rb}	Regenerative breaking efficiency [-]
$\eta_{transmission}$	Transmission efficiency for BEV [-]
η_{TtW}	Tank to wheels efficiency [-]
ρ_{air}	Air density [kg/m^3]
ρ_{fuel}	Density of the fuel [kg/m^3]
ω_e	Engine angular velocity [rad/s] defined by the user between a minimum (idle) and a maximum value
$\omega_e(T_{max})$	Angular speed of the motor corresponding to the maximum torque that can be supplied [rad/s]
$\omega_e(P_{max})$	Angular speed of the motor corresponding to the maximum power that can be supplied [rad/s]