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Optimal designs for efficient mobility service for hybrid electric vehicles

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ABSTRACT

The priority of the automotive industry is to reduce the energy consumption and the emissions of the future passenger cars and to deliver an efficient mobility service for the customers.

The improvement of the efficiency of vehicle energy systems promotes an active search to find innovative solutions during the design process. Engineers can use computer-aided processes to find automatically the best design solutions. This kind of approach named "multi-objective optimization" is based on genetic algorithms. The idea is to obtain simultaneously a population of possible design solutions corresponding to the most efficient energy system definition for a vehicle. These solutions will be optimal from technical, economic and environmental point of view. The "genetic intelligence" is tested for the holistic design of the environomic vehicle powertrain solutions. The environomic methodology for design is applied on D-class hybrid electric vehicles, in order to explore the techno-economic and environmental trade-off for different hybridization level of the vehicles powertrains. For powertrain efficiencies between 0.25 and 0.35 the electrification of the powertrain reduces the global CO_2 emissions. Hybrid electric and plug-in hybrid electric vehicles are reaching these levels. The break point of the electrification effect on the GWP occurs on 0.35 % of powertrain efficiency.For battery capacity value higher than 13 kWh the global reduction of the CO_2 emissions is not obvious. The method gives also an overview of the evolution of environmental categories indicators as a function of the cost of the vehicles. A direct relation links the economic and the environmental performances of the solutions.

Keywords:

Environomics;
Hybrid electric vehicles;
Multi-objective optimization;
Vehicles powertrains;

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1. Introduction

Decarbonisation and emission reduction from road transport are the main drivers for the electrification of the vehicles.

Around 2030 electric vehicles are expected to increase their market penetration and to bring evolution concerning the main technologies for energy storage and conversion, the drive train components and the energy management [1]. The industrialisation of those components on high scale and volume contributes to the reduction of the high cost of the electrification and to its democratisation on all vehicles segments. Hybrid electric vehicles with different levels of hybridisation are adapted for the different vehicles segments. They are designed for urban and peri-urban drives, and allow zero emissions drives from thank-to-wheels perspective for 25 km or 50 km. Hybrid electric vehicles with zero emission vehicles (ZEV) modes are supported by incentives for circulation in the big cities centres.

The scarcity of not only fuel resources but also the adverse effects of the operation of energy intensive systems on the environment (pollution, degradation) have to

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Abbreviations

BEV	Battery electric vehicle
CVT	Continuous variable transmission
HEV	Hybrid electric vehicle
HVB	High voltage battery
GWP	Global warming potential
ICE	Internal combustion engine
MGB	Manual gear box
MOO	Multi objective optimization
LCA	Life cycle assessment
ODP	ozone depletion
SoC	State of charge
PHEV	Plug-In hybrid electric vehicle
F	Force, N
m_{fuel}	Fuel rate, kg/s
P	power, kW
q_{batt}	battery capacity, kWh
T_x	Torque, Nm
V	speed, m/s
ZEV	Zero emission vehicle

Greak letters

γ	gear ratio
η	efficiency, -
ω	rotation speed, rpm

Subscripts and superscripts

BT	battery
EM	Electric machine
ICE	Internal combustion engine
s	shaft
SC	Supercapacitor
w	wheels

be taken into consideration. Thus, the system can be properly designed and operated. The systematic consideration of thermodynamic, economic and environmental aspects for this purpose is called environomics [2]. Environomic analysis is an extension of thermo-economics [3]. In addition to flows of energy, exergy and costs, flows of other resources consumed as well as flows of pollutants enter in the picture. Environomic design of electric and hybrid electric vehicles are studies in [4, 5].

The automotive product is increasingly restricted by environmental regulations, including reducing emissions of CO_2 and pollutants in exhaust pipes of vehicles. One solution implemented in the automotive industry is plug-in hybrid electric vehicle (PHEV) that use an electric traction battery. To help vehicle manufacturers in their choice of traction battery from an environmental point of view, a simulation method of environmental impacts generated by the phase where the vehicles is used is proposed in [6]. This method takes into account the possible usages of the vehicle and potential developments of electric mix, with the formulation of a constraint satisfaction problem solved using constraint programming techniques. Delogu et al. investigate in [7] the lightweight design and electrified powertrain as important strategies in the automotive industry to reduce fuel demand and break down emissions respectively. Lightweighting of Electric Vehicles (EVs) is considered a step forward because advantages of both EVs and lightweight design could be combined to reduce environmental impacts even further. Alegre et al. showed in [8] a modelling of electric and parallel-hybrid electric vehicle using Matlab/Simulink environment which allows us to access different aspects of the vehicle such as engine power, type and size of the battery or weight and to observe how changes can affect the performance and the distance travelled. The model was simulated in order to obtain the electric vehicle's autonomy. Through the use of a Geographic Information System together with a mathematic algorithm based on genetic algorithms the planning of charging stations was obtained, where the installation investment cost was minimized and the geographic distribution was improved in order to increase the quality of the service by improving reliability. Electric-drive vehicles, including hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, fuel cell electric vehicles and fuel cell hybrid electric vehicles are emerging as less polluting alternatives to internal combustion engine vehicles. Therefore, it is important to assess their penetration in the vehicle market in the future. A 'two-step' approach is used in [9] to estimate the optimum market penetration of lightweight and electric-drive vehicles in the long-term and the impact on the light-duty vehicle fleet, focusing on Japan. First, an optimization model is used to estimate the vehicle market composition in 2050. Then, a vehicle stock turnover model is used to estimate light-duty vehicle fleet energy and material consumption, CO_2 emissions and cost.

In [10] the authors analyse different charging strategies for a fleet of electric vehicles. Along with increasing the realism of the strategies, the opportunity for acting on the regulating market is also included. They test the value of a vehicle owner that can choose when and how to charge.

Particularly, strategies are chosen from uncontrolled charging through deterministic optimization, to modelling the charging and bidding problem with stochastic programming.

The authors analyse in [11] the scenario of development by the Danish Climate Commission. In the short term, it is investigated what the effects will be of having flexible or inflexible electric vehicles and individual heat pumps, and in the long term it is investigated what the effects of changes in the load profiles due to changing weights of demand sectors are. The results show that even with a limited short-term electric car fleet, these will have a significant effect on the energy system; the energy system's ability to integrated wind power and the demand for condensing power generation capacity in the system.

Alternative scenarios for energy planning are proposed for the transportation sector in [12]. The analysis of the projection of energy demand and Greenhouse Gas emission, in the form of $CO_{2,}$ NO_x, and CH_4, was conducted. The results show that by implementing an efficient vehicle scenario, global warming potential can be reduced by 15.80%. The implementation of an integrated scenario reduced global warming potential by 24.76% compared to the reference scenario.

The novelty of the present study is the application of the environomic optimization methodology for optimal design and operation parameters of the vehicle energy system. Methods, techniques to analyze, improvement and optimizations of energy systems have to deal not only with the energy consumption and economics, but also with the environmental impacts. The word environomics includes all this activity.

2. Methodology

The methodology used in this article combines in a computational platform models of technologies, techniques of energy integration, evaluation of the economics and assessment of the life cycle impacts. The superstructure possibilities are explored by using multi- objective optimization techniques and allows defining optimal design solutions. Genetic algorithm governs the master optimization and mixed integer nonlinear programming solves discontinuous mathematical problems. This approach is holistic and innovative in comparison of the traditional heuristic design engineering method, based on iterations of designs and their cost evaluation. The generic computational framework for environomic design of a vehicle energy system is illustrated on Figure 1. The vehicle simulation model contains dynamic and thermal layouts. The economic model is presented by the cost equations. The optimization is based on a genetic algorithm. The set of decision variables includes the types and the size of the equipment. The problem is solved by an evolutionary algorithm with 3 objectives: the minimization of the fuel consumption, the minimization of the investment cost and the environmental impacts for the technologies (Figure 1). The results of the multi-objective optimization converges on the Pareto frontier curve.

The energy integration model uses the results from the dynamic and thermal flows calculations. The energy

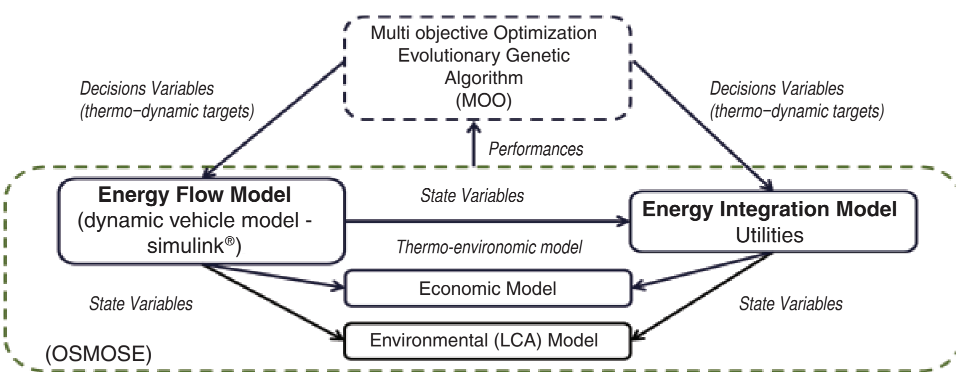

Figure 1: Computational framework of environomic optimization

integration is not applied in this article. Applications and results from the energy integration method are available in [13, 14, 15].

2.1. Hybrid electric vehicle simulation model

The vehicle is modelled under SIMULINK®. The vehicle model is based on mechanical and electrical flows. The thermal layout of the internal combustion engine is constructed from measurement maps and included in the vehicle model. The technique of the modelling is quasi-static. The vehicle follows dynamic profiles generated from a library of driving cycles. The model is controlled by an energy management structure in loop, linked to the required mechanical power, to follow the dynamic cycle. This energy management loop is called "back and forward". Thanks to it, for a given design of the vehicle powertrain the model estimates the energy consumption of the vehicle, on the given driving profile. The energy flow is computed backwards from the wheels to the energy sources. The backwards mode insures the flexible and fast nature of the simulations. This is an important advantage for an optimization study. However the quasi-static modeling level is limited in its non-causality. The main characteristics of the hybrid electric simulation model are summarized in Table 1.

Table 1: D- Class vehicle characteristics

Sub-System	Characteristic	Value
Vehicle	Nominal mass [kg]	1660
Gear box	CVT efficiency [–][16]	0.84
	MGB efficiency [–]	0.95
	6 gears	
Engine	Displacement [l]	2.2
	Number of cylinder	4
	Rated power [kW] at 4000 rpm	120
	Max. speed [rpm]	4500
	Max. Torque [Nm] at 2000 rpm	380
	Idle speed [rpm]	800
	Idle fuel consumption [l/h]	0.33
	Deceleration Fuel cut- off	Yes
Fuel	Type	Diesel
	Density [kg/l]	0.84
	Lower heating value [MJ/kg]	42.5
Electric motor	Power [kW]	27
Battery	Ni MH	
	Capacity [kWh]	1.2

The initial model represents a commercial D class diesel hybrid electric vehicle. Figure 2 illustrates the generic units that constitute the vehicle powertrain and the backwards approach to estimate the energy consumption. The presentation of the hybrid electric vehicle model including the energy distribution strategy is presented in [17].

2.2. Cost model

The cost of the vehicle is evaluated for each run as a function of the size and efficiency of the energy converters and energy storage devices. The cost of the equipment comes from the literature and is related to the size of the components. Table 2 presents the cost equations – Eq. (1) – Eq. (5).

The car shell is defined as a completely equipped vehicle (body, interior equipment, wheels), except the powertrain.

A simplified objective cost function is constructed Eq. (7), taking into account the vehicle powertrain cost (production) Eq. (6) and vehicle nominal cost Eq. (5).

$$Cost_{powertrain} = Cost_{ICE} + Cost_{EM} + Cost_{battery} + Cost_{supercapacitors} \tag{6}$$

$$Cost_{vehicle} = Cost_{powertrain} + Cost_{car\_shell} \text{ in } [€] \tag{7}$$

2.3 Environmental model:

In this article, the Life Cycle Assessment method is applied as an indicator for the evaluation of vehicle energy system design. The functional unit used for the study, for LCA vehicle study is to transport persons on 150000 km for 10 years.

This study refers to the CML short impact. This impact is used from the most part of the automotive industry. The categories included in the impact are: the Global Warming Potential (GWP for 100 years of perspective), the eutrophication, the acidification and the ozone depletion. The impact category GWP- 100y considers the impact for 100 years, and presents the advantage to be largely used. Usually the life cycle of a

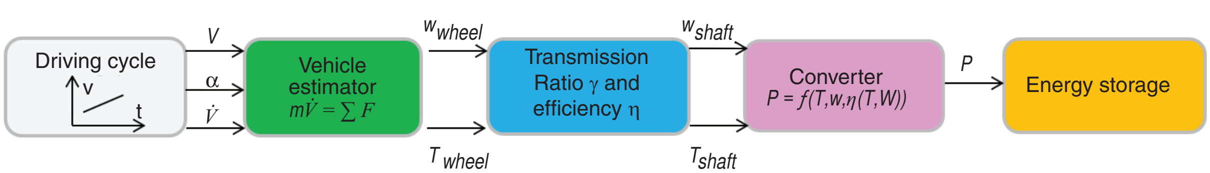

Figure 2: Quasi- static model of the parallel thermal electric hybrid

Table 2: Equations for the economic model [17]

Components	Costs [€]	
Converters		
Electric motor	30 [€/kW]*P_{EM} [kW]	(1)
Thermal engine	15 [€/kW]* P_{TE} [kW]	(2)
Storage system		(3)
Battery	$600*[€/kWh]*q_{bat}^{0.2477*\log o(bat_{specifmass}(battpe)+0.5126}[kWh]$	
Supercapacitor	15 [€/kW]* P_{SC} [kW]	(4)
Body		(5)
Nominal cost (car shell)	17.3*car_shell_mass[kg]-3905.4 [€]	
Vehicle use in France 2013		
Electricity household	0.14269 [€TTC/kWh]	
Electricity industry	0.07768 [€TTC/kWh]	
Gasoline	1.645 [€/L]	
Diesel	1.451 [€/L]	

Table 3: Drive cycles characteristics

Cycle	Distance (km)	Duration (s)	Average speed (km/h)
NEDC	11.023	1180	32.26

product, a system or a service has three distinct phases that succeed: the production phase, the use phase and the end-of-life phase. The unitary processes and the raw materials for the production of the parts come from the Eco Invent® database [18]. The automobile is divided into seven substructures, which allows distinguishing the powertrain: electric machine, low voltage battery, high voltage battery, power unit, thermal engine, gearbox, vehicle body (car shell). The use phase corresponds to the energy consumption of the vehicle. The inventory for the corresponding energy vector production (electricity and diesel) comes from the Eco Invent® database. The end-of-life phase is represented by the average car disposal process. They are also issued by the Eco Invent® database. The cars are considered to be operated in France with the French electricity mix and Diesel produced in France. Commercial vehicles are characterized on the normalized driving cycle – New European Driving Cycle (NEDC). Table 3 summarizes the characteristics of the NEDC, which is well known and well referenced.

3. Results- multi-objective environomic optimization

3.1 Definition of the optimization problem

A hybrid vehicle characterized with multiple propulsion systems can operate them independently or together. The model contents are the electric machine, battery,

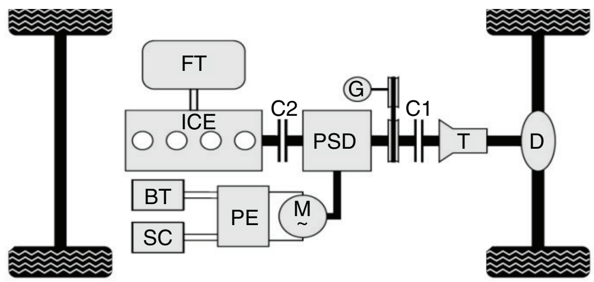

Figure 3: Parallel hybrid electric architecture: FT – fuel tank, ICE – internal combustion engine, BT – high voltage battery, SC – super capacitor, PE – power electronics, M– electric motor, PSD – power split device, G – electric generator, C1- clutch 1, C2- clutch 2, T- Transmission, D- Differential

supercapacitors, thermal engine and fuel tank, with diesel fuel. The thermal electric hybrid powertrain model characteristics are given in Table 1. The model represents a commercial D-class [19] vehicle with a parallel thermal (diesel) and electric powertrain (Figure 3). The target is to size the components of the hybrid powertrain: the converters and the storage tanks and to evaluate on a simultaneous way, the environmental and the economic impacts of the solutions.

A multi objective optimization with three objectives is considered to define design solutions optimal from efficiency, economic and environmental point of view.

For every iteration of the model, the mean powertrain efficiency in traction mode is calculated according Eq. (8):

$$\eta_{powertrain} = mean\left(\frac{P_{wheel}}{P_{fuel}+P_{BT}+P_{SC}}\right) \tag{8}$$

Where P_{BT} and P_{SC} are respectively the battery and the super capacitors powers in kW and P_{wheel} is the power on the wheels in kW.

The vehicle cost is computed for each set of the decision variables, according Eq. (7). The GWP is the category considered as environmental objective. The GWP has to be minimized. The GWP objective function for the environomic optimization considers the equivalent CO_2 emissions during the vehicle life cycle (production, use phase). It is defined over the life cycle functional unit of 150000 km. The end of life is neglected, because of the high recycling ratio in the automotive industry and the consideration that the high voltage battery has a second life as storage device in the electricity distribution grid.

The Eq. (9) defines the GWP objective function:

$$GWP_{total} = GWP_{production} + GWP_{use\_phase} \text{ in kg. } CO_2 \text{ eq.} \tag{9}$$

In the case of hybrid electric vehicles, the use phase includes the GWP due of the CO_2 tank-to-wheels emissions emitted by the ICE during the vehicle operation over 150000 km.

The use phase contains also the GWP impact of the production of the energy vectors for charging the vehicles storage tanks – the diesel for the fuel tank and the electricity for the charging of the high voltage battery, over 150000 km. This is adding the well-to-wheels aspect of the study. The impact of electricity is considered only for the plug-in hybrid electric vehicles and the range extender vehicles. This means for vehicles equipped with high voltage battery capacity superior to 3 kWh. On that way, the Eq. (9) is detailed in Eq. (10).

$$\begin{aligned} GWP_{weel\text{-}to\text{-}wheel} &= GWP_{total} = GWP_{vehicle\_production} + \\ & GWP_{tank\text{-}to\text{-}wheel\_CO2} + GWP_{diesel\_production} + \\ & GWP_{electricity\_production} \end{aligned} \quad ,\text{kg.}CO_{2eq.} \tag{10}$$

The environomic optimization is defined in Eq. (11):

$$\min(-\eta_{powertrain}(x))Investment\_cost(x)),GWP_{total}(x)), \; x \in X_{decision\ variables} \tag{11}$$

The other three categories of the impact are introduced as well, as environmental objectives to be minimized. Equations (9) to (11) are valid also for the other categories.

The decision variables for the powertrain design are defined in Table 4:

3.2 Multi objective environomic optimization

The solutions of the three objective environomic optimization converged on a Pareto Frontier optimal curve. They are projected in the 2D total GWP – powertrain efficiency vision (Figure 4). This represents the trade-off between the energy consumption and the total GWP impact of the vehicles. From this representation, it is visible that the GWP decreases with the powertrain efficiency. This is due to the reduction of the CO_2 emissions during the driving.

For powertrain efficiencies between 0.25 and 0.35 the electrification of the powertrain reduces the global CO_2 emissions. This corresponds on the families of hybrid electric and plug-in hybrid electric vehicles. The break point of the electrification effect on the GWP occurs on 0.35 % of powertrain efficiency. This corresponds on a battery capacity higher than 13 kWh. From this battery, capacity value the global reduction of the CO_2 emissions is not obvious.

Figure 5 illustrates the correspondence between the high voltage battery capacity and the hybridization ratio of the vehicle. The hybridization ratio is defined as the as the ratio between the electric power and the total power and represents the power contribution of the electric side of the powertrain.

Table 4: Decision variables for powertrain design

Decision variables for design	Range
ICE displacement volume [l]	[0.8-1-1.4-1.6-2.2]
Electric motor rated power [kW]	[1-150]
Battery energy [kWh]	[5-50]
Number of super capacitors [-]	[1-10]

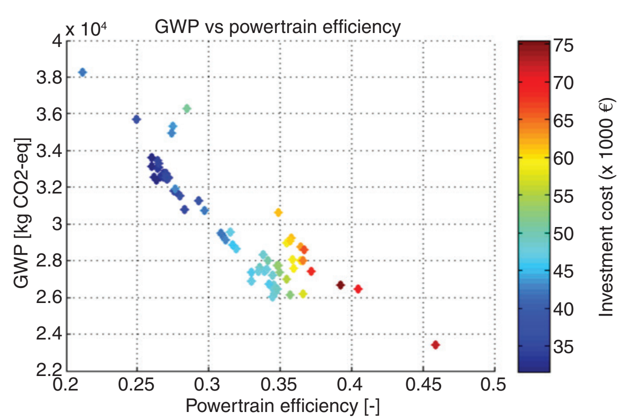

Figure 4: Pareto curve – total GWP to powertrain efficiency, investment cost in color bar, NEDC.

The linear fit between the GWP and the powertrain efficiency is illustrated in Figure 6. It is defined according to the linear Eq. (12). This equation is valid for the domain 25% -50% of powertrain efficiency. A quadratic utility function with balanced weight of the coefficients a and b between the cost and the powertrain efficiency is applied on the Pareto solution from Figure 4. The maximum of the utility function is obtained for points concentrated around values of powertrain efficiency of 35% and investment cost of 45000 € (Figure 7a and 7b). The positive quadratic utility function with balanced techno-economic coefficients shows that utility maximums are in the PHEV zone, between 30% and 35% of powertrain efficiency (Figure 6 and Figure7).

$$GWP = 48749 - 59592 * \eta_{powertrain} \text{ in [kg } CO_2 \text{ eq.]} \quad (12)$$

The total GWP is also related to the investment cost. Figure 7 proposes a macroscopic linear fit of the relation between the total GWP and the vehicle investment cost. The relation is given in Eq. (13). The relation is valid in the domain of 25%-50% of powertrain efficiency.

$$GWP = 38428 - 0.18267 * Investment\_cost_{vehicle} \text{ in[kg} CO_2 \text{eq.]} \quad (13)$$

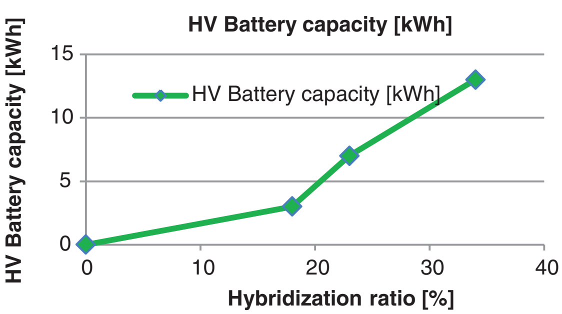

Figure 5: Correspondence between the high voltage battery capacity and the hybridization ratio.

The total GWP decreases with the increasing of the total investment cost. Vehicles with higher powertrain efficiency require higher investment cost. Thus they are less fuel consuming in the operation phase and emit less CO_2 emissions. One can consider that if one maximizes the powertrain efficiency one minimizes the total GWP. The GWP can be considered as an indicator related to the other 2 objectives. This allows simplifying the optimization problem from 3 dimensional to 2 dimensional. The techno-economic optimization brings also optimal environmental solutions in the defined range of decisions variables for hybrid electric vehicles and so defines environomic solutions. The main interest of this conclusion is to simplify the optimization from 3D to 2D techno-economic with activated environmental model, which allows evaluating the environmental impacts of each solution of the techno-economic Pareto curve. The vehicle use phase (including the operation CO_2 emissions and the emissions due to the energy vectors production) is clearly the major contributor to the total equivalent CO_2 emissions, in comparison of the equivalent CO_2 emissions for the vehicle production phase, for powertrain efficiencies between 25% and 35%. The design choices are visible on the impacts of the production phase. With the increasing of the powertrain efficiency over 35% and respectively the hybridization ratio (heavy

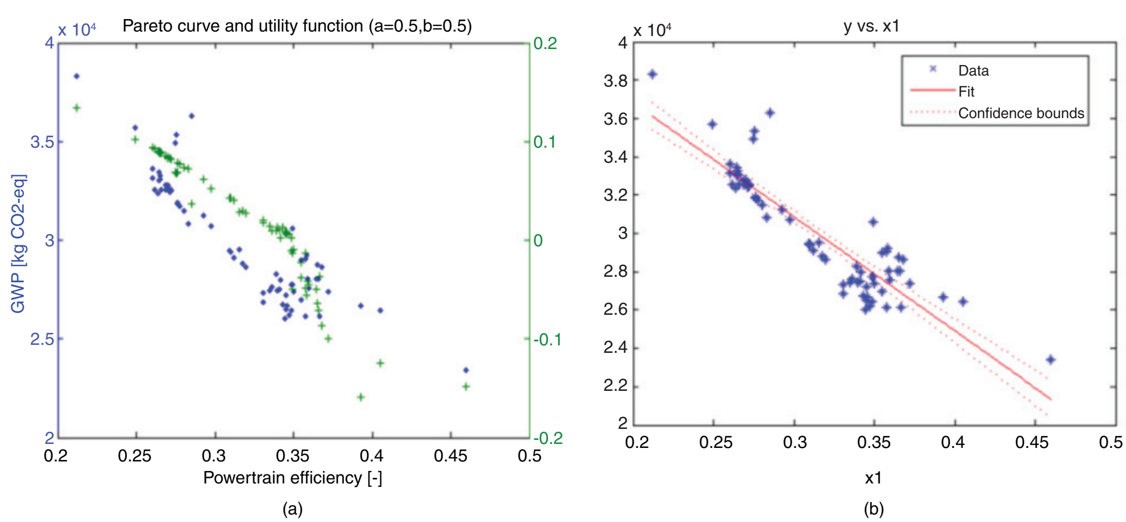

Figure 6: Evolution of the total GWP as a function of the powertrain efficiency a) GWP as a function of the powertrain efficiency, b) linear fit between the GWP and the powertrain efficiency, y = GWP and x_1 = powertrain efficiency

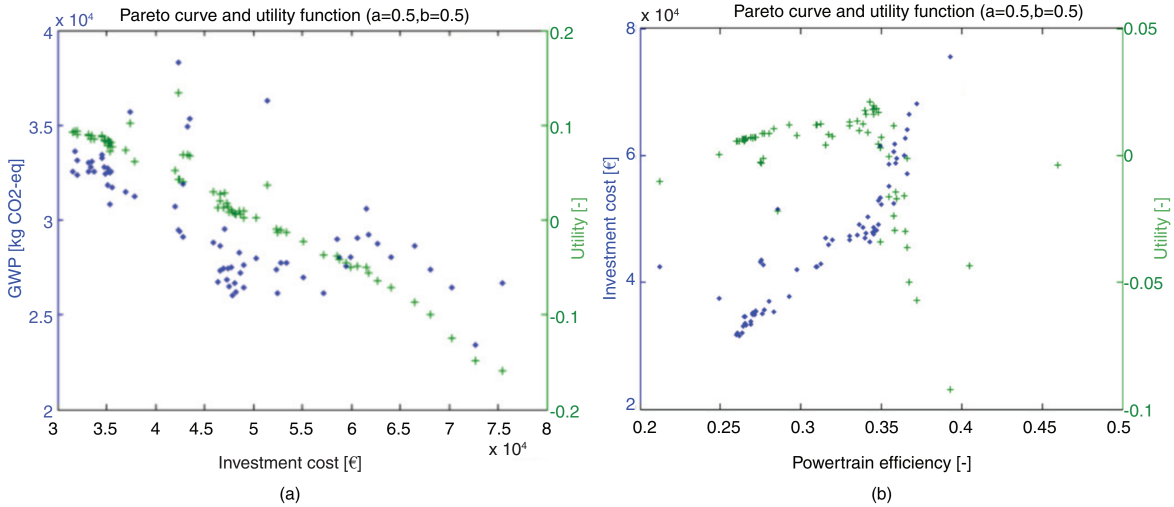

Figure 7: Evolution of a) the total GWP as a function of the vehicle investment cost b) the investment cost as a function of the powertrain efficiency..

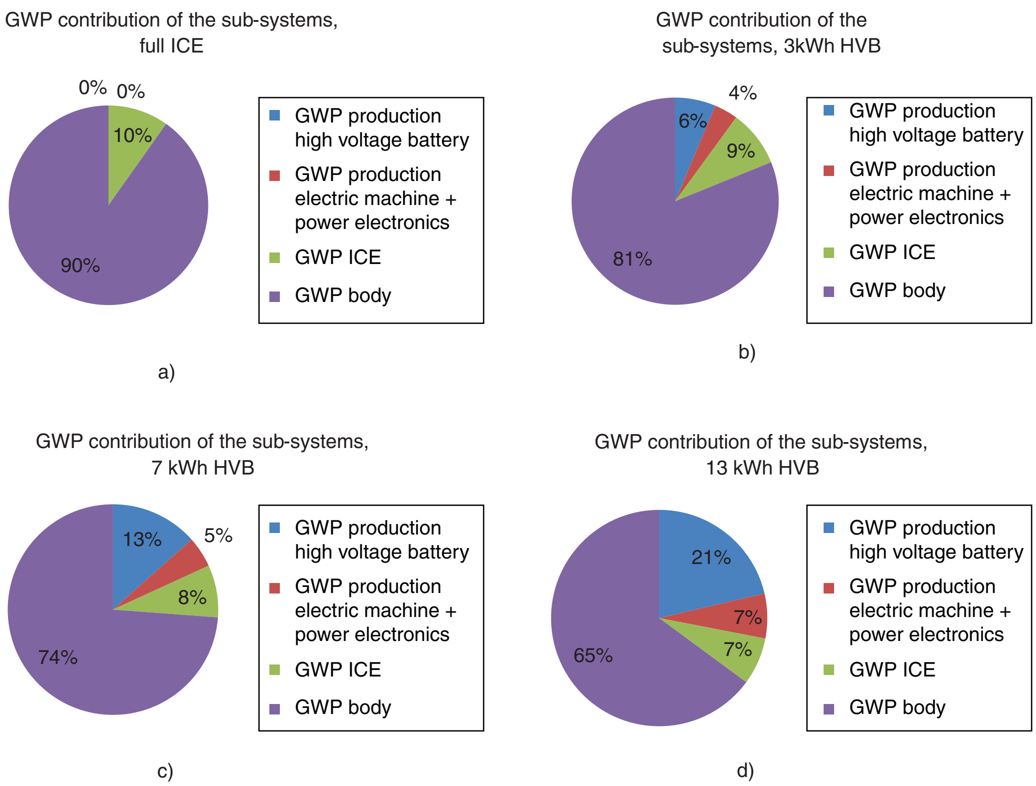

Figure 8: GWP contribution for the production phase of the vehicles sub-systems a)Full ICE, b) 3 kWh of HVB, c) 7 kWh of HVB, d) 13 kWh of HEV

plug-in hybrid electric vehicles and range extenders) and the size of the electric part of the powertrain, the impact of the vehicles production phase increases. This is due to the increasing of the mass of the materials needed for production of the high voltage battery and the electric machine. Orders of magnitude for the total GWP evolution and the repartition of the impact for the different subsystems and for the production phase are given in Figure 8 for different sizes of high voltage battery –this means for different hybridization ratio. The major impact

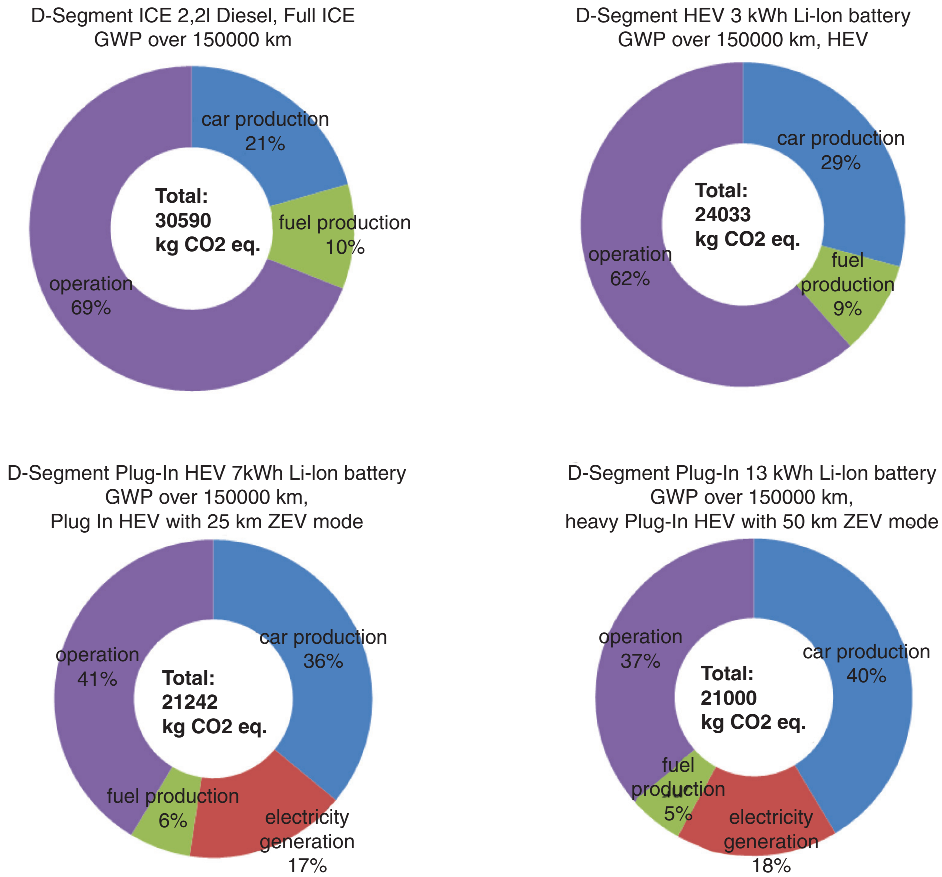

Figure 9: Evolution of the total GWP and repartition of the contribution of reach phase as a function of the hybridization ratio, D –Class vehicles

is due to the body production. The second contributor to the GWP is the production of the high voltage battery and its part increases with the increasing of the on board battery capacity. With the increasing of the electrification of the powertrain, the vehicle mass increases and so the power range of the machine and the associated power electronics also increases. Thus the part production impact of the electric machine and the power electronics increases. As the thermal engine is downsized, its impact decreases with the increasing of the hybridization ratio. The environmental model uses the CML short impact as explained in section 2.3.

Orders of magnitude for the total GWP evolution and the reparation of the impact of the different life cycles phases are given in Figure 9 for different sizes of high voltage battery –this means for different hybridization ratio. The vehicles are considered to be operated in France with European diesel and French electricity mix production. This means that the emissions due to the energy vectors are thus estimated for an optimistic scenario.

The operation of the Plug –In vehicles in countries with high carbon percentage use in the electricity generation (Germany, Poland, and China) will increase the contribution of the equivalent CO_2 emissions, coming from the electricity generation. The functional unit is 150000 km.

3.3 Life cycle impact categories and relations

The environmental model of the computational superstructure uses the CML_01 short impact as explained in section 2. The GWP is one of the categories of this impact but there are also three other categories – the acidification, the eutrophication and the ODP. Figure 11 illustrates the evolution of these categories as a function of the investment cost, thus the powertrain efficiency.

The eutrophication is following the same tendency and increases with increasing hybridization ratio. These two categories are influenced from the vehicles

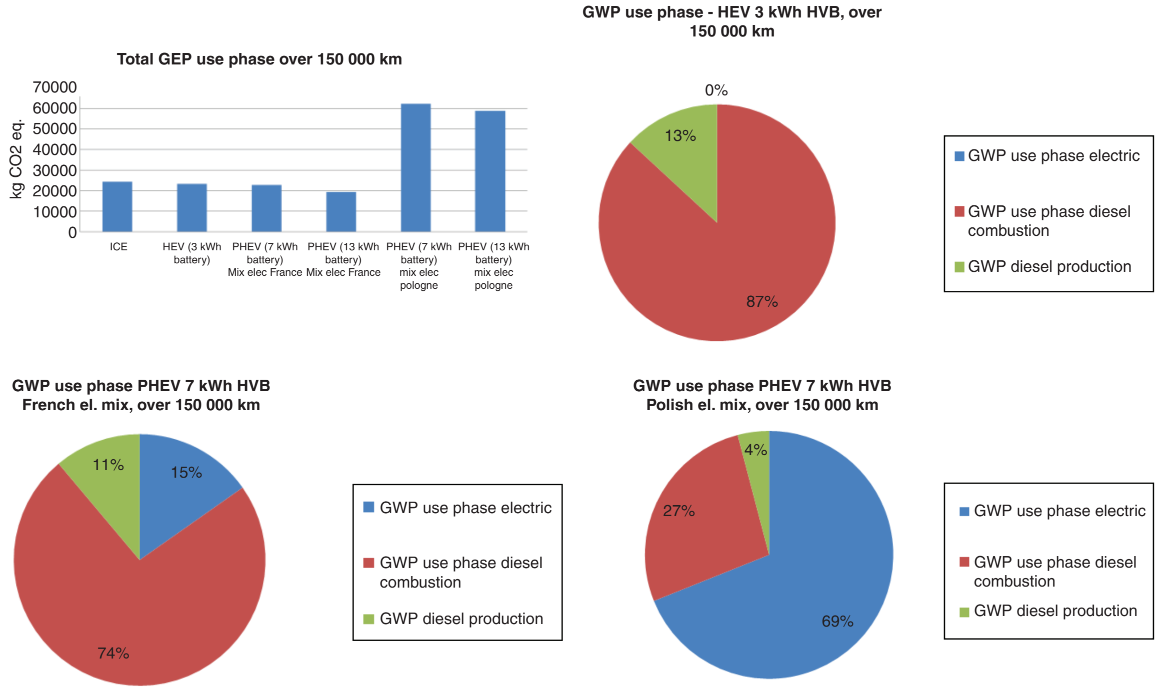

Figure 10: Use phase: GWP evolution as a function of the hybridization ration and contribution of the energy vectors (diesel and electricity production)

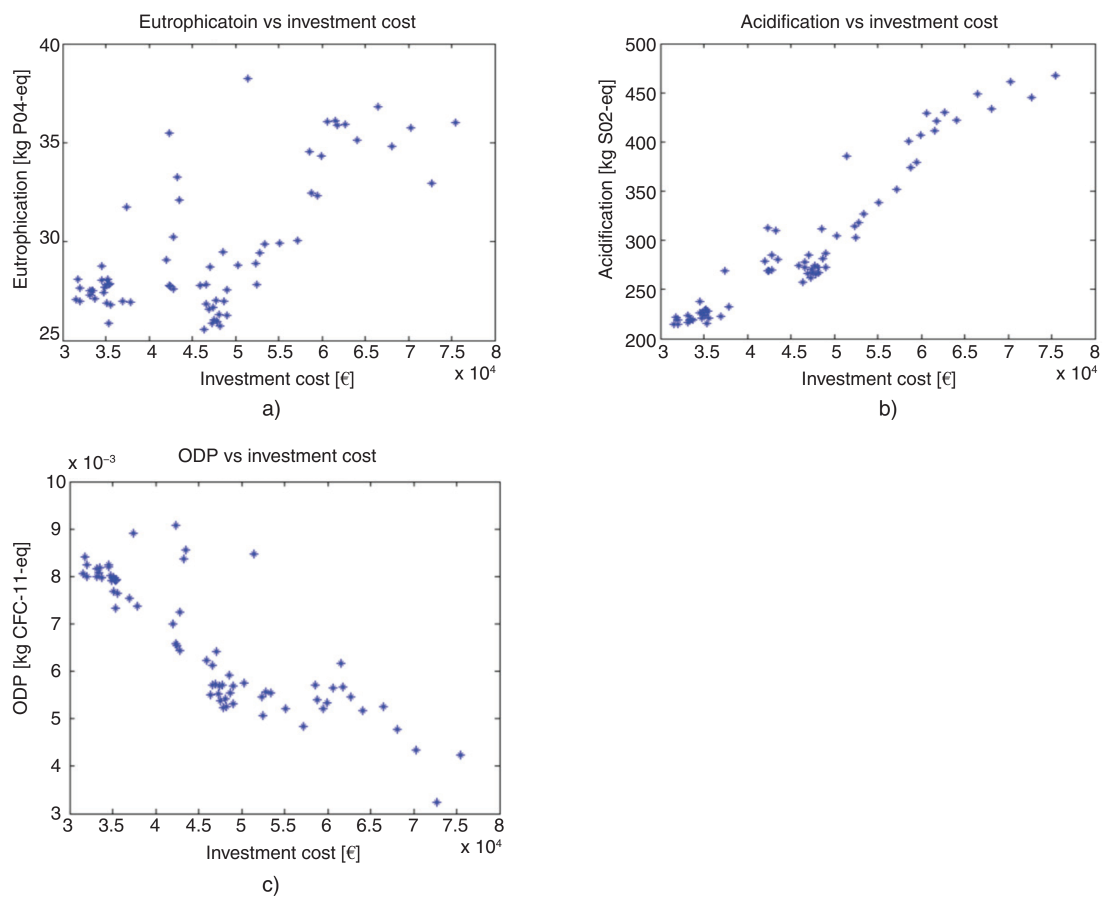

Figure 11. Evolution of the CML impact categories a) eutrophication, b) acidification c) ODP as a function of the investment cost

production phase (Figure 11). On the opposite the ODP category decreases with the investment cost, thus the hybridization ratio (Figure 11).

The acidification is increasing with the powertrain efficiency (hybridization ratio). The main contributors are the increasing material extraction need for bigger size of the high voltage battery and the electric machine. The materials used in the high hybridization ratio vehicles definitions increase and their impact on the acidification impact is visible. The eutrophication is following the same tendency and increases with increasing hybridization ratio. These two categories are influenced from the vehicles production phase. On the opposite the ODP category decreases with the investment cost, thus the hybridization ratio. The ODP is related exactly as the GWP with the vehicle use phase and the use of fossil fuels and prime energy for the energy vectors production.

Thus, when the GWP is minimized, the ODP is also minimized. In the environmental model for hybrid electric vehicles, one can consider that the GWP 100 years is the main impact category and thus simplifies the environmental impact evaluation of the environmental Pareto frontier curve.

The GWP is one of the categories of this impact but there are also three other categories – the acidification, the eutrophication and the ODP. Figure 11 illustrates the evolution of these categories as a function of the investment cost, thus the powertrain efficiency. The acidification is increasing with the powertrain efficiency (hybridization ratio). The main contributors are the increasing material extraction need for bigger size of the high voltage battery and the electric machine. The materials used in the high hybridization ratio vehicles definitions increase and their impact on the acidification impact is visible.

The GWP can be considered as an indicator related to the other 2 objectives. This allows simplifying the optimization problem from 3 dimensional to 2 dimensional. The techno-economic optimization brings also optimal environmental solutions in the defined range of decisions variables for hybrid electric vehicles and so defines environomic solutions. The main interest of this conclusion is to simplify the optimization from 3D to 2D techno-economic with activated environmental model, which allows evaluating the environmental impacts of each solution of the techno-economic Pareto curve. This simplified optimization approach is applied for the definition of environomic designs of hybrid electric vehicles on the customers driving cycles – urban and holiday. The main interest is the reduced computation time.

The relation between the economic investment and the environmental performance was demonstrated through the multi-objective optimization. The investment in the technology improves the efficiency and the reduces the CO_2 emissions. The correlation confirms the link between the economy and the environment. The effort done for the development of efficient energy storage and conversion technologies is sustainable from environmental point of view.

4. Conclusion

This paper presents a powertrain design study on hybrid electric vehicles, considering different vehicle usages through adapted driving profile – normalized cycle. The optimal environomic configurations are researched by using multi objective optimization techniques. The optimization methodology is based on a genetic algorithm and is applied for defining the optimal set of decision variables for powertrain design. The analysis of the environomic Pareto curves on NEDC illustrates the relation between the economic and the environmental performances of the solutions. The life cycle inventory allows calculating the environmental performance of the optimal techno-economic solutions. The environmental and the economic trades-off are defined for the different impact categories. Their impact for the production phase and the use phase of the vehicle is studied. The sensitivity of the impacts categories on the electricity production mix is as well studied.

In a second step the optimization is extended to a three objective optimization, integrating the environmental impacts as objective. The analysis of the evolution of the four impacts categories allows choosing one main environmental category, the GWP, to be minimized.

The analysis of the environomic Pareto curves on NEDC illustrates the relation between the economic and the environmental performances of the solutions. The optimization problem is then simplified from 3 objectives to 2 objectives optimization. The life cycle inventory allows calculating the environmental performance of the optimal techno-economic solutions.

The solutions in the lowest emissions zone show that the maximal powertrain efficiency on NEDC is limited on

Table 5. Parameters and performances bands for the optimal designs on NEDC cycle

Parameters& indicators	NEDC
CO_2 emissions [g/km]	[140–30]
Powertrain efficiency [-]	[0.25–0.45]
Battery capacity [kWh]	[5–50]
EM Power [kW]	[20–50]
ICE displacement [l]	[2.2–0.8]
GWP [kg CO_2 eq]	[3.6 104–2.3 104]
Investment cost [€]	[30000–70000]

45.2% and the minimal tank-to-wheel CO_2 emissions are 30 g CO_2 / km. They have the maximal cost – 75000 Euros.

The increase of the electric part of the powertrain increases all environmental categories, because of the materials and the processes to produce the electric components. The parameters and the performances bands for the optimal designs on NEDC cycle are summarized in Table 5.

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