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Environomic design of hybrid electric vehicles

Zlatina Dimitrova[a] , François Maréchal[a]

[a]Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, zlatina.dimitrova@epfl.ch
[a]Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, francois.machechal@epfl.ch

Abstract:

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 define the powertrain configurations, to estimate the cost of the powertrain equipment and to show the environmental impact of the technical choices. The optimal designs are researched for the new European driving cycle.

Keywords:

Multi-objective optimization, hybrid electric vehicles, environomics

1. Introduction

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 be taken into consideration, not only qualitatively but also quantitatively. Thus, the system can be properly designed and operated. The systematic consideration of thermodynamic, economic and environmental aspects for this purpose is called environomics [1]. During the 70s and 80s, the depletion of energy resources has been one of the primary concerns. Terms like thermoeconomics, exergo economics etc., have been coined to imply the attempts to save energy (exergy) by proper analysis and design of thermal and chemical plants. Environomic analysis is an extension of thermo-economics [2]. In addition to flows of energy, exergy and costs, flows of other resources consumed as well as flows of pollutants enter in the picture. Recently, environomics have been studied also for processes optimization in [3], for CO_2 sequestration process and H_2 production in [4] or district heating networks design in [5]. Gerber in [3] presents a systematic methodology for the integration of LCA in the conceptual design of renewable energy systems using process design, process integration and multi-objective optimization techniques. All these studies are about grid related energy systems.

Recent fuel economy gains have been driven by consumer reaction to rising prices and tightening policy (e.g. CO_2 emissions limits in Europe and CAFE standards in the US). These gains have been made possible thanks to technology improvements. Efficiency gains are likely to be sustained with new car fuel economy in the US, EU and China improving by 2.5%-3% p.a. over the outlook period. The gains come initially from powertrain enhancements (direct injection, stop-start, engine downsizing, boosting) and other measures such as light-weighting followed by the gradual penetration of hybrid powertrains into the vehicle fleet (Figure 1).

By 2035, sales of conventional vehicles fall to a quarter of total sales, while hybrids dominate (full hybrids 23%, mild hybrids 44%). Plug-in vehicles, including full battery electric vehicles (BEVs), are forecast to make up 7% of sales in 2035. Plug-ins have the capability to switch to oil for longer distances and are likely to be preferred to BEVs based on current economics and consumer attitudes towards range limitations.

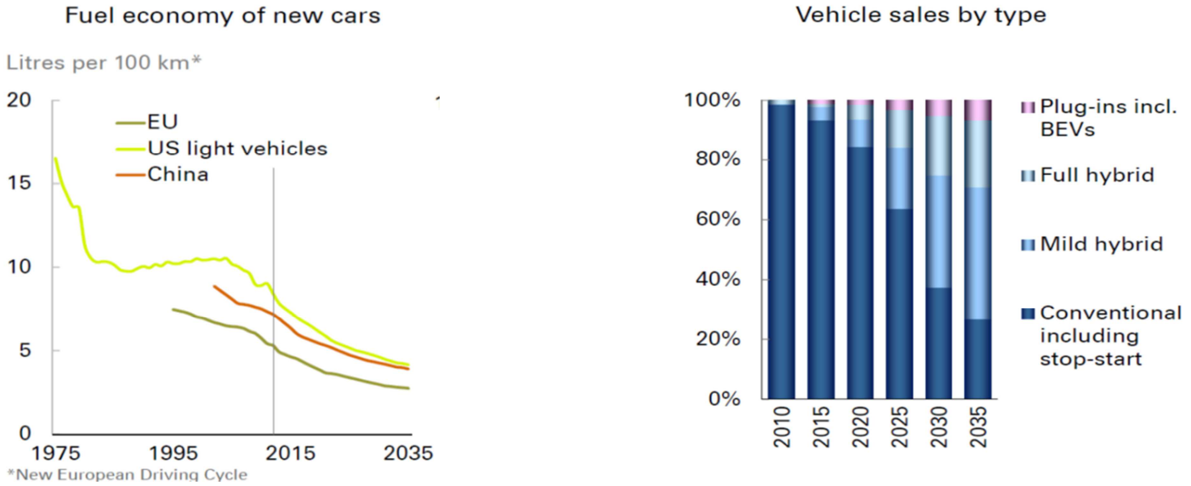

Fig. 1: Future fuel economy of new cars - commercial mix evolution [6]

Many researches are performed on the energy conversion balance on the vehicle board. They are based on analytical methods. Katrasnik proposes in [7] analytically based method to calculate corrected fuel consumption of parallel and series hybrid electric vehicles (HEVs) at balanced energy content of the electric storage devices. The energy conversion phenomena are explained in [8]. Energy flows and energy conversion efficiencies of commercial plug-in hybrid-electric vehicles (PHEV) are analyzed for parallel and series PHEV topologies. The analysis is performed by a combined analytical and simulation approach. Various type models and algorithms derived from simulation and experiment are explained in details in [9]. Finesso et al. focus in [10] on the design, optimization and analysis of a complex parallel hybrid electric vehicle, equipped with two electric machines on both the front and rear axles. Bayindir et al. present in [11] an overview of HEVs with a focus on hybrid configurations, energy management strategies and electronic control units. Poullikkas presents in [12] an overview regarding electric vehicle technologies and associated charging mechanisms is carried out. The review covers a broad range of topics related to electric vehicles, such as the basic types of these vehicles and their technical characteristics, fuel economy and CO_2 emissions, the electric vehicle charging mechanisms and the notions of grid to vehicle and vehicle to grid architectures. In particular three main types of electric vehicles, namely, the hybrid electric vehicles (HEVs), the plug-in electric vehicles (PHEVs) and the full electric vehicles (FEVs) are discussed in detailed.

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. Figure 2 illustrates the generic computational framework for environomic design of a vehicle energy system.

2. Methodology

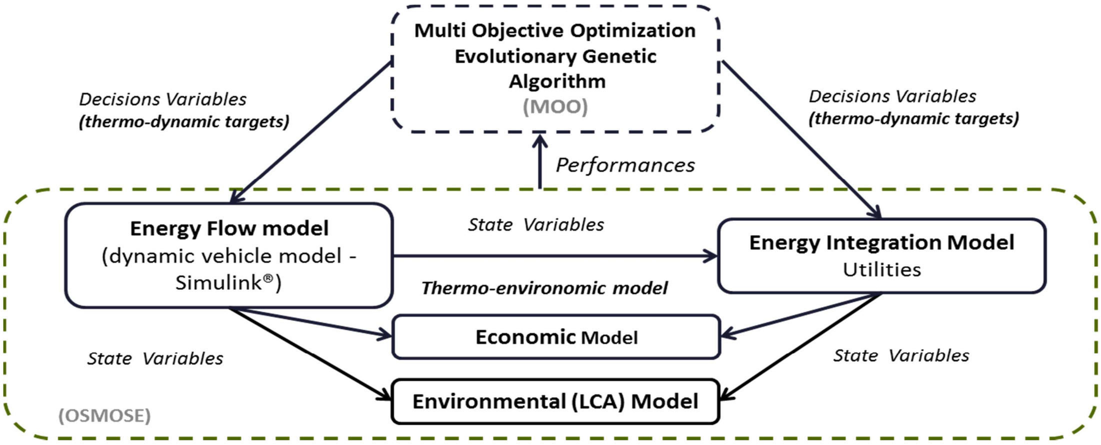

Fig. 2: Computational framework of environomic optimization

The energy integration model uses the results from the dynamic and thermal flows calculations. The optimizer in OSMOSE is based on a genetic algorithm. This optimization technique is multi- modal and gives local optimums. The optimization is decomposed into four major parts – a master multi objective optimization (MOO), a thermo economic simulation (TES), a slave optimization (energy integration - EI), where the energy integration occurs. The last part is the techno-economic evaluation (TEE). The life cycle impact assessment (LCIA) can be used as objective and implemented in the master optimization. Thus the environmental optimization occurs.

2.1 Hybrid electric vehicle dynamic model:

The vehicle simulation tool is 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 level of the model is quasi-static. The vehicle is able to follow dynamic profiles generated from a library of driving cycles. The model has a loop energy management structure, linked to the required mechanical power, to follow the dynamic cycle. This energy management loop is called “back and forward” and allows, for a given design of the vehicle powertrain to simulate the energy consumption of the vehicle, on the given driving profile. The energy flow is computed *backwards* from the wheels to the energy sources. Proceeding in this manner insures the flexible and fast nature of the simulations. This is an important advantage for an optimization study. However the quasi-static approach is limited in its non-causality. The main characteristics of the hybrid electric simulation model are given in Table 1.

Table 1. D- Class vehicle characteristics

Sub-System	**Characteristic**	**Value**
Vehicle	Nominal mass [kg]	1660
Gear box	CVT efficiency [-][15]	0.84
	MGB efficiency [-]	0.95
	6 gears	
Engine	Displacement [l]	2.2
	Number of cylinder	4
	Rated power [kW]	120
	Max. speed [rpm]	4500
	Max. Torque [Nm]	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 model is based on a commercial D class diesel hybrid electric vehicle. Some adaptations due to the optimization predisposal and the non-normalized driving cycle's evaluations are done. The results coming from the model in one run simulation are compared with commercial vehicles performances in Table 2:

Table 2. Model validation

CO_2 emissions [g/km]	ICE 2.2 l Diesel	HEV with 2.2 l Diesel
Simulation	151	93
Commercial vehicles [19]	154	95

The difference is less than 10% and this could be acceptable for an optimization study. Figure 3 illustrates the generic units that are modeled in the vehicle powertrain and the backwards approach to estimate the energy consumption. The detailed presentation of the HEV model including the energy distribution strategy is presented in [16].

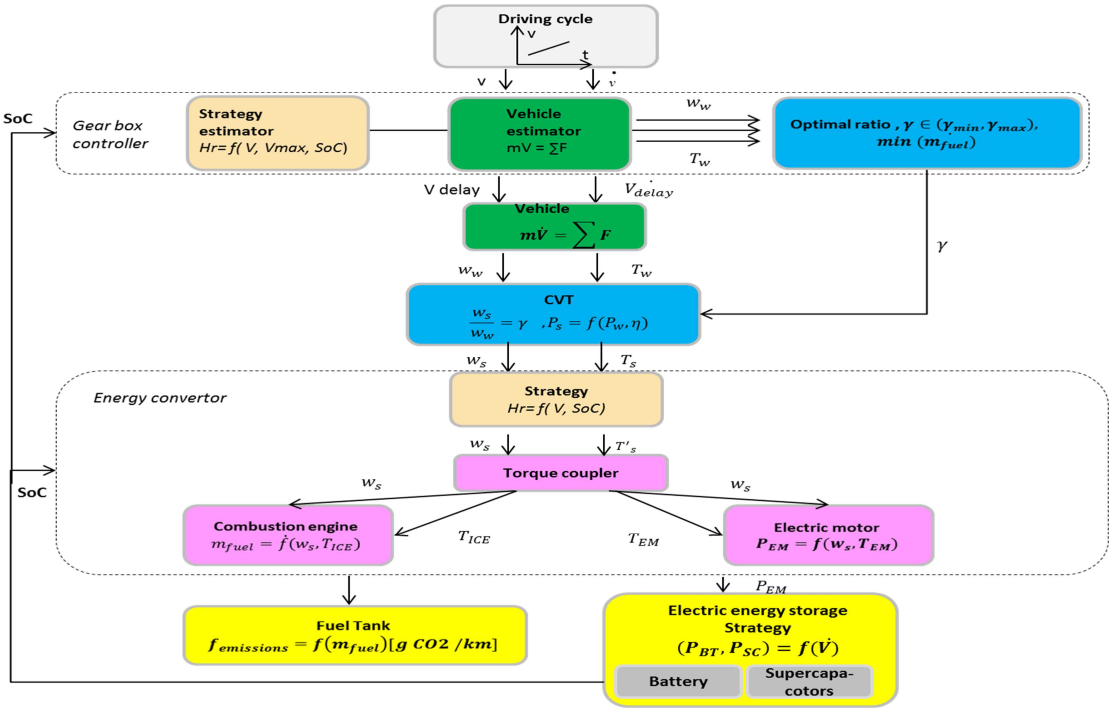

Fig. 3 : Quasi- static model of the parallel thermal electric hybrid

2.2 Vehicle cost model:

The cost of the vehicle is computed 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. The Table 3 summarizes the cost equations.

Table 3. Equations for the economic model

Components	**Costs [€]**	
Converters		
Electric motor [106]	30 [€/kW]*P_{EM} [kW]	(1)
Thermal engine [106]	15 [€/kW]*P_{TE} [kW]	(2)
Storage system		
Battery [106]	600*[€/kWh]*$q_{bat}^{0.2477*\log(bat_{specifmass}(battpe)+0.5126}$ [kWh]	(3)
Supercapacitor [106]	15 [€/kW]* P_{SC} [kW]	(4)
Body		
Nominal cost (car shell)	17.3*car_shell_mass[kg]-3905.4 [€]	(5)
Vehicle use in France 2013 [17]		
Electricity household	0.14269 [€TTC/kWh]	
Electricity industry	0.07768 [€TTC/kWh]	
Gasoline	1.645 [€/L]	
Diesel	1.451 [€/L]	

The cost of the electric motor includes the cost of the power unit. The battery cost is sensitive to the battery type and the energy storage capability of the material. The nominal cost represents the vehicle shell cost, without the powertrain components. This linear correlation (5), (Table 3) takes into account the price of the parts and the manufacturing cost of the vehicle shell and includes the margin of the carmaker. The correlation is built using the official customer prices for different vehicle classes and illustrates the link between the increasing cost and the increasing size and mass of the vehicle (Figure 4). The car shell is defined as a completely equipped vehicle (body, interior equipment, wheels), except the powertrain.

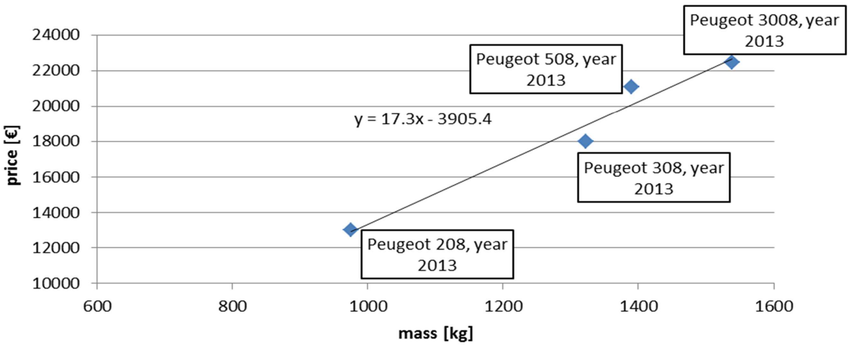

Fig. 4: Linear correlation between the car shell mass and price

For each calculation, a new vehicle mass is calculated and updated with the mass of the defined powertrain.

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

$Cost_{powertrain=} Cost_{ICE} + Cost_{EM} + Cost_{battery} + Cost_{supercapacitors}$ in [€] (6)

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

2.3 Environmental model:

In this work the Life Cycle Assessment is applied as an indicator for the vehicle energy system design. The literature shows that the functional unit for LCA vehicle study is to transport persons on 150000 km for 10 years [18] and this functional unit is also used for the study.

This study refers to one category from the CML short impact, used from the most part of the automotive industry, the Global Warming Potential (GWP) 100 years. The life cycle of a product, a system or a service has usually three distinct successive phases: the production phase, the use phase and the end-of-life phase. The vehicle unitary processes and flow diagram are defined in Figure 5. The unitary processes and the raw materials for the production of the parts come from the Eco Invent® database. The vehicle 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 carrier" production comes from the Eco Invent® database (Table 4).

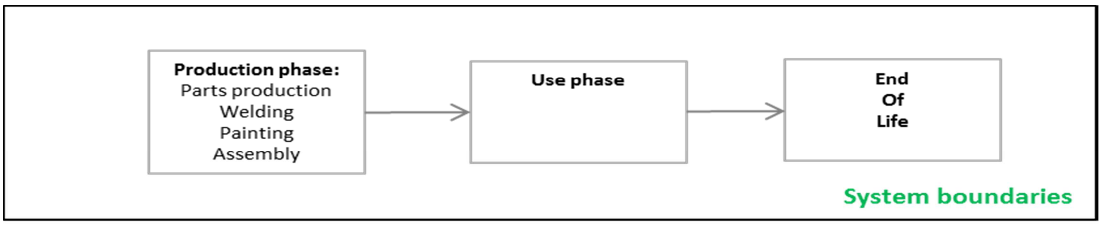

Fig. 5. Vehicle unitary processes flow chart – system definition

The end-of-life phase is represented by the average car disposal process, issued by the Eco Invent® database. The vehicles are considered operated in France with the French electricity mix.

Table 4. Energy vectors database (data of 2005) (EcoInvent Data base)

Energy vector	Eco Invent process number	Description
Electricity	Nuclear (France) #700	77% Nuclear, 12% hydro

2.4 Vehicle driving cycles

Commercial vehicles are characterized on the current normalized driving cycle – New European Driving Cycle (NEDC). This cycle has an urban and extra urban part with repetitive patterns of low accelerations and constant speeds. Table 5 summarizes the characteristics of the driving cycles used in this study.

Table 5. Drive cycles characteristics

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

3. Results – multi objective environomic optimization

3.1 Problem definition:

A hybrid vehicle with multiple propulsion systems can be operated independently or together. The model contents are the electric machine, battery, supercapacitors, thermal engine and fuel tank, with diesel fuel. The thermal electric hybrid powertrain model characteristics are given in Table 1. The vehicle model represents a commercial D-class [19] vehicle with a diesel electric powertrain (Figure 6). In this study, instead of defining one vehicle with a set of parameters and then studying its performances over various driving cycles, the opposite is done. It is the usage of the vehicle that is the starting point of the study – the new European driving cycle. For this use, the powertrain components and the energy management parameters are optimized. The objective is to size the components of the hybrid powertrain, the converters and the storage tanks, and to define optimal operating strategy regarding the energy consumption and the cost objectives.

A multi objective optimization with 3 objectives is considered to define design solutions optimal from efficiency, economic and environmental point of view.

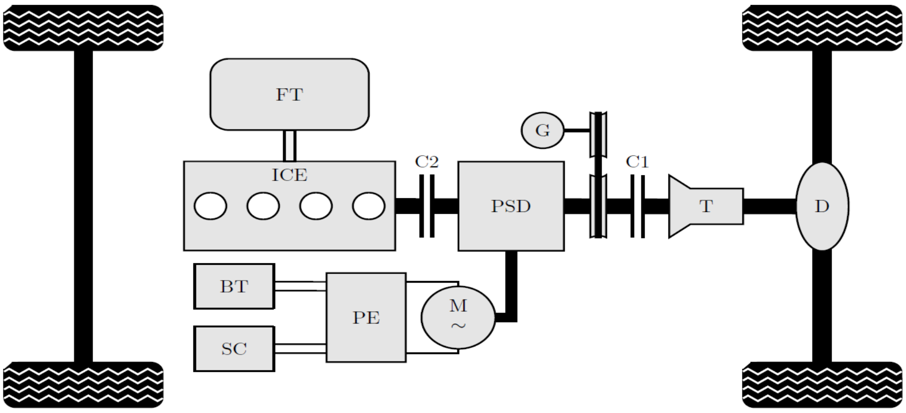

Fig. 6: Parallel hybrid electric architecture: FT – fuel tank, ICE – internal combustion engine, BT – high voltage battery, SC – super capacitor, PE – power electronics, M- electric motor, PSD – power split device, G – electric generator, C1- clutch 1, C2- clutch 2, T- Transmission, D- Differential

After each iteration of the model, the mean powertrain efficiency in traction is calculated according (8):

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

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 recomputed for each iteration of the decision variables. The vehicle cost is defined in equation (5) of the Table 3.

The GWP 100 years is the category considered as environmental objective 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) and is defined over the life cycle functional unit of 150000 km. The end of life is neglected.

The following equation 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. To add the wheel-to-wheels aspect 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. The impact of electricity is considered only for the PHEV and REX vehicles, this means for vehicles equipped with high voltage battery capacity superior to 3 kWh. So the equation (9) is detailed in equation (10).

$$\begin{aligned} GWP_{weel-to-wheel} &= GWP_{total} = GWP_{vehicle\_production} + GWP_{\tan k-to-wheel\_CO2} + \\ &GWP_{diesel\_production} + GWP_{electricity\_production} \end{aligned} \text{ in kg. } CO_2 \text{ eq.} \tag{10}$$

Thus the environomic optimization is defined as:

$$\min(-\eta_{powertrain}(x)) Investment\_\cos t(x), GWP_{total}(x)), \ x \in X_{\text{decision variables}} \tag{11}$$

The decision variables for the powertrain design are defined in Table 6:

Table 6. 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]

3.2 Multi objective environomic optimization

The solutions of the three objective environomic optimization converged on a Pareto Frontier optimal curve (Figure 7), representing the trade-off between the energy consumption and the cost and the total GWP impact of the vehicles on normalized driving cycle. The 3D Pareto curve is projected in the 2D total GWP –powertrain efficiency vision (Figure 8). From this representation one can see that the GWP decreases with the powertrain efficiency. 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 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.

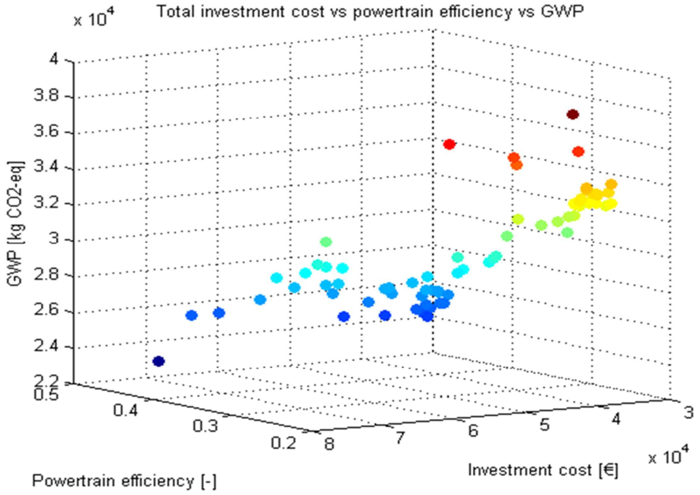

Fig. 7. 3D Pareto frontier curve: environomic optimization, NEDC cycle

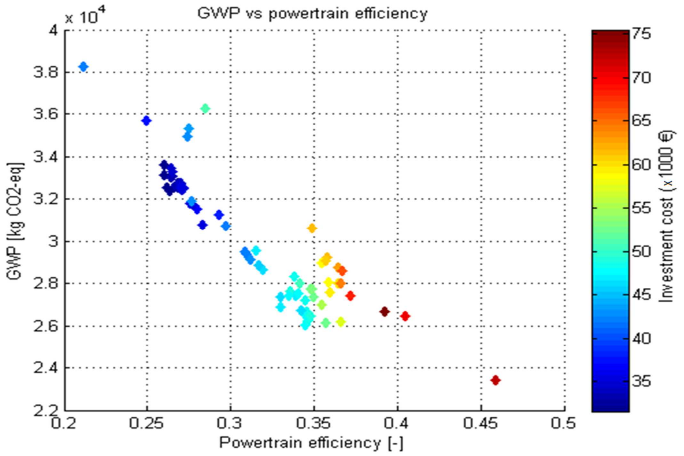

Fig. 8. Pareto curve – total GWP to powertrain efficiency, investment cost in color bar, NEDC

The functional unit is 150000 km. The total GWP decreases with the increasing of the total investment cost (Figure 8), because vehicles with higher investment cost have higher powertrain efficiency. 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. 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.

4. Conclusion

This article 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.

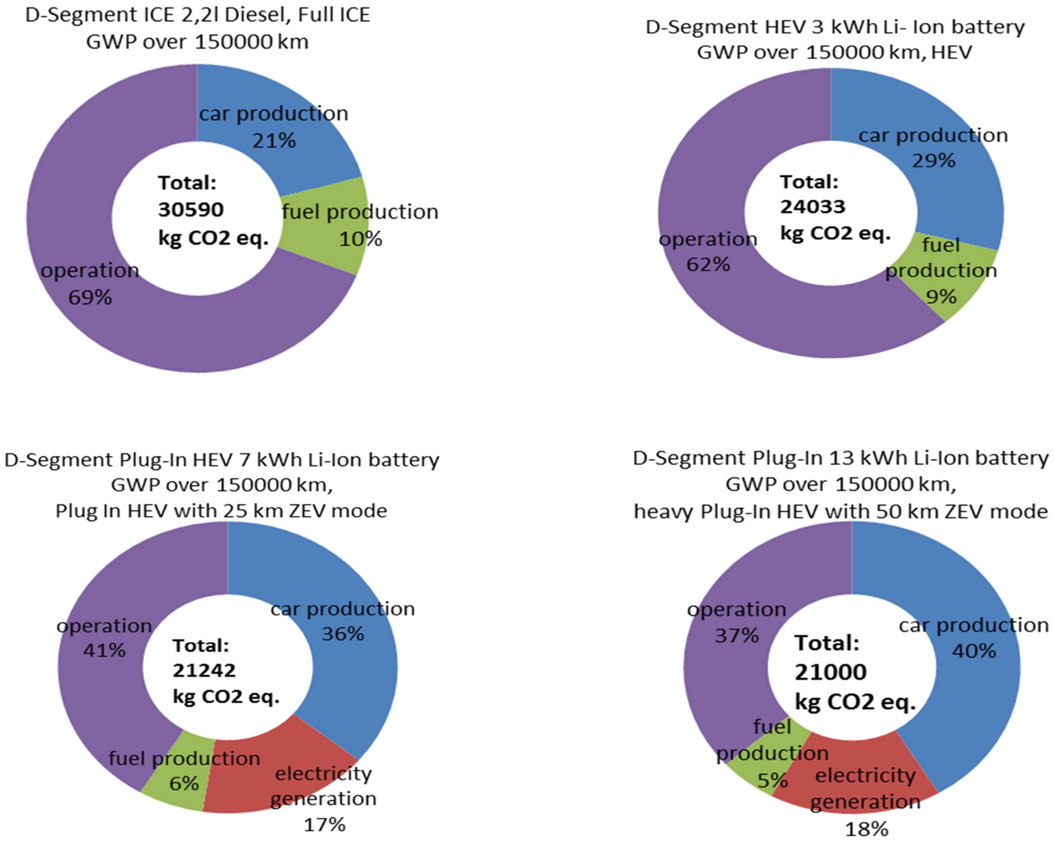

Fig. 9. Evolution of the total GWP and repartition of the contribution of reach phase as a function of the hybridization ratio, D –Class vehicles

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 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 parameters and the performances bands for the optimal designs on NEDC cycle are summarized in Table 7.

Table 7. Parameters and performances bands for the optimal designs on NEDC

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 10^4-2.3 10^4]
Investment cost [€]	[30000-70000]
Optimal annualized cost [€/year]	6516

Finally, a D-Class vehicle has to combine optimal solutions for antagonist usages – urban and long way drives. A compromise for that can be a hybrid electric vehicle with powertrain efficiency of around 30% and cost of 45000 Euros.

Acknowledgments

I would like to thank Professor François Maréchal for the technical support.

Nomenclature

Abbreviations

CAFE	Corporate average fleet emissions
CVT	Continuous variable transmission
ICE	Internal combustion engine
MGB	Manual gear box
SoC	State of charge
H_r	Hybridation ratio, -
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

Greak letters

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

Subscripts and superscripts

BT	battery
EM	Electric machine
s	shaft
SC	Supercapacitor
w	wheels

References

[1] C.A. Frangopoulos, 1983, “Thermoeconomic Functional Analysis: A Method for Optimal Design or improvement of Complex Thermal Systems, “Ph.D. Thesis, Georgia Institute of Technology, Atlanta, USA.

[2] El- Sayed, Y. M. and Evans, R. B., 1970, “Thermoeconomics and the Design of Heat Systems” Journal of Engineering for Power, Vol. 92, No. 1, pp. 27-35.

[3] L. Gerber, 2012, Integration of life cycle assessment in the conceptual design of renewable energy conversion systems, Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

[4] L. Tock, 2013, Thermo-environomic optimization of fuel decarbonization alternative processes for hydrogen and power production, Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

[5] S. Fazlollahi, 2014, Decomposition optimization strategy for the design and operation of district energy systems, Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

[6] BP Energy outlook to 2035, edition 2014,

http://www.bp.com/content/dam/bp/pdf/Energy-economics/Energy-Outlook/Energy_Outlook_2035_booklet.pdf, accessed on 30.04.2015

[7] T. Katrašnik, Analytical method to evaluate fuel consumption of hybrid electric vehicles at balanced energy content of the electric storage devices, Applied Energy, Volume 87, 2010, Pages 3330-3339

[8] T. Katrašnik, Energy conversion phenomena in plug-in hybrid-electric vehicles, Energy Conversion and Management, Volume 52, 2011, Pages 2637-2650

[9] M.A. Hannan, F.A. Azidin, A. Mohamed, Hybrid electric vehicles and their challenges: A review, Renewable and Sustainable Energy Reviews, Volume 29, 2014, Pages 135-150

[10] R. Finesso, E. Spessa, M. Venditti, Layout design and energetic analysis of a complex diesel parallel hybrid electric vehicle, Applied Energy, Volume 134, 2014, Pages 573-588

[11] K. Çağatay Bayindir, M. Ali Gözüküçük, A. Teke, A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units, Energy Conversion and Management, Volume 52, 2011, Pages 1305-1313

[12] A. Poullikkas, Sustainable options for electric vehicle technologies, Renewable and Sustainable Energy Reviews, Volume 41, January 2015, Pages 1277-1287

[13] Z. Dimitrova, F. Maréchal, Environomic design of vehicle energy systems for optimal mobility service, Energy, Volume 76, 1 November 2014, Pages 1019-1028

[14] Z. Dimitrova, F. Maréchal, Environomic design of vehicle integrated energy systems-application on a hybrid electric vehicle energy system, CET, volume 39, 2014, p. 475-480, DOI:10.3303/CET1439080

[15] CVT Nissan technology http://www.nissanglobal.com/EN/TECHNOLOGY/OVERVIEW/cvt.html, accessed on 20.10.14

[16] Z. Dimitrova, F. Maréchal, Techno-economic design of hybrid electric vehicles, Energy Journal (2015)

[17] French government, 2013, Sustainable development statistics e.g. (Statistiques de développement durable), <www.statistiques.developpement-durable.gouv.fr/energie-climat/s/prix-energies.html>, accessed 03.06.2013

[18] S. Richet, P. Tonnelier, 2013, PSA Peugeot Citroën, internal unpublished report, PSA Peugeot Citroën, Vélizy, France.

[19] La centrale, fiche technique de la Peugeot 508 SW, http ://www.lacentrale.fr/fiche-technique-voiture-peugeot-508-sw+2.2+hdi+204+fap+gt+bva6-2014.html, accessed on 17.09.14