

# Vehicle propulsion systems design methods

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**Abstract.** To meet the targets of sustainable development and greenhouse emission reduction of the future vehicles fleet, the automotive industry needs to deploy cost-competitive and efficient advanced energy conversion systems for the future commercial personal vehicles. The efficiency improvement needs induce to search new structured methodologies allowing the integration of the efficiency/cost vision for different vehicle energy technologies, in the earlier design stage of the new vehicles and their propulsion systems. This article proposes a method to compare systematically different vehicles design options under different economic and environmental scenarios. The proposed methodology combines flowsheeting vehicles models, energy integration techniques, economic evaluation and life cycle assessment in a computational platform. The methodology is applied on electric vehicles and hybrid electric vehicles. This article presents the application of a systematic environomic optimization for vehicle energy systems. The efficiency, economic and environmental performances are assessed for different energy technology options and their integration in advanced vehicles powertrains. The performances indicators are compared and the trade-off are assessed to support decision making and to identify optimal energy systems configurations.

## 1 Introduction

The mobility is important for the economic and social development of the population, but also has to respect the environment. Many efforts from the research and the industry came to improve the efficiency of the vehicles, their comfort and security. The modern vehicles are characterized by low emissions and diversification of the powertrain for the energy integration adaptation. The new energy systems are more complex – additional electric motors, storage devices, torque converters and etc. are added with the intention to improve the system behavior [1]. For such complex system the heuristic design approaches fail. In this context the aim of the article is to propose and employ mathematical models and to use these models in a systematic model-based approach for powertrain design. In the traditional energy scenario by 2040, 90% of the global transportation will run on liquid petroleum based fuels [2]. The proliferation of hybrid and other advanced vehicles, along with the improvement of the conventional vehicle efficiency, will result in a flattening demand in petrol for personal transportation even as the number of personal vehicles in the world doubles [2].

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, are forecast to make up 7% of sales in 2035. Alternative fuels should be prospected for reducing the CO<sub>2</sub> impact of transport but also others environmental impacts have to be taken into account through an integrated approach based on the

Well-to-Wheels analysis and Life Cycle Assessment (LCA) tools.

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 [3]. 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 [4]. Many researches are performed on the energy conversion balance on the vehicle board. They are based on analytical methods. Katrasnik proposes in [5] 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 [6]. 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 [7]. Frequently they are based on quasi-static and or dynamic models of the vehicles. The

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design of the converters and the stockers is optimized for global best tank-to-wheel efficiency. Genetic algorithms are mostly used for the design optimizations. Eren et al. in [8] deal with optimal sizing of HEV and propose a methodology for the optimization of HEV components using the multi-objective approach considering the minimization of operating cost, weight and volume simultaneously. In this work, it is proposed to use an optimization methodology to design environomic vehicle energy systems. This integrated methodology is needed to guide the evaluation of different energy vectors and vehicles propulsion systems combinations.

## 2 Methodology

The developed methodology combines flowsheeting models of technologies, energy integration techniques, economic evaluation and life cycle assessment in a computational platform. Multi-objective optimization techniques are used to explore the superstructure possibilities and to find the optimal design solution. The master optimization is done by using a genetic algorithm and mixed integer nonlinear programming. Such an integrated approach is innovative in comparison of the traditional heuristic design engineering method, based on iterations of designs and their cost evaluation. Fig. 1

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

The superstructure contains a physical vehicle simulation model, with dynamic and thermal layouts. The cost equations are written in the economic model. The optimizer is based on a genetic algorithm. The optimization is decomposed into four major parts – a master multi objective optimization (MOO), a thermo economic simulation, a slave optimization (energy integration), where the energy integration occurs. The last part is the techno-economic evaluation. **Master Optimization:** The set of decision variables includes the types and the size of the equipment. The master optimization 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 (Fig. 2). **Thermo-economic simulation:** in a second step the thermodynamic and economic state of the selected equipment is calculated by using a thermo-economic simulation models. **Economic evaluation:** the selected superstructure in the master level and the result of the slave optimization are used in the techno-economic evaluation phase to calculate objective functions of the master optimization – cost, and CO<sub>2</sub> emission. The multi-objective optimization results converged to the Pareto frontier curve.

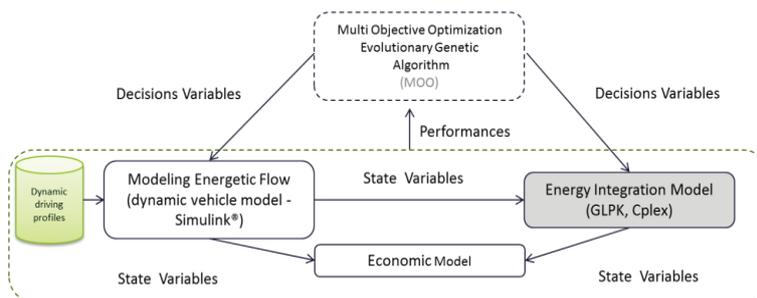


Fig. 1. Computational framework of environomic optimization.

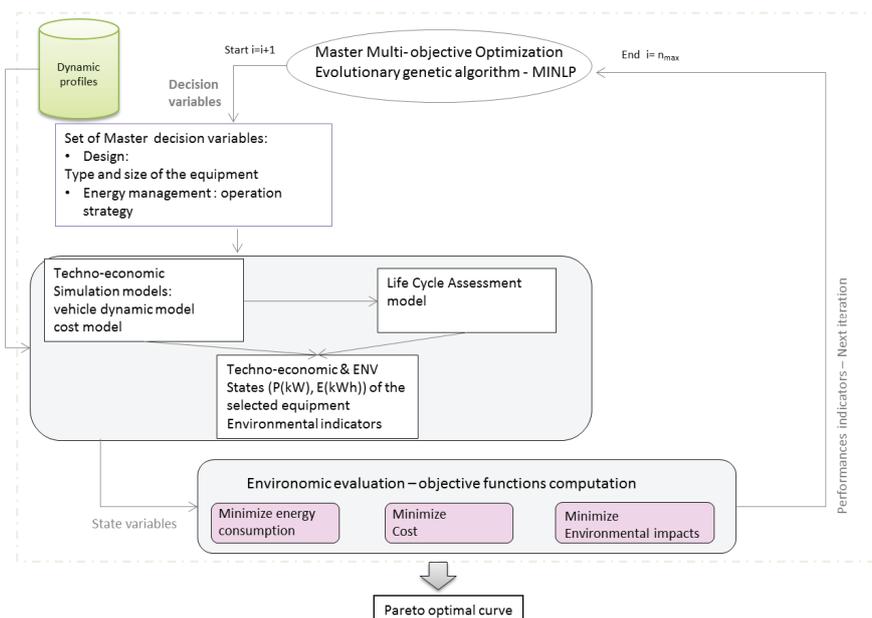


Fig. 2. Structure for multi-objective environomic optimization.

This article considers only the environomic optimization. The energy integration could be also activated in the superstructure. The energy integration method is presented in additional articles [9], [10], [11], and uses principles of energy and exergy analysis described in [12] for waste heat recovery from the cooling system and exhaust gases of the thermal engine.

### 2.1 Vehicles simulation models

The model components are modeled using differential equations and constitute the powertrain architecture. On the powertrain architecture a backwards approach is applied to estimate the energy consumption (Fig. 3). The energy flow is computed from the wheels to the energy sources.

**Driving cycle:** the input of the model is a predefined speed profile. The profile also defines the gear engaged along the cycle. **Vehicle model:** the vehicle model uses Newton’s second law of motion to compute the traction force at the wheels  $F_t$  at every time step of the speed profile in order to find the power demand. It takes into account the rolling and the aerodynamic resistance and the uphill force if driving a slope. **Transmission model:** A transmission is used between the wheels and the energy converter to adapt the speed and the torque levels. The major part of the vehicle transmissions are 5 and 6 speed manual gear boxes. The gear ratio is imposed just in the New European Driving cycle (NEDC). More complex transmission such as continuously variable transmission (CVT) is also modeled. The advantage of the CVT is to choose the optimal fuel consumption gear ratio for every given drive profile. This is very suitable for customer’s drives profiles. **Energy converters:** The energy converter transforms the energy (chemical or electrical) from the energy storage unit into mechanical power. As the dynamics of these converters can be complex the modeling is simplified using efficiency maps. These maps are obtained by measurement on test bench and usually represent the conversion efficiency as a function of the load and the speed demand of the primary shaft.

### 2.2 Vehicles 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 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 1) 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 [14]. The car shell is defined as a completely equipped vehicle (body, interior equipment, wheels), except the powertrain. All symbols in the equations are explained in the nomenclature.

**Table 1.** Equations for the economic model.

Components	Cost [€]
Electric motor [13]	$30 [€/kW] \times P_{EM} [kW]$ (1)
Thermal engine [13]	$15 [€/kW] \times P_{TE} [kW]$ (2)
Battery [13]	$600[€/kWh] \times 0,2477 \log(battery_{specific\ mass} (bat\_type) + 0,5126q_{bat}) [kWh]$ (3)
Supercapacitor [13]	$15 [€/kW] \times P_{SC} [kW]$ (4)
Nominal cost (car shell)	$17,3 \times car\_shell\_mass[kg] - 3905,4 [€]$ (5)
Electricity household [14]	$0,14269 [€/kWh]$
Diesel [14]	$1,451 [€/L]$

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

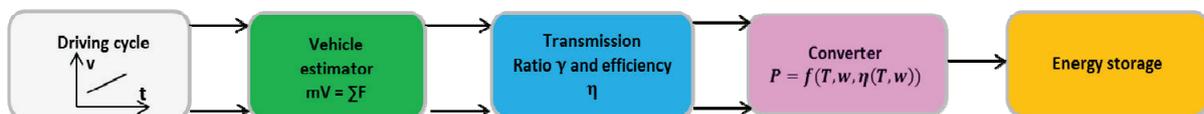
$$Cost_{powertrain} = Cost_{ICE} + Cost_{EM} + Cost_{battery} + Cost_{supercapacitors} \quad (6)$$

$$Cost_{vehicle} = Cost_{powertrain} + Cost_{car\_shell} \quad (7)$$

### 2.3 Environmental model

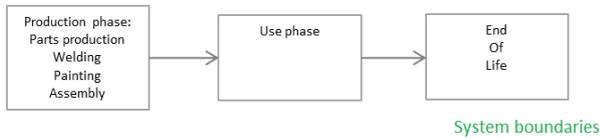
In this work the Life Cycle Assessment (LCA) is applied as an indicator for the vehicle energy system design. The results of LCA are used to communicate on ecological labels and to demonstrate the CO<sub>2</sub> print improvement due to the introduction of new technologies: the powertrain efficiency progress or the light weighting of the vehicles, using new materials and innovation production processes. The literature shows that the functional unit for LCA vehicle study is to transport persons on 150000 km for 10 years [16] and this functional unit is also used for the study.

This study refers to one category from the CML short impact [17], used from the most part of the automotive industry, the Global Warming Potential (GWP) 100 years. The vehicle unitary processes and flow diagram are defined in Fig. 4 and includes three distinct successive phases: the production phase, the use phase



**Fig. 3.** Backwards simulation approach.

and the end-of-life phase. The life cycle inventory of the unitary processes is considered from the EcoInvent® database and from industrial data, concerning the vehicles production plants.



**Fig. 4.** Vehicle unitary processes flow chart – system definition.

### 3 Results—Application on electric and hybrid electric vehicles

#### 3.1 Problem definition – environomic design of electric vehicles

In this paragraph a multi- objective optimization is performed for electric cars. The environmental impacts are chosen as optimization functions, in addition to the cost and the efficiency. The environomic optimization is applied and discussed for electric vehicles. The environmental impact category GWP (Global Warming Potential) is coming from the LCA model as performance indicator in the superstructure, and is used as an objective function. The decision variables are defined in Table 2:

**Table 2.** Decisions variables for design – multi-objective optimization problem.

Electric propulsion system components	Range	Unit
Electric machine	[15-50]	kW
Battery Ni-MH, 30 Wh/kg	[10-50]	kWh
Number of super capacitors in a parallel structure	[0-5]	[-]
Max Power of super capacitors	87,5	kW

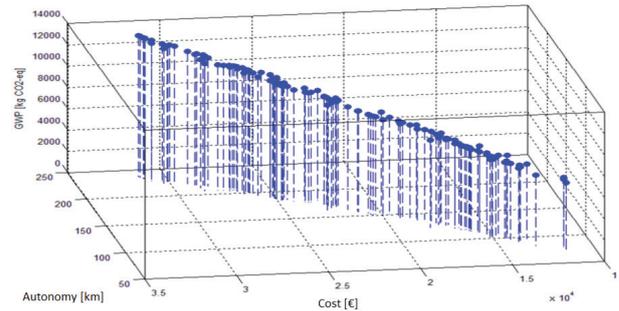
The electric propulsion components are defined as decision variables for the design of the system. The optimization function  $p$  is defined in the equation (8):

$$p = \left( \min(Cost(x), Env\_impacts(x), -Autonomy(x)), \right)_{x \in X_{Decision\_Variables}} \quad (8)$$

The Pareto curve is displayed in Fig. 5.

There is a correlation between the autonomy, the cost and the battery energy capacity. The major impact of the cost comes from the battery size, proportional to the battery energy. The coefficient of proportionality between the cost and the energy in the battery is 600 €/kWh. The cost-GWP plane allows visualizing the dependency between the cost and the GWP. There is a linear correlation with a positive slope. The cost optimum is reached with the GWP one. It enables to consider the cost or the GWP as the second objective for the multi-objective optimization, the first objective being

the autonomy to maximize. Furthermore one can reduce the dimension of the optimization problem from 3 to 2.

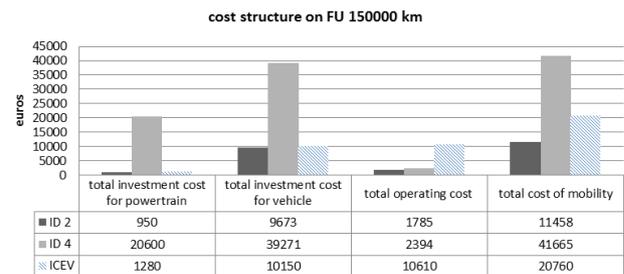


**Fig. 5.** 3D MOO Pareto frontier curve- electric vehicle.

The optimal solutions are detailed for two points with a characteristic autonomy:

- urban car adapted to commuting mobility (ID 2, 80 km)
- car with normal autonomy for electric propulsion (ID 4, 250 km)

The autonomy is related to the battery’s energy capacity. The cost structure is shown in Fig. 6. A conventional vehicle with an internal combustion engine is given as a reference for comparison. The powertrain cost is related to the size of the powertrain components – power of the electric machine and the energy capacity of the battery. When increasing the autonomy, the customer investment cost for the powertrain increases despite the environmental bonus delivered by the government. The operating cost is related to the electricity consumption of the vehicle and to the price of electricity during the vehicle use phase and depends on the place of use. The calculation here is done with the hypothesis that the vehicle is driven in France with an electricity price of 0.14 €/kWh.

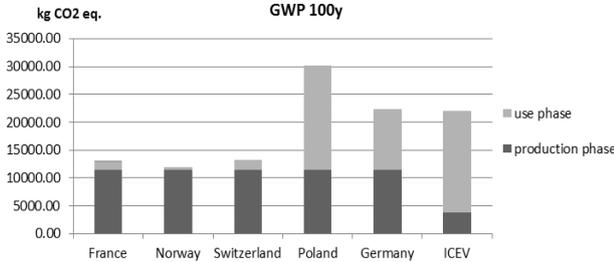


**Fig. 6:** Cost structure for the optimal solutions, FU – functional unit.

The operating cost is related to the electricity consumption of the vehicle and to the price of electricity during the vehicle use phase and depends on the place of use. The calculation here is done with the hypothesis that the vehicle is driven in France with an electricity price of 0.14 €/kWh. The internal combustion engine vehicle (ICEV) is characterized with equivalent investment and operating cost. The total mobility cost is of around 20000 €. Because of the high conversion efficiency of the electric powertrain and the price of the electricity, the operating cost of electric vehicles, based on the

functional unit of 150000 km, is very competitive in comparison with vehicles with a conventional thermal powertrain.

The life cycle model is used to calculate the environmental impacts for the life cycle of the electric vehicle and especially the influence of the electricity production mix in the use phase (Fig. 7).



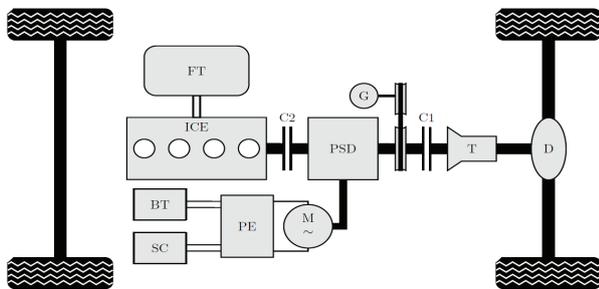
**Fig. 7:** GWP results for an electric car during the use phase in different countries.

In the electric powertrain production phase, the high voltage battery represents the major environmental impact - around 60%. An internal combustion engine vehicle from the same class is indicated for reference with 22000 kg CO<sub>2</sub> equivalent emissions. The ICEV is characterized with 17% of the equivalent emissions due to the production phase and the major part 83% of the emissions is due to its operation phase.

### 3.2 Problem definition – environomic design of electric vehicles

The vehicle model used in this case represents a commercial D-class [18] vehicle with a diesel electric powertrain (Fig. 8).

In the case of hybrid electric vehicles the use phase includes the GWP due of the CO<sub>2</sub> tank-to-wheels emissions emitted by the internal combustion engine 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.



**Fig. 8:** 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.

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 a high voltage battery capacity superior to 3 kWh. The GWP is measured in kg CO<sub>2</sub> equivalent, and the total GWP is defined from well-to-wheels perspective in (9).

$$GWP_{well-to-wheels} = GWP_{total} = GWP_{vehicle\_production} + GWP_{tank-to-wheels\_CO2} + GWP_{diesel\_production} + GWP_{electricity\_production} \quad (9)$$

Thus the environomic optimization for hybrid electric vehicles is defined as:

$$\min(-\eta_{powertrain}(x)) Investment\_Cost(x), GWP_{total}(x), \quad (10)$$

$x \in X_{decision\_variables}$

The decision variables for the powertrain design are defined in Table 3.

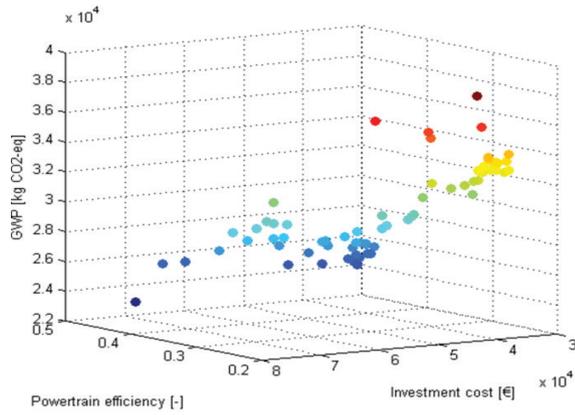
**Table 3.** Decision variables for design.

Decision variable 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]

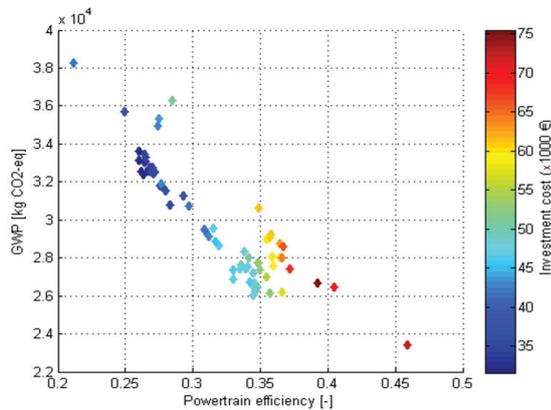
The solutions of the three objective environomic optimization converged on a Pareto Frontier optimal curve (Fig. 9), representing the trade-off between the energy consumption and the cost and the total GWP impact of the vehicles on normalized driving cycle.

The vehicle use phase (including the operation CO<sub>2</sub> emissions and the emissions due to the energy vectors production) is clearly the major contributor to the total equivalent CO<sub>2</sub> emissions, in comparison of the equivalent CO<sub>2</sub> emissions for the vehicle production phase, for powertrain efficiencies between 25% and 35%. With the increasing of the powertrain efficiency over 35% and respectively the hybridization ratio (heavy Plug-in HEV and REX) and the size of the electric part of the powertrain, the impact of the vehicles production phase increases (Fig. 10). This is due to the increasing of the mass of the materials needed for production of the high voltage battery, the electric machine and the electronics.

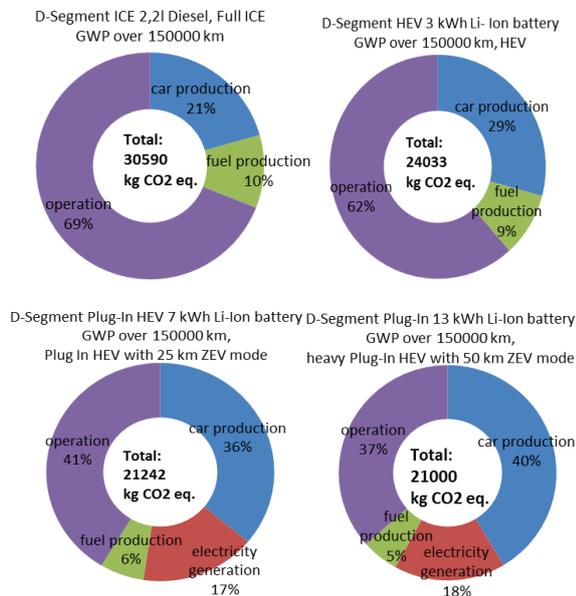
Orders of magnitude for the total GWP evolution and the repartition of the impact of the different life cycles phases are given in Fig. 11, for different sizes of high voltage battery –this means for different hybridization ratio. The vehicles are considered to be operated in France with European diesel 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<sub>2</sub> emissions, coming from the electricity generation. The functional unit is 150000 km.



**Fig. 9.** 3D Pareto frontier curve: environomic optimization, NEDC cycle.



**Fig. 10.** Pareto curve – total GWP to powertrain efficiency, investment cost in color bar, NEDC.



**Fig.11.** Evolution of the total GWP and repartition of the contribution of reach phase as a function of the hybridization ratio, D –Class vehicles.

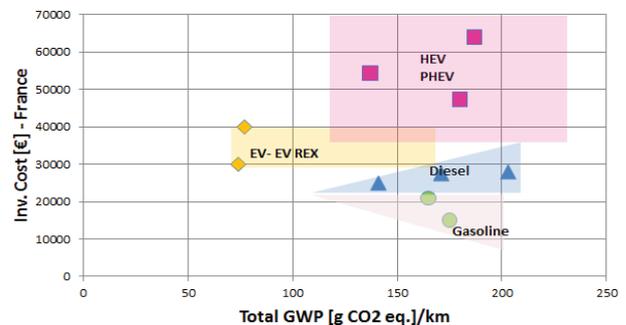
## 4 Conclusions

The design methodology is applied on electric vehicles and hybrid vehicles. The competitiveness and the trade-

off of different advanced powertrains are assessed and optimal design configurations are pointed out (Fig. 12).

The electric vehicles (EV) are suitable for urban mobility. The battery represents the biggest impact on the powertrain cost 75%-90% depending on the targeted autonomy of the vehicle. The energy density of the battery conditions the autonomy. The investment cost is high because of the important cost of the electric powertrain. The operating cost is particularly low – 0.0119 €/km (order of magnitude for France). The environmental impact of the electric vehicle during the use phase is related directly to the place of use and the electricity production mix of the country. The hybrid electric vehicles appear to be a balanced solution between autonomy, cost and environmental impact. They combine the advantages of the low CO<sub>2</sub> emissions and low operating cost of the electric vehicles and overcome their limited autonomy problems. There are different categories of hybrid electric vehicles– non plug-in HEV, plug-in HEV and range extenders (REX). The use phase of the plug –in hybrid electric vehicles (PHEV) and REX is sensitive to the place of use of the vehicles and the electricity production mix. The PHEV present advantages in term of total GWP. PHEV with battery capacity of around 7 kWh seems to be the optimal environomic solution.

The cost/efficiency vision of the vehicles propulsion systems studied with the environomic design method is given in the Fig. 12. The equivalent CO<sub>2</sub> emissions are considered integrating the life cycle perspective and the well-to-wheels energy conversion chain.



**Fig. 12.** Cost/ efficiency vision of the vehicles propulsion systems, well-to-wheels CO<sub>2</sub> emissions.

The methodology of environomic design can support automotive engineers to emerge advanced energy conversion systems concepts, taking into account economic, efficiency and environmental criteria on a holistic way. The proposed methodology combines flowsheeting vehicles models, energy integration techniques, economic evaluation and life cycle assessment in a computational platform. Multi- objective optimization techniques are used to explore the superstructure possibilities and to find the optimal design solutions, corresponding to the most efficient energy system definition for a vehicle. Such an integrated approach is innovative in comparison of the traditional heuristic design engineering method, based on iterations of designs and their cost evaluation.

## Nomenclature

CML – Impact assessment method  
EM – Electric motor  
EV – Electric vehicle  
 $F$  – Force in [N]  
FU – Functional unit  
GLPK, Cplex – Solvers  
GWP – Global Warming Potential  
HEV- Hybrid Electric Vehicle  
 $m$  – Vehicle mass in [kg]  
MOO – Multi Objective Optimization  
MINLP– Mixed Integer Non Linear Programming  
NEDC – New European Driving cycle  
 $P$  – Power of the drive shaft in [kW]  
 $P_{battery}$  – Power delivered from the battery in [kW]  
 $P_{EM}$  – Power of the electric motor in [kW]  
 $P_{SC}$  – Power of the supercapacitors in [kW]  
 $P_{TE}$  – Power of the thermal engine in [kW]  
PHEV – Plug-in hybrid electric vehicle  
 $q_{bat}$  – Capacity of the battery in [kWh]  
REX – Range extender vehicle  
 $T$  – Torque on the drive shaft in [Nm]  
 $V$  – Vehicle speed in [m/s]  
 $w$  – Rotation speed [rpm]  
ZEV – Zero emissions vehicles  
 $\gamma$  – Gear ratio [-]  
 $\eta$  – Efficiency [-]  
 $\eta_{powertrain}$  – Powertrain efficiency in [-]

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