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Procedia Structural Integrity 24 (2019) 906–925

Structural Integrity Procedia

www.elsevier.com/locate/procedia

AIAS 2019 International Conference on Stress Analysis

Sustainability assessment for different design solutions within the automotive field

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Abstract

Sustainability is a critical issue for the automotive industry, making that car manufacturers have to address also environmental issues additionally to the traditional ones. Within this context, many research and industry activities have been concentrated in the field of lightweighting through the development of innovative materials and manufacturing technologies.

This study deals with the sustainability assessment of two alternative design solutions for a door demonstrator module: a reference steel-based door structure is compared to a re-engineered variant which is mainly constituted of state-of-the art aluminum. Environmental impact, energy consumption and cost are chosen as sustainability pillars and the results are expressed respectively in terms of Global Warming Potential (kg CO_2 eq), Primary Energy Demand (MJ) and total cost (Euro). The analysis follows a cradle-to-gate approach, capturing the contributions due to raw materials extraction, component manufacturing and operation; the use stage is evaluated for both Internal Combustion Engine Vehicle (ICEV) and Electric Vehicle (EV) variants. The inventory for energy and impact assessment is mainly based on primary data directly measured on process site.

The overall profile of the different design solutions is assessed and the main, environmental, energy and cost life-cycle hotspots are identified and critically discussed. The dependence of indicators on life-cycle mileage is investigated for both ICEV and EV case studies by means of the break-even point analysis. Finally, the effective convenience of reference and lightweight alternatives is evaluated considering the overall set of sustainability aspects through a multi-criteria decision analysis.

Peer-review under responsibility of the AIAS2019 organizers

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Peer-review under responsibility of the AIAS2019 organizers
10.1016/j.prostr.2020.02.080

Keywords: Lightweight design; Life Cycle Assessment; Life Cycle Costing; Sustainability; Comparative assessment

1. Introduction

The automobile traffic contributes about 12% to the overall carbon dioxide emissions in the European area (UNECE, 2015) and it is one of the major contributor to a large series of environmental impact categories. From a legal perspective, many countries have put regulations in order to reduce fuel consumption and air emissions, including high taxes on fuels to promote energy conservation. As a consequence, environmental protection has become one of the pillars of automotive design, along with performance, functionality, safety and structural integrity requirements (Bein and Meschke, 2011).

The industry response to the ever growing demand for sustainable products and manufacturing processes is the development of eco-design strategies (De Medina, 2006; Mayyas et al., 2012; Andriankaja et al., 2015). Eco-design incorporates several guidelines and procedures which allow to expand the concept of sustainability from the traditional design issues (i.e. performance, functionality and reliability) to other basic aspects, such as the environment, cost and energy conservation (Alves at al., 2010; Delogu et al., 2018).

One of the most widespread eco-design strategy to achieve performance, energy, environmental and cost benefit within the automotive sector is lightweighting (Baroth et al., 2012). Lightweight design focuses on three main areas: use of lightweight materials, use of stronger materials and design optimization. The first approach envisages to reduce vehicle weight and improve fuel economy through the adoption of materials characterized by low density (i.e. aluminum, fiber reinforced composites, sandwich materials and structures) (Duflou, 2009; Luz et al., 2010; Das, 2011). Against the undeniable energy advantages during vehicle operation, lightweighting often implies negative consequences in production and End-of-Life (EoL) stages (Dhingra and Das, 2014). Indeed many light materials such as aluminum, magnesium or carbon fibre are energy-intensive to produce and involve higher air emissions prior to the operation stage if compared, for instance, with conventional steel (Poulikidou et al., 2015). At the same time, the manufacturing processes are characterized by high costs and technological complexity, which represent further substantial issues that need to be addressed when adopting novel material solutions (Vinodh and Jayakrishna, 2011). The second area of lightweighting is based on the use of stronger metal materials (such as advanced high strength steels, modified steel alloys and grades). This solution allows to achieve use stage environmental benefits without increasing significantly the impact of production but, on the other hand, it involves high economic expenditure for tooling and machinery (Del Pero et al., 2019). The last field of lightweighting is design optimization which focuses mainly on optimized cross-sectional shapes structures and reduction of components gauges while maintaining the same construction material. The beneficial effects of this strategy are lower energy and resources consumption during operation while the major drawback is the high time consumption of design and development process.

All considerations regarding sustainability advantages achievable through lightweighting apply equally to conventional and electric cars (Raugei et al., 2015). For Internal Combustion Engine Vehicles (ICEV) the reduction of consumption provide benefits in both fuel production and operation sub-stages. Indeed, lower consumption means on one hand lower environmental burdens and costs associated with the fuel supply chain, and on the other hand lower air emissions during car driving (Kim and Wallington, 2013). Clearly, for Electric Vehicles (EV) the advantage from lightweighting is located only in the energy production phase. However, the need for mass reduction is even more crucial for EVs than conventional cars, as additional weight involves either decrease of driving range or heavier and more expensive battery and powertrain systems (Girardi et al., 2015; Egede, 2017).

Literature provides several works dealing with the effects of lightweighting on the sustainability of an automotive asset. Most of them take into account the environmental or the economic assessment of novel design solutions with application to specific vehicle modules (Kelly et al., 2015; Kim and Wallington, 2013; Schau et al., 2011; Swarr et al., 2011). Witik et al. (2011), Simoes et al. (2016) and Delogu et al. (2016) are the only studies that perform a proper sustainability assessment of lightweight design combining the environmental and economic issues. Witik et al. (2011) carries out a Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) aiming at evaluating the potential benefits of composite automotive parts. The environmental profile and the manufacturing costs of different suitable lightweight plastic composite components are compared to magnesium and conventional steel with application to a representative vehicle component. The outcomes of the research show that mass reduction does not always translate into lower environmental impacts and costs. In particular, lightweight materials involve increased environmental burdens and costs associated with production stage which are counterbalanced by positive effects during operation, thus resulting in very limited benefits over the entire component Life Cycle (LC). Simoes et al. (2016) assesses three different design solutions for car chassis component: the reference module made of steel is compared to a series of innovative alternatives which provide material substitution (polymer matrix composite and aluminum), design changes (lower mass and fewer parts) as well as novel processing technologies (assembly line simplification). The analysis takes into account both environmental and economic aspects through the LCA and LCC methodologies. The results are in line with Witik et al. (2011), stressing negative effects in production and energy/emissions saving during component operation. The conclusion is that use phase benefits compensate the increase in cost and environmental burdens of manufacturing for high values of LC mileage. Delogu et al. (2016) combines LCA and LCC to investigate the effects on sustainability of material change in the automotive lightweight perspective. The case study is a vehicle dashboard panel for which a reference design solution (based on talc filler-reinforced composite) is compared to a novel lightweight one (based on hollow glass micro-spheres). The study reveals that that the lightweight dashboard variant is definitely preferable from an environmental point of view for those LCA categories whose impact is mostly associated with the operation phase. Concerning the LCC section, despite a higher cost for raw materials extraction and production of hollow glass micro-spheres, the novel solution is proven to be economically convenient thanks to lower costs associated with component operation.

This paper is a follow-up study of Del Pero et al. (2019) and it performs the sustainability assessment of two different design solutions for an automotive door structure module. The alternatives taken into account are a reference steel-based door and a re-engineered lightweight variant which is mainly made of state-of-the art aluminum. The assessment captures the environmental impact, energy consumption and cost associated with raw materials extraction, manufacturing and use stages and it is carried out by the LCA and LCC methodologies. The inventory is mainly based on primary data directly measured on process site. The aim of the work is investigating the implications of lightweighting over a comprehensive set of sustainability aspects, critically discussing and interpreting potential opposite effects as well as combining results in order to identify the optimal design alternative.

2. Materials and method

This section reports the objectives, development and boundary conditions of the study as well as the description of the two design alternatives for the door module. Afterwards, LCA and LCC methodologies are illustrated, including inventory data collection.

2.1. Case study and boundary conditions

Environmental impact, energy consumption and cost are evaluated in terms of Global Warming Potential (GWP), Primary Energy Demand (PED) and cost. GWP and PED indicators are calculated through the LCA methodology while the cost is provided by the LCC. The analysis follows a cradle-to-gate approach, capturing the contributions due to raw materials extraction and module manufacturing up to the use stage. The operation is evaluated for both ICE and electric vehicle variants. For EV the production of electricity consumed during operation is modelled taking into account the average European grid mix (EV_EU28) and two additional grid mixes, Polish (EV_PL) and Norwegian (EV_NO). The choice of Polish and Norwegian grid mixes is that they are characterized by opposite sustainability performance (electricity produced by renewable resources for the Norwegian grid mix and energy supply mainly based on fossil fuels for the Polish grid mix), thus allowing a comprehensive overview on the environmental and energy effects of the electricity supply chain.

The reference module is conceived in a steel intensive design with a total mass of 19.7 kg, while the innovative concept foresees mainly the application of aluminum materials from the 6000-series resulting in a total mass of 11.0 kg. Lightweight door variant allows achieving 8.7 kg mass saving, which is equivalent to about 44 % weight reduction. Both module alternatives are intended to be mounted on a current M-segment gasoline turbocharged car.

2.2. Life Cycle Assessment

The scope of the LCA section (ISO14040:2006; ISO 14044:2006) is comparing the reference and lightweight door structure variants basing on GWP and PED impact categories. The Functional Unit (FU) is defined as the module installed on the vehicle over a 150000 LC mileage. The system boundaries include materials, production and use stages. Materials phase takes into account impacts due to raw material extraction up to the production of semi-finished products (i.e. steel billet). Production evaluates manufacturing activities required to obtain the end module. Finally, use stage assesses the operation of the car basing on the Worldwide harmonized Light-duty Test Cycle (WLTC), including both fuel/electricity production as well as emissions during car driving. Joining, painting, assembly and transportation processes during manufacturing are outside the system boundaries. The GWP assessment is performed by the CML 2001 method (University of Leiden, 2001).

The Life Cycle Inventory (LCI) is carried out by means of the Gabi software (Thinkstep, 2019). The following describes the LCI modelling as well as data collection for each stage of module LC.

Materials and production stages. The inventory is modelled through a breakdown approach, which provides that each mono-material component is assessed separately. Therefore, the environmental impact of the module is obtained as the sum of contributions of the single mono-material parts. The assessment includes also materials recycling during manufacturing activities (open loop recycling) taking into account the environmental credits due to the substitution of virgin raw materials. The modelling is mainly based on primary data collected directly on process site. Secondary sources from the GaBi process dataset are used when primary data are not available. Table 1 reports an overview of primary data collection regarding materials and manufacturing stages, including material composition and manufacturing processes parameters.

Table 1. Primary data collection for materials and manufacturing stages

	Material composition [kg]		Manufacturing process	Energy consumption [kWh/kg]	Scrap rate [%]
	Material	Mass [kg]			
Reference module (total mass: 19.7 kg)	Steel - DC06	16.8	Deep-Drawing	0.22 – 0.28	Range* 33.3 - 60.2
	Aluminum 6060	0.2			
	Steel - DP1000	1.7			
	Steel - DP600	1.0			
Lightweight module (total mass: 11.0 kg)	DIN EN 6016 / e170	3.0	Deep-Drawing	0.22 – 0.28	Range* 33.3 - 60.2
	DIN EN 6016 / e600PX	3.7			
	DIN EN 6016 /e200	2.6			
	Steel - DP1000	1.7			

* Variability range depending on specific module part

Use stage. The use stage inventory is modelled separately for ICE and electric vehicle configuration. For ICEV the analysis captures the impacts associated with both fuel production and CO_2 emissions during car driving. The LCI model is based on the Fuel Reduction Value (FRV) approach described in the following equations (Del Pero et al., 2017):

$$FC_{module} = \frac{FRV * m_{module} * mileage_{use}}{10000} * \rho_{fuel} \quad (1)$$

$$CO_{2\,module} = CO_{2\,km} * mileage_{use} * \frac{FC_{module}}{FC_{veh}} \tag{2}$$

$$FC_{veh} = \frac{FC_{100km}}{100} * mileage_{use} * \rho_{fuel} \tag{3}$$

$$FC_{100km} = \frac{CO_{2\,km}}{2370} * 100 \tag{4}$$

FC_{module} = amount of Fuel Consumption associated with the module [kg]
FRV = 0.178 [l/100 kg*100 km] for gasoline turbocharged D-class vehicle (Del Pero et al., 2017)
m_{module} = module mass [kg]
$mileage_{use}$ = use stage mileage (150000 [km])
ρ_{fuel} = fuel density (0.741 [kg/l])
$CO_{2\,module}$ = amount of CO_2 emissions associated with the component [g]
$CO_{2\,km}$ = vehicle CO_2 emissions per-kilometer (192 [g/km]) (EEA, 2019; Mock et al., 2014)
FC_{veh} = vehicle Fuel Consumption (kg)
FC_{100km} = vehicle Fuel Consumption per 100 km [l/100km]
2370 = mass of CO_2 per liter of petrol [g/l] (Amit et al., 2014)

For EV the analysis captures the impacts due to use stage electricity production. The LCI is modelled according to the following equation which evaluates the electricity consumption associated with the module:

$$EC_{module} = \frac{ERV * \frac{m_{module}}{100} * \frac{mileage_{use}}{100}}{eff_{batt} * eff_{cha}} \tag{5}$$

EC_{module} = Electricity Consumption associated with the module [kWh]
ERV = 0.69 [kWh/100 kg*100 km] (ALIVE, 2012)
m_{module} = module mass [kg]
$mileage_{use}$ = use stage mileage 150000 [km]
eff_{batt} = battery efficiency (85 %)
eff_{cha} = charger efficiency (95 %)

2.3. Life Cycle Costing

The LCC section is aimed at comparing the LC cost of reference and lightweight door structure variants. Similarly to LCA, system boundaries for the economic assessment include material (from raw material extraction up to the production of semi-finished products), production (manufacturing activities required in order to obtain the end module) and use (fuel/electricity production and emissions during car driving) stages.

LCC inventory. The inventory for materials and production stages is performed through the break-down approach presented above for the LCA. The materials cost of the mono-material parts is determined according to the specific features of the component itself (material type, component mass, geometry and volume). On the other hand, the production cost is estimated taking into account the following information: inherent properties of mono-material parts, peculiarities of manufacturing processes, module structure, assembling sequence. All cost items and subsequent steps needed for module manufacturing and production are identified and broken down, including human/physical capital requirements (machinery, tooling, consumables, industrial space and employees) and related cost/price. The following relationship shows model parameters and variables that determine materials and production cost:

Cost = f (Material price, Material density, Part box volume, Part projected area, Part mass, Manufacturing cycle time, Machinery cost, Machinery life time, Tooling cost, Tooling life time, Consumables price, Consumables quantities, Employment requirement, Labour force, Labour hourly rate, Energy consumption, Scrap rates)

The overall materials and production cost is obtained by summing up all contributions of the different mono-material parts. Joining, painting, assembly and transportation processes during manufacturing are outside the system boundaries.

$$Cost_{Production} = Cost_{Manufacturing} + Cost_{Energy} + Cost_{Labour} \quad (6)$$

$$Cost_{Manufacturing} = Cost_{Machinery} + Cost_{Tooling} + Cost_{Consumables} \quad (7)$$

The inventory for the use stage consists in the price of fuel and electricity respectively for ICE and electric vehicle configurations.

Finally, the total cost of the door module is obtained as the sum of a series of sub-cost items, which in turn depends on a large number of parameters and variables. The equation below illustrates the analytical model used to determine the total cost of the module.

$$Cost_{Module} = Cost_{Materials} + Cost_{Production} + Cost_{Use} \quad (8)$$

Table 2 describes the different model variables. These are primarily distinguished in four different categories (input parameters, model parameters, assumptions and output) according to the source of the data and its function in the model.

Table 2. Model parameters, assumptions and output

Input parameters	Part geometry X, Y, Z [m]; Box volume [m^3]; Mass [kg]; Projected area [m^2]; Material type; Manufacturing process
Model parameters	Energy consumption [MJ]; Cycle time [s]; Scrap rate [%]; Cost of ma-chinery [€]; Lifetime of machinery [years]; Cost of tooling [€]; Lifetime of tooling [years]; Cost of con-sumables [€]; Volume of consumables [kg], [items], [L]; Price of material [€]; FTE
Assumptions	Cost of electricity [€/kWh] (national and average EU-28, Poland and Norwegian grid mixes); Cost of natural gas [€/kWh]: national and average EU-28 values; Cost of labor [€/h]: labour cost per hour worked per technology for each of the EU-28 countries; Annual production [ve-hicles/year]: 100000 vehicles/year; Price of gasoline [€/L]: 1.19 €/L (EU-28 aver-age); Average car mass [kg]: 1392 kg; Lifetime distance [km]: 150000 km - ICEV consumption: 5.85 [l/100 km]:
Output	Material cost; Production cost (machinery, tooling, consumables, labour, energy, use stage)

3. Results and discussion

Table 3 reports GWP, PED and cost for both reference and lightweight door structure variants; results are shown for both total value and single LC stages.

Table 3. GWP, PED and cost of reference and lightweight design solution

				Use				Total			
		Materials	Production	ICEV	EV_EU28	EV_PL	EV_NO	ICEV	EV_EU28	EV_PL	EV_NO
Reference	GWP [kgCO_2 eq]	97.3	2.7	161.8	105.0	251.0	7.7	261.8	205.1	351.1	107.8
	PED [MJ]	1110.0	66.5	2980.0	2730.0	3030.0	1250.0	4156.5	3906.5	4206.5	2426.5
	Cost [€]	23.0	32.4	82.7	30.3	22.7	21.5	138.1	85.7	78.1	76.9
Lightweight	GWP [kgCO_2 eq]	71.1	2.1	90.5	58.8	140.0	4.3	163.7	132.0	213.2	77.5
	PED [MJ]	1350.0	54.3	1670.0	1520.0	1690.0	698.0	3074.3	2924.3	3094.3	2102.3
	Cost [€]	64.0	24.8	45.3	16.9	12.7	12.0	134.1	105.7	101.5	100.8

3.1. Comparison reference/lightweight variants

The comparison reference/lightweight design solutions is carried out separately for the three assessment indicators.

Global Warming Potential. Figure 1 shows the GWP percentage variation reference/lightweight solution for all the considered operation case studies; data are reported for both total value and single LC stages. Figure 2 illustrates the contribution analysis by LC stage of GWP basing on absolute impacts for the two alternatives.

Figure 1 stresses that lightweight design allows achieving about 27 % GWP reduction in materials stage, which translates into 26.2 kgCO_2 eq absolute reduction (see Figure 2). This effect is mainly due to the material composition of the module: despite raw materials extraction and production processes of aluminum are by far more energy intensive with respect to steel, the lower amount of material used (44 % mass reduction) results in a lower impact of the lightweight module. Another relevant percentage GWP decrease occurs in production stage (about 22 %) but, considering that production provides a very low contribution to total impact (within the range 1-3 % depending on operation case study - see Figure 2), the absolute GWP saving is very low (0.6 kgCO_2 eq).

Concerning use stage, the novel solution provides 44 % impact reduction for all the operation case studies: lightweighting involves a reduction of FC, which in turn allows achieving both impact reduction in fuel/energy supply chain and abatement of CO_2 exhaust air emissions. It has to be noted that

- the percentage benefit is unaltered passing from one propulsion technology to another
- percentage reduction in GWP and mass are the same.

The reason for this is that use stage impact has a linear proportionality with respect to mass for both ICEV and EV case studies (this rule applies also to PED indicator). On the other hand, the absolute use stage GWP strongly depends on propulsion technology and electricity grid mix: impact quota associated with operation is higher for EV_PL, ICEV and EV_EU28 where the energy is mainly from fossil resources, while it is lower for EV_NO where electricity is almost totally made from renewable resources. As a consequence, the percentage decrease in total GWP derives directly from the significance of the use stage for the different operation case studies, with higher values for EV_PL, ICEV and EV_EU28 (within the range 36-39 %) and lower benefit for EV_NO (28 %). The absolute GWP variation are 137.9, 97.3, 73.1 and 30.3 kgCO_2 eq respectively for EV_PL, ICEV, EV_EU28 and EV_NO.

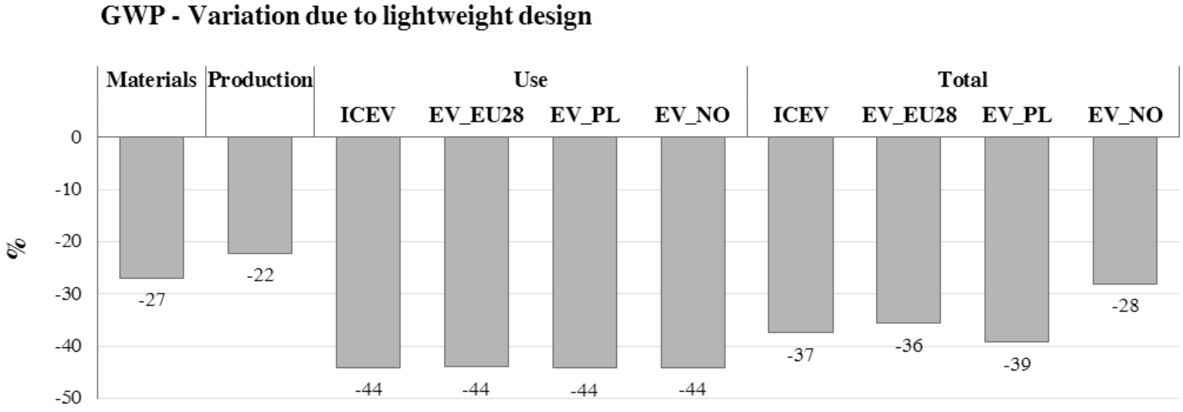


Figure 1. Global Warming Potential: impact variation due to lightweight design

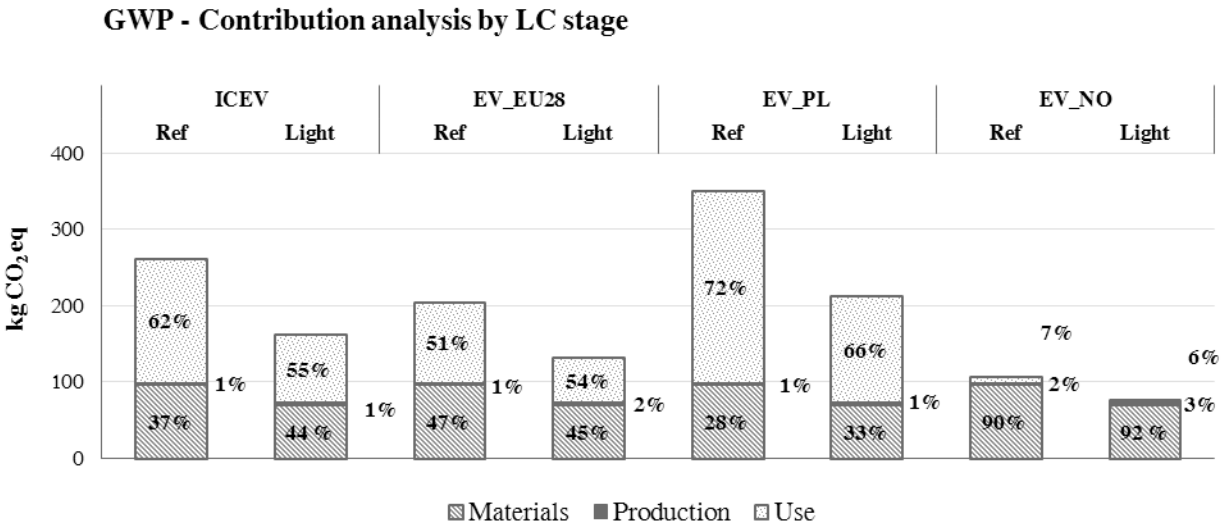


Figure 2. Global Warming Potential: contribution analysis by LC stage

Primary Energy Demand. Figure 3 shows the PED percentage variation reference/lightweight solution for all the considered operation case studies; data are reported for both total values and single LC stages. Figure 4 illustrates the contribution analysis by LC stage of PED basing on absolute impacts for the two alternatives.

Figure 3 points out that the novel design variant involves a 22 % PED increase in the materials stage (240 MJ absolute increase - see Figure 4). This is mainly due to the notable consumption of non-renewable resources caused by raw material extraction and production of aluminum, in particular natural gas, hard coal, crude oil and uranium. On the other hand, a significant percentage PED reduction occurs in the production stage due to the lower energy intensity of manufacturing processes of aluminum parts with respect to steel ones. However, the absolute impact decrease is very low, since the production represents a very low contribution to total PED (within the range 1-3 % depending on operation case study - see Figure 2). Considering use stage, the 44 % impact reduction is due to the lower amount of energy resources used for fuel/electricity production. Unlike GWP, the absolute PED variation is more or less the same for ICEV, EV_EU28 and EV_PL (about 1340 MJ), against a value of about 4000 MJ for the reference solutions. The lowest use stage absolute reduction occurs for EV_NO (about 550 MJ), due to the lower quota of PED impact associated with operation (see Figure 4). The opposite effects of lightweighting on different LC stages (impact decrease in production/operation stages and impact increase in materials stage) result in a reduction of total PED of about 25-26 % for ICEV, EV_EU28 and EV_PL (absolute reduction within 1000 - 1100 MJ) while for EV_NO the advantage is 13 % (about 320 MJ).

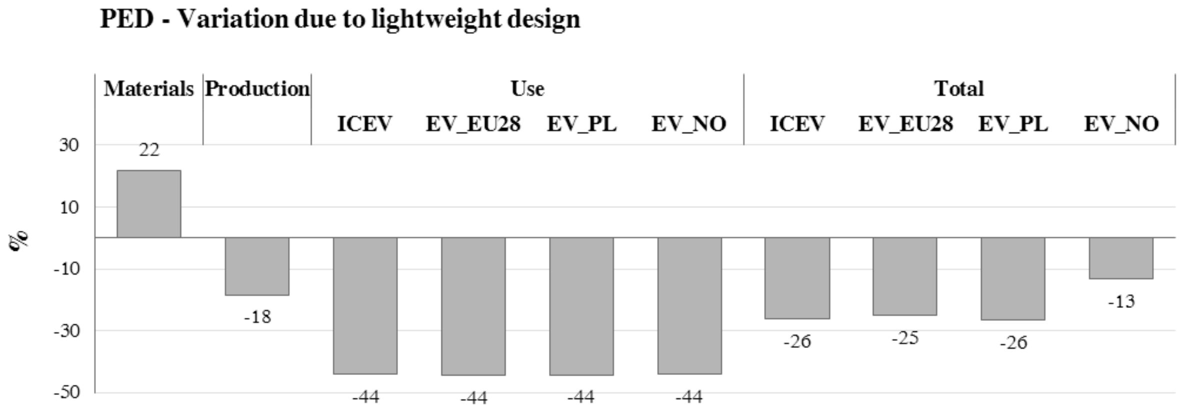


Figure 3. Primary Energy Demand: impact variation due to lightweight design

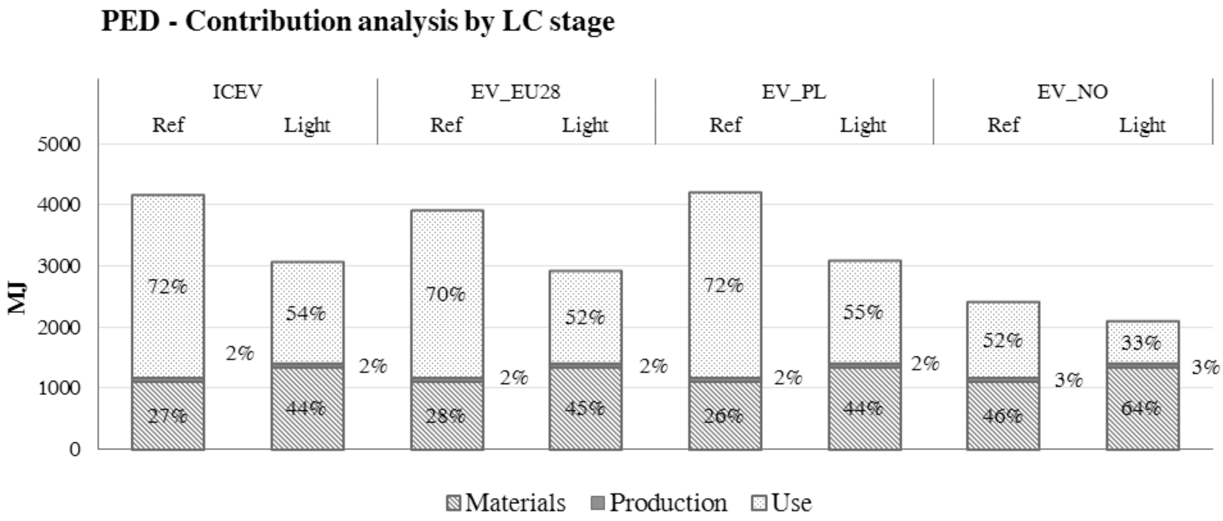


Figure 4. Primary Energy Demand: contribution analysis by LC stage

Cost. Figure 5 shows the cost percentage variation reference/lightweight solution for all the considered operation case studies; data are reported for both total values and single LC stages. Figure 6 illustrates the contribution analysis by LC stage of cost basing on absolute impacts for the two alternatives.

Figure 5 reveals that the lightweight design alternative involves a very high percentage increase in materials stage (about 178 %), which translates into 41 € additional cost. The increase in materials phase is due to the bigger cost of semi-finished aluminum products with respect to steel ones. On the other hand, the production provides a significant reduction (-23 %), which is mainly due to the lower energy intensity of manufacturing processes of aluminum components than steel parts. However, in absolute terms the reduction in production stage is not so relevant (about 7.6 €). Concerning use, the percentage decrease (about 44-45 % depending on operation case study) is due to the lower amount of fuel/energy associated with the lightweight module, which means lower cost for resources extraction, fuel refining (ICEV case study) and electricity production (EV case studies). The absolute reduction in operation cost is higher for conventional car (about 34.1 €) than electric powertrain vehicles (values are comprised within the range 9 - 13 €), due to the greater cost per kilometer of fuel with respect to electricity. Looking at total values, the analysis reveals that lightweight design is economically convenient only for the ICEV (barely 3 % cost reduction - see Figure 5), while the reference module is cheaper for the EV case studies (additional cost of aluminum variant is 23 %, 30 %, 31 % respectively for EV_EU28, EV_PL and EV_NO). The reason for this is that for electric powertrain cars use stage represents a lower quota of the total cost (values do not exceed 29 % - see Figure 6), while for the ICEV the contribution of operation is 60 %.

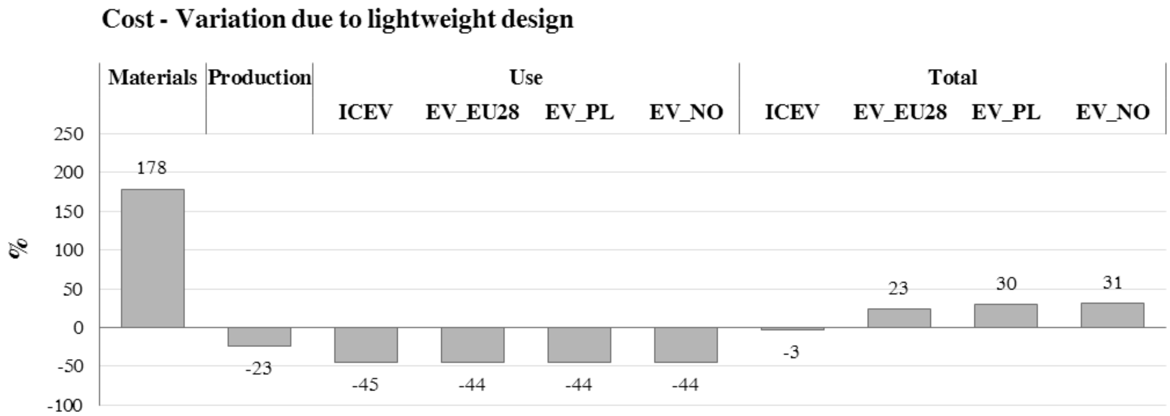


Figure 5. Cost: variation due to lightweight design

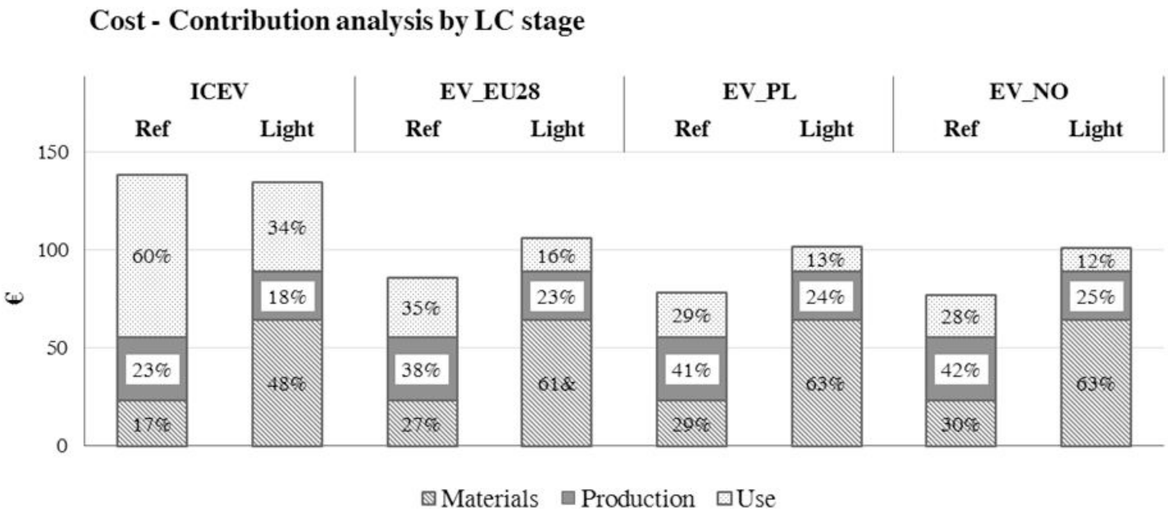


Figure 6. Cost – Contribution analysis by LC stage

3.2. Sustainability indicators

Overall, the different sustainability indicators provide conflicting results when considering different LC stages and operation case studies. In order to have a thorough view of the effects of novel design solution on module sustainability, a performance indicator, relating the differences in terms of mass and impact, is calculated by means of equation 9.

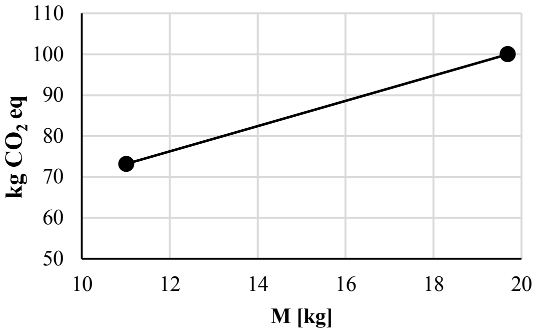
$$\phi = \frac{Delta_{impact}}{Delta_{mass}} = \frac{Impact_{ref} - Impact_{light}}{Mass_{ref} - Mass_{light}} \quad (9)$$

Such an indicator is calculated for assessing the relationship between mass reduction and impact for the different LC stages and the total impact values. The extension of the analysis to the entire panel of propulsion technologies and electricity grid mixes allows to quantify contrasting effects between LC stages for several operation case studies, thus representing valuable indications for eco-design and LCA practitioners. The following diagrams report the impact in function of mass for the reference and lightweight module. Figures 7, 8 and 9 refer respectively to GWP, PED and cost indicators; within each sustainability indicator graphs are related to materials/production stages, use stage and total impact. In the diagrams reference and lightweight solutions are represented by a point pairs while the sustainability indicator ϕ is identified as the slope of the line through points.

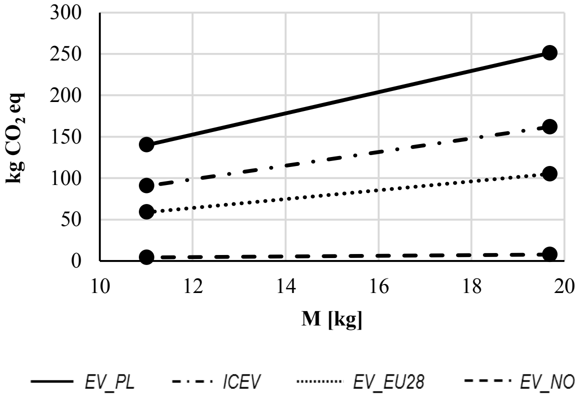
ϕ_{GWP} is about 3.1 kgCO_2 eq/kg for materials and production stages, meaning that for each kilogram mass saving the GWP impact observes a 3.1 kgCO_2 eq reduction. On the other hand, the specific impact reduction in the use stage shows a strong dependency on powertrain technology and electricity grid mix. For ICEV, EV_EU28 and EV_PL the value of ϕ_{GWP} is respectively 8.2, 5.3 and 12.8 kgCO_2 eq/kg. These results directly derive from the dependency on fossil resources of the fuel/electricity supply chain. For ICEV mass reduction leads to a decrease of consumption which lowers both impact due to fuel production and CO_2 emissions during operation. For EV_PL the measure of ϕ_{GWP} is even higher, since electricity Polish grid mix is based by 88 % on hard coal and therefore energy consumption reduction heavily affects GWP impact. EV_EU28 presents more moderate measure as the average European grid mix has a composition almost equally distributed between renewable (about 27 %), nuclear (about 27 %) and fossil resources (46%) (EEA, 2019). On the other hand, ϕ_{GWP} for EV_NO is very low (0.4 kg CO_2 eq/kg) because the production of electricity through the Norwegian grid mix is almost totally from hydropower (more than 96 %) and therefore it provides a very low contribution to GWP. The measures of ϕ GWP referring to total impact is obtained as the sum of contributions from different LC stages. As a consequence, for ICEV and EV_PL impact reduction (respectively ϕ_{GWP} = 11.3 and 15.9 kg CO_2 eq/kg) is mainly associated with GWP benefit in use stage, while for the EV_EU28 (ϕ_{GWP} = 8.4 kg CO_2 eq/kg) the effect is more balanced between materials/production and operation. Finally, for EV_EU28 most part of GWP decrease is in materials/production (ϕ_{GWP} = 3.5 kg CO_2 eq/kg).

Global Warming Potential – Mass specific impact reduction (ϕ_{GWP}) [kg CO_2 eq/kg]

Materials and Production



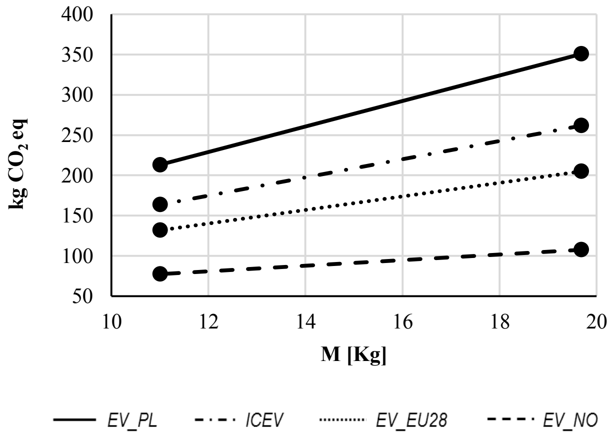
Use



$\phi_{GWP} = 3.1$

$\phi_{GWP\ ICEV} = 8.2$ $\phi_{GWP\ EV\_EU28} = 5.3$ $\phi_{GWP\ EV\_PL} = 12.8$ $\phi_{GWP\ EV\_NO} = 0.4$

Total GWP



$\phi_{GWP\ ICEV} = 11.3$	$\phi_{GWP\ EV\_EU28} = 8.4$	$\phi_{GWP\ EV\_PL} = 15.9$	$\phi_{GWP\ EV\_NO} = 3.5$

Figure 7. ϕ_{GWP} for LC stages and total impact

Concerning PED, the slope of the line in the materials stage diagram is negative (-26.2 MJ/kg), that is the energy demand grows at mass decreasing. This effect is mainly due to the high energy demand of raw materials extraction and production processes of aluminium semi-finished products with respect to steel ones. On the other hand, lightweighting involves a strong benefit during operation since lower fuel/energy consumption translates into reduced impacts thanks to the lower amount of non-renewable energy resources needed by the fuel supply chain (hard coal, natural gas, crude oil and lignite being the most relevant ones). ϕ_{PED} presents similar values for ICEV, EV_EU28 and EV_PL (around 140-150 MJ/kg) while for EV_NO the sustainability indicator is definitely lower (63.6 MJ/kg), but the difference is not so large as for the GWP. Indeed, use stage PED of EV_NO is the same order of magnitude as ICEV and EV case studies (see Figure 3), due to the significant contribution of renewable resources (especially hydropower which represents 88 % of total use stage). Looking at total impacts, the beneficial effects of lightweight during operation counterbalance definitely the increase of energy demand in materials/production stages, thus obtaining measures of ϕ_{PED} comprised within 37.3 MJ/kg (EV_NO) and 128.1 MJ/kg (EV_PL).

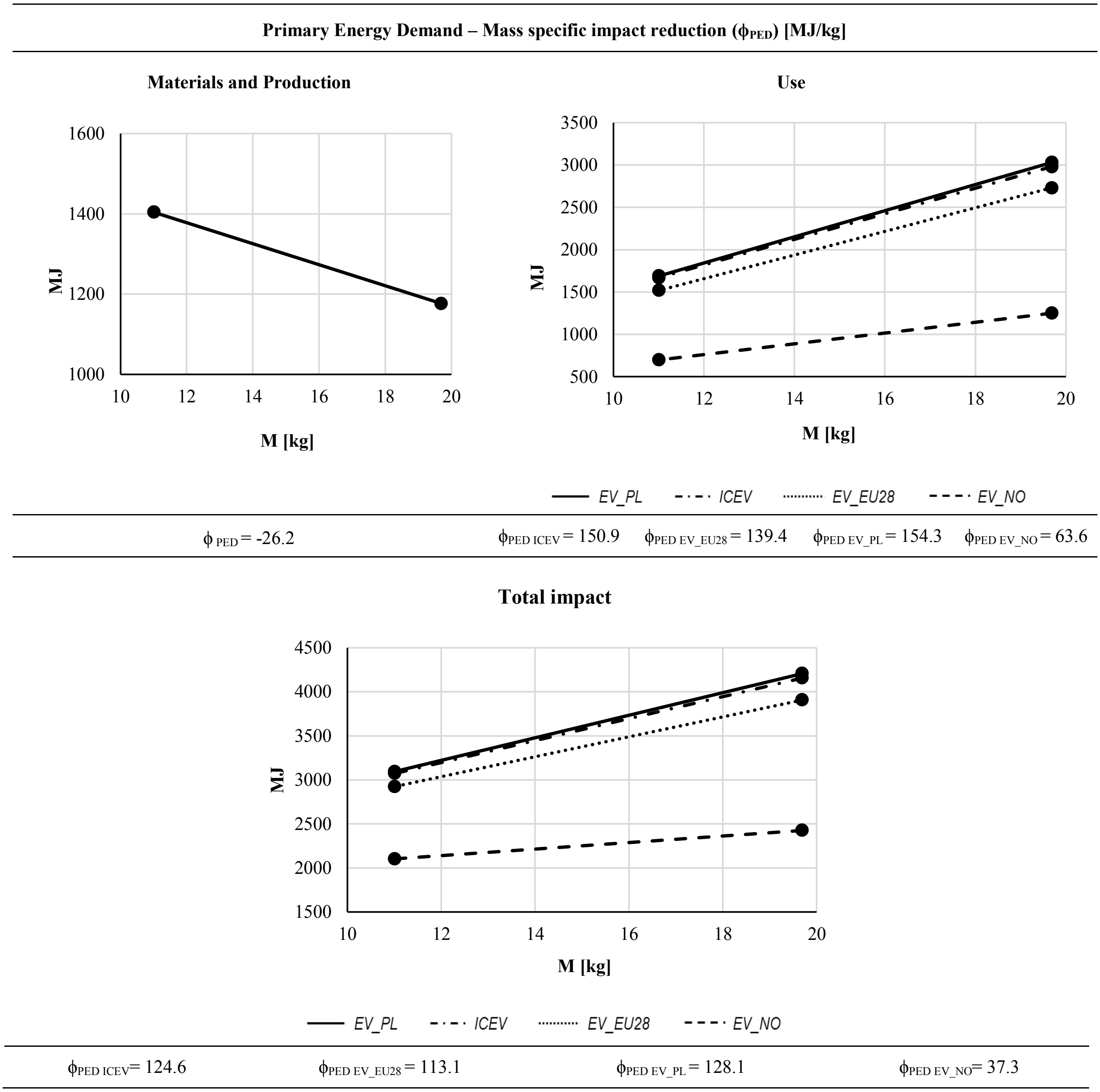
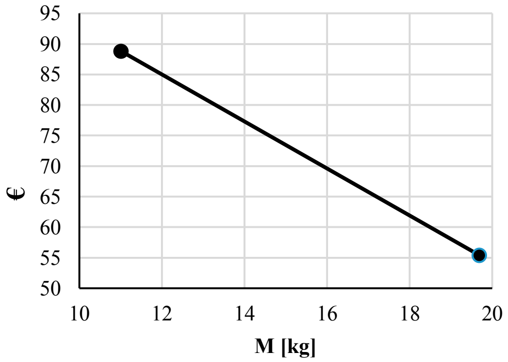


Figure 8. ϕ_{PED} for LC stages and total impact

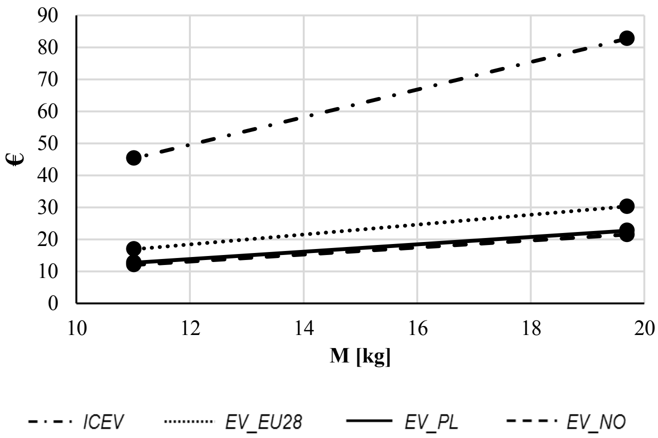
The qualitative trend of ϕ_{cost} is the same as ϕ_{PED}, that is higher expenditure for aluminum in materials/production stages (3.9 €/kg) and cost saving during operation due to the lower consumption of lightweight solution (use stage cost saving comprised within 1.1 €/kg (EV_NO) and 4.4 €/kg (ICEV). However, the use stage benefit offsets the cost increase in the materials/production stages just for the ICEV case study. Nevertheless, for all EV case studies the cost increase in materials/production is predominant. Therefore, ϕ_{cost} is positive only for the ICE configuration (0.5 €/kg) while for electric powertrain cars the additional cost is around 2.5 € per kilogram saved.

Cost – Mass specific impact reduction (ϕ_{cost}) [€/kg]

Materials and Production

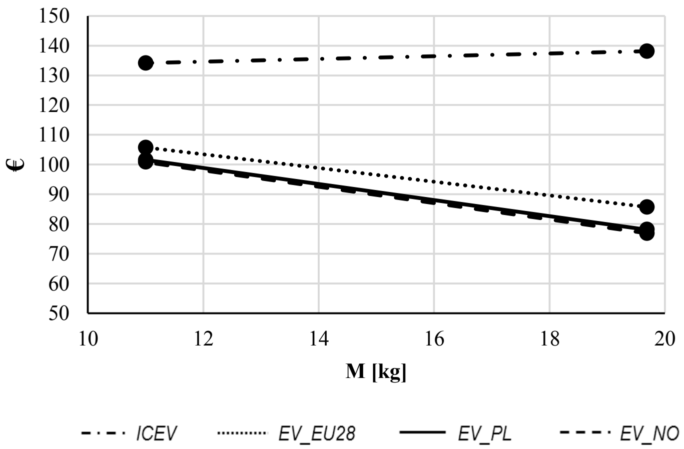


Use



ϕ_{cost} = - 3.8	$\phi_{cost\ ICEV}$= 4.3	$\phi_{cost\ EV\_EU28}$ = 1.5	$\phi_{cost\ EV\_PL}$ = 1.2	$\phi_{cost\_EV\_NO}$= 1.1

Total cost



$\phi_{cost\ ICEV}$ = 0.5	$\phi_{cost\ EV\_EU28}$ = -2.3	$\phi_{cost\ EV\_PL}$ = -2.7	$\phi_{cost\ EV\_NO}$ = -2.8

Figure 9. ϕ_{cost} for LC stages and total impact

3.3. Dependence on LC mileage

This section investigates the dependence of sustainability indicators on LC mileage with the scope to quantify the sensibility of results with respect to operation distance. The following diagrams report the break-even point analysis for both reference and lightweight design variant as well as for all operation case studies considered. The left end of the graphs shows the contribution of mileage-independent LC phases, that are materials and production, while on the right side the contribution of use stage in function of LC mileage is illustrated. The range of operation distance taken into account is 0-250000 km.

Figure 10 stresses that for GWP the contribution of reference design in materials and production stages is higher than the one of the innovative module. As a consequence, the impact of novel design is lower for any value of LC mileage and FC/emissions saving achieved through mass reduction makes that the advantage of lightweight module becomes larger at LC distance growing. Therefore, no break-even point during use stage occurs. However, there are significant differences between operation case studies. For EV_PL the advantage at 250000 km provided by novel solution is the highest one (more than 210 kg CO_2 eq), with lower benefit values for ICEV and EV_EU28 (about 140 and 100 kg CO_2 eq respectively). The lowest GWP saving at 250000 km occurs for EV_NO (about 30 kg CO_2 eq), since the operation lines referring to reference and lighweight modules are more or less parallel. These results directly derive from the relevance of use stage on total impact for the different operation case studies, which in turn is a result of the dependency on fossil resources of fuel/energy production.

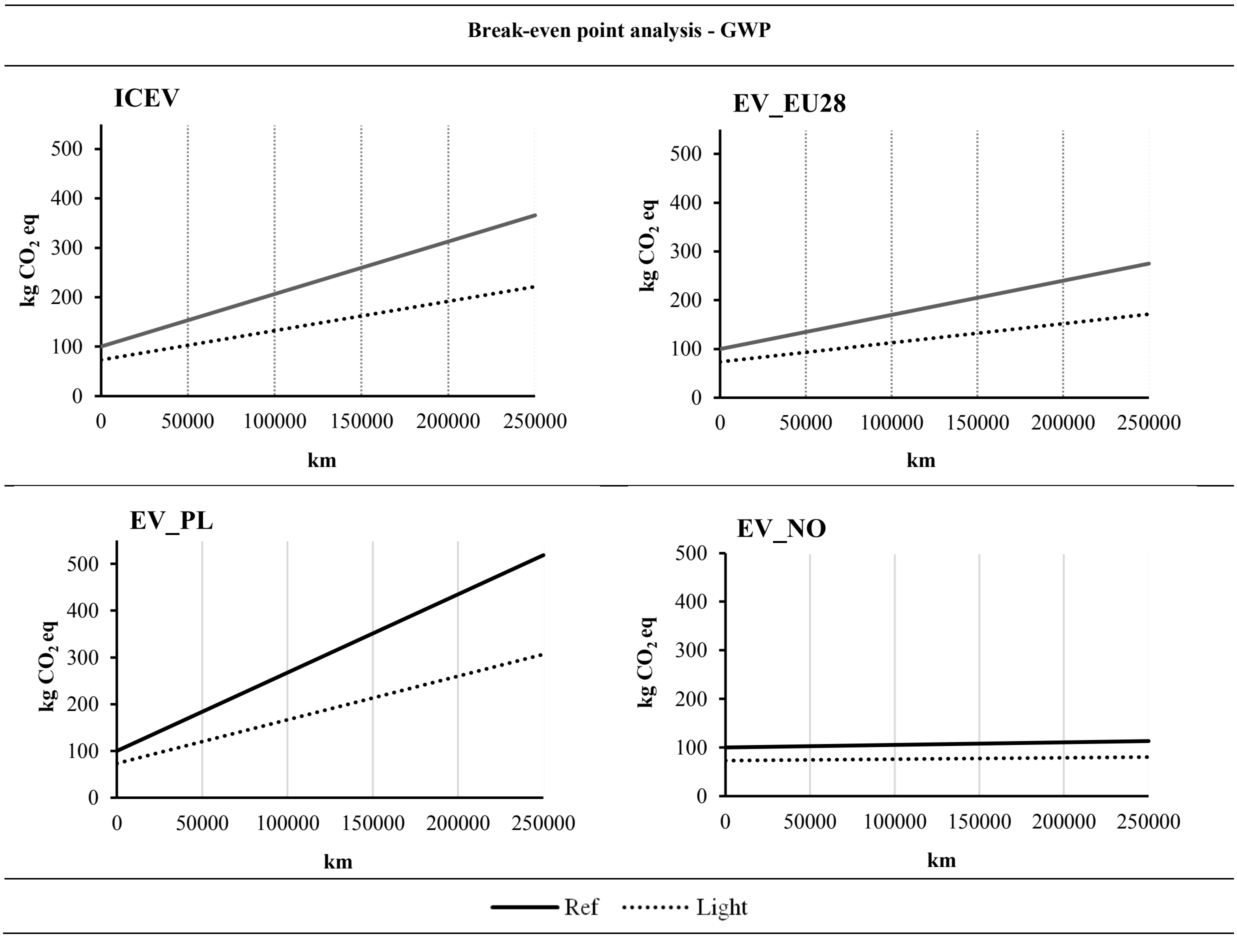


Figure 10. Break-even point analysis: GWP

For PED (Figure 11) it is found the same qualitative trend as GWP. The difference is that at 0 km the PED of novel solution is about 220 MJ higher than the reference one and fuel/energy saving during operation allows achieving a break-even point for all the sustainability indicators. The convenience of lighweight alternative occurs very early in the LC mileage (about 25000 - 30000 km) for ICEV, EV_EU28 and EV_PL. On the other hand, for EV_NO the break-even point moves definitely forward (about 62000 km), but still well within the 150000 km LC mileage assumed in the FU. The reason for this is the lower impact on PED of renewable resources with respect to fossil ones, which requires higher mileage to counterbalance the bigger energy expenditure in mileage-independent LC stages.

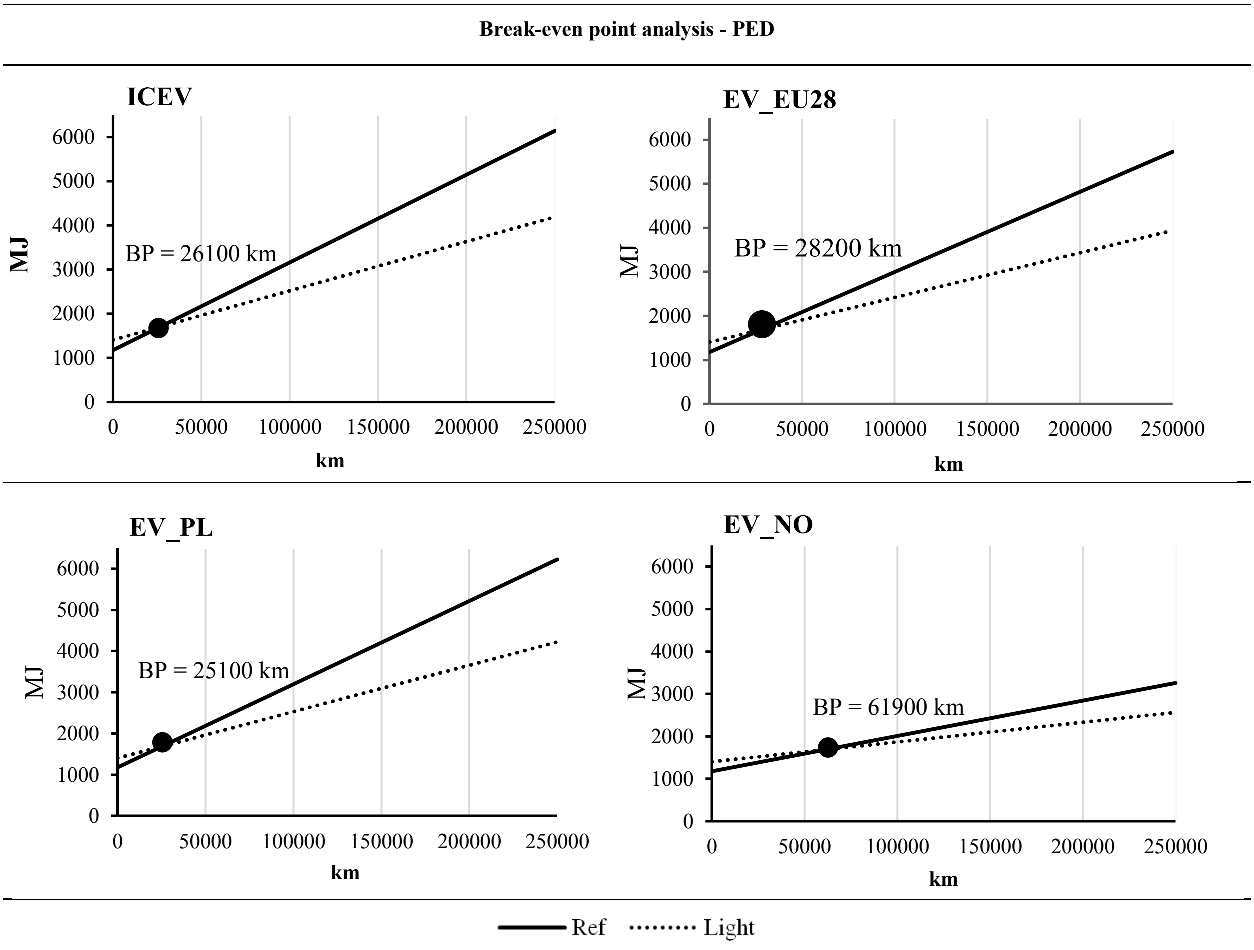


Figure 11. Break-even point analysis: PED

Similarly to PED, the cost analysis shows that the lightweight alternative is not preferable at 0 km (about 30 € higher expenditure). However, the break-even point is achieved only for the ICEV while for the EV case studies the benefit during operation is not sufficient to compensate the additional costs during materials/production. The reason for this lies in the higher cost per-kilometer of fuel with respect to electricity which makes bigger the beneficial effect of lightweighting. However, the break-even point for the ICEV occurs at definitely high value of mileage (about 147000 km, almost equal to the LC distance assumed in the FU) and the cost benefit of novel alternative is bout 3 % (see Figure 5).

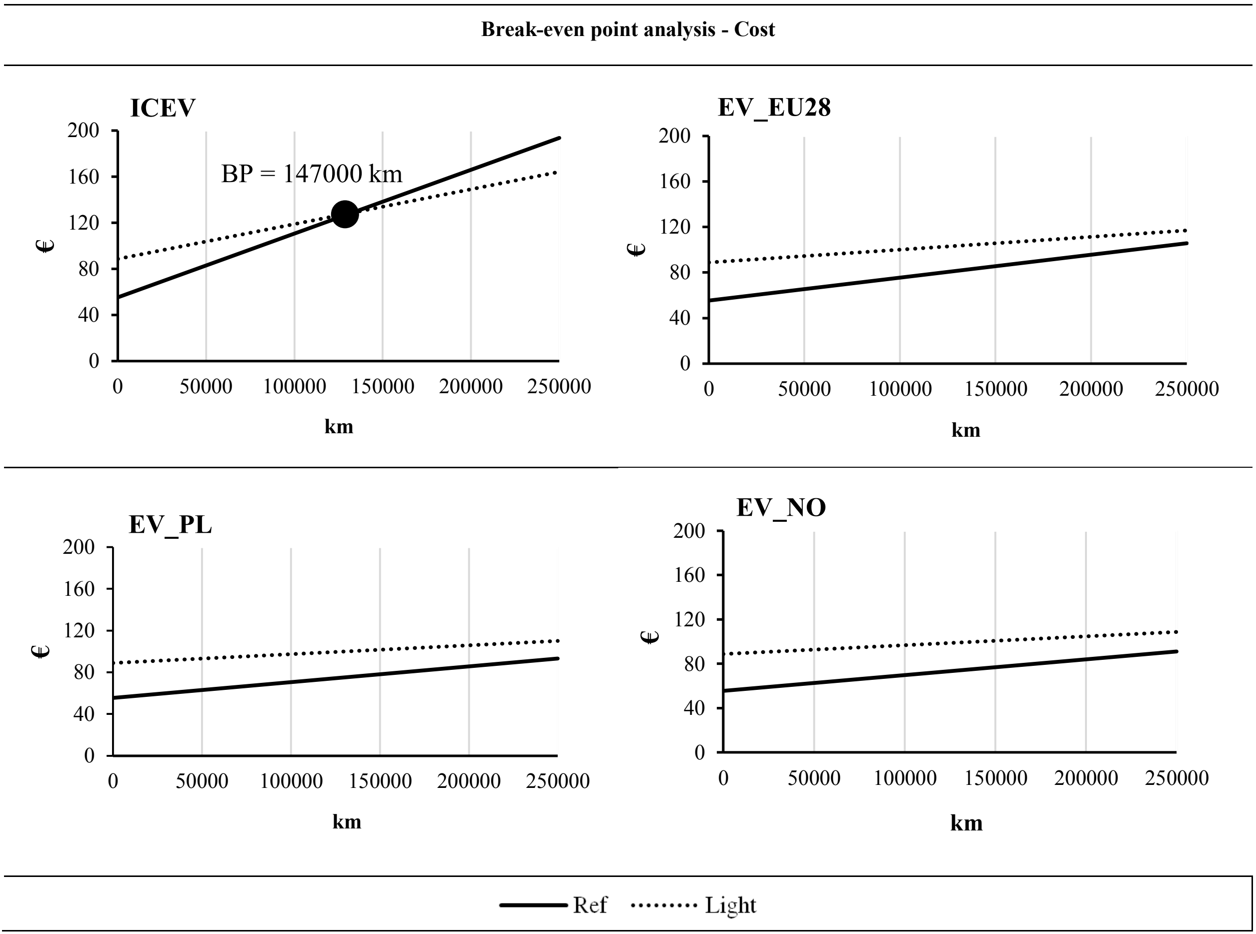


Figure 12. Break-even point analysis: cost

3.4. Integrated assessment

Results stress that the lightweight solution is undoubtedly preferable with respect to the reference one when applied to the ICEV case study, since it involves a benefit for each of sustainability indicators. On the other hand, when considering the electric powertrain case studies the aluminum alternative results in a convenience for GWP and PED while it provides negative effects on the cost aspect. This paragraph applies the TOPSIS method (Dattilo et al., 2017) to the overall set of results reported in Table 4 (decision matrix) in order to

- provide a quantitative measure of the effective convenience of lightweight design solution for the different operation case studies
- identify the more sustainable solution when applying unbalanced weight values for the three sustainability indicators.

Table 4. Decision matrix

		GWP [kgCO_2 eq]	PED [MJ]	Cost [€]
		C1	C2	C3
EV_EU28	A1	132.0	2924.3	105.7
	A2	205.0	3906.5	85.7
EV_PL	A1	213.2	3094.3	101.5
	A2	351.1	4206.5	78.1
EV_NO	A1	77.5	2102.3	100.8
	A2	107.8	2426.5	76.9

The TOPSIS analysis is performed by using four different weighting sets. Table 5 reports the weighting sets considered: additionally to the reference one where all indicators have the same relative importance, the investigation is performed for three additional sets that attribute a slightly higher importance to one of the three sustainability aspects.

Table 5. Weighting sets

	Weighting set		
	GWP	PED	Cost
Set 1	0.333	0.333	0.333
Set 2	0.400	0.333	0.333
Set 3	0.333	0.400	0.333
Set 4	0.333	0.333	0.400

Results highlight that when applying the reference weighting set the innovative module is definitely better with respect to the reference one, with value of relative closeness to the ideal solution (see Table 6) of 0.710, 0.685 and 0.568 respectively for EV_EU28, EV_PL and EV_NO. By repeating calculations with sets n°2 and 3, the convenience of aluminum variant becomes greater, with EV_EU28 operation case study being once again the most favorable application field followed by EV_PL and EV_NO. Finally, when using weighting set n°4, the overall sustainability advantage of novel design decreases, and even for EV_NO the steel alternative results little better than the aluminum one.

Table 6. Value of relative closeness to the ideal solution

		Set 1	Set 2	Set 3	Set 4
EV_EU28	Reference	0.289	0.247	0.268	0.352
	Lightweight	0.710	0.752	0.731	0.647
EV_PL	Reference	0.314	0.269	0.293	0.379
	Lightweight	0.685	0.730	0.706	0.620
EV_NO	Reference	0.431	0.370	0.416	0.502
	Lightweight	0.568	0.629	0.583	0.497

4. Conclusions

The study deals with the sustainability assessment of two different design solutions for an automotive door module: a reference steel-based door structure and a re-engineered lightweight variant mainly made of aluminum.

The evaluation is performed through the LCA and LCC methodologies, and it captures the GWP, PED and costs associated with raw materials extraction, module manufacturing and module operation. Emphasis is placed on the use stage, which is evaluated for both ICEV/EV variants and different electricity grid mixes.

Results show that lightweight design allows achieving significant GWP and PED reduction for all the operation case studies considered. Impact percentage reduction is variable depending on powertrain technologies and electricity grid mixes, with higher values for ICEV, EV_EU28 and EV_PL (about 38 % and 26 % respectively for GWP and PED) and lower benefits for EV_NO (-28 % GWP and -13 % PED). The main reason for this is that for EV_NO the use stage represents a lower quota of total impact, and consequently also the benefits achievable through consumption reduction are smaller. On the other hand, the novel design results to be not convenient from an economic point of view, with about 23-30 % cost increase in electric powertrain vehicles, while for ICEV the expenditure remains more or less unchanged. The break-even point analysis reveals that the aluminum module is preferable at any value of LC mileage, since it involves a lower impact in raw materials extraction and production processes. Notable advantages are found also in terms of PED, with convenience of novel design that occurs at about 25000 km for ICEV, EV_EU28, EV_PL and 62000 km for EV_NO. From a cost point of view, there is a break-even point only for the ICEV (about 147000 km) while for the other operation case studies the reference design solution results to be better at any value of operation distance.

TOPSIS method is applied in order to comprehensively evaluate all the sustainability aspects as well as quantify the effective convenience of lightweight design for the EV operation case studies. Results show that aluminum design provides major benefits for EV_EU28 and EV_PL, while for EV_NO the advantage is lower, with reference steel solution even preferable when giving higher relative importance to the cost aspect.

Acknowledgments

The presented work was funded by the European Commission within the project ALLIANCE (Grant agreement No: 723893): http://lightweight-alliance.eu/.

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