Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1

TASK 6 Report

Design options

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August 2019

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Project website: https://ecodesignbatteries.eu/

Version history:

Version 1: draft for discussion in the stakeholder meeting on 2/5/2019

Version 2: Revised version based on comments from 2nd stakeholder meeting

EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

Directorate C – Industrial Transformation and Advanced Value Chains

Unit Directorate C1

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Luxembourg: Publications Office of the European Union, 2019

ISBN number [TO BE INCLUDED]

doi:number [TO BE INCLUDED]

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ABBREVIATIONS

Abbreviations	Descriptions
BAT	Best Available Technologies
BC	Base case
BNAT	Best Not-yet Available Technologies
BOM	Bill-of-Material
Co	Cobalt
CRM	Critical Raw Materials
EoL	End-of-life
EV	Electric vehicle
FU	Functional Unit
LCA	Life Cycle Assessment
LCA	Life Cycle Assessment
LFP	Lithium-Ion Phosphate
LLCC	Least Life Cycle Costs
MEErP	Methodology for Ecodesign of Energy related Products
Mn	Manganese
Ni	Nickel
NMC	Lithium-ion Nickel Manganese Cobalt Oxide
OPEX	Operational expenditure
PEF	Product Environmental Footprint
QFU	Quantity of Functional Units
SOH	State of Health

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6. Task 6: Design options

AIM OF TASK 6:

The aim is to identify design options, their monetary consequences in terms of Life Cycle Cost for the user, their economic and possible social impacts, and pinpointing the solution with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT). Therefore, this task relies on input from Tasks 4 and 5.

The BAT indicates a target in the shorter term that would probably be more subject to promotion measures than to restrictive action. The Best Not (yet) Available Technology (BNAT) indicates possibilities in the longer term and helps to define the exact scope and definition of possible measures. Intermediate options between the LLCC and the BAT may also be assessed.

The subsequent Task 7 draws up scenarios quantifying the improvements that can be achieved versus a Business-as-Usual (BAU) scenario and compares the outcomes with EU environmental targets, the societal costs, etc.

SUMMARY OF TASK 6:

In task 6 report three design options are defined for further analyses. They are derived from the insights from previous tasks 4 and 5. The first design option is aiming at a reduction of the active and passive materials, while offering a comparable service and thus on a reduction of the GWP due to the used materials. This approach is based on a substitution of the battery cells in the BOM by its successor. The second design option addresses the extension of a products lifetime beyond its 1st life by reuse of the battery system in a same application. Accordingly, the resulting "additional lifetime" and the FU (Functional Unit) provided during this 2nd life application is calculated. Finally, the third design option focuses on the impact of the energy mix used for the production of the battery system by using a low carbon electricity mix. This last design option is not calculated within this task report due to the limitations of the MEErP EcoReport tool[1], making it impracticable to change the electricity related GHG emissions of the production of all the materials within the tool.

The LCA and LCC analysis revealed that the reduced material design option is the best option for BC1 based on the GWP impact and LCC. For BC3, 5, 6, and 7 this was also the case, however the extended lifetime design option is similar to the BAU situation. In addition, it showed that for BC2 and 4 the reduced material option has the least LCC and the extended lifetime option the lowest GWP impact in comparison with the other options.

Furthermore, also potential rebound effects which might occur due to the design options are mentioned. The report includes a discussion of the long-term technical potentials and changes to the total system.

[1] EcoReport tool is design for ecodesign, which cannot include requirements for the energy mix during production.

6.1. Subtask 6.1: Design options

AIM OF TASK 6.1:

Available design options have been identified by investigating different design option against each Base-Case (using the MEErP EcoReport 2014).

The design options should not have a significant degradation of the functionality, the quality of the produced products, of the primary or secondary performance parameters compared to the Base-Case.

The design option must have a significant potential for improvement regarding at least one of the following ecodesign parameters without deteriorating others: the consumption of energy, water and other resources, use of hazardous substances, emissions to air, water or soil, weight and volume of the product, use of recycled material, quantity and nature of consumables needed for proper use and maintenance, ease for reuse and recycling, extension of lifetime or amounts of waste generated.

The design option should not entail excessive costs to the end user seen over the lifetime of the product. Therefore, the assessment of the monetary impact for categories of users includes the estimation of the possible price increase due to implementation of the design option and calculation of the LCC.

The aim of this subtask is to identify and describe the design options that can contribute to improve the environmental performance of batteries.

According to the MEErP methodology, typically 3 to 8 design options are considered as manageable number for Ecodesign preparatory studies.

While in most of the previous Ecodesign preparatory studies the major environmental impact was due to the use phase, this study on batteries indicates a different situation. As the results of task 5 point out, the sourcing and production of the battery has a significantly higher environmental impact than the use phase. This also opens the floor for other design options, which are, for example not strictly based on the technical improvement of specific components, but also allows considering conceptual design options on a more aggregated level. Such an approach seems even more reasonable when looking at different LCA studies, which are focusing at a meta-level, e.g. the effect of using a battery with higher energy density, a reduction of amount of materials needed or increased lifetime (Romare and Dahllöf 2017; Hall and Lutsey 2018). Based on the results of task 4 and task 5 in this study, the following design options have been considered:

1. Reduced active and passive materials
2. Extended lifetime, here as "re-use" option
3. Low carbon energy mix for the production of the battery

In the following subsections, the listed design options will be described in more detail. Although a combination of the three or of two out of the three design options is quite possible in reality, combinations are not further elaborated in this task report (in the scenario analysis of task 7 combined options are considered).

6.1.1. Reduction of active and passive materials

This design options are established on the basis of the description of potential improvement options in task 4. Currently many different scientific approaches are pursuing the same goal, to reduce the amount of active and passive materials in the battery, while providing at least the same service. As described in task 4 this can be achieved for example by using improved cell materials, reducing the amount or weight of passive materials, optimizing the design and so on. This also goes along with an increase in energy density of the battery cell, module or system. The aim of this report is not to describe and analyse the potential environmental impact of every single possible improvement option, but rather to assess if such a reduction has a positive influence on the environmental impact at all, how high it is and what the costs are. Such a positive impact may result from lower amount of materials needed to provide the same service or in the case of a mobile application, less mass has to be moved, which improves also the energy efficiency of the vehicle.[2]

For analysing the effect of using a battery with a lower amount of active and passive materials, the BOM for different industrial battery cells as depicted in task 4 is updated. Succeeding generations of the cells used in task 4 were identified and their corresponding BOM displayed. By using this approach, it is possible to analyse the influence of improved and reduced cell materials (e.g. Ni-rich materials, thinner current collectors, etc.) based on the same cell design. This allows to avoid side effects resulting from e.g. a lower or higher amount of materials due to another cell design, which would falsify the assessment of environmental impact. The BOM of the five different cells is depicted in Table 1.

[2] This effect has not been considered in this preparatory study since it is out of the scope of the system boundaries

Table 1: Updated versions of cell types

			Improved (NMC) Pouch cell	Improved PHEV Pouch cell	Improved (Blended) Prismatic cell	Improved (NCA) Cylindrical cell	Improved (LFP) Prismatic cell	
General Information	Format		Pouch	Pouch	Prismatic	Cylindrical	Prismatic	
	Chemistry		NCM 811	NCM 622	NCM622/NCA(80/15/5)/LMO - 6/2/2	NCA (92/5/3) - Gr/Si	LFMP	
	Ah			32	94	4.75	250	
	Wh		220	126	347.8	17.1	875	1
	V		3.60	3.7	3.7	3.6	3.5	
	Wh/kg		210	230	185	264	140	
	W/mm			171	173	21.3	410	
	H/mm			233	125	70.3	146	
	T/mm			7.5	45	21.3	58	
BOM Cell level		Material	Amount per Wh in g	Amount per Wh in g	Amount per Wh in g	Amount per Wh in g	Amount per Wh in g	
Cathode	Cathode active material		1.48	1.48	1.69	1.32	1.91	
	Cathode active material 1	Fe	0.00	0.00	0.00	0.00	0.20	
	Cathode active material 2	Co	0.08	0.17	0.14	0.04	0.00	
	Cathode active material 3	Ni	0.67	0.50	0.50	0.68	0.00	
	Cathode active material 4	Mn	0.08	0.16	0.31	0.00	0.47	
	Cathode active material 5	Al	0.00	0.00	0.00	0.02	0.00	
	Cathode active material 6	Li	0.20	0.20	0.19	0.18	0.08	
	Cathode active material 7	P	0.00	0.00	0.00	0.00	0.38	
	Cathode active material 8	O	0.46	0.45	0.54	0.41	0.78	
	Cathode conductor	Carbon	0.08	0.08	0.07	0.02	0.27	
	Cathode binder	PVDF	0.17	0.08	0.06	0.01	0.09	
	Cathode additives	ZrO2	0.00	0.00	0.00	0.00	0.00	
	Cathode collector	Al foil	0.39	0.23	0.15	0.10	0.34	
	Total cathode		2.13	1.87	1.97	1.46	2.61	
Anode	Anode active material	Graphite	0.98	0.95	0.98	0.93	1.14	
	Anode binder 1	SBR	0.00	0.04	0.02	0.01	0.03	
	Anode binder 2	CMC	0.00	0.00	0.02	0.01	0.03	
	Anode collector	Cu foil	0.75	0.42	0.47	0.26	0.73	
	Anode heatresistnt layer	Al	0.00	0.00	0.05	0.00	0.00	
	Total anode		1.73	1.41	1.54	1.21	1.94	
Electrolyte	Formulated electrolyte		0.00	0.61	0.86	0.40	1.26	
	Fluid	LiPF6	0.12	0.08	0.11	0.05	0.16	
	Fluid	LiFSI	0.00	0.00	0.00	0.00	0.00	
	Solvents	EC	0.34	0.20	0.28	0.13	0.40	
	Solvents	DMC	0.34	0.20	0.28	0.13	0.40	
	Solvents	EMC	0.00	0.14	0.20	0.09	0.29	
	Solvents	PC	0.00	0.00	0.00	0.00	0.00	
	Total electrolyte		0.81	0.61	0.86	0.40	1.25	
Separator	Separator	PE 10 micron+AL2O3	0.02	0.00	0.00	0.00	0.00	
	Separator	PP 15 micron + AL2O	0.07	0.14	0.00	0.00	0.00	
	Separator	PP/PE/PP	0.00	0.00	0.13	0.00	0.25	
	Separator	PE-Al2O3	0.00	0.00	0.00	0.09	0.00	
	Total separator		0.09	0.14	0.13	0.09	0.25	
Cell Packaging	Tab with film	Al Tab	0.00	0.04	0.00	0.00	0.00	
		Ni Tab	0.00	0.13	0.00	0.00	0.00	
	Exterior covering	PET/Ny/Al/PP/ Lamin	0.01	0.15	0.00	0.00	0.00	
	Collector parts	Al leads	0.00	0.00	0.01	0.00	0.02	
	Collector parts	Cu leads	0.00	0.00	0.03	0.00	0.05	
	Collector parts	Plastic fasteners/cove	0.00	0.00	0.05	0.00	0.02	
	Cover	Valve, rivet terminals,	0.00	0.00	0.29	0.12	0.11	
	Case	Al	0.00	0.00	0.35	0.00	0.91	
	Case	Ni plating Iron	0.00	0.00	0.00	0.44	0.00	
	Total cell packaging		0.01	0.32	0.72	0.56	1.12	

Based on these five different cells, a virtual product was calculated for each Base Case considering the share of the different cells according to their market share (calculation is following the same way as described in task 4). For the virtual product the BOM was determined and used to calculate the environmental impact.

Similar as in Task 5, the 2018 version of the GREET2 Model by UChicago Argonne, LLC[3] was used as source of the life cycle inventory (LCI) data of the different battery chemistries. It was modelled and calculated in SimaPro version 8.52 with version 3.4 of the ecoinvent database, and added as extra materials in the EcoReport. Table 2 shows how the data sets of three additional cell chemistries of task 6 were modelled.

[3] https://greet.es.anl.gov/greet.models

Table 2: Data set of the added successor cell chemistries (modelling all based on GREET2 model)

Chemistries	LCI data record	Amount (/kg product)	Unit
NCM811	NMC811 precursor (see below for LCI)	0.95	kg
	Lithium hydroxide {GLO}| market for | Cut-off, U	0.38	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	26.18	MJ
NCM811 precursor	Nickel sulfate {GLO}| market for | Cut-off, U	1.34	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.17	kg
	Manganese sulfate {GLO}| market for | Cut-off, U	0.17	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.89	kg
	Ammonia, liquid {RoW}| market for | Cut-off, U	0.12	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ
NCA (92/5/3) [4]	Lithium hydroxide {GLO}| market for | Cut-off, U	0.25	kg
	Oxygen, liquid {RoW}| market for | Cut-off, U	0.04	kg
	NCA (91/2/3) precursor (see below for LCI)	0.95	kg
	Electricity, medium voltage {CN}| market group for | Cut-off, U	26.18	MJ
NCA (92/5/3) precursor	Ammonia, liquid {RoW}| market for | Cut-off, U	0.37	kg
	Nickel sulfate {GLO}| market for | Cut-off, U	1.55	kg
	Cobalt {GLO}| market for | Cut-off, U (used as worst proxy for proxy Cobalt Sulfate, like PEF)	0.08	kg
	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.87	kg
	Aluminium sulfate, without water, in 4.33% aluminium solution state {GLO}| market for | Cut-off, U	0.06	kg
	Water, deionised, from tap water, at user {RoW}| market for water, deionised, from tap water, at user | Cut-off, U	0.64	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.04	GJ

[4] NCA (92/5/3) and its precursor are not such modelled within the GREET2 model. Therefore the LCI of NCA (92/5/3) is drafted based upon the modelling of the NCA (80/15/5) composition that is included in the GREET2 model and the chemical equation of NCA (92/5/3).

Chemistries	LCI data record	Amount (/kg product)	Unit
LFMP (proxy)[5]	Lithium hydroxide {GLO}| market for | Cut-off, U	0.27	kg
	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, U	0.37	kg
	Iron sulfate {GLO}| market for | Cut-off, U	0.17	kg
	Manganese(III) oxide {GLO}| market for | Cut-off, U	0.40	kg
	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Cut-off, U	0.03	GJ

6.1.2. Extended lifetime

While the first design option mainly addressed the composition of batteries and thus focused on the environmental impact due to sourcing and production of the materials, the second option sets the focus at extending the useful lifetime. As reported in task 4, this can be achieved by increasing the durability and the first lifetime of the battery or by 2nd life application. The latter one offers the possibility to prolong the service life of a product and thus enables it to increase the QFU (Quantify of Functional Unit). Task 4 report points out that there are different possibilities for 2nd life applications such as repurposing and reuse. Out of the perspective of wanting to assess the environmental impact of these possibilities, both options are heading into the same direction. While repurposed batteries are rather used in stationary applications, reused batteries are used again in the same application e.g. automotive (also if not in the same vehicle). A difference lies in the effort to enable a reuse or repurposing. In the latter case, the effort is a bit higher since some components may have to be changed (what also may be the case for the first option if they are e.g. damaged). Cusenza et al. 2018 are listing the additional inventory (although this might differ from case to case) needed to enable a repurposing for 2nd life stationary application, see Table 3.

Table 3: Components inventory for repurposing (based on Cusenza et al. 2018)

Components	Unit of measure	Mass	Source
Battery tray	[kg]	14.88	(Ellingsen et al., 2014)
Battery retention	[kg]	5.45	(Ellingsen et al., 2014)
Electricity consumption	[kWh]	8.72	Calculation based on JRC Petten data
* For the analysis, only the electricity consumption of testing is considered; the disassembly is assumed to be a manual disassembly			

Apart of the higher QFU of the battery system, the main difference between reuse and repurposing regarding the environmental impact may lie in these additional components.

However, as in the case of the first design option, it is not the aim of this report to conduct an in-depth analyses of the environmental impact of different 2nd life options but rather to assess the general potential of such a prolonged product lifetime. For this reason, this report focusses

[5] LFMP is not included in the GREET2 model, to model LFMP the LFP composition within the GREET2 model was taken as starting point and changed by replacing 70% of the Iron sulfate input by Manganese oxide.

on the effect of an extended lifetime due to battery reuse on the environmental impact of the batteries.

The design option offers the possibility to reuse a battery, which reaches the end of its 1st life (mostly at 70 % to 80 % SOH) in the same application. An example would be to reuse the battery of a high capacity EV in a smaller city car (as initial or battery or replacement). Although the capacity may not decrease in a linear manner anymore, the remaining capacity might still be sufficient to fulfil the expected service of the vehicle. This option becomes even more reasonable when looking at Figure 1 that compares the annual travel distances of different vehicle segments.

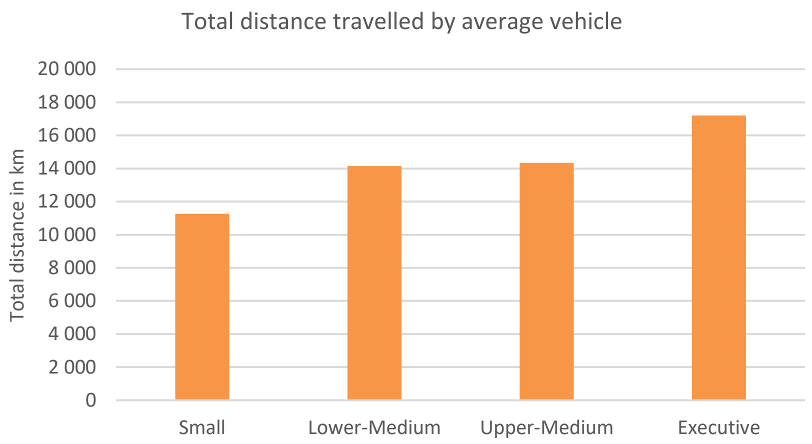

Figure 1: Average annual driven kilometres of a small car in the EU (Papadimitriou 2013)

The figure illustrates that smaller cars are less driven.[6] Thus it could make economically less sense to install a new battery system, since a reused battery would also be sufficient for only a part of the costs[7].

To analyse the potential impact of a prolonged battery life-time due to reuse, we considered for the PC BEV and Truck BEV a prolonged lifetime of the battery. For the PHEV versions the end-of-first life was assumed at ~ 60% SOH. Due to this low SOH a further reuse seems not applicable.

For the stationary systems, the reuse of batteries in other systems does not seem to be appropriate and is not further investigated here. Also the reuse of a battery from a BEV in a ESS is according to a stakeholder not appropriate since the used BEV battery won't meet the requirements of the ESS in terms of cycle lifetime. Anyhow, since the point of interest is whether or not there is a positive influence on the environmental impact, the focus on BEV appears suitable. For the BEV it is assumed, that after the battery reaches its end of first life, the battery is reused until it reaches ~ 60% SOH. Afterwards, the batteries are disposed.

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[6] Please note, that this figure does not say anything about the typical driving distance of the vehicles per trip. But it can be assumed that the driving range of smaller cars is comparatively lower than the one of higher segments.

[7] Thereby it is assumed, that with increasing age of the car, the km per trip are also decreasing (A lot of cars are used in fleets at the beginning of their lifetime or are used for long range purpose, where a high reliability of the car is needed. With growing age, cars change hands and the new users may have another pattern of usage and the car is rather used for short distance trips.

6.1.3. Low carbon energy mix for the production of the battery

The analyses in task 4 regarding the most relevant contributors of GWP revealed that the electricity consumption during the manufacturing process of the cell plays a crucial role and contributes greatly to the overall greenhouse gas emissions during production (see figure 21 in task 4 report). Furthermore, this is also backed by the calculations conducted in task 5. Considering that, and as depicted in task 4, the electricity consumption has next to the cathode materials the highest GWP impact, it seems inevitable to consider the reduction of the environmental impact due to electricity consumption as another relevant design option.

This is an issue that has been observed by many other studies (see for example Romare and Dahllöf 2017, Thomas et al. 2018; Ellingsen et al. 2014). Furthermore those studies identified the electricity mix as the biggest lever for reducing the GWP. Ellingsen et al. 2014 provided within one of their studies a sensitivity analysis based on different energy sources.

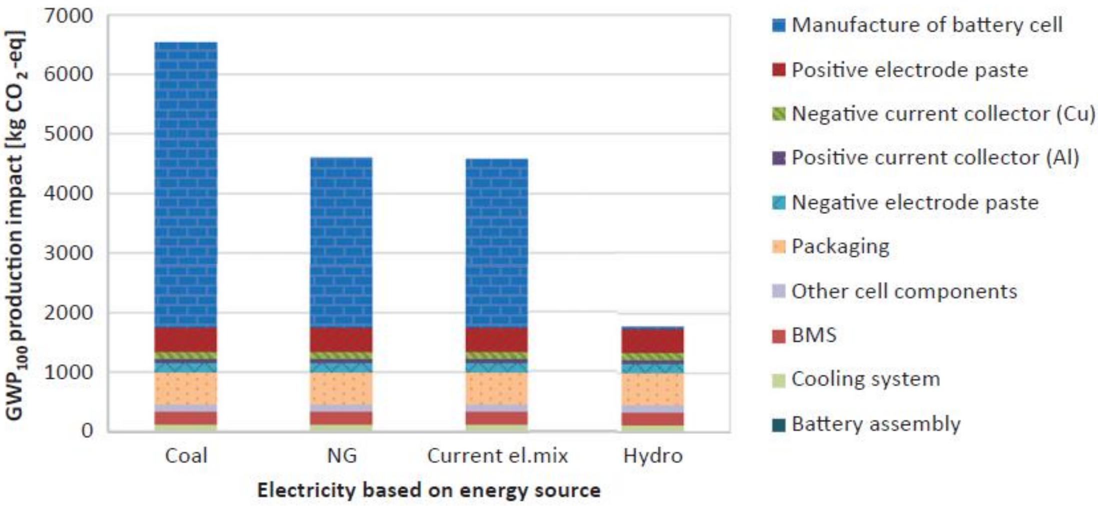

Figure 2: Influence of different energy sources on the GWP (based on Ellingsen et al. 2014)

The figure reveals that depending on the energy source used for the production of the battery, the GWP emissions differ significantly. The lowest emissions can be observed in the case on hydro energy[8]. Considering this, the use of low-carbon energy during the production of the batteries also contains a high potential to reduce the environmental impact and should thus be considered as a design option and be further analysed.

[8] Which should rather be seen here as a proxy for renewable energy.

6.2. Subtask 6.2: Impacts of the design options

AIM OF TASK 6.2:

The aim of this subtask is to describe the impacts of the design options on the base cases. With regard to the analysis of impacts, it should be noted that the analysis is done from a perspective where the design options are directly “designed and built-into” new batteries.

6.2.1. Performance

In this chapter the influence of the design options on the performance indicators and the BOM will be displayed.

6.2.1.1. Reduction of active and passive materials

Reducing the amount of active and passive materials in a battery system is one of the previously listed most promising design options. To determine the effect of this option, the cells used for determining the BOM of the virtual battery in the task 4 report are replaced by the improved successors of these cells. The reason to use similar cells from the same product line, is that these cells mostly are similar or at least only show minor modifications regarding their design. The difference mainly comes from another used cell chemistry or the reduction of passive materials. However, both effects also lead to an increased gravimetric and volumetric energy density and thus to the effect that a less materials are used to provide the same battery capacity as defined in task 4. This design option has the highest influence on the environmental impact of the material consumption. Hereby it has to be noted, that it is not simply a reduction of the formerly used materials[9] but also a substitution by new materials (e.g. Mn in the case of LFMP) or an increase in the share of formerly used materials (e.g. the share of Ni in the case NMC). Thus, in general, one cannot be sure if the reduction in the demand for materials used is not countered by a potentially higher environmental impact due to the new or higher share of materials (which is not the case here as Table 8 indicates). The corresponding performance indicators to this design options are listed in Table 4.

The overview of the performance indicator for this design options reveals, that the indicators are quite similar to those of the BAU of the Base Cases. However, as already addressed before, the major difference lies in the BOM and thus in the amount and kind of materials used, which can be found in in the last 8 lines of Table 4. Furthermore, the use of such materials as well as the reduction of passive materials leads to a reduction in the costs per kWh[10] as listed in the line named "Battery systems costs".

[9] By using materials with a higher energy density (kg/kWh) less materials (in kg) are needed to realize the same required battery capacity (in kWh) as with materials with a lower energy density.

[10] It should be noted, that one stakeholder raised doubts regarding the cost decrease for ESS cell materials, especially LFMP.

Table 4: Performance indicators for design option with reduced active and passive materials

BaseCase		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Short Description		PC BEV HIGH	PC BEV LOW	PC PHEV	Truck BEV	Truck PHEV	Residential ESS	Commercial ESS
Main application		eMobility					stationary	
Parameter	unit	BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Typical capacity of the application	[kWh]	80	40	12	360	160	10	30 000
Economic life time of application (Tapp)	[y]	13	14	13	14	12	20	20
Percent of braking energy recovery in AS	[-]	20%	20%	20%	12%	6%	n.a.	n.a.
Application service energy (AS)	[kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 000 000
Charger Efficiency (ηcharger)	[-]	85%	85%	85%	92%	92%	98%	98%
Consumption	[kWh/km]	0.2	0.16	0.18	1.2	1.4	n.a.	n.a.
Annual kilometers	[km/a]	14000	11000	7000	50000	50000	n.a.	n.a.
C-rate for charging	[-]	0.2 - 0.5	0.2 - 0.5	0.5	1.0	1.0	0.5	1.0
C-rate for normal discharge	[-]	0.33 - 1	0.33 - 1	1.0	1.0	1.0	1.0	1.0
C-rate for braking	[-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Nominal battery system capacity according to ISO ..	[kWh]	80	40	12	30	20	10	10
Number of battery systems per application	[-]	1	1	1	12	8	1	3 000
Maximum calendar life-time of the installed battery (no cycling ageing)	[year]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke)	[-]	80%	80%	75%	80%	75%	80%	80%
Average stroke (SoC - DoD)	[-]	24%	31%	73%	50%	69%	60%	75%
Energy delivered in first cycle (Edc).	[kWh/cycle]	64	32	9	24	15	8	8
Number of cycles per year (#)	cycles	120	120	120	300	600	250	250
Maximum number of cycles for battery system until EoL (no calendar ageing)	[-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
SoH @ EoL of battery system relative to declared capacity (SoHcap)	[-]	80%	80%	60%	80%	60%	70%	70%
Average energy delivered per average cycle until EoL	[kWh/cycle]	19.44	12.22	8.75	178.57	110.06	6.00	22 500.00
number of batteries in the application	[-]	1.00	1.00	1.00	12.00	8.00	1.00	3 000.00
Actual quantity of functional units (QFU) over battery system lifetime (per battery) *(1 FU = 1 kWh over battery lifetime)*	[-]	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
Service life of first battery (years)	[year]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Battery system costs	[€/kWh]	140	140	185	129	185	499	499
CAPEX for decomissioning	[EURO/ battery]	1 200	600	180	450	300	150	150
OPEX replace battery	[EURO/ battery]	700	700	700	400	400	100	100
ηcoul x ηv =average energy efficiency of battery system over life time	[-]	92%	92%	92%	92%	92%	92%	92%
Auxiliary heating energy for a battery system relative to functional unit	kW	5.0	5.0	-	5.0	-	-	-
Self discharge per month(@STC)	[-]	2%	2%	2%	2%	2%	2%	2%
Total weight of a battery system	[kg]	521	261	98	221	163	101	101
Total weight of cells	[kg]	391	195	68	166	114	66	66
Specific energy density cell level	[Wh/kg]	205	205	176	181	176	152	152
Weight of Cobalt (pro battery system)	[kg]	5	3	1	1	1	0	0
Weight of Graphite (pro battery system)	[kg]	79	40	13	31	21	11	11
Weight of Nickel (pro battery system)	[kg]	44	22	4	12	6	1	1
Weight of Manganese (pro battery system)	[kg]	12	6	4	7	6	4	4
Weight of Lithium (pro battery system)	[kg]	13.9	7.0	1.7	4.5	2.8	1.0	1.0

6.2.1.2. Extended lifetime

The design option of a prolonged lifetime aims on increasing the QFU of the battery since it is used for a longer period of time. As described in task 4 and the previous section, there are different options existing to extend the 1st and 2nd lifetime of the battery. While naturally also the options to extend the 1st life are of interest, this design options deals with the extension of the 2nd lifetime of the battery. For this assessment we focused on the reuse of the battery e.g. in a smaller city car. Since it is assumed that also in this application the SOH should not fall below 60% SOH we calculated the additional lifetime based on this restriction. Furthermore, this also means that the PHEV applications are not considered for since it was assumed, that these batteries are already used until they reach the 60 % SOH. Same for the stationary applications: The SOH of battery systems used in stationary applications may also go below 70% SOH and thus make a reuse of the battery rather difficult and up to now, according to a stakeholder, no 2nd life approaches are known for stationary systems. The following Table 5 shows how this design option influences the different performance indicators.

The major difference (compared to BAU or for the design option of reduced active and passive materials) of this design options can be observed in the additional lines in Table 5 marked in red[11]. These lines are used for the calculation of the additional lifetime, the average energy delivered per cycle considering the lower SOH of the battery and finally the resulting additional FU provided by the battery in this timeframe. The total QFU is then considered as the sum of both: the QFU from the first lifetime and from the re-use phase. However, this design option has a low influence on the BOM (also there might be some exchanges to enable the reuse) and thus, the BOM and the connected data are the same as for the Base Case. Only a slightly higher OPEX was considered for some additional adjustments.

[11] Between the lines "Service life of first battery" and "Battery system costs"

Table 5: Performance indicators for design option with extended lifetime

BaseCase		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Long Description		Passenger Car - BEV high battery capacity	Passenger Car - BEV lower battery capacity	Passenger Car PHEV	Truck BEV	Truck PHEV	Residential ESS	Grid supporting ESS
Main application		eMobility					stationary	
Parameter	unit	BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Typical capacity of the application	[kWh]	80	40	12	360	160	10	30 000
Economic life time of application (Tapp)	[y]	13	14	13	14	12	20	20
Percent of braking energy recovery in AS	[-]	20%	20%	20%	12%	6%	n.a.	n.a.
Application service energy (AS)	[kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 000 000
Charger Efficiency (ηcharger)	[-]	85%	85%	85%	92%	92%	98%	98%
Consumption	[kWh/km]	0.2	0.16	0.18	1.2	1.4	n.a.	n.a.
Annual kilometers	[km/a]	14000	11000	7000	50000	50000	n.a.	n.a.
C-rate for charging	[-]	0,2 - 0,5	0,2 - 0,5	0.5	1.0	1.0	0.5	1.0
C-rate for normal discharge	[-]	0,33 - 1	0,33 - 1	1.0	1.0	1.0	1.0	1.0
C-rate for braking	[-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Nominal battery system capacity according to ISO ..	[kWh]	80	40	12	30	20	10	10
Maximum calendar life-time of the installed battery (no cycling ageing)	[year]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke)	[-]	80%	80%	75%	80%	75%	80%	80%
Average stroke (SoC - DoD)	[-]	24%	31%	73%	50%	69%	60%	75%
Energy delivered in first cycle (Edc).	[kWh/cycle]	64	32	9	24	15	8	8
Number of average cycles per year (#)	cycles	120	120	120	300	600	250	250
Maximum number of full cycle equivalents for battery system until EoL (no calendar ageing)	[-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
SoH @ EoL of battery system relative to declared capacity (SoHcap)	[-]	80%	80%	60%	80%	60%	70%	70%
Average energy delivered per average cycle until EoL	[kWh/cycle]	19.44	12.22	8.75	178.57	110.06	6.00	22 500.00
number of batteries in the application	[-]	1.00	1.00	1.00	12.00	8.00	1.00	3 000.00
Actual quantity of functional units (QFU) over battery system lifetime (per battery) (1 FU = 1 kWh over battery lifetime)	[-]	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
Service life of first battery (years)	[year]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
Prolonged lifetime due to Reuse (quadratic aging)	[y]	3.60	3.36	0.00	2.01	0.00	0.00	0.00
Load level as compared to first life (e.g. lower maximum energy per cycle)	[%]	70%	70%	70%	70%	70%	70%	70%
Average SoH during Reuse-phase	[%]	0.70	0.70	0.00	0.70	0.00	0.00	0.65
SoH @ EoL of re-use-phase	[%]	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Maximum energy deliverable per cycle @ Reuse phase	[kWh/cycle]	56.00	28.00	0.00	252.00	0.00	0.00	0.00
Average energy delivered per cycle @ Reuse phase	[kWh/cycle]	13.61	8.56	0.00	125.00	0.00	0.00	0.00
Maximum additional FU due to Reuse	[-]	19 353.60	9 026.87	0.00	121 538.76	0.00	0.00	0.00
Actual additional FU due to Reuse	[-]	5 880.00	3 447.76	0.00	75 358.85	0.00	0.00	0.00
Actual QFU including first use and re-use of battery	[-]	46 200	27 090	13 440	557 656	373 177	25 532	95 744 681
battery system cost/declared initial capacity	[EURO/kWh]	206	206	254	220	212	683	683
CAPEX for decomissioning	[EURO/ battery]	1 200	600	180	450	300	150	150
OPEX replace battery	[EURO/ battery]	840	840	840	480	480	120	120
ηcoul x ηv =average energy efficiency of battery system over life time	[-]	92%	92%	92%	92%	92%	92%	92%
Auxiliary heating energy for a battery system relative to functional unit	kW	5.0	5.0		5.0			
Self discharge per month(@STC)	[-]	2%	2%	2%	2%	2%	2%	2%
Total weight of a battery system	[kg]	609	304	126	256	210	128	128
Total weight of cells	[kg]	456	228	88	192	147	83	83
Specific energy density cell level	[Wh/kg]	175	175	136	156	136	120	120
Weight of Cobalt (pro battery system)	[kg]	10	5	1	3	2	0	0
Weight of Graphite (pro battery system)	[kg]	87	44	16	36	26	14	14
Weight of Nickel (pro battery system)	[kg]	36	18	3	10	6	1	1
Weight of Manganese (pro battery system)	[kg]	17	9	3	2	4	0	0
Weight of Lithium (pro battery system)	[kg]	14	7	2	5	3	1.2	1.2

6.2.1.3. Usage of low carbon electricity mix

The usage of low-carbon electricity mix has no direct influence on the materials or energy consumption and hence the BOM and the performance indicators are identical with those of the BAU for the Base Cases (see Table 6). This option has an environmental impact through reducing the emissions caused by the electricity used for the battery production. The resulting environmental impact strongly depends on the current electricity mix (as also Figure 2 indicates). For this design option the impact of the usage of two different electricity mixes and their corresponding GHG emissions are calculated. The first one is intended to reflect the current electricity mix. According to the PRIMES model, the electricity mix in the EU28 accounts currently for about 0.38 kg CO_2eq/kWh. However, depending on the technology, GHG emissions power generation can range between 1.284 kg CO_2eq/kWh and 0.004 kg CO_2eq/kWh[12]. In addition, many batteries are currently produced outside the EU with other electricity mixes and carbon emissions. Based on two values values taken from ecoinvent, the resulting GHG emissions during the production are calculated in the scenario analysis of task 7 with a different separate spreadsheet than the MEErP EcoReport tool. Due to the limitations of the MEErP EcoReport tool, it is impracticable to change the electricity related GHG emissions of the production of all the materials. Therefore, there are no EcoReport results included on the usage of a low carbon electricity mix in this task 6 report and we refer you to the figures included in task 7.

[12] To determine this range, the GWP impact of the available high voltage electricity generating technologies within the ecoinvent LCI database (version 3.4) were calculated within SimaPro (version 8.52). In ecoinvent there are 21 high voltage power generating processes. Germany was taken as region to represent a European average, as there are no European mixes available of the high voltage power generating processes only country-specific processes. The power generator with the highest GWP impact is electricity production from lignite and the one with the lowest is run-of-river hydroelectricity. The impact was increased with 5% in order to include the losses when transforming high voltage electricity to medium voltage electricity.

Table 6: Performance indicators for base cases and design option low-carbon electricity mix

BaseCase		BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Long Description		**Passenger Car - BEV with higher battery capacity**	**Passenger Car - BEV with lower battery capacity**	**Passenger Car PHEV**	**Truck BEV**	**Truck PHEV**	**Residential ESS**	**Grid stabilisation ESS**
Main application		eMobility					stationary	
Parameter	unit	BC 1	BC 2	BC 3	BC 4	BC 5	BC6	BC7
Typical capacity of the application	[kWh]	80	40	12	360	160	10	30 000
Economic life time of application (Tapp)	[y]	13	14	13	14	12	20	20
Percent of braking energy recovery in AS	[-]	20%	20%	20%	12%	6%	n.a.	n.a.
Application service energy (AS)	[kWh/Tapp]	43 680	29 568	19 656	940 800	890 400	40 000	120 000 000
Charger Efficiency (ηcharger)	[-]	85%	85%	85%	92%	92%	98%	98%
Consumption	[kWh/km]	0.2	0.16	0.18	1.2	1.4	n.a.	n.a.
Annual kilometers	[km/a]	14000	11000	7000	50000	50000	n.a.	n.a.
C-rate for charging	[-]	0.2 - 0.5	0.2 - 0.5	0.5	1.0	1.0	0.5	1.0
C-rate for normal discharge	[-]	0.33 - 1	0.33 - 1	1.0	1.0	1.0	1.0	1.0
C-rate for braking	[-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Nominal battery system capacity according to ISO ..	[kWh]	80	40	12	30	20	10	10
Number of battery systems per application	[-]	1	1	1	12	8	1	3 000
Maximum calendar life-time of the installed battery (no cycling ageing)	[year]	20	20	20	20	20	25	25
Maximum SoC - maximum DoD (Stroke)	[-]	80%	80%	75%	80%	75%	80%	80%
Average stroke (SoC - DoD)	[-]	24%	31%	73%	50%	69%	60%	75%
Energy delivered in first cycle (Edc).	[kWh/cycle]	64	32	9	24	15	8	8
Number of cycles per year (#)	cycles	120	120	120	300	600	250	250
Maximum number of cycles for battery system until EoL (no calendar ageing)	[-]	1 500	1 500	2 000	2 000	3 000	8 000	10 000
SoH @ EoL of battery system relative to declared capacity (SoHcap)	[-]	80%	80%	60%	80%	60%	70%	70%
Average energy delivered per average cycle until EoL	[kWh/cycle]	19.44	12.22	8.75	178.57	110.06	6.00	22 500.00
number of batteries in the application	[year]	1.00	1.00	1.00	12.00	8.00	1.00	3 000.00
Actual quantity of functional units (QFU) over battery system lifetime (per battery) *(1 FU = 1 kWh over battery lifetime).*	[-]	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
Service life of first battery (years)	[year]	14.40	13.43	10.67	8.04	5.33	17.02	17.02
battery system cost/declared initial capacity	[EURO/ kWh]	206	206	254	220	212	683	683
CAPEX for decomissioning	[EURO/ battery]	1 200	600	180	450	300	150	150
OPEX replace battery	[EURO/ battery]	700	700	700	400	400	100	100
ηcoul x ηv =average energy efficiency of battery system over life time	[-]	92%	92%	92%	92%	92%	92%	92%
Auxiliary heating energy for a battery system relative to functional unit	kW	5.0	5.0		5.0			
Self discharge per month(@STC)	[-]	2%	2%	2%	2%	2%	2%	2%
Total weight of a battery system	[kg]	609	304	126	256	210	128	128
Total weight of cells	[kg]	456	228	88	192	147	83	83
Specific energy density cell level	[Wh/kg]	175	175	136	156	136	120	120
Weight of Cobalt (pro battery system)	[kg]	10	5	1	3	2	0	0
Weight of Graphite (pro battery system)	[kg]	87	44	16	36	26	14	14
Weight of Nickel (pro battery system)	[kg]	36	18	3	10	6	1	1
Weight of Manganese (pro battery system)	[kg]	17	9	3	2	4	0	0
Weight of Lithium (pro battery system)	[kg]	14	7	2	5	3	1.2	1.2

6.2.2. Selection of the key environmental impact category and supplementary parameters

MEErP considers 13 environmental impact categories. Each impact category has its own unit, e.g. global warming potential is characterised as kg CO_2 eq. and acidification potential in g SO_2 eq. Due to the different units, it is difficult to compare the different impact categories to know which category is most decisive. To make comparison possible, characterised LCA results can be normalised and/or weighted so they are expressed in a similar unit. Therefore, normalising LCA results also allows aggregation of the different environmental indicators into a single score. External environmental costing is a method to normalise and weigh characterised environmental indicators in one step into monetary values. This step is also included in the MEErP EcoReport tool as “calculation of the marginal external damages” also mentioned as societal LCC (see section 5.3.2 of the task 5 report for explanation on how the societal LCC are calculated within the EcoReport).

When looking at the detailed societal LCC results of all seven BCs (see Task 5 report, sections 5.3.2.1 – 5.3.2.7), the top three impact categories with the highest societal LCC are: acidification potential, greenhouse gases/global warming potential, and particulate matter. However, the external marginal costs rates are outdated when comparing them to more recent studies on external environmental costing[13].

The review paper by Peters et al. (2017) mentions that the majority of existing LCA studies on Li-ion batteries focus on greenhouse gas emissions or energy demand, despite the high relative importance of environmental impacts related to human toxicity, acidification, and resource depletion[14]. The relative importance of the latter impact categories is shown by Peters et al. by normalising the mean value of the environmental impacts over the reviewed studies by comparing to the average annual impacts in Europe in 1995. According to Peters et al. it is mainly the mining and production of materials such as nickel or cobalt that cause significant toxicity impacts. They also noted that few data points are available for the categories acidification and resource depletion. Thus the results in these categories have a very high uncertainty and further research would be needed in that area.

In the position paper “(Right) indicators needed on sustainable batteries” by EUROBAT (2019) considering CO_2 eq. content is communicated as one of the key priorities in the framework of the current discussion on battery sustainability. In addition, they believe that recyclability and socio-economic considerations are important indicators that need to be included when addressing the sustainability of batteries. Regarding socio-economic considerations, EUROBAT sees it involving both the environmental conditions of mines and the social conditions of workers.

Based on the above, the results of Task 4 and 5, and seeing Commission communications that mentions that sustainable batteries are linked to a low carbon footprint and seen as one

[13] E.g. De Nocker & Debacker, 2018; The Bruyn et al., 2018; Korzhenevych et al., 2014

[14] The impact category depletion of abiotic resources includes substances such as CRMs.

of the technologies to mitigate climate change[15], the following key environmental impact category and supplementary indicator are selected:

Key environmental impact category

- Global warming potential [kg CO2 eq.]

Supplementary indicator:

- The (non-)critical raw materials ((n-)CRM) within batteries
    - Cobalt [kg]
    - Lithium [kg]
    - Manganese [kg]
    - Natural graphite [kg]
    - Nickel [kg]

6.2.3. Summary of key performance indicators and results

The following two tables summarise all key performance indicators from the analysed design improvement options and Business-As-Usual (BAU) BCs. Table 7 gives the key performance indicators and Table 8 the results of the key environmental impact category, global warming potential.

[15] EC COM(2019) 176 final, p. 6: "Sustainable batteries – produced with responsible sourcing, the lowest carbon footprint possible and following a circular economy approach, can be at the core of the EU's competitive advantage.".
Europe on the Move - Clean Mobility – Implementing the Paris Agreement (2018): "Why Europe needs a 'battery ecosystem': • Improve air quality & mitigate climate change → Protecting public health and environment means drastically cutting greenhouse gas emissions […]".

Table 7: Overview of the key performance indicators

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Actual quantity of functional units per battery application system (QFU for total number of battery systems in its application) [kWh]	BAU	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
	Low carbon	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
	Reduced materials	40 320	23 642	13 440	482 297	373 177	25 532	95 744 681
	Extended lifetime	46 200	27 090	13 440	557 656	373 177	25 532	95 744 681
Battery system costs per declared initial capacity [EUR/kWh]	BAU	206	206	254	220	212	683	683
	Low carbon	206	206	254	220	212	683	683
	Reduced materials	140	140	185	129	185	499	499
	Extended lifetime	206	206	254	220	212	683	683
Specific energy density on cell level [Wh/kg]	BAU	175	175	136	156	136	120	120
	Low carbon	175	175	136	156	136	120	120
	Reduced materials	205	205	176	181	176	152	152
	Extended lifetime	175	175	136	156	136	120	120
Weight of cobalt (pro battery system) [kg]	BAU	9.6	4.8	1.3	2.8	2.1	0.3	0.3
	Low carbon	9.6	4.8	1.3	2.8	2.1	0.3	0.3
	Reduced materials	5.3	2.7	0.8	1.2	1.4	0.1	0.1
	Extended lifetime	9.6	4.8	1.3	2.8	2.1	0.3	0.3
Weight of lithium (pro battery system) [kg]	BAU	14.4	7.2	2.0	4.7	3.4	1.2	1.2
	Low carbon	14.4	7.2	2.0	4.7	3.4	1.2	1.2
	Reduced materials	13.9	7.0	1.7	4.5	2.8	1.0	1.0
	Extended lifetime	14.4	7.2	2.0	4.7	3.4	1.2	1.2
Weight of manganese (pro battery system) [kg]	BAU	17.1	8.6	2.6	1.9	4.3	0.2	0.2
	Low carbon	17.1	8.6	2.6	1.9	4.3	0.2	0.2
	Reduced materials	11.9	5.9	3.5	6.5	5.9	3.8	3.8
	Extended lifetime	17.1	8.6	2.6	1.9	4.3	0.2	0.2
Weight of graphite (pro battery system) [kg]	BAU	87.3	43.6	15.9	36.4	26.5	14.5	14.5
	Low carbon	87.3	43.6	15.9	36.4	26.5	14.5	14.5
	Reduced materials	79.2	39.6	12.5	31.1	20.9	11.1	11.1
	Extended lifetime	87.3	43.6	15.9	36.4	26.5	14.5	14.5
Weight of nickel (pro battery system) [kg]	BAU	35.9	18.0	3.4	10.0	5.7	1.2	1.2
	Low carbon	35.9	18.0	3.4	10.0	5.7	1.2	1.2
	Reduced materials	43.7	21.8	3.8	12.1	6.4	1.3	1.3
	Extended lifetime	35.9	18.0	3.4	10.0	5.7	1.2	1.2

Table 8: Overview of the key environmental impact category global warming potential, impact per FU (kWh delivered over application lifetime) [kg CO_2 eq./FU] and battery system [kg CO_2 eq./battery][16, 17]

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
GWP production + distribution phase [kg CO_2 eq./FU]	BAU	0.19	0.29	0.18	0.09	0.08	0.08	0.08
	Reduced materials	0.17	0.26	0.14	0.08	0.06	0.06	0.06
	Extended lifetime	0.17	0.24	0.18	0.08	0.08	0.08	0.08
GWP use phase [kg CO_2 eq./FU]	BAU	0.09	0.09	0.09	0.07	0.07	0.05	0.05
	Reduced materials	0.09	0.09	0.09	0.07	0.07	0.05	0.05
	Extended lifetime	0.09	0.08	0.09	0.06	0.07	0.05	0.05
GWP EOL phase [kg CO_2 eq./FU]	BAU	-0.02	-0.04	-0.03	-0.01	-0.01	-0.01	-0.01
	Reduced materials	-0.02	-0.03	-0.02	-0.01	-0.01	-0.01	-0.01
	Extended lifetime	-0.02	-0.03	-0.03	-0.01	-0.01	-0.01	-0.01
GWP total life cycle [kg CO_2 eq./FU]	BAU	0.27	0.35	0.25	0.15	0.14	0.12	0.12
	Reduced materials	0.25	0.32	0.21	0.14	0.13	0.11	0.11
	Extended lifetime	0.25	0.28	0.25	0.12	0.14	0.12	0.12
GWP production + distribution phase [kg CO_2 eq./battery]	BAU	8 619	4 312	1 759	3 438	2 929	1 546	1 546
	Reduced materials	7 640	3 824	1 391	3 040	2 315	1 241	1 241
	Extended lifetime	8 619	4 312	1 759	3 438	2 929	1 546	1 546
GWP use phase [kg CO_2 eq./battery]	BAU	4 117	1 402	925	2 859	2 761	1 061	1 061
	Reduced materials	4 117	1 402	925	2 859	2 761	1 061	1 061
	Extended lifetime	4 663	1 406	925	2 522	2 761	1 061	1 061
GWP EOL phase [kg CO_2 eq./battery]	BAU	-1 051	-525	-253	-437	-422	-192	-192
	Reduced materials	-925	-462	-207	-390	-346	-166	-166
	Extended lifetime	-1 051	-525	-253	-437	-422	-192	-192
GWP total life cycle [kg CO_2 eq./battery]	BAU	11 685	5 189	2 431	5 860	5 269	2 415	2 415
	Reduced materials	10 833	4 763	2 108	5 508	4 731	2 135	2 135
	Extended lifetime	12 231	5 192	2 431	5 518	5 269	2 415	2 415

[16] As mentioned in section 6.2.1.3 it is impracticable to calculate tool the impacts of using low carbon electricity mix for the complete production mix with the MEErP EcoReport and are therefore excluded from this overview.

[17] The figures of the extended lifetime design option of BC3, 5, 6, and 7 are coloured grey, as the lifetime of these base cases cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

6.3. Subtask 6.3: Costs

6.3.1. Introduction to calculating the Life Cycle Costs

As explained in more detail in Task 5, section 5.1.2, Life Cycle Costing (LCC) is a concept that aims to estimate the full cost of a system. Therefore, the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are calculated and converted to their net present value (NPV) with a discount rate.

The consumer LCC in MEErP studies is to be calculated using the following formula:

[€]= $\Sigma CAPEX$+ $\Sigma(PWF\ x\ OPEX)$

where,

LCC is the life cycle costing,
CAPEX is the purchase price (including installation) or so-called capital expenditure,
OPEX are the operating expenses per year or so-called operational expenditure,
PWF is the present worth factor with PWF = $1/(1+r)^N$
N is the product life in years,
r is the discount rate which represents the return that could be earned in alternative investments.

The Levelized Cost Of Energy (LCOE) is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, and cost of capital. The LCOE is defined for the purpose of these calculations as:

$$\mathrm{LCOE}[€/\mathrm{kWh}] = \frac{\text{net present value of sum of costs of electricty stored over its lifetime}}{sum\ of\ electrical\ energy\ deliveredover\ its\ life\ time}$$

The LCOE calculation of costs per kWh generated aligns with the FU defined in Task 1. In this definition the life cycle environmental impacts of the battery system or component are normalized to 1 kWh of electricity stored.

As a consequence there is a direct relationship between LCOE, LCC and the quantity of FUs of a battery system:

LCOE = LCC/QFU [euro/kWh]

Using this approach allows comparison between the LCC of different design options per FU or in other words the LCOE.

For the LCC calculations of this task, the same economic parameters as in Task 5 are used (for more explanation on these parameters, see section 5.1.2.5 of Task 5):

- Discount rate: 4% (expect for electricity costs which is calculated with 0% discount rate following the MEErP methodology and are based on the PRIMES electricity rates which are already recalculated to an NPV).
- Electricity rate industry: 0.101 EUR per kWh.
- Electricity rate households: 0.213 EUR per kWh.

Extending these user-based LCC**,** societal LCC are calculated, as well. These include the costs for external damage of air emissions based on a given list of fixed prices (see section 5.3.2 of the task 5 report). These values are to be multiplied with the total mass of emissions calculated in the EcoReport tool and are added to the consumer LCC to sum up to the total LCC.

6.3.2. Life cycle costs of the individual design options

This section presents four tables: first table (Table 9) is an overview of the CAPEX and OPEX assumptions per BC and design option used in the LCC calculations, followed by three results tables with the consumer LCC results (Table 10), societal LCC results (Table 11), and the total LCC (Table 12), i.e. consumer plus societal LCC. For more explanation on the economic input parameters, please go to section 5.1.2 of the task 5 report, and on the LCC and societal cost calculations to section 5.3 of task 5.

Table 9: Overview of CAPEX and OPEX assumptions of the BCs for BAU, low carbon, reduced materials, and extended lifetime design options (based on Task 3 and Table 7)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
CAPEX battery system cost per declared initial capacity [EUR/kWh]	BAU	206	206	254	220	212	683	683
	Low carbon	206	206	254	220	212	683	683
	Reduced materials	140	140	185	129	185	499	499
	Extended lifetime	206	206	254	220	212	683	683
OPEX battery replacement [EUR/service]	All options	700	700	700	400	400	100	100
CAPEX decommissioning at EOL [EUR/battery sys.]	All options	1 200	600	180	450	300	150	150

Table 10: Overview of the consumer life cycle costing results per BC for BAU, low carbon, reduced materials, and extended lifetime design options (calculation based application level)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Consumer LCOE or LCC per FU [EUR/kWh delivered]	BAU	0.461	0.547	0.377	0.177	0.125	0.293	0.278
	Reduced materials	0.340	0.404	0.306	0.117	0.113	0.223	0.208
	Extended lifetime	0.410	0.453	0.377	0.155	0.125	0.293	0.278
Consumer LCC total for all batteries in application per Tapp [EUR]	BAU	20 152	16 179	7 401	166 397	111 511	11 723	33 328 317
	Reduced materials	14 872	11 954	6 014	109 699	100 722	8 938	24 974 497
	Extended lifetime	20 327	16 520	7 401	168 926	111 511	11 723	33 328 317

Table 11: Overview of the societal life cycle costing results per BC for BAU, low carbon, reduced materials, and extended lifetime design options (calculation based application level)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Societal LCC per FU [EUR/kWh delivered]	BAU	0.050	0.072	0.034	0.021	0.017	0.013	0.013
	Reduced materials	0.052	0.075	0.031	0.021	0.015	0.012	0.012
	Extended lifetime	0.045	0.058	0.034	0.018	0.017	0.013	0.013
Societal LCC total for all batteries in application per Tapp [EUR]	BAU	2 189	2 119	663	19 924	14 830	531	1 582 515
	Reduced materials	2 277	2 209	611	20 059	13 785	471	1 413 800
	Extended lifetime	2 291	2 120	663	19 522	14 830	531	1 582 515

Table 12: Overview of the total (consumer + societal) LCC results per BC for BAU, low carbon, reduced materials, and extended lifetime design options (calculation based application level)

Performance indicator	**Design option**	**BC1** PC BEV HIGH	**BC2** PC BEV LOW	**BC3** PC PHEV	**BC4** Truck BEV	**BC5** Truck PHEV	**BC6** Resid. ESS	**BC7** Comm. ESS
Total LCC per FU [EUR/kWh delivered]	BAU	0.511	0.619	0.410	0.198	0.142	0.306	0.291
	Reduced materials	0.393	0.409	0.337	0.138	0.129	0.235	0.220
	Extended lifetime	0.455	0.511	0.410	0.173	0.142	0.306	0.291
Total LCC total for all batteries in application per Tapp [EUR]	BAU	22 341	18 299	8 064	186 321	126 341	12 254	34 920 832
	Reduced materials	17 148	14 163	6 625	129 758	114 507	9 410	26 388 296
	Extended lifetime	22 545	18 640	8 064	188 448	126 341	12 254	34 920 832

6.4. Subtask 6.4: Analysis of BAT and LLCC

AIM OF TASK 6.4:

The aim of this task is to combine the previous design options (if possible) and to identify the Best Available and also the Least Life Cycle Cost (LLCC) solution.

Therefore, the design option identified in subtask 6.1 should be ranked regarding the Best Available Technology (BAT) and the Least (minimum) Life Cycle Costs.

6.4.1. Ranking of individual design options

The following seven figures show the ranking of the design options per BC. Based on the ranking, it can be concluded that:

- The reduced material option is the best design option from an environmental point of view based on the GWP impact and from an economical point of view based on the least LCC for BC1, BC3, BC5, BC6, and BC7. However, it needs to be noted that for the BC3, BC5, BC6, and BC7, the extended lifetime option is similar to BAU.

- For BC2 and BC4, the reduced material option has the least LCC but not the lowest GWP impact as the extended lifetime option has the lowest GWP impact in comparison.

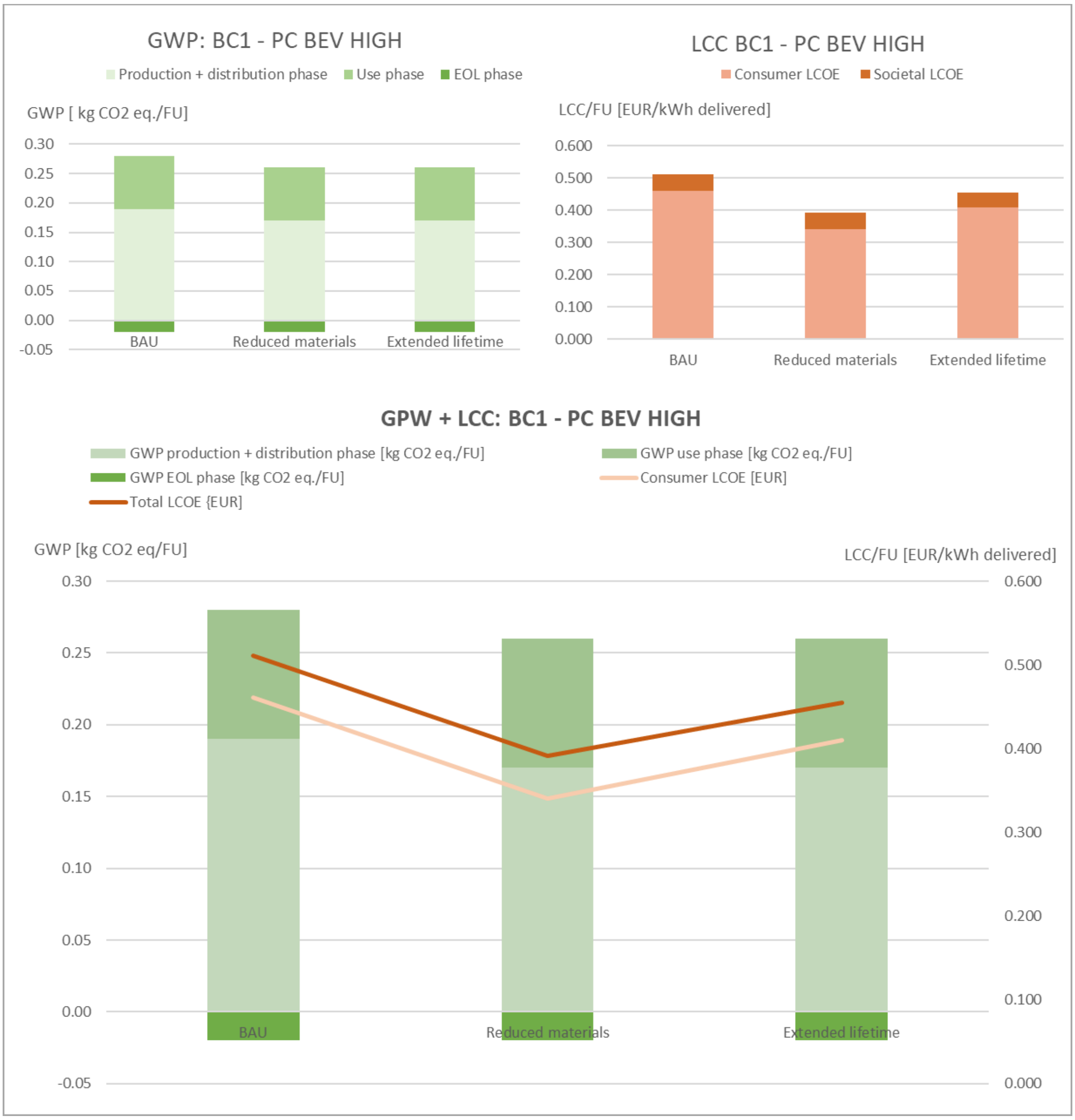

Figure 3: Ranking of the design options for BC1 – passenger car BEV with a high battery capacity.

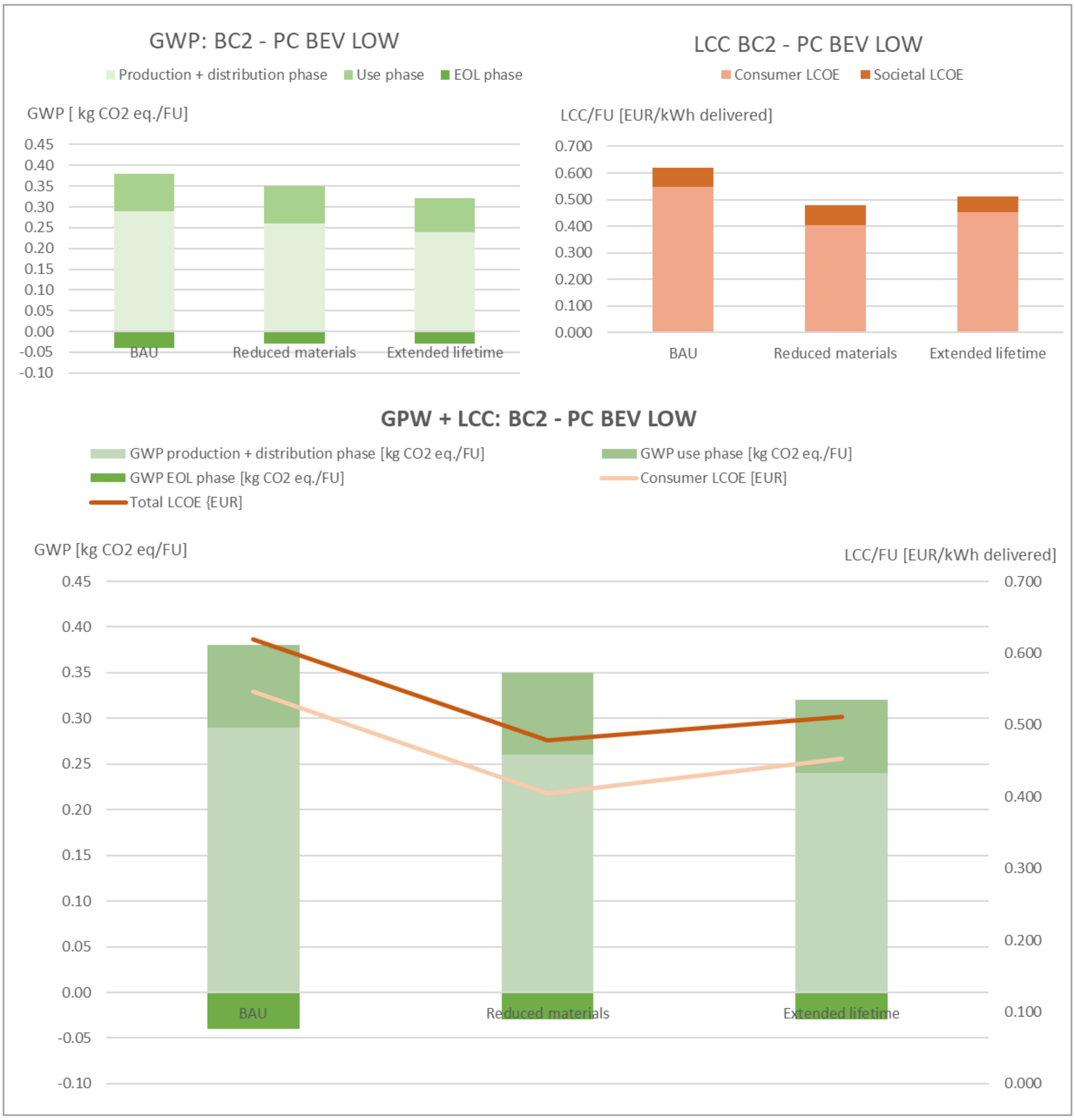

Figure 4: Ranking of the design options for BC2 – passenger car BEV with a low battery capacity.

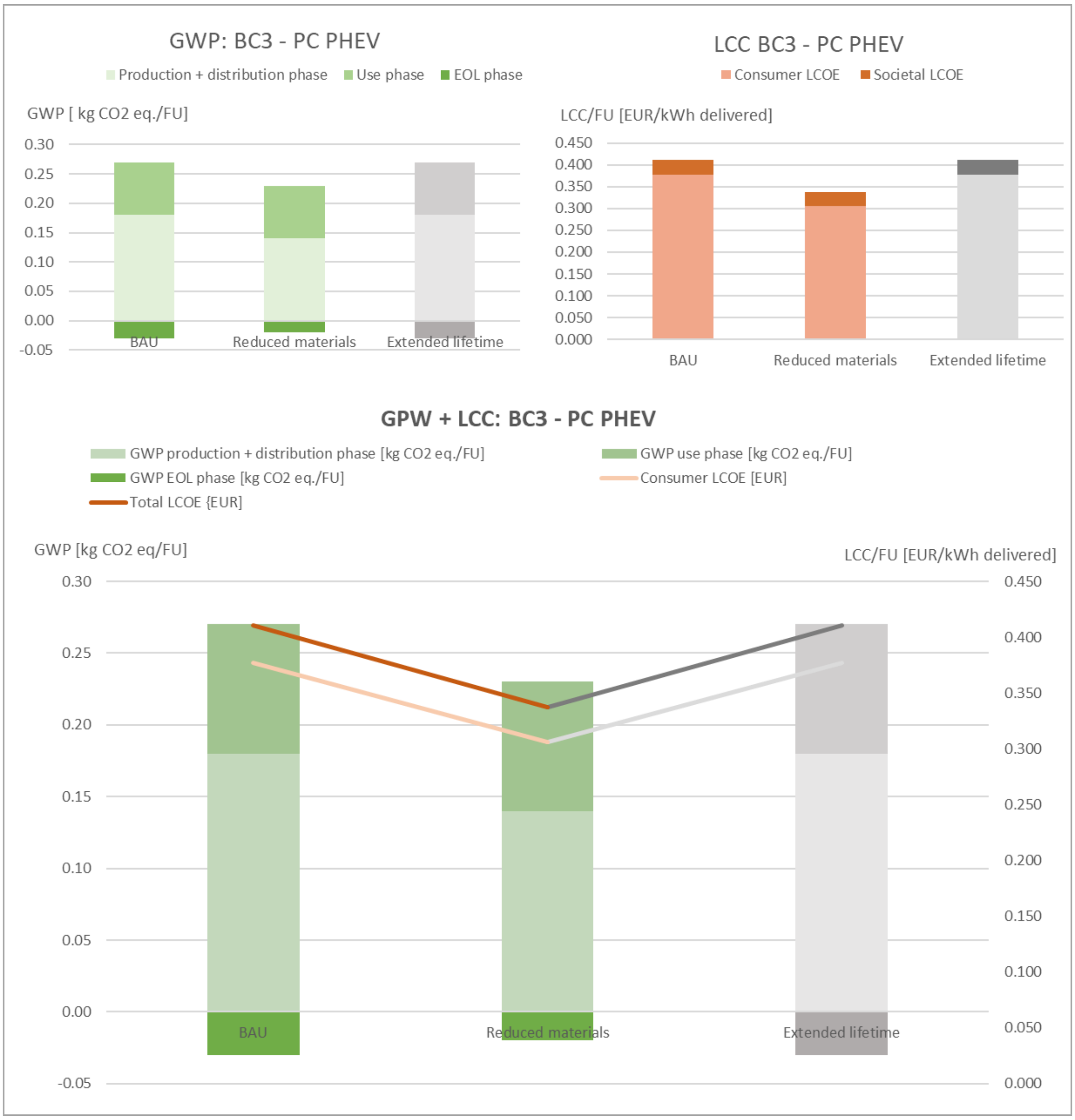

Figure 5: Ranking of the design options for BC3 – passenger car PHEV[18].

[18] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

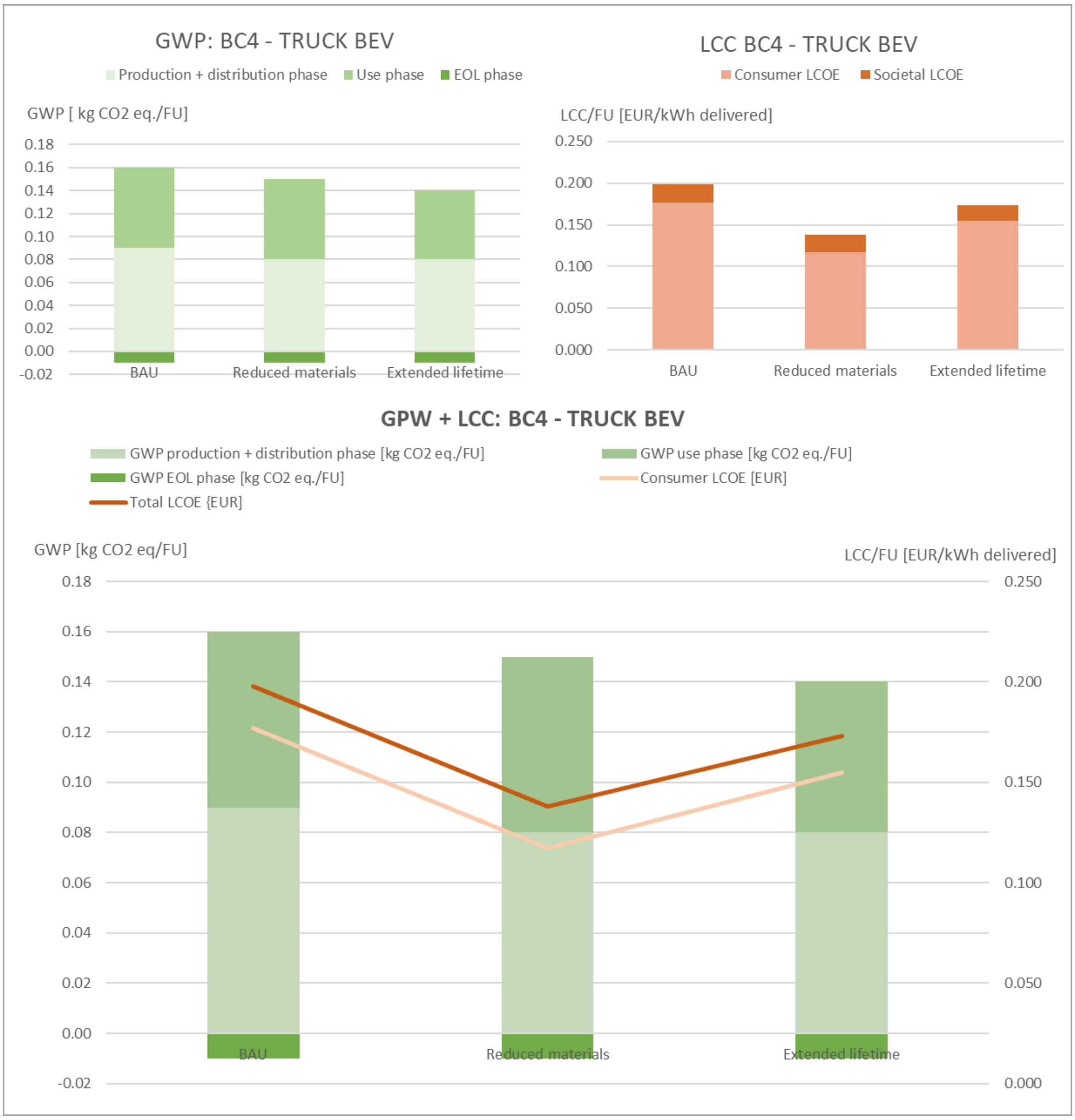

Figure 6: Ranking of the design options for BC4 – truck BEV

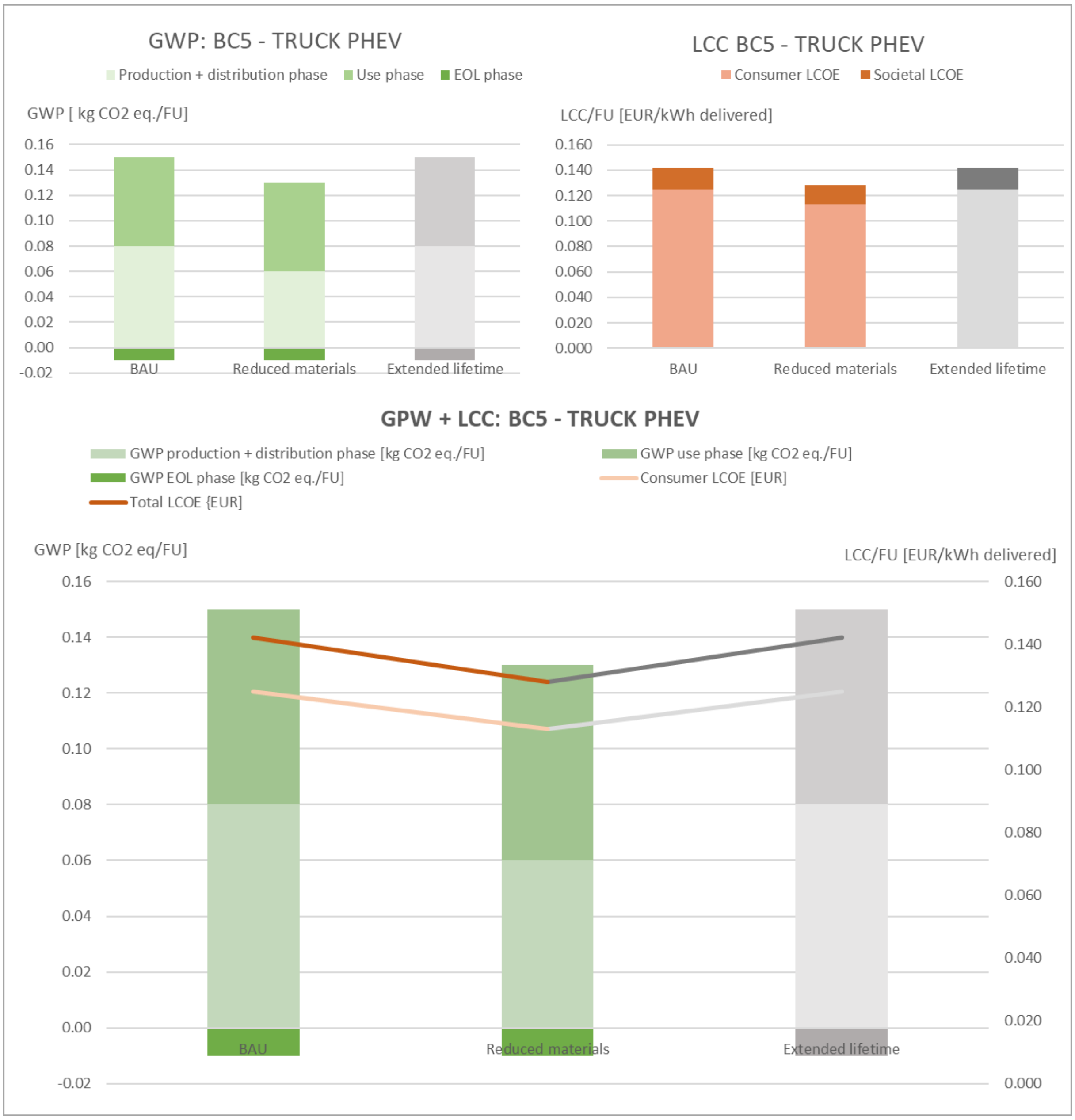

Figure 7: Ranking of the design options for BC5 – truck PHEV[19]

[19] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

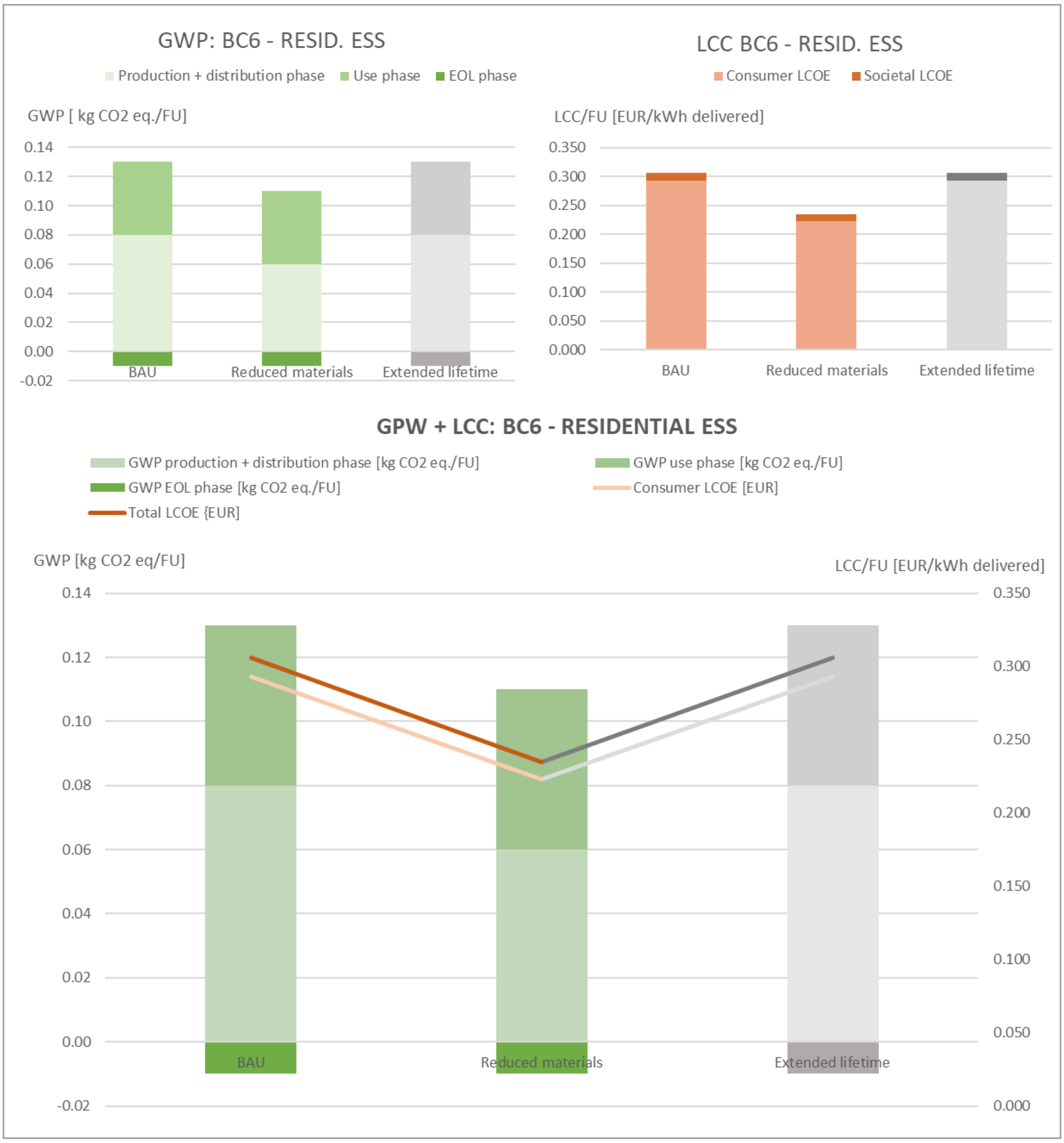

Figure 8: Ranking of the design options for BC6 – residential ESS[20]

[20] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

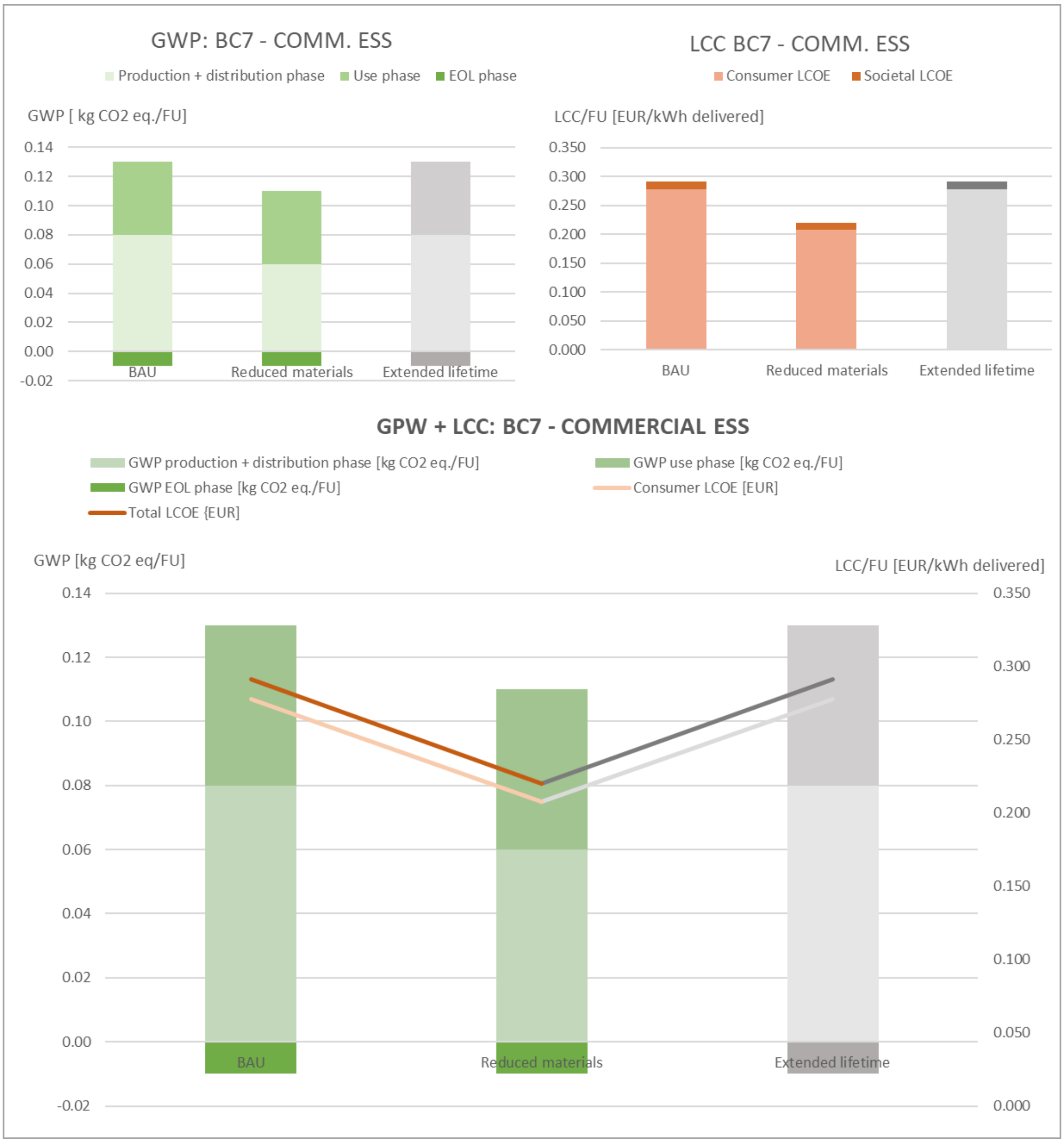

Figure 9: Ranking of the design options for BC7 – commercial ESS[21]

6.4.2. Possible positive or negative ('rebound') side effects of the individual design measures

The previous chapter highlighted the positive influence of the design options on the environmental impact of batteries. Anyhow, besides this positive effect the design options also

[21] The figures of the extended lifetime design option are coloured grey, as the lifetime of this BC cannot be extended usefully thus cannot have additional QFU; in other words the extended lifetime option is similar to the BAU option.

bear the potential for negative side effects. Those effects will be briefly discussed in the following.

Reduction of active and passive materials

Improvements in cell chemistry and design leads to an increasing energy density out of a gravimetric and volumetric perspective. A general potential rebound effect might thereby result from the substitution of materials with a low environmental impact by materials with a higher impact, which could counter the positive effect from the reduction of material content. This potential effect was considered and as Table 8 indicates is not the case at this point. Furthermore, it should also be considered, that (as described in task 4 report) there might also occur issues regarding safety and durability by reducing the active and passive materials and especially when changing or substituting the cell chemistries. Another potential rebound effect may result from the fact that the volumetric energy density directly influences the volume of the final battery pack. Thus, the volume of the battery pack might be reduced or some additional cells might be installed in the gained space to increase the battery capacity. If the user does not use the product according to the additional higher capacity, this could also lead to an increased environmental impact.

Prolonged lifetime

The reuse and repurposing of batteries offer the possibility to extend the battery lifetime and thus to increase the QFU. However, also for this design options some negative side effects might occur. One aspect might be, that batteries containing a high amount of materials with a relatively high environmental impact (such as cobalt) could have a potentially higher positive influence if they are directly recycled instead of reused. An example therefore are batteries containing a relative high share of cobalt (such as those using NMC111). If those batteries are recycled instead of used for 2nd life, the recovered cobalt could be used again to produce a higher amount of cathode materials (with a lower share of cobalt), since newer cell chemistries typically need a lower share of cobalt (such as NMC 532or NMC622). Another rebound effect might be that batteries are removed before they are reaching a SOH of 70-80%, the guarantee that the batteries are still usable for 2nd life applications. In such a case, the battery might have been able to deliver some additional QFU in the first usage, which is lost when the battery system is removed too early. On the contrary it is also thinkable that a battery is used for a 2nd life application, although it is not anymore in the condition to provide the necessary service. This might lead to an unplanned exchange of the battery system.

Low-carbon energy mix

The usage of low-carbon energy mix might have a direct effect on the production costs of a battery system, even if low carbon electricity can be cheap in some regions. This is especially the case when regenerative energies are used which are still mostly more expensive than the conventional electricity mix. This might also affect the final product such as cars or ESS and might hinder the diffusion of these products. In the case of ESS this could also go along with a reduction of solar panels installed on rooftops, which again might affect the share of renewable energy available. Furthermore, it also possible that rebound effects might occur from the usage of “unsustainable” low GWP electricity sources, such as ecosystem losses or nuclear waste generation.

6.5. Subtask 6.5: Long-term targets (BNAT) and systems analysis

AIM OF TASK 6.5:

The aim of this final subtask within Task 6 is twofold by looking beyond the specific design options that are available as BAT in the long term. First, the long-term technical potentials based on outcomes of applied and fundamental research which still address the context of the present product archetype as best not yet available technologies (BNAT) are discussed. Second, the long-term potential based on changes to the total system to which the present archetype product belongs is discussed.

6.5.1. Long-term technical potentials based on BNAT

Based on the analysis of resources in the context of setting up the design options, two kinds of different BNAT design options could be identified. The first kinds are based on the steadily improvement of already used components such as cell chemistries or passive components. The second kind of BNAT therefore are based on a new kind of cell designs such as all-solid-state batteries or even more ambitious designs such as Li-air. Yet their impacts on energy demand are not yet known, since there is a lack of information regarding the corresponding performance indicators. All-solid-state batteries for example will offer the opportunity to connect a high number of electrode packages in parallel already at room temperature without the necessity for an intermediate housing of the cells. This offers a high freedom in design.

Anyhow, considering those developments, it furthermore seems inevitable to revise this study periodically to adapt the analyses to the new insights on technologies and testing methods. Out from today's perspective the long-term potentials can hardly be quantified.

6.5.2. Long-term changes to the total system

The performance of future battery systems will have to follow the requirements of the final applications they are used for. In the case of automotive applications, the batteries will have to be able to be charged in a shorter time and thus the batteries will have to be able to deal with comparatively high currents. Also this is already of relevance for today it will become even more important in future. This also sets high requirements regarding the battery management and the external cooling of the battery system. Furthermore, the current discussion points out that customers product awareness is rising steadily and "green" products might play a more prominent role in the future. This means that not only the vehicle has to be charged with low-carbon energy but also the whole battery has to be produced with a low environmental impact. In the case of stationary applications, a cost reduction of the systems may be in the focus for the upcoming years, to increase the economic benefit of stationary systems. However, the listed changes will play a crucial role in the future for the battery system. But a fundamentally long-term change, especially in the design of battery systems is rather unlikely (except for a continuous downsizing and standardization).

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