Energy Local Storage Advanced system

D5.5 Final assessment of the environmental impact at local level related to all demo sites

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Erratum of 7.2.2019:	Corrections on p.4/p.42 (figures for impacts in text now correctly broken down to 1 kW and 1 yr) and p.6/p.53 (a minus sign has been added for avoided non-RE primary energy use).

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Executive Summary

Energy Storage Systems (ESS) generate environmental impacts in their production, use and end-of-life phases. However, they cannot be seen in isolation. Electric vehicles replace vehicles with combustion engines and ESS in stationary applications modify energy flows in the energy system where they are integrated. Hence, an assessment of the environmental impact of ESS must compare a specific operation scenario with an alternative (baseline) scenario without ESS. Compared to the alternative scenario, the specific operation scenario might have a lower environmental impact. If this is the case, ESS can be said to have a net positive environmental impact within a specific operation scenario.

In this study, a full Life Cycle Assessment (LCA) of the forthcoming commercial ELSA battery systems and similar ESS (altogether denoted as ELSA-type ESS) and an assessment of the overall impact of the services provided by such ESS on the environmental footprint of electricity generation, transmission and distribution in case of their wider deployment in distribution grids has been made. The distinctive feature of ELSA-type ESS compared to other ESS with 2nd-life batteries is that the vehicle batteries are not dismantled to cell level before being used in the 2nd life. Instead, they are taken out of the vehicle with their casing and a major part of the electronics used in the vehicle is also used in the 2nd life. For this reason, ELSA-type ESS do not only have a lower environmental impact in their production phase than ESS with new batteries, but also compared to ESS with 2nd-life batteries with cells from dismantled used electric vehicle (EV) batteries.

Existing LCA studies on the environmental impact of Li-Ion batteries in EV have shown that the Li-ion batteries are, in fact, not the dominating factor regarding the environmental impact of electric mobility. The batteries' share of the total environmental impact of an EV during its life-time is estimated to be 15 %. If Li-ion batteries are used for stationary applications, the environmental impact of the operation phase depends very much on the way how they are used. Generally, much less is known about the impact in stationary use than in vehicles.

The procedure of LCA has been standardised as part of the ISO 14000 environmental management standards (ISO 14040 and 14044). According to these standards, conducting an LCA involves four main phases: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation.

The goal and scope of the LCA presented here was specified by two questions to which the study should provide an answer:

1. What is the environmental impact that is avoided by using a not dismantled vehicle battery instead of a new battery in a 2nd-life ESS?

2. What is the environmental impact avoided in national, regional or local electricity supply systems by the services which can be provided by an ELSA-type ESS?

The following environmental impact categories have been chosen: (1) Abiotic Depletion Potential (ADP), (2) Acidification Potential (AP), (3) Eutrophication potential (EP), (4) Global Warming Potential (GWP), (5) Photochemical Ozone Creation Potential (POCP), and (6) Primary energy consumption from non-renewable resources (non-RPE).

The environmental impact has been related to the functional unit of 1 kW of nominal stationary ESS power and 1 year of operation. ELSA-type ESS have been defined to have a capacity of 11 kWh, a power of 12 kW and a use time of 5 years, i.e. each one corresponds to 60 functional units.

For responding to the first question specified in the goal and scope definition, a stand-alone LCI and LCIA for a 24 kWh Nissan EV Li-Ion battery pack has been performed, which covers the extraction of raw materials and production of the battery including all the components composing the battery pack (casing, management system, internal cabling, etc.), its dismantling from the vehicle at the end of the first life, and related transports of the battery.

It has been assumed that the average usable capacity for stationary applications is 16.5 kWh, the average available power 18 kW and the use time 15 years. A stationary ESS with a new Nissan EV battery thus corresponds to 270 functional units, 4.5 times more than an ELSA-type ESS. That means a 2^{nd}-life battery in an ELSA-type ESS replaces one 4.5th = 22 % new batteries if properties similar to new, respectively used, Nissan EV batteries are assumed. Breaking the results of the stand-alone LCI and CLIA for a 24 kWh Nissan EV Li-Ion battery pack further down to the functional unit of 1 kW*yr the answer to the question 1 above is:

The environmental impact avoided by using a not dismantled 2^{nd}-life battery from an EV instead of a new battery in a 2^{nd}-life ESS is about 6.7 kg $CO_{2\text{-}eq}$/kW/yr, 0.04 kg $SO_{2\text{-}eq}$/kW/yr and 104 MJ/kW/yr of non-renewable primary energy. This is almost entirely due to the avoided battery production. The other environmental impacts are marginal.

For responding to the second question specified in the goal and scope definition, a change-oriented LCA of selected services similar to those provided by or simulated for the six ELSA pilot sites has been performed. An abstraction has been made from these pilot systems and it was assumed that the investigated ELSA-type ESS has the technical characteristics of the forthcoming commercial ELSA battery systems. The services have been analysed and mechanisms with a potential to create or avoid environmental impact have been identified. For the LCI and the LCIA, a model of an electricity supply system has been developed, in which an ELSA-type ESS is supposed to operate.

The system boundaries enclose (1) the ELSA-type ESS, (2) a unit “generation” with an electricity flow which represents the aggregated local electricity generation, and (3) a unit “grid” with an electricity flow which reflects the aggregated external electricity generation, transmission and distribution system. Finally, all changes in the environmental impacts of the use phase of the ELSA-type ESS have been related to changes of amount and origin of the electricity from on-site generation and of the electricity drawn from the grid.

Eight different life cycle phases have been distinguished:

(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years;

(4) Processing of materials and components used only in the ELSA-type ESS for 10 years;

(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years

(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system;

(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS;

(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS.

The environmental impact created in the life phases (1), (2) and (7) is independent from the existence of the ELSA-type ESS. For this reason, it **is allocated entirely to the vehicle** from which the components are taken to be used for the ELSA-type ESS and it is not considered in the assessment of the environmental impact of the services provided by an ELSA-type ESS.

The environmental impact of the life phases (1), (2) and (5) has been assessed by the stand-alone LCI and LCIA for a 24 kWh Nissan EV Li-Ion battery pack. For estimating the environmental impact of the life phases (3) and (4), literature values on an LCA of a 2.5 kW PV inverter were adapted to the case of an ELSA-type ESS. The impact of the life phases (7) and (8) was neglected. The resulting estimate is that **the environmental impact of the hardware**

which is installed only for the 2nd life is about twice to five times higher than the environmental impact that is avoided by using a 2nd-life battery instead of a new one.

For the calculation of the environmental impact of the life phase (6), the use phase, a common effect of different use cases and services was taken considered: the avoidance of renewable electricity curtailment. A use scenario was designed with a local self-supply of 43 % from a PV plant whose generation is curtailed by 5 % without an ELSA-type ESS. After installation of the latter, the curtailment is reduced. **This leads to a net lower environmental impact in all categories if the percentage of curtailment is lowered by at least 2.5 %.**

This scenario has been chosen because it shows the most relevant effect of large-scale deployment of decentralised ESS: avoiding curtailment of renewable electricity generation and consequently avoiding back-up operation of fossil power plants and related environmental impacts. This point has been discussed in more detail in the ELSA deliverable D5.4, chap. 6.2 which refers itself to the comprehensive study of (Strbac, et al., 2012). While the economic effects on a national electricity supply system are discussed in D5.4, the environmental effects are discussed here.

The tables E1 and E2 below summarize the environmental impact which is avoided (1) by using a 2nd-life battery in an ELSA-type ESS instead of a new battery and (2) by operating an ELSA-type ESS such that local PV curtailment of 5 % is reduced to zero. It can be seen that both actions lead to a lower net environmental impact, notably with regard to GWP, AP, and non-RPE. The effect of operating the ESS such that renewable electricity curtailment is avoided is 1-2 orders of magnitude stronger than the effect of using a 2nd-life battery instead of a new one. Further, the effect of avoided curtailment largely overcompensates the environmental impact of the production of the hardware needed exclusively in the 2nd life.

If the environmental impact of the production and logistics of the 2nd life battery is accounted entirely to the 1st life in the vehicle and an ELSA-type ESS is operated such that 5 % PV curtailment is avoided in a scenario with local self-supply from PV of 43 % and a carbon-rich electricity mix for covering the residual demand, the net environmental impact is -304 kg $CO_{2\text{-eq}}$/kW/year, -0,15 kg $SO_{2\text{-eq}}$/kW/year, and -2,506 $MJ_{\text{non-RPE}}$/kW/year. The other environmental impacts are marginal.

These findings are in line with assessments of the environmental impact of different electricity storage systems, e.g. (Oliveira, et al., 2015), as well as in LCA studies on electric vehicles with different battery technologies, e.g. (Matheys, et al., 2006), (Notter, et al., 2010).

One has to note that the exact net environmental impact depends very much on the concrete framework in which an ELSA-type ESS is operated. For instance, operation in a national electricity system with a lower fraction of electricity generation from lignite and hard coal as considered in this study will lead to a lower net environmental benefit.

Table E1: GWP, AP and non-RPE avoided (1) by using not dismantled 2nd-life battery instead of new one and (2) reducing PV curtailment with ELSA-type ESS

Life cycle phase	impact of using undismantled 2nd life battery instead of new one			impact of ELSA-type ESS avoiding 5% of local PV curtailment		
	GWP [kg CO2eq/kW/yr]	AP [kg SO2eq/kW/yr]	non-RE PE [MJ/kW/yr]	GWP [kg CO2eq/kW/yr]	AP [kg SO2eq/kW/yr]	non-RE PE [MJ/kW/yr]
(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for (2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	-6.7	-0.04	-104	-	-	-
(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years (4) Processing of materials and components used only in the ELSA-type ESS for 10 years	-	-	-	21	0.18	386
(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	-	-	-	0.0	0.00	0.0
(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system	-	-	-	-325	-0.33	-2,891
(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS	-	-	-	-	-	-
(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS	-	-	-	-	-	-
Sum	-6.7	-0.04	-104	-304	-0.15	-2,506

Table E2: ADP, EP and POCP avoided (1) by using not dismantled 2nd-life battery instead of new one and (2) reducing PV curtailment with ELSA-type ESS

	impact of using undismantled 2nd life battery instead of new one			impact of ELSA-type ESS avoiding 5% of local PV curtailment		
Life cycle phase	ADP [kg Sbeq/kW/yr]	EP [kg PO4eq/kW/yr]	POCP [kg ethylene-eq/kW/yr]	ADP [kg Sbeq/kW/yr]	EP [kg PO4eq/kW/yr]	POCP [kg ethylene-eq/kW/yr]
(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years (2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	0.00	-0.01	0.00	-	-	-
(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years (4) Processing of materials and components used only in the ELSA-type ESS for 10 years	-	-	-	-	0.02	0.02
(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	-	-	-	-	0.00	0.00
(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system	-	-	-	-84.97	-0.10	-4.44
(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS	-	-	-	-	-	-
(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS	-	-	-	-	-	-
Sum	0.00	-0.01	0.00	-84.97	-0.09	-4.42

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List of Acronyms and Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BEMS	Building Energy Management System
D	Deliverable
DR	Demand Response
ESS	Energy Storage System
ELSA	Energy Local Storage Advanced system
EEMS	ELSA Energy Management System
EP	Eutrophication Potential
EV	Electric Vehicle
GHG	Green House Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCPD	Directive on Large Combustion Plants
Li	Lithium
LMO	Lithium Manganese Oxide
LV	Low Voltage
PE	Primary Energy
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
RES	Renewable Energy Sources
TRL	Technology Readiness Level
WP	Work Package

1 Background

1.1 The Elsa Project

Decentralised small and medium-size energy storage systems (ESS) represent a flexible element of energy supply systems, alongside flexible generation units, and flexible energy consumers. They can help to optimise the energy supply of buildings and districts, and enable the integration of a higher share of intermittent renewable energy sources (RES). Yet, though many storage solutions are already technically mature and economically viable, their widespread application is hindered by lacking awareness of potential ESS operators, a low level of existing experience in ESS operation, and by the current legal and regulatory framework which does not take the value into account which ESS can provide to the overall energy supply system (see detailed investigation in ELSA deliverable 5.4, notably chap. 6.2).

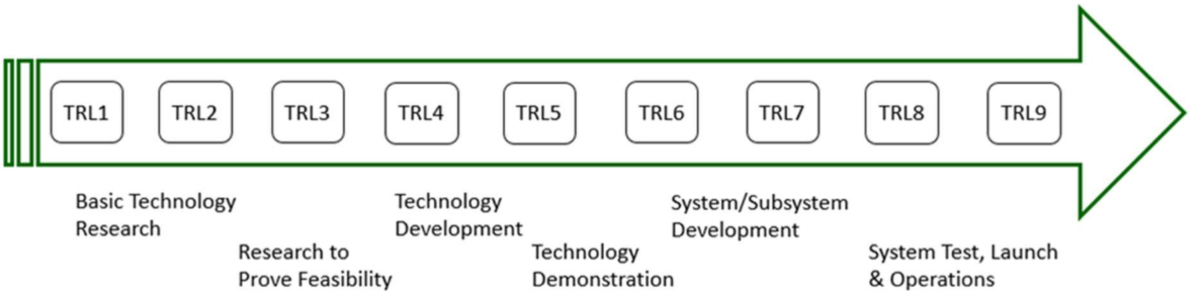


Figure 1: Technology Readiness Levels; Source: Nasa Technology Readiness Level

The aim of the ELSA (Energy Local Storage Advanced system) project has been to bring distributed stationary ESS from the Technology-Readiness-Level 6 (TRL) to TRL 9 that are based on used batteries from electric vehicles which remain in their original casing without being dismantled to battery cell level before being used further in stationary applications. Such 2nd-life ESS based on not dismantled vehicle batteries have a minimum capacity which equals that of the vehicle battery at the end of their 1st life in the vehicle that is after 10 years of use. However, they need rather much space compared to ESS produced directly for stationary use or ESS based on battery cells taken out of dismantled used vehicle batteries. For this reason, they are mainly suitable for small, but not very small, to medium size applications, characterised by an energy storage capacity in the range of 11 kWh to 88 kWh – and up to a few MWh if several ESS are operated in parallel at one site.

The objective of ELSA has been to enable the integration of such 2nd-life battery systems into the energy system and to prepare their commercial use. ELSA has addressed remaining technical development needs as regards the use of not dismantled 2nd-life batteries in ESS and the development of an innovative local information and communication technology-based (ICT-based) ELSA Energy Management System (EEMS) in order to provide a low-cost, scalable and easy-to-deploy ESS.

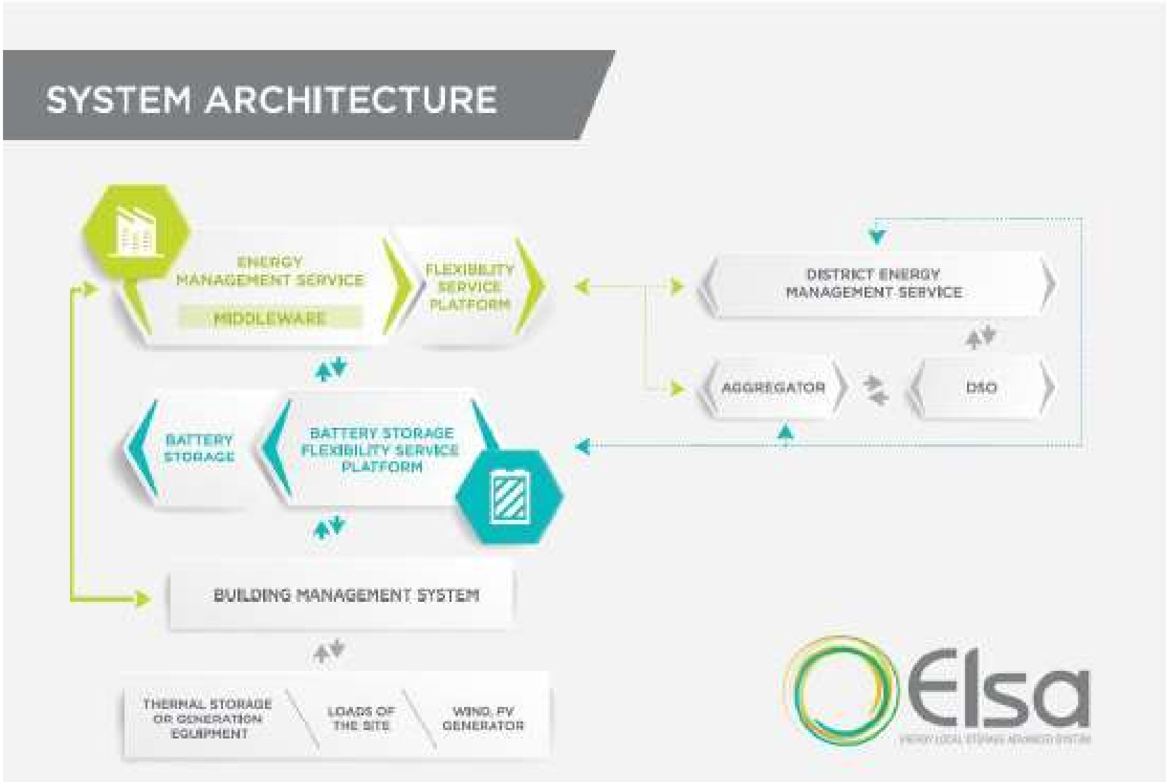


Figure 2: ELSA architecture; Source: B.A.U.M.

ELSA has developed technology that was already close to maturity. ELSA storage systems have been applied at six demonstration sites representing different use cases, that is, different application contexts and services provided such as peak demand shaving, demand response provision, ancillary (grid) services, power quality improvement, PV power generation smoothing, etc. Several feedback loops and the constant involvement of relevant stake holders have guaranteed the optimal implementation of the pilots. Validation and evaluation of the storage systems at six trial sites have ensured the scalability and feasibility of the results beyond the project.

The focus has been on the energy services provided by the ESS to an operator, a customer or the electricity supply system as a whole. Existing legal and regulatory barriers have been analysed, international standards have been pushed forward, and innovative service-oriented business models have been developed. Sustainability and social acceptance have been taken into account through comprehensive environmental and socio-economic impact assessments as well as the involvement of citizens and stakeholder groups.

1.2 WP5: economic and environmental impact assessments

Work package 5 (WP5) comprised an assessment of (1) the economic and (2) environmental impact of ESS similar to those installed at the ELSA pilot sites, but with technical characteristics of the forthcoming commercial ELSA battery systems ("ELSA-type ESS") taking into account the full integration into the local electricity grid, the distributed generation and the further deployment of RES. The investigation of the economic impacts has been further subdivided in an investigation of business models (Task 5.1, see deliverable D5.6) and an evaluation of the economic impact of the implementation of such business models on the electric grid operation and, moreover, the general electricity supply system (Task 5.2, see deliverable D5.4). Key business success factors related to system costs, direct value generation, integration in virtual power plant schemes and services provided to grid stakeholders have been evaluated. Task 5.3 has covered the assessment of the environmental impact of ELSA-type ESS by conducting a life cycle assessment (LCA). The preliminary results of this work have been presented in deliverable D5.2. This deliverable presents the final results.

1.3 Task 5.3: Environmental impact of large-scale storage deployment

The European Commission Directive on Large Combustion Plants (LCPD) shows the potential impact of traditional electricity generation on the environment. The LCPD aims at reducing acidification, ground level ozone and particle concentration in the atmosphere throughout Europe by controlling emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter from large combustion plants (LCPs). These pollutants contribute significantly to acid deposition in soils and freshwater, plant and aquatic habitat damage as well as corrosion of building materials.

The central measure to reduce the environmental impact of traditional electricity generation is a comprehensive change towards RES-based energy generation. However, the technologies with the highest potential, PV and wind power, make use of intermittent RES and generate electricity with a strongly fluctuating output, often not in pattern with the demand. Here, storage comes into play. Its main role consists in allowing a higher share of RES to be used, thus reducing the impact of traditional electricity generation.

ESS generate environmental impacts in their production, use and end-of-life phases. However, they cannot be seen in isolation. Electric vehicles replace vehicles with combustion engines and ESS in stationary applications modify energy flows in the energy system where they are integrated. Hence, an assessment of the environmental impact of ESS must compare a specific operation scenario with an alternative (baseline) scenario without ESS. The question which has been investigated in this study is if there is net reduction of the environmental impact if ESS with 2^{nd}-life batteries from vehicles are used in stationary ESS.

For evaluating this question, a full LCA of the forthcoming commercial ELSA battery systems and similar ESS (altogether denoted as ELSA-type ESS) and an assessment of the overall impact of the services provided by such ESS on the environmental footprint of electricity generation, transmission and distribution in case of their wider deployment in distribution grids has been made.

2 Li-ion battery technology and environmental impact

2.1 Li-ion battery technology

With a high power and energy density, Lithium (Li)-ion batteries have a clear advantage over other chemical battery compositions (Armand, et al., 2008), which makes them the number one choice of battery for hybrid and full electric vehicles today (Wikipedia, 2016).

Lithium is the chemical element with the highest reduction potential, which means that Li-ion batteries have the highest possible cell potential (voltage). Furthermore, Lithium as one of the smallest and lightest existing atoms allows producing batteries with a high gravimetric and volumetric capacity. The power density of Li-ion batteries depends on the chemistry and is also high for some types.

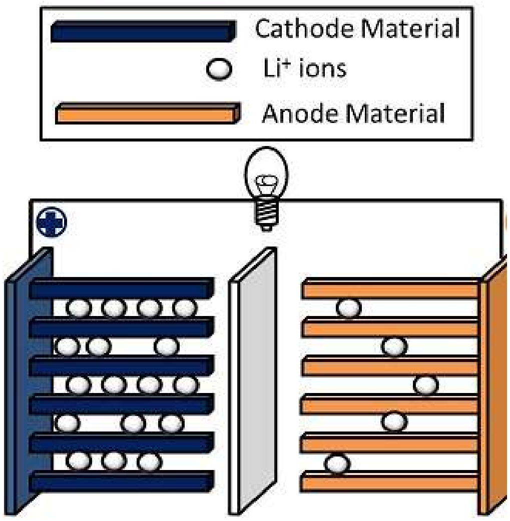


Figure 3: Schematic of a Li-Ion battery; source: (Wikipedia, 2015)

These properties of Li-Ion batteries render them interesting for diverse applications, notably for electric mobility, but also for electric grid applications including grid-balancing services allowing for an increased power feed-in from renewable energy sources (Nitta, et al., 2015). Considering the global expansion of electric vehicles (Statista, 2016), the still relatively high production cost of Li-ion batteries, and notably potential bottlenecks in lithium production and refinery, the interest from both research and industry in re-using batteries from electric vehicles is high.

A Li-ion battery consists of three primary functional components: a positive electrode (cathode), a negative electrode (anode) and electrolyte. The designation of cathode and anode refer to the discharging mode. In charging mode, the role of the electrodes is inversed. As the relative electric potential has always the same polarity (the negative electrode has always a negative potential relative to the positive electrode), the names positive and negative electrode are clearer.

In most cases, the anode consists of carbon (graphite) with intercalated lithium ions, while the cathode is a metal oxide with a lithium ion content that depends on the state of charge. A lithium salt in an organic solvent forms the electrolyte (Silberberg, 2006). Battery performance, cost and safety characteristics depend on the battery chemistry (Wikipedia, 2016). The battery packs installed in the ELSA storage system (Renault Kangoo ZE and Nissan Leaf batteries) are lithium manganese oxide (LMO) based batteries.

2.2 Environmental impact of Li-ion batteries

From an environmental perspective, Li-ion batteries are considered the "lesser evil" as they contain less toxic material than e.g. lead or cadmium-based batteries. In general, Li-ion batteries are categorised as non-hazardous waste.

Existing LCA studies on the environmental impact of Li-Ion batteries in electric vehicles (EV) have shown that the Li-ion batteries are, in fact, not the dominating factor regarding the environmental impact of electric mobility. Rather, the environmental impact is for the largest part dominated by the operation phase of the vehicle that is the generation of electricity for powering the vehicle. Generation of the electricity from RES rather than fossil fuels can tremendously reduce the environmental impact of the vehicle's operation and improve the total environmental balance. Also, electric vehicles powered by electricity from RES have a much better environmental performance than conventional fossil fuel powered vehicles.

The batteries' share of the total environmental impact of an EV during its life-time is estimated to be 15 %. Of that, only a small share of the environmental impact is caused by the extraction and treatment of lithium. The main environmental burden must be ascribed to other components of the battery and the battery system (Notter, et al., 2010). The main share of the environmental impact of the battery production is ascribed to metal supply (especially copper and aluminium) and process energy. Metals are used in the production of the cathode and anode as well as the battery management system and battery pack. Copper is used in the production of the anode as the collector foil. Additionally, copper is used in other components, such as cables. Aluminium is used in the collector of the anode, which is made of aluminium foil. The battery pack and battery management system can contain different metals, such as iron (or steel), tin, gold or copper. A particularly high energy demand is associated to the production of aluminium, the production of graphite, the productions of wafers for the battery management system, the roasting process for manganese carbonite and heat for drying the electrodes (Notter, et al., 2010).

If Li-ion batteries are used for stationary applications, the environmental impact of the operation phase depends very much on the way how they are used. Generally, much less is known about the impact in stationary use than in vehicles.

3 The methodology of Life Cycle Assessment

The introduction to LCA presented here is essentially based on the textbook by Baumann et al. (2004) The Hitch Hiker's Guide to LCA – An orientation in life cycle assessment and application. LCA is a methodology for assessing the environmental impact of a product from "cradle to grave" – meaning through all stages of the product's life from extraction of raw materials through material processing, manufacture, distribution, use, repair and maintenance to disposal or recycling. The procedure of LCA has been standardised as part of the ISO 14000 environmental management standards (ISO 14040 and 14044). According the ISO standards, conducting an LCA involves four main steps:

- Goal and scope definition
- Life cycle inventory (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation

3.1 Goal and scope definition

The first step of an LCA is the "goal and scope definition". It determines the overall objective of, and the exact questions to be answered by the LCA. During this process, a number of decisions must be taken. Traditionally, the goal and scope definition is done in close cooperation of the commissioning party of the LCA and the practitioner who conducts the LCA. Thereby, the scope and the requirements for the LCA study are determined based on the study's goal. This step is integral for every LCA study, as different goals require different approaches regarding LCA methodology. Apart from the reasons for conducting the study, in this step also information is collected on how the results will be used and who will have access to them. Altogether, the decisions and choices to be made comprise:

- Exact questions to be answered.
- Specific products, product designs or process options to be studied.
- LCA type. In general, a distinction is made between accounting, change-oriented and standalone-type LCA studies. Standalone-type LCA studies usually describe a single product with the objective to gather information on its environmental characteristics. An accounting-type LCA compares different options, but takes a retrospective view, while a change-oriented LCA is also comparative, but has a "looking into the future" component. Thus, change-oriented LCA studies can be applied to assess the environmental impacts of different courses of action.

- Functional unit, a reference flow to which all other flows are related. The functional unit must be quantitative and relate to the studied system. It further enables a comparison between different systems.
- Environmental impact categories. This influences which kind of data has to be collected for the Life Cycle Inventory (LCI). The impact categories should be chosen to reflect, as far as possible, the complete impacts of the inputs and outputs of the studied product system rather than the goal for conducting the LCA study. In (Hawkins, et al., 2012), a comparative study on the environmental impacts of conventional and electric vehicles, for example, the impact categories global warming potential, terrestrial acidification, particulate matter formation, photochemical oxidation formation, human toxicity, freshwater eco-toxicity, terrestrial eco-toxicity, freshwater eutrophication, mineral resource depletion and fossil resource depletion were chosen.
- System boundaries in relation to the natural system in space and time, and in relation to technical systems. In setting the system boundaries – deciding which flows to include and exclude for the LCA study – a number of assumptions and limitations, under which the study is conducted, are formed.
- Way how impacts are allocated if processes are linked to more than one product or function. An allocation problem is handled most commonly in one of three ways: increasing the level of detail of the studied system, allocation through partitioning or by system expansion. If partitioning is chosen as allocation method, the environmental load is divided between the products or functions while in system expansion the studied system is credited with the environmental load avoided by replacing an equivalent product on the market.

3.2 Life cycle inventory

In the Life Cycle Inventory (LCI) step, the flows from and to nature for the studied product system or processes are analysed. To conduct the LCI, a flow model of the technical system detailing the input and output flows of the system is constructed based on available data. Apart from raw material input, input of water and energy as well as their release to air, water or land are taken into account. The flow model adheres to the system boundaries set in the goal and scope definition and is restricted to flows relevant to the product system's environmental impact.

After data collection, resource use and emissions connected to the investigated system are calculated in relation to the functional unit.

3.3 Life cycle impact assessment

In the Life Cycle Impact Assessment (LCIA) step, the significance of potential environmental impacts is evaluated based on the LCI flow result. This step in an LCA consists mainly of three parts:

- Classification (assignment of inventory parameters to impact categories)
- Characterisation (calculation of relative contribution of emissions and resource consumption to the different categories of environmental impact)
- Weighting

3.4 Interpretation

The interpretation chapter summarises the results from the inventory analysis and impact assessment. The outcome of the interpretation step is usually a set of conclusions and recommendations. In a standard LCA, this step includes:

- Identification of significant issues based on the results of the LCI and LCIA
- Evaluation of the study (completeness and consistency check)
- Conclusions, recommendations and reporting

4 Goal and scope of LCA within ELSA

4.1 Questions to be answered

ELSA comprises basically two different developments: (1) the technical development of ESS based on not dismantled 2nd-life batteries and (2) the development of services based on such ESS. It is assumed that both developments reduce environmental impacts created in alternative scenarios without 2nd-life batteries, notably (1) the environmental impact of the production of batteries and (2) the environmental impact of national, regional or local electricity supply systems. The latter can be traced back to the use of fossil fuels in power plants and is an effect which is independent from 2nd-life battery use. It can also be achieved with new batteries. In order to verify these two effects, the goal of the LCA has been put down in the form of two questions:

1. What is the environmental impact that is avoided by using a not dismantled vehicle battery instead of a new battery in a 2nd-life ESS?
2. What is the environmental impact avoided in national, regional or local electricity supply systems by the services which can be provided by an ELSA-type ESS?

4.2 Specific product to be studied

For the purpose of the LCA study, an abstraction has been made from the concrete ELSA pilot systems which have been installed within the ELSA project. It has been assumed that the investigated ESS has the technical characteristics of the forthcoming commercial ELSA battery systems. For keeping in mind that this abstraction is made, the notion "ELSA-type ESS" is generally used in this study. The distinctive feature of ELSA-type ESS compared to other ESS with 2nd-life batteries is that the vehicle batteries are not dismantled to cell level before being used in the 2nd life. Instead, they are taken out of the vehicle with their casing and a major part of the electronics used in the vehicle is also used in the 2nd life. For this reason, ELSA-type ESS do not only have lower costs and a lower environmental impact in their production phase than ESS with new batteries, but also compared to other ESS with 2nd-life batteries.

Figure 4 shows the general architecture of ELSA battery storage systems. A system is composed of a number of batteries, power electronics and control units. The main technical characteristics which are relevant for the services which can be provided are:

- maximum energy that can be discharged from a single battery: e_{2nd} = 11 kWh
- permitted range state of charge (SOC): 0 < SOC < 100%
- maximum charge / discharge power of a single battery: p_{2nd} = 12 kW

- reaction time: short enough to provide all services, i.e. in the range of milliseconds[1]

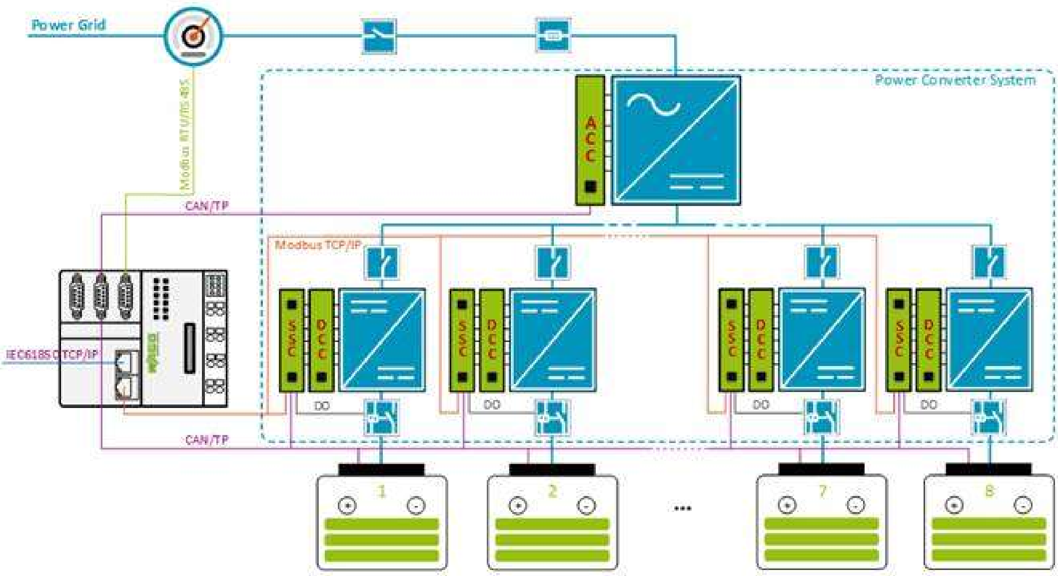


Figure 4: Architecture of a future commercial ELSA battery system

4.3 Type of LCA

For responding to the question about the environmental impact that is avoided by using a not dismantled vehicle battery instead of a new battery in a 2nd-life ESS, it was decided to perform a stand-alone LCA (see 3.1 for definition) for a 24 kWh Nissan EV Li-Ion battery pack, which covers the extraction of raw materials and production of the battery including all the components composing the battery pack (casing, management system, internal cabling, etc.), its dismantling from the vehicle at the end of the first life, and related transports of the battery.

For responding to the question about the environmental impact avoided in national, regional or local electricity supply systems by the services which can be provided by an ELSA-type ESS, it was decided to perform a change-oriented LCA of selected services similar to those provided by or simulated for the six ELSA pilot sites. The services have been analysed and mechanisms with a potential to create or avoid environmental impact have been identified.

[1] The information on the measured reaction time of the installed DT5-ESS was not available for the establishment of this deliverable.

For the LCI and the LCIA, a model of an electricity supply system has been developed, in which an ELSA-type ESS is supposed to operate.

4.4 Functional unit

The functional unit describes the "quantified performance of a product system for use as a reference unit" (DIN EN ISO 14040:2009-11). See also the information box on the specification of the functional unit according to ISO 14044:2006.

As described in chapter 3.1, the functional unit defines what precisely is being studied and quantifies the service delivered by the product system or process in order to provide a reference point to which the inputs and outputs can be related. The functional unit further enables a comparison and analysis of alternative goods or services.

The functional unit chosen in LCA studies on Li-Ion batteries in EVs is most often related to a certain distance driven (Amarakoon, et al., 2013). In a study focused on the contribution of Li-ion batteries to the environmental impact of EVs, the functional unit was e.g. set as one average kilometre driven by a vehicle with electric drivetrain on the European road system (Notter, et al., 2010).

In contrast, the functional unit chosen in the framework of LCA studies on battery energy storage systems is often related to capacity or consumption. In a study quantifying the environmental impact of combined PV storage systems, the functional unit was set at 1 kW_{el} (Jülch, et al., 2015). A comparative analysis of the environmental performance of different electricity storage systems utilized the functional unit of 1 kWh of energy delivered back to the grid from the storage system (Oliveira, et al., 2015).

After having considered various options for defining an appropriate functional unit for the purpose of this study (e.g. 2,000 charging-discharging cycles or 1 year of operation), and in the light of the assessment of the gross economic value of an ELSA-type ESS for the overall electricity supply system (see ELSA deliverable D5.4, chap. 6.2), it was decided to take **1 kW of nominal ESS power for 1 year of operation** as functional unit. The alternative, to relate to the storage capacity, is less suitable because the nominal capacity of a 2nd-life battery does not really reflect the real storage capacity, but rather the confidence of the supplier to guarantee this capacity for the prospective life-time. Hence, there might be a number of quite diverting indications for the storage capacity of a 2nd-life battery system, while the nominal power is rather fixed by the converter.

Functional unit according to ISO 14044:2006

A system may have a number of possible functions and the one(s) selected for a study depend(s) on the goal and scope of the LCA. The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. It is important to determine the reference flow in each product system, in order to fulfil the intended function, i.e. the amount of products needed to fulfil the function.

Example: In the function of drying hands, both a paper towel and an air-dryer system are studied. The selected functional unit may be expressed in terms of the identical number of pairs of hands dried for both systems. For each system, it is possible to determine the reference flow, e.g. the average mass of paper or the average volume of hot air required for one pair of hand-dry, respectively. For both systems, it is possible to compile an inventory of inputs and outputs on the basis of the reference flows. At its simplest level, in the case of paper towel, this would be related to the paper consumed. In the case of the air-dryer, this would be related to the mass of hot air needed to dry the hands.

The scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied.

The functional unit shall be consistent with the goal and scope of the study. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore the functional unit shall be clearly defined and measurable. Having chosen the functional unit, the reference flow shall be defined. Comparisons between systems shall be made on the basis of the same function(s)', quantified by the same functional unit(s) in the form of their reference flows. If additional functions of any of the systems are not taken into account in the comparison of functional units, then these omissions shall be explained and documented. As an alternative, systems associated with the delivery of this function may be added to the boundary of the other system to make the systems more comparable. In these cases, the processes selected shall be explained and documented.

An appropriate flow shall be determined for each unit process. The quantitative input and output data of the unit process shall be calculated in relation to this flow. Based on the flow chart and the flows between unit processes, the flows of all unit processes are related to the reference flow. The calculation should result in all system input and output data being referenced to the functional unit.

4.5 Impact categories

In the framework of this study, the following environmental impact categories have been chosen:

- CML2001- Apr 2013: Abiotic Depletion Potential (ADP) elements [kg Sb-Equiv.]
- CML2001- Apr 2013: Acidification Potential (AP) [kg SO_2-Equiv.]
- CML2001- Apr 2013: Eutrophication Potential (EP) [kg Phosphate-Equiv.]
- CML2001- Apr 2013: Global Warming Potential (GWP) 100 years [kg CO_2-Equiv.]
- CML2001- Apr 2013: Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equiv.]
- Primary energy from non-renewable resources (net cal. value) [MJ]

CML stands for Centrum voor Milieukunde (centre for environmental studies) of the University of Leiden / The Netherlands and thus for a specific approach in deriving the environmental impact for different impact categories from input and output flows of energy and materials in an investigated system, and Apr 2013 for the month of publication of the corresponding rules.

The most important impact category in this list is global warming potential (GWP 100 years; kg CO_2-Equiv.). It describes the amount of heat a (mix of different) greenhouse gas(es) traps in the atmosphere in 100 years relative to the amount of heat trapped by 1 kg of carbon dioxide in 100 years. Thus, the GWP enables assessing the environmental impact of emissions of different (mixtures of) gas(es) and expresses them in terms of the equivalent amount of carbon dioxide which has the same environmental impact as the investigated amount of emitted gases.

Different gases have a different capacity to hold infrared (heat) radiation back in the atmosphere. Further, they remain in the atmosphere for different times. To display the difference in GWP of the same amount of different gases, the notion of relative GWP exists. The relative GWP is the ratio of the GWP of a specific gas (mixture) to the GWP of carbon dioxide. For the relative GWP different values exist in literature. Table 1 gives an overview of the relative GWP of different gases as used by the International Panel on Climate Change (IPCC) in (IPCC AR5, 2013).

In the same way, the impact in the other categories is expressed in kg-Equiv. of a reference output, antimony (Sb) in the case of the abiotic depletion potential, sulphur dioxide (SO_2) in the case of the acidification potential, etc.

Table 1: Relative GWP values for a time horizon of 100 years according to IPCC AR5 (2013)

Greenhouse gas	Relative GWP (100 years time horizon)
Carbon dioxide (CO_2)	1
Methane (CH_4)	28
Nitrous oxide (N_2O)	265
Chlorofluorocarbons, e.g. $CClF_3$	13,900
Fluorinated hydrocarbons, e.g. CHF_3	12,400
Nitrogen trifluoride (NF_3)	16,100
Sulfur hexafluoride (SF_6)	23,500

4.6 System boundaries in time

In performing an LCA for a product or a product system, its system boundaries must be specified in several dimensions: boundaries between the technological system and nature, life cycle inventory, limitation of the geographical area and time limit, boundaries between production and production of capital goods, boundaries between life cycle of the product system and related life cycles of other products (Baumann, et al., 2004).

Within the framework of the ELSA project, notably the boundary between (1) the vehicle from which the battery pack is taken and (2) the ELSA-type ESS must be defined and the environmental impact of the different life phases must be allocated. Independently from the specific application and services provided, the following life phases of ELSA-type ESS can be defined in line with (Matheys, et al., 2006):

(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years;

(4) Processing of materials and components used only in the ELSA-type ESS for 10 years;

(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years

(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system;

(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS;

(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS.

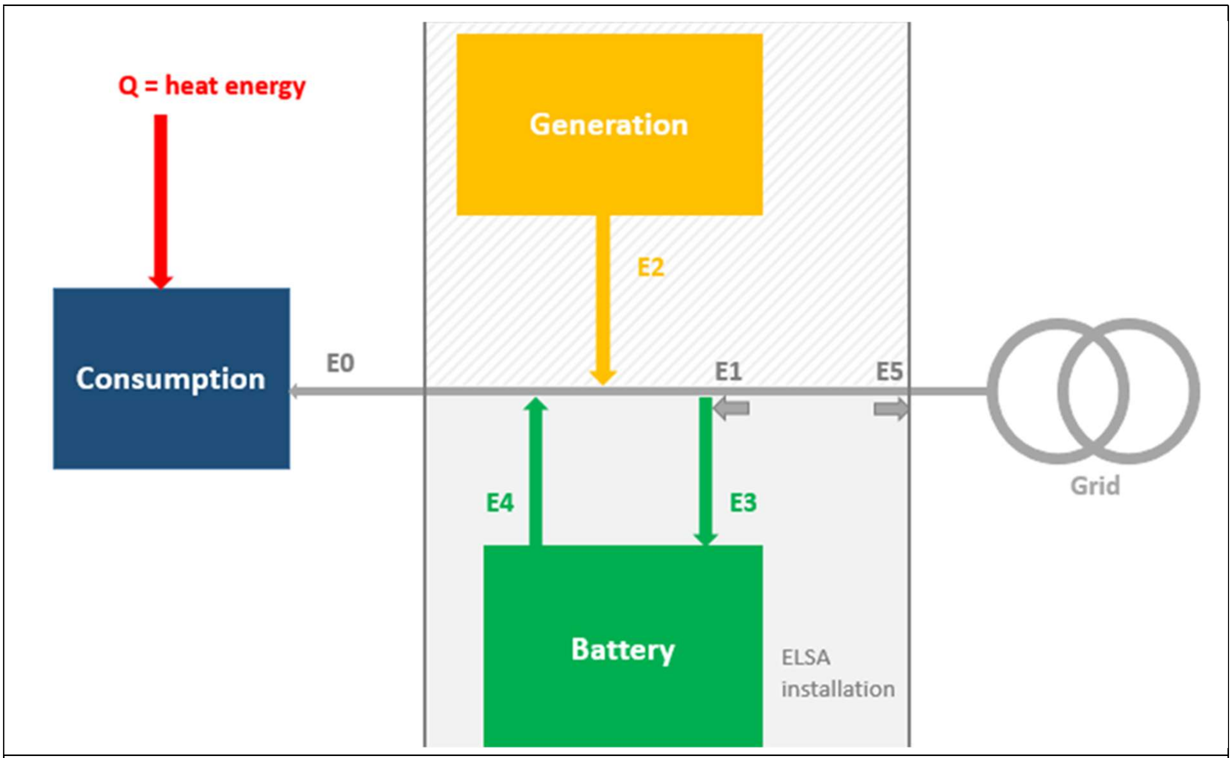
The environmental impact created in the life phases (1), (2) and (7) is independent from the existence of the ELSA-type ESS. For this reason, it **is allocated entirely to the vehicle** from which the components are taken to be used for the ELSA-type ESS and it is not considered in the assessment of the environmental impact of the services provided by an ELSA-type ESS. However, the environmental impact created in the life phases (1) and (2) has been assessed for evaluating **the difference between the environmental impact created by an ESS with a new battery pack and an ELSA-type ESS** (see subchapter 5.1).

4.7 System boundaries in space

4.7.1 ELSA-type ESS including communication and control infrastructure

In the following, the notion "ELSA site" is used for denoting an entity (office building, industrial site, residential district or other) within which an ELSA-type ESS is installed and operated for a duration of 10 years. Basically, an ELSA-type ESS changes the electric power flows within an ELSA site and between the ELSA site and the overall electricity supply system. This leads indirectly to changes of the amount and the mix of origin of electricity generated at the ELSA site and elsewhere. This corresponds to a change in the amount and mix of fuels which are consumed and the amount of emissions released, thus inducing a differential environmental impact, i.e. a change in the environmental impact created at the ELSA site or elsewhere in the electricity supply system.

For example, the operation of an ELSA-type ESS might lead to a net increase of power generation from RES in the overall electricity supply system because renewable electricity can be stored when it is available and used later when it is needed, thus reducing the curtailment of renewable electricity. This leads generally to a reduction of fossil fuel-based electricity generation and thus to a reduction of the related environmental impact. The operation of the ELSA-type ESS might also lead to smoothening the ramp rate of fossil power plants, thus improving their efficiency and reducing fuel consumption and related environmental impacts, even though the total amount of generated electricity is merely not changed.



Consumption: Totality of all electricity and/ or heat consuming elements of the ELSA site
Generation: Totality of all electricity generating elements of the ELSA site
Battery: ELSA-type ESS
Depicted are further the different energy flows with (grey background) and without the installation of the ELSA-type ESS. Electricity generation plants might be installed together with an ELSA-type ESS (shaded grey). Distinguished are:
E0: sum flow of electricity consumed within the boundaries of the ELSA site (excluding losses within the battery and on-site generation units)
E1: flow of electricity from the grid to the ELSA site
E2: sum flow of electricity generated within the boundaries of the ELSA site
E3: flow of electricity into the ELSA-type ESS
E4: flow of electricity out of the ELSA-type ESS
E5: flow of electricity from the ELSA site into the grid
Q: amount of heat consumed within the boundaries of the ELSA site

Figure 5: Schematic representation of the energy flows in an ELSA site and across its boundaries

Figure 5 depicts and describes the different energy flows assumed to be potentially relevant for changes induced in the environmental impact of an ELSA site through the operation of an ELSA-type ESS. Though the latter is the system whose environmental impact is assessed, a system extension is needed in order to assess all the changes in the environmental impact induced somewhere by the ELSA-type ESS.

4.7.2 System extensions “generation” and “grid”

The reduction of environmental impact takes place in the wider national, regional or local electricity supply system (system of generation, transport, distribution and use of electricity including embedded generation) whose functioning is modified through the operation of an ELSA-type ESS. The following modifications of the wider electricity supply system’s functioning might lead to a lower environmental impact:

- more generation from / less curtailment of RE and less conventional back-up generation
- less grid losses
- less rapid up and down ramping and improved average efficiency of thermal power plants
- lower conventional power plant and grid capacity and, in the long-term, less environmental impact due to less power plant and grid construction and dismantling

These modifications are finally induced by, respectively can be related to, changes of:

- the flow of electricity from the grid to the site
- the flow of the local generation of electricity E2
- the flow of the local generation of heat energy Q (disregarded in the following)

The reader may note that the losses in the ELSA-type ESS, E3 – E4, lead to a change in local generation E2 or the electricity drawn from the grid E1 and are thus implicitly taken into account if these changes of energy flows are considered.

Hence, the system boundaries enclose in space:

- the ELSA-type ESS including communication and control infrastructure needed for providing services;
- a unit “generation” with a flow E2 which represents the aggregated local electricity generation;
- a unit “grid” with a flow E1 which reflects the aggregated external electricity generation, transmission and distribution system.

The last two bullet points reflect the system expansion in space beyond the ELSA-type ESS itself (including communication and control infrastructure). For simplification, only the use phase of the extensions “generation” and “grid” is considered. This means that changes in the processing and end-of-life of power plants and grid infrastructure induced by the ELSA-type ESS are disregarded.

4.7.3 Disregarded long-term effects

In fact, if many ELSA-type ESS are installed, this might in the long term also affect the mix of power plants and grids for the general supply with electricity. For instance, ELSA-type ESS might lead to a much flatter electricity demand profile. This leads to more even use of electric grids lines thus allowing for a lower nominal capacity of grid lines if the total electricity consumption is not much changed. Hence, in the long term, ELSA-type ESS might save investments in grid infrastructure, thus leading to lower related environmental impacts.

A more constant overall electricity demand allows also for providing a higher share of electricity with power plants whose output cannot be changed very quickly. I.E. a higher share could be provided by nuclear or lignite power plants instead of gas power plants. In the short term, this changes only the amount of fuels used for power generation and the related emissions, but in the long term, it also impacts on investments into power generation, thus leading to lower related environmental impacts.

However, if ELSA-type ESS are just used for cost-minimization by the respective operators without regard on the effects for the overall electricity system, the inverse might happen and load or generation peaks be created in the grid. This might in the mid-term lead to even higher needs for grid capacity and higher related environmental impacts.

For the sake of simplicity, these potential long-term effects are not taken into account in this study. This simplification is justified by existing calculations of the economic impact of distributed ESS on the overall electricity supply system. These calculations show that the impact is mainly on the operation of power plants and less on the required total power plant capacity (see ELSA deliverable D5.4, chap. 6.2).

4.8 Services provided by ELSA pilot sites

Though this study abstracts from the concrete ELSA pilot sites and investigates the environmental impact of an ELSA-type ESS, i.e. an ESS with the same technical characteristics as the forthcoming commercial ELSA battery systems (ELSA-DT5-ESS), an investigation of the services tested at the ELSA pilot sites is helpful for detecting the mechanisms which finally lead to an environmental impact.

Figure 6 provides an overview of the six ELSA project pilot sites and indicates the respective environment in which they have been integrated: DSO (distribution grid), building or district (residential district in Kempten and university campus Aachen).

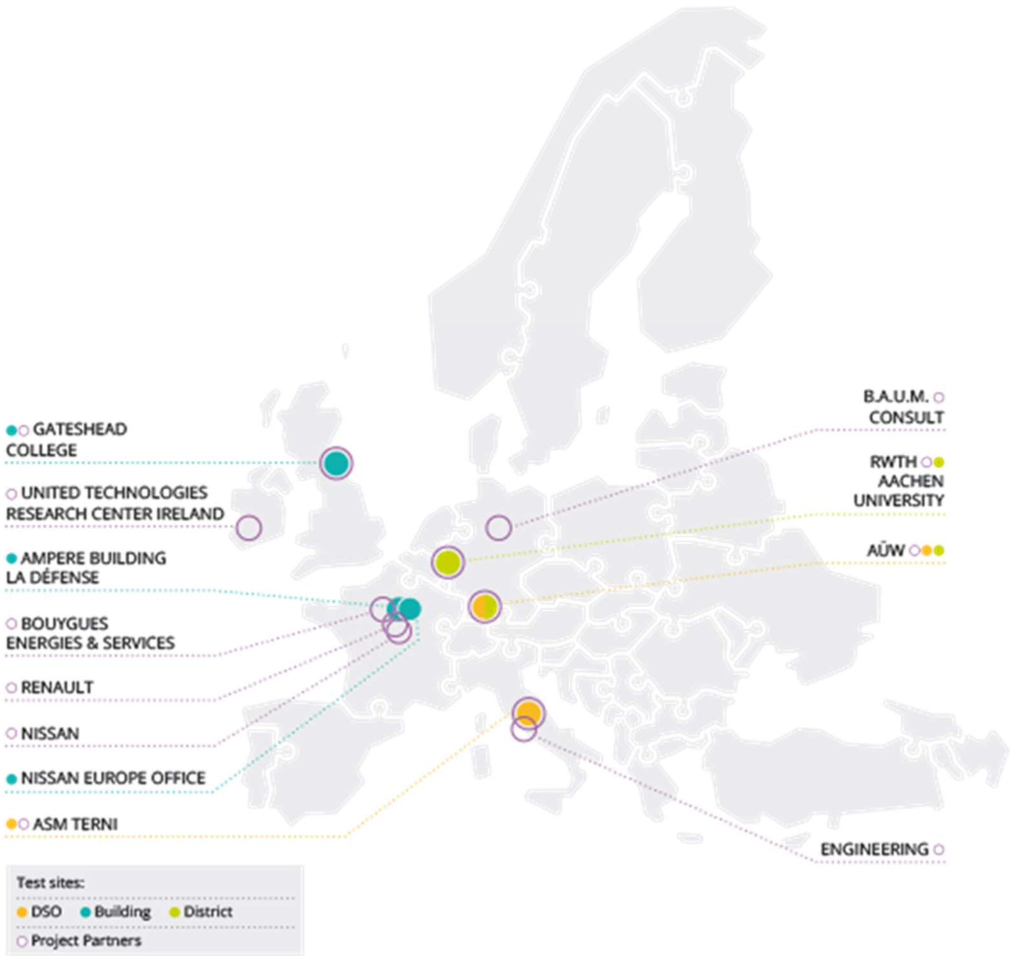


Figure 6: ELSA demonstration sites, Source: (ELSA consortium, 2018)

Table 2 provides an overview of the different use cases which have been tested or simulated at the ELSA pilot sites. A comprehensive description of the use cases is provided in the ELSA deliverable D1.5. Some of these use cases correspond to a service provided to the respective operator itself, some others to a service to a stakeholder of the electricity supply system. For the purpose of the environmental assessment, it is relevant which use case generates a change in the flow of energy and materials, and thus a change of the environmental impact, at the ELSA site itself or somewhere outside. If the change happens outside the ELSA site, the system boundaries must be extended in order to assess the environmental impact appropriately.

Table 2: Use cases tested or simulated at ELSA pilot site

City of Terni						Ampere Building					Nissan Office		RWTH Aachen				City of Kempten						SASMI Building				
UC 1	U C	U C	U C	U C5	U C6	UC 1	UC 2	UC 3	UC 4	UC5	UC1	UC 2	UC 1	UC 2	UC 3	UC 4	UC 1	UC 2	UC 3	UC 4	UC 5	UC 6	UC 1	UC 2	UC 3	UC 4	UC5
Power Quality – Power Balance	Primary Reserve	Dynamic Reactive Power Control	Reactive Power Compensation	Peak Shaving Consumption to Reduce Peak Loads in Peak Hour	PV power smoothing	Peak Shaving for Power Subscription Cost Optimization	Provide DR Auto Consumption on Building Level	Energy Purchase Time Shifting	Provide DR Cost Minimization on Building Level	Provide DR - Flexibility for Building and District	Peak Shaving for Power Subscription Cost Optimization	Energy Purchase Time Shifting	Provide DR CO_2 Minimization for District Optimization	Provide DR Auto Consumption for District Optimization	Provide DR Cost Minimization for District Optimization	Provide DR - Flexibility for Building and District	Provide DR Auto Consumption for District Optimization	PV Self-consumption Maximization by Power Smoothing	Balance Group Optimization	Participation to the Energy Trade Market	District Provides Primary Reserve	DSO Manages the Reactive Power Compensation	Peak Shaving for Power Subscription Cost Optimization	Provide DR Auto Consumption on Building Level	Energy Purchase Time Shifting	Provide DR Cost Minimization on Building Level	Provide DR - Flexibility for Building and District

4.8.1 Ampere Building at La Défense (SOGEPROM)

Category: Building

Location: Paris, France

Owned by the real estate company SOGEPROM, the Ampere Building is a 10-floor office building built in 1985 in the business district La Défense. It underwent a complete renovation and modification to became a sustainable construction.

The contribution of the project ELSA comprises an electrical storage out of a 22 kWh Kangoo 2nd-life batteries (DT3) and an 88 kWh Kangoo 2nd-life batterie (DT5).

Additionally, the office building is equipped with

- a heat pump for heat and cold generation of 130 kW
- a connection to the heat distribution network of La Défense
- solar panels
- a "Gen 2 Switch" system for the elevator (Otis elevator with a battery) and
- 30 recharging spots for a fleet of EV for employees.

The so-called "Reservoir of Energy" is expected to lower energy costs and the environmental footprint, and to serve as a showcase of the transformation of an existing building into a sustainable one. ELSA's storage solution is expected to satisfy the most stringent safety and security specifications in such a critical office environment.

The services provided by the ELSA pilot system comprise:

- PV power smoothing
- Peak shaving
- Demand response
- Time shifting

4.8.2 Gateshead College at its Skills Academy for Sustainable Manufacturing and Innovation (SASMI) facility

Category: Building

Location: Sunderland, United Kingdom

At the SASMI site, an ELSA battery energy storage system consisting of three 2nd life Nissan Leaf batteries with a total capacity of 48 kWh has been deployed. Additionally, a 50 kWp photovoltaic system has been installed on SASMI's rooftop – consisting in total of 191 solar panels covering an area of 320 m^2. The existing BMS was upgraded to include a number of new meters, sensors and weather instruments that are also incorporated within the ELSA Building Energy Management System (EBEMS) enabling more efficient control of the building services with SASMI.

The primary objective of the Gateshead College site is to reduce the amount of energy being consumed from the grid through a combination of the ELSA battery storage system with a photovoltaic (PV) installation.

The complete list of services that have been trialled at the pilot site at the SASMI is:

- Increasing self-consumption
- Maximise usage from a fluctuating PV system
- Demonstrate the ‘plug and play’ capability of the design of the battery storage system
- Cost minimisation
- Flexibility
- Peak shaving (simulation)

4.8.3 Nissan Europe Office

Category: Office Building

Location: Paris, France

In April 2017, the personnel of Nissan Europe SAS moved to a bigger and more modern building in the city of Montigny, near Paris. The building has more than 12.000 square meters of office area, 800 workstations, 500 parking spaces and about 100 EV charging stations. The maximum electrical consumption of the site is a bit more than 2 MW.

A container-based battery system is installed on the premises allowing to experiment with the implementation of relocatable storage. The battery system has the following general characteristics: 12 second life Nissan LEAF batteries with a total capacity of 132 kWh, 6 power converters produced by ABB developed in the framework of the ELSA project - the converters have a power of 24 kW each forming a 144 kW-system. Each converter manages 2 batteries. The installed converters are a pre-commercial version that will first be tested at this pilot site. One of the main objectives of this pilot site is testing the scalability of the ELSA system.

The services provided by the ELSA pilot system comprise:

- Peak shaving
- Energy arbitrage
- Demand response

4.8.4 E.ON Energy Research Center (ERC) at RWTH Aachen University

Category: District

Location: Aachen, Germany

The E.On Energy Research Center (ERC) is part of the multi-disciplinary research institution of the RWTH Aachen University. The ERC consists of three buildings: the main building, one office building and an experimental hall. The main building has been designed as an experiment in itself containing an advanced Building Management System to investigate different solutions for heating and cooling (including geothermal storage, CHP and cold via open sorption) and a set of solar panels on its roof. The experimental hall, which is equipped with a heating rod, and an office building complete the scenario together with a small wind turbine (Enercon 500 kW). For the purpose of ELSA, these three buildings are considered as a small district. The ELSA pilot system uses 6 ZOE batteries with a total power of 72 kW and a total capacity of 66 kWh.

The services provided by the ELSA pilot system comprise:

- DR CO_2 Minimization for District Optimization
- DR Auto Consumption for District Optimization
- DR Cost Minimization for District Optimization
- DR - Flexibility for Building and District

4.8.5 City of Kempten

Category: Distribution system, district

Location: Kempten, Germany

The city of Kempten is located in the Oberallgäu region in Bavaria. Already, about 33 % of the electric energy consumed within the city of Kempten and the Oberallgäu region is produced from renewable energy sources, mainly run-of-the-river hydropower and solar energy, but also from biogas and wind.

The pilot site “Auf dem Bühl” is an existing residential area with six multi-family houses and a total of 81 apartments. On three of the six houses, rooftop solar panels (37.1 kWp) have been installed. In the framework of the ELSA project, the following will be installed:

- 6 Renault Kangoo 2nd-life batteries (total capacity up to 66 kWh)
- 7 egrid measurement boxes
- Bouygues battery Energy Storage Management System (ESMS)

The main goal at the Kempten pilot site is to maximise the district’s self-supply with PV electricity and to mitigate the difference of PV power and electricity demand fluctuations, that is the residual demand, at city quarter level. The complete list of services that is trialled at the pilot site in Kempten include:

- Increasing self-consumption
- PV power smoothing
- Providing primary reserve (simulative)
- DSO manages the Reactive Power Compensation (simulative)

- Balance group optimisation (simulative)
- Participation to the energy trade market (simulative)

4.8.6 City of Terni

Category: Distribution system

Location: Terni, Italy

ASM Terni has been continuously investing in the electricity grid in order to increase the feed-in share of electrical energy generated from RES. Currently, approximately 20 % of the city's overall electricity demand is covered by RES.

The ASM TERNI pilot site is a district and its objectives are to mitigate and smooth the fluctuating power output generated by the nearby PV farm in order to follow, ultimately, the requests from the DSO in terms of grid efficiency. The said district is composed of 4 Blocks of energy units:

1. 240 kWp equivalent (180 kWp + 60 kWp) PV farm, connected to the LV section of the network (existing)
2. 66 kWh ELSA battery energy storage, capable to be charged with a peak of 18 kW and able to supply 72 kW of power, to be installed as part of the ELSA project
3. ASM Terni buildings comprising i) a 4,050 m2 three-storey office building; ii) a 2,790 m2 single-storey building consisting of technical offices, a computer centre and an operation control centre and iii) a 1,350 m2 warehouse (existing).
4. One electric vehicle (EV), called Renault Zoe R240 and featuring a 22 kWh lithium-ion battery (to be on site by the end of 2016).

Two scenarios have been explored at the Terni pilot site:

Scenario 1: The battery provider offers services to the district manager

In this scenario, the district manager (DM) offers aggregated flexibility to the Distribution System Operator (DSO). The DSO requests a profile from the DM, who manages the battery, the Electric Vehicle (EV) charging station, the building and the PV system. The trialled services are:

- PV power smoothing
- Peak shaving

Scenario 2: DSO operates the storage

The trialled services are:

- Power quality

- Ancillary services (primary reserve, dynamic reactive power control, reactive power compensation)

4.8.7 Environmental impact of use cases

The different use cases of ELSA-type ESS do not automatically lower the environmental impact of the electricity supply system in which they are integrated. Basically, this is only achieved if one of the following mechanisms is activated:

- Storage of renewable electricity which would otherwise be curtailed, thus avoiding environmental impact of fossil (back-up) power plant operation. This is notably achieved if the ESS is operated at grid bottlenecks created by high renewable generation.
- Storage leading to smoother operation of fossil power plants, thus avoiding inefficient quick ramping and related energy losses. This can be achieved whenever the difference between electricity generation and consumption is flattened, e.g. by demand control or by provision of frequency response and reserve. It can also be achieved if quick re-dispatch is avoided.
- Storage reducing number of starting operations of fossil power plants and related inefficient operation, notably of peak power plants. This effect is only achieved if storage reduces consumption peaks at such a level that the number of starts of a peak power plant can be completely avoided.
- Storage increasing the rate of direct local and regional supply, thus reducing the average distance over which electricity is transmitted between power plants and consumers, and related grid losses.
- Storage reducing the reactive power component in grids. This can be achieved if reactive power compensation of non-ohmic loads is done locally thus avoiding the transmission and distribution of reactive power.

Table 3 provides an overview of the most likely achieved effects of the different use cases tested at the ELSA pilot sites which might lower the environmental impact. If these effects are generated depends not only on the ESS and its operation, but very much on the concrete situation in the local, regional and national electricity supply system in which the ESS is integrated. An increase of the environmental impact might result from operating an ESS if the losses within the ESS are higher than the reduction of environmental impact in the electricity system.

Table 3: Most likely environmental impact mechanisms of use cases investigated in ELSA

Use case	less RE curtail-ment / less fossil genera-tion	smoother operation of fossil power plants	less starts of fossil power plants	less losses in the grid
Power Quality – Power Balance		√		√
Primary Reserve		√		
Dynamic Reactive Power Control				√
Reactive Power Compensation				√
Peak Shaving Consumption to Reduce Peak Loads in Peak Hour		√	√	√
PV power smoothing	√	√		√
Peak Shaving for Power Subscription Cost Op-timization		√	√	√
Provide DR Auto Consumption on Building Level		√		√
Energy Purchase Time Shifting		√		√
Provide DR - Flexibility for Building and District		√		√
Energy Purchase Time Shifting		√	√	√
Provide DR CO_2 Minimization for District Opti-mization	√			√
Provide DR Auto Consumption for District Op-timization	√			√
Provide DR Cost Minimization for District Opti-mization	√			
PV Self-consumption Maximization by Power Smoothing	√	√		
Balance Group Optimization				√
Participation to the Energy Trade Market		√		
District Provides Primary Reserve		√		
DSO Manages the Reactive Power Compensa-tion				√
Peak Shaving for Power Subscription Cost Op-timization		√	√	√
Provide DR Cost Minimization on Building Level	√			

5 Life cycle inventory and impact assessment

5.1 Production of the battery pack

A LCI and LCIA of a 24 kWh Nissan EV battery pack produced at the Nissan UK production site in Sunderland has been performed by Nissan Motor co. Ltd. The battery pack includes the battery, the casing, the battery management system and the internal cabling. It is equivalent to 4.5 battery packs of an ELSA-type ESS. The LCI and LCIA cover those life cycle phases out of the phases defined in subchapter 4.6 which are highlighted in the following list:

(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years;

(4) Processing of materials and components used only in the ELSA-type ESS for 10 years;

(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years

(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system;

(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS;

(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS.

The results of the LCI, only an intermediate step in the study, are confidential, but Table 4 summarises the results of the LCIA in terms the chosen six environmental impact categories. For the calculation, CML 2001 was chosen as impact assessment method.

Table 4 shows that the environmental impact of life cycle phase 5, extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years, is marginal.

If one considers this and neglects the environmental impact of life cycle phase 7, recycling, final disposal or incineration[2] of materials and components used first in the vehicle and later in an ELSA-type ESS, the sum of the environmental impacts of life cycle phases 1, 2 and 7, i.e. those life cycles phases which are attributed to the vehicle, but not to the stationary ESS, is approximately given by the sum of the impacts of phases 1, 2 and 5 in the rightmost column of Table 4.

Table 4: Result of the LCI and LCIA performed for a 24 kWh Nissan EV battery pack for the life phases of production and logistics

Environmental impact category	Production	Logistics for production	Logistics for gathering from ELV	Total
CML2001- Apr 2013: Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	0.13	0.00	0.00	0.13
CML2001- Apr 2013: Acidification (AP) [kg SO2-Equiv.)	11.00	1.00	0.00	12.00
CML2001- Apr 2013: Eutrophication Potential (EP) [kg Phosphate-Equiv.]	1.80	0.10	0.00	1.90
CML2001- Apr 2013: Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	1,765.00	43.00	0.00	1,809.00
CML2001- Apr 2013: Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.77	0.03	0.00	0.81
Primary energy from non-renewable resources (net cal. value) [MJ]	27,366.00	638.00	0.10	28,004.00

In order to access to the answer of the first of the two questions specified in the goal and scope definition - what is the environmental impact that is avoided by using a not dismantled vehicle battery instead of a new battery in a 2nd-life ESS? – one needs to take into account (1) that a new 24 kWh Nissan EV battery can replace the batteries of more than one ELSA-type ESS if it is used directly for a stationary application, and (2) a new Nissan EV battery can presumably be used in total for 15 years for a stationary application, while a Nissan

[2] Confidential LCA studies for EV which were available to the authors show that the environmental impact of the recycling, final disposal and incineration phase is in fact neglectable compared to the other life cycle phases, in particular to the use phase.

EV battery which has already been used for 10 years in an EV can only be used for 5 years for a stationary application. Hence, the environmental impact avoided by using 2nd-life batteries instead of new ones is only a fraction of the impact shown in Table 4.

In order to estimate this fraction, it has been assumed that the average usable capacity of a new Nissan EV battery used for stationary applications is 16.5 kWh, the average available power 18 kW and the use time 15 years. A stationary ESS with a new Nissan EV battery thus corresponds to 270 functional units, 4.5 times more than an ELSA-type ESS (12 kW*5 years = 60 kW*years). That means a 2nd-life battery in an ELSA-type ESS replaces 1/4.5 = 0.22 new batteries if properties similar to new, respectively used, Nissan EV batteries are assumed. Hence, for calculating the environmental impact avoided by using a 2nd-life battery instead of a new one the impact shown in Table 4 need to be divided by 4.5. The results are shown in Table 5. Breaking the figures further down to one functional unit of 1 kW*yr, the answer to the first of the two questions specified in the goal and scope definition is:

The environmental impact avoided by using a not dismantled 2nd-life battery from an EV instead of a new battery in a 2nd-life ESS is about 6.7 kg $CO_{2\text{-eq}}$/kW/yr, 0.04 kg $SO_{2\text{-eq}}$/kW/yr and 104 MJ/kW/yr of non-renewable primary energy. This is almost entirely due to the avoided battery production. The other environmental impacts are marginal.

Table 5: Environmental impact avoided in 5 years by using a 12 kW 2nd-life battery instead of an equivalent new one

Environmental impact category	Production	Logistics for production	Logistics for gathering from ELV	Total
CML2001- Apr 2013: Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	0.03	0.00	0.00	0.03
CML2001- Apr 2013: Acidification (AP) [kg SO_2-Equiv.)	2.44	0.22	0.00	2.67
CML2001- Apr 2013: Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.40	0.02	0.00	0.42
CML2001- Apr 2013: Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.]	392.22	9.56	0.00	402.00
CML2001- Apr 2013: Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.17	0.01	0.00	0.18
Primary energy from non-renewable resources (net cal. value) [MJ]	6,081.33	141.78	0.02	6,223.11

5.2 Production of the hardware components used only for 2nd life

Out of the phases defined in subchapter 4.6 those which are highlighted in the following list concern the production, recycling etc. of the ELSA-type ESS's hardware components which are only used for the 2nd life:

(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years;

(4) Processing of materials and components used only in the ELSA-type ESS for 10 years;

(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years;

(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system;

(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS;

(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS.

For estimating the environmental impact, a survey of LCA studies of different electric products has been made. Finally, the LCA for a PV inverter published in (Fischer, et al., 2012) has been selected as basis of the estimate. This LCA investigates a 2.5 kW PV inverter with a weight of 18.5 kg. The publication provides the LCIA results for 1 kWp and one year of use for five out of the six chosen environmental impact parameters and almost in pattern with the same assessment method as that chosen for the battery pack (CML 2009 instead of CML 2001, IPCC 2007 for the GWP).

It is assumed here that "1 kWp" designates the nominal power of the inverter and not of a PV installation of which the inverter is a part of. In order to compare with the electronics of the ELSA-type ESS which is only used for 10 years, that means that they have a higher impact per year of operation, the figures published by (Fischer, et al., 2012) have been multiplied by

15/10. The results are shown in Table 6. The last column relates the figures to the respective environmental impact of the production and logistics of the battery pack. It shows that the environmental impact of the hardware which is installed only for the 2nd life is about twice to five times higher than the environmental impact that is avoided by using a 2nd-life battery instead of a new one.

Table 6: Estimated environmental impact in 5 years of the production of the hardware used only in the 2nd life of a 12 kW ELSA-type ESS

Environmental impact category	Impact of production	% of avoided battery pack impact
CML2009: Abiotic Depletion (ADP elements) [kg Sb-Equiv.]		
CML2009: Acidification (AP) [kg SO_2-Equiv.)	0.18	405%
CML2009: Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.02	213%
IPCC 2007: Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.]	20.90	312%
CML2009: Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.02	506%
Primary energy from non-renewable resources (net cal. value) [MJ]	385.92	372%

According to (Fischer, et al., 2012), the environmental impact of the recycling, final disposal and incineration phase of a 2.5 kW inverter is about one tenth of the impact of the production phase. Hence, it can be neglected.

5.3 Use phase of ELSA-type ESS

5.3.1 Scenario set-up for avoided PV curtailment

The only remaining life cycle phase out of those defined in subchapter 4.6 is phase 6: Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system.

Out of the mechanisms described in section 4.8.7 by which the various use cases of ELSA-type ESS can avoid environmental impacts of the electricity system in which the ESS is integrated, the mechanisms of avoiding renewable generation curtailment and related back-up fossil electricity generation, is presented here in more detail. All the other mechanisms are difficult to quantify, that is the exact impact depends much too strongly on the exact way how the ELSA-type ESS is operated and modifies the electricity power flows in the local, regional and national electricity system.

Finally, all changes in the environmental impacts of the use phase of the ELSA-type ESS are related to changes of amount and origin of the electricity from on-site generation and of the electricity drawn from the grid (see subchapter 4.6). To illustrate how an ELSA-type ESS might modify the environmental impact of a site, a scenario has been investigated which is explained in the following on the example of the calculation of the avoided Greenhouse Warming Potential (GWP).

5.3.2 Greenhouse warming potential

An overview of the calculation and the figures mentioned in the following can be found in Table 7.

- Let an ELSA site have an annual electricity consumption of 700,000 kWh.
- Let 300,000 kWh of the electricity consumption be met by a local PV plant (E2) and 400,000 kWh from the grid (E1).
- Let the value of E2 be the result of a curtailment by 5 % due to the impossibility to make use of the entire electricity that the local PV plant might generate. That means it was 315,789 kWh without curtailment.
- Let no electricity be fed into the grid (E5 = 0). Then, E0 = E1 + E2 and E3 = E4 = 0.
- Let the mix of origin of the electricity from the grid (E1) be the same as the German electricity mix in 2015.

- Let the specific emission factors for different origins of electricity for the GWP be the same as those published by the German Federal Environmental Agency in 2013 (Umweltbundesamt, 2014).
- Then the GWP of the electricity consumed at the ELSA site is 213.6 tons of $CO_{2\text{-eq}}$ before the installation of an ELSA-type ESS.
- Let now an ELSA-type ESS be installed with a nominal power of 96 kW and a nominal capacity of 88 kWh. Let it be charged and discharged once per day, the state of charge varying between 0 % and 100 %. Hence, the energy charged into the battery per year, E3, equals 32,120 kWh.

Table 7: GWP of an ELSA site before and after the installation of an ELSA-type ESS[3]

origin of electricity	specific GWP [g CO2eq/kWh]	share of origin for	without ELSA-type ESS		with ELSA-type ESS	
			E1 [kWh]	E2 [kWh]	E1 [kWh]	E2 [kWh]
PV	55.2	6.0%	24,000	300,000	23,419	315,789
lignite	1070.1	24.0%	96,000		93,675	
hard coal	919.0	18.0%	72,000		70,256	
natural gas	429.7	9.0%	36,000		35,128	
petrol	777.3	1.0%	4,000		3,903	
wind (onshore)	8.8	12.0%	48,000		46,838	
wind (offshore)	4.3	2.0%	8,000		7,806	
hydropower	2.7	3.0%	12,000		11,709	
geothermal energy	217.2	0.0%	0		0	
solid biomass (mix)	25.4	4.0%	16,000		15,613	
biogas (mix)	422.6	4.0%	16,000		15,613	
liquid biofuels (mix)	316.8	0.0%	0		0	
sewage gas CHP	26.2	1.5%	6,000		5,855	
landfill gas CHP	25.7	1.5%	6,000		5,855	
nuclear energy	5.0	14.0%	56,000		54,644	
sum	**-**	**100.0%**	**400,000**	**300,000**	**390,313**	**315,789**
sum	**-**	**-**	**700,000**		**706,103**	
GWP [tons CO2eq]	-	-	197.0	16.6	192.3	17.4
GWP [tons CO2eq]	**-**	**-**	**213.6**		**209.7**	

[3] Figures for specific GWP are taken from (Umweltbundesamt, 2014)

- Let further be the losses per charging cycle be 19 % of E3 that is 6,103 kWh (charging and discharging efficiency are both 90 %, the round-trip efficiency 81 %; self-discharge losses are neglected). Hence, the energy discharged from the battery per year, E4, equals 26,017 kWh, and the total consumption at the site E0 = E1 + E2 +E3 – E4 = 706,103 kWh, i.e. increased by the amount of the energy losses in the ESS.
- Let it now be possible to make use of the full generation potential of the local PV plant thanks to the ELSA battery system. The curtailment is zero and E2 is 315.789 kWh. E1 is lowered accordingly. Let its mix of origin not be changed, nor the efficiency and related specific GWP of power plants.
- Then the GWP of the electricity consumed at the dummy pilot site is 209.7 tons of CO_{2eq} after the installation of an ELSA storage system.
- The GWP reduction of 3.9 tons of CO_{2eq} per year is due to the avoided curtailment of the PV plant. This more than compensates the GWP increase related to the energy losses in the battery.
- A closer analysis shows that GWP increase related to the energy losses in the battery is exactly compensated by the GWP decrease related to the reduced curtailment of the PV plant, if the latter is 2.2 % before the installation of an ELSA-type ESS.
- **The specific GWP reduction is 325 kg $CO_{2\text{-}eq}$/kW/yr.**

In a similar way, the avoided environmental impact for the other five impact categories has been calculated.

5.3.3 Abiotic depletion potential

The calculation for the abiotic depletion potential (ADP) is shown in Table 8. The main results based on these figures are:

- The ADP reduction achieved by the avoided curtailment of the PV plant is 1,020 kg Sb_{eq}/yr, respectively **85 kg Sb_{eq}/kW/yr.**
- The net reduction is zero if the avoided PV curtailment is only 2.0 %.

Table 8: Annual ADP of an ELSA site before and after the installation of an ELSA-type ESS[4]

origin of electricity	specific ADP [g Sb-eq/kWh]	share of origin for	without ELSA-type ESS		with ELSA-type ESS	
			E1 [kWh]	E2 [kWh]	E1 [kWh]	E2 [kWh]
PV	9.281	6.0%	24,000	300,000	23,419	315,789
lignite	8.172	24.0%	96,000		93,675	
hard coal	674.921	18.0%	72,000		70,256	
natural gas	260.899	9.0%	36,000		35,128	
petrol	290.333	1.0%	4,000		3,903	
wind (onshore)	9.281	12.0%	48,000		46,838	
wind (offshore)	9.281	2.0%	8,000		7,806	
hydropower	1.413	3.0%	12,000		11,709	
geothermal energy	9.281	0.0%	0		0	
solid biomass (mix)	12.078	4.0%	16,000		15,613	
biogas (mix)	12.078	4.0%	16,000		15,613	
liquid biofuels (mix)	12.078	0.0%	0		0	
sewage gas CHP	12.078	1.5%	6,000		5,855	
landfill gas CHP	12.078	1.5%	6,000		5,855	
nuclear energy	6.944	14.0%	56,000		54,644	
sum	**-**	**100.0%**	**400,000**	**300,000**	**390,313**	**315,789**
sum	**-**	**-**	**700,000**		**706,103**	
ADP [kg Sbeq]	-	-	42,105	0	41,085	0
ADP [kg Sbeq]	**-**	**-**	**42,105**		**41,085**	

[4] Figures for specific ADP have been calculated using values from (Baumann, et al., 2004), Appendices 1 (p. 489 - 490) and 2 (p. 509)

5.3.4 Acidification potential

The calculation for the acidification potential (AP) is shown in Table 9. The main results based on these figures are:

- The AP reduction achieved by the avoided curtailment of the PV plant is 3.9 kg $SO_{2\text{-}eq}$/yr, respectively **326 g $SO_{2\text{-}eq}$/kW/yr.**
- The net reduction is zero if the avoided PV curtailment is only 2.5 %.

Table 9: Annual AP of an ELSA site before and after the installation of an ELSA-type ESS[5]

origin of electricity	specific AP [g SO2eq/kWh]	share of origin for	without ELSA-type ESS		with ELSA-type ESS	
			E1 [kWh]	E2 [kWh]	E1 [kWh]	E2 [kWh]
PV	0.113	6.0%	24,000	300,000	23,419	315,789
lignite	1.065	24.0%	96,000		93,675	
hard coal	0.835	18.0%	72,000		70,256	
natural gas	0.408	9.0%	36,000		35,128	
petrol	1.488	1.0%	4,000		3,903	
wind (onshore)	0.027	12.0%	48,000		46,838	
wind (offshore)	0.013	2.0%	8,000		7,806	
hydropower	0.007	3.0%	12,000		11,709	
geothermal energy	0.278	0.0%	0		0	
solid biomass (mix)	0.717	4.0%	16,000		15,613	
biogas (mix)	1.723	4.0%	16,000		15,613	
liquid biofuels (mix)	2.220	0.0%	0		0	
sewage gas CHP	0.773	1.5%	6,000		5,855	
landfill gas CHP	0.736	1.5%	6,000		5,855	
nuclear energy	0.000	14.0%	56,000		54,644	
sum	**-**	**100.0%**	**400,000**	**300,000**	**390,313**	**315,789**
sum	**-**	**-**	**700,000**		**706,103**	
AP [kg SO2eq]	-	-	235.3	33.9	229.6	35.7
AP [kg SO2eq]	**-**	**-**	**269.2**		**265.3**	

[5] Figures for specific AP are taken from (Umweltbundesamt, 2014)

5.3.5 Eutrophication potential

The calculation for the eutrophication potential (EP) is shown in Table 10. The main results based on these figures are:

- The EP reduction achieved by the avoided curtailment of the PV plant is 1.25 kg PO_{4-eq}/yr, respectively **0.1 kg PO_{4-eq}/kW/yr.**
- The net reduction is zero if the avoided PV curtailment is only 2.0 %.

Table 10: Annual EP of an ELSA site before and after the installation of an ELSA-type ESS[6]

origin of electricity	specific EP [kg PO4eq/MWh]	share of origin for E1	without ELSA-type ESS		with ELSA-type ESS	
			E1 [kWh]	E2 [kWh]	E1 [kWh]	E2 [kWh]
PV	0.005	6.0%	24,000	300,000	23,419	315,789
lignite	0.264	24.0%	96,000		93,675	
hard coal	0.276	18.0%	72,000		70,256	
natural gas	0.196	9.0%	36,000		35,128	
petrol	0.238	1.0%	4,000		3,903	
wind (onshore)	0.005	12.0%	48,000		46,838	
wind (offshore)	0.005	2.0%	8,000		7,806	
hydropower	0.002	3.0%	12,000		11,709	
geothermal energy	0.002	0.0%	0		0	
solid biomass (mix)	0.118	4.0%	16,000		15,613	
biogas (mix)	0.118	4.0%	16,000		15,613	
liquid biofuels (mix)	0.118	0.0%	0		0	
sewage gas CHP	0.118	1.5%	6,000		5,855	
landfill gas CHP	0.118	1.5%	6,000		5,855	
nuclear energy	0.005	14.0%	56,000		54,644	
sum	**-**	**100.0%**	**400,000**	**300,000**	**390,313**	**315,789**
sum	**-**	**-**	**700,000**		**706,103**	
EP [kg PO4eq]	-	-	51.7	0.0	50.4	0.0
EP [kg PO4eq]	**-**	**-**	**51.7**		**50.4**	

[6] Figures for specific EP have been calculated using values from (Baumann, et al., 2004), Appendices 1 (p. 489 - 490) and 2 (p. 515)

5.3.6 Photochemical ozone creation potential

The calculation for the Photochemical Ozone Creation Potential (POCP) is shown in Table 11. The main results based on these figures are:

- The POCP reduction achieved by the avoided curtailment of the PV plant is 53 kg ethylene-eq/yr, respectively **4.4 kg ethylene-eq/kW/yr.**
- The net reduction is zero if the avoided PV curtailment is only 2.0 %.

Table 11: Annual POCP of an ELSA site before and after the installation of an ELSA-type ESS[7]

origin of electricity	specific POCP [kg ethylene-eq/MWh]	share of origin for	without ELSA-type ESS		with ELSA-type ESS	
			E1 [kWh]	E2 [kWh]	E1 [kWh]	E2 [kWh]
PV	0.284	6.0%	24,000	300,000	23,419	315,789
lignite	15.329	24.0%	96,000		93,675	
hard coal	9.266	18.0%	72,000		70,256	
natural gas	3.321	9.0%	36,000		35,128	
petrol	11.686	1.0%	4,000		3,903	
wind (onshore)	0.284	12.0%	48,000		46,838	
wind (offshore)	0.284	2.0%	8,000		7,806	
hydropower	0.051	3.0%	12,000		11,709	
geothermal energy	0.284	0.0%	0		0	
solid biomass (mix)	1.787	4.0%	16,000		15,613	
biogas (mix)	1.787	4.0%	16,000		15,613	
liquid biofuels (mix)	1.787	0.0%	0		0	
sewage gas CHP	1.787	1.5%	6,000		5,855	
landfill gas CHP	1.787	1.5%	6,000		5,855	
nuclear energy	0.183	14.0%	56,000		54,644	
sum	**-**	**100.0%**	**400,000**	**300,000**	**390,313**	**315,789**
sum	**-**	**-**	**700,000**		**706,103**	
POCP [kg ethylene-eq]	-	-	2,199.0	0.0	2,145.8	0.0
POCP [kg ethylene-eq]	**-**	**-**	**2,199.0**		**2,145.8**	

[7] Figures for specific POCP have been calculated using values from (Baumann, et al., 2004), Appendices 1 (p. 489 - 490) and 2 (p. 514)

5.3.7 Primary energy consumption from non-renewable resources

For the calculation of the reduction of primary energy consumption from non-renewable resources (see Table 12), it was assumed that lignite, hard coal and petrol-fuelled power plants have an efficiency of 40 %, gas power plants 50 % and nuclear power plants 33 %. This is taken into account by non-renewable primary energy (PE) factors of, respectively, 2.5, 2 and 3, by which the generated electricity is multiplied in order to calculate the consumed primary energy. The main results are:

- The net reduction of primary energy consumption from non-renewable sources which is achieved by the avoided curtailment of the PV plant is 34,700 MJ/yr, respectively **2,891 MJ/kW/yr.**
- The net reduction is zero if the avoided PV curtailment is only 2.0 %.

Table 12: Annual non-renewable primary energy use of an ELSA site before and after the installation of an ELSA-type ESS

origin of electricity	non-renewable PE factor	share of origin for	without ELSA-type ESS		with ELSA-type ESS	
			E1 [kWh]	E2 [kWh]	E1 [kWh]	E2 [kWh]
PV	0.0	6.0%	24,000	300,000	23,419	315,789
lignite	2.5	24.0%	96,000		93,675	
hard coal	2.5	18.0%	72,000		70,256	
natural gas	2.0	9.0%	36,000		35,128	
petrol	2.5	1.0%	4,000		3,903	
wind (onshore)	0.0	12.0%	48,000		46,838	
wind (offshore)	0.0	2.0%	8,000		7,806	
hydropower	0.0	3.0%	12,000		11,709	
geothermal energy	0.0	0.0%	0		0	
solid biomass (mix)	0.0	4.0%	16,000		15,613	
biogas (mix)	0.0	4.0%	16,000		15,613	
liquid biofuels (mix)	0.0	0.0%	0		0	
sewage gas CHP	0.0	1.5%	6,000		5,855	
landfill gas CHP	0.0	1.5%	6,000		5,855	
nuclear energy	3.0	14.0%	56,000		54,644	
sum	**-**	**100.0%**	**400,000**	**300,000**	**390,313**	**315,789**
sum	**-**	**-**	**700,000**		**706,103**	
non-renewable PE [MJ]	-	-	1,432,800	0	1,398,102	0
non-renewable PE [MJ]	**-**	**-**	**1,432,800**		**1,398,102**	

6 Interpretation

Table 13 and Table 14 summarize the environmental impact which is avoided per kW of nominal ESS power and per year of operation (1) by using a 2nd-life battery in an ELSA-type ESS instead of a new battery and (2) by operating an ELSA-type ESS such that local PV curtailment of 5 % is reduced to zero in a scenario like that described in section 5.3.1. This scenario has been chosen because it shows the most relevant effect of large-scale deployment of decentralised ESS: avoiding curtailment of renewable electricity generation and consequently avoiding back-up operation of fossil power plants and related environmental impact. This point has been discussed in more detail in the ELSA deliverable D5.4, chap. 6.2 which refers itself to the comprehensive study of (Strbac, et al., 2012). While the economic effects on a national electricity supply system are discussed in D5.4, the environmental effects are discussed here.

Table 13 and Table 14 show that (1) using a 2nd-life battery in an ELSA-type ESS instead of a new battery and (2) operating an ELSA-type ESS such that renewable electricity curtailment is avoided lead both to a lower net environmental impact, notably with regard to GWP, AP and non-RPE. The effect of operating the ESS such that renewable electricity curtailment is avoided is 1-2 orders of magnitude more important than the effect of using a 2nd-life battery instead of a new one. Further, the effect of avoided curtailment largely overcompensates the environmental impact of the production of the hardware needed exclusively in the 2nd life.

If the environmental impact of the production and logistics of the 2nd life battery is accounted entirely to the 1st life in the vehicle and an ELSA-type ESS is operated such that 5 % PV curtailment is avoided in a scenario with local self-supply from PV of 43 % and a carbon-rich electricity mix for covering the residual demand, the net environmental impact is -304 kg $CO_{2\text{-eq}}$/kW/year, -0,15 kg $SO_{2\text{-eq}}$/kW/year, and -2,506 $MJ_{\text{non-RPE}}$/kW/year. The other environmental impacts are marginal.

These findings are in line with assessments of the environmental impact of different electricity storage systems, e.g. (Oliveira, et al., 2015), as well as in LCA studies on electric vehicles with different battery technologies, e.g. (Matheys, et al., 2006), (Notter, et al., 2010).

One has to note that the exact net environmental impact depends very much on the concrete framework in which an ELSA-type ESS is operated. For instance, operation in a national electricity system with a lower fraction of electricity generation from lignite and hard coal as considered in this study will lead to a lower net environmental benefit.

Table 13: GWP, AP and non-RPE avoided (1) by using not dismantled 2nd-life battery instead of new one and (2) reducing PV curtailment with ELSA-type ESS

Life cycle phase	impact of using undismantled 2nd life battery instead of new one			impact of ELSA-type ESS avoiding 5% of local PV curtailment		
	GWP [kg CO2eq/kW/yr]	AP [kg SO2eq/kW/yr]	non-RE PE [MJ/kW/yr]	GWP [kg CO2eq/kW/yr]	AP [kg SO2eq/kW/yr]	non-RE PE [MJ/kW/yr]
(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for (2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	-6.7	-0.04	-104	-	-	-
(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years (4) Processing of materials and components used only in the ELSA-type ESS for 10 years	-	-	-	21	0.18	386
(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	-	-	-	0.0	0.00	0.0
(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system	-	-	-	-325	-0.33	-2,891
(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS	-	-	-	-	-	-
(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS	-	-	-	-	-	-
Sum	-6.7	-0.04	-104	-304	-0.15	-2,506

Table 14: ADP, EP and POCP avoided (1) by using not dismantled 2nd-life battery instead of new one and (2) reducing PV curtailment with ELSA-type ESS

Life cycle phase	impact of using undismantled 2nd life battery instead of new one			impact of ELSA-type ESS avoiding 5% of local PV curtailment		
	ADP [kg Sbeq/kW/yr]	EP [kg PO4eq/kW/yr]	POCP [kg ethylene-eq/kW/yr]	ADP [kg Sbeq/kW/yr]	EP [kg PO4eq/kW/yr]	POCP [kg ethylene-eq/kW/yr]
(1) Extraction of raw materials for all components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years (2) Processing of materials and components (the battery pack) used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	0.00	-0.01	0.00	-	-	-
(3) Extraction of raw materials for all components used only in the ELSA-type ESS for 10 years (4) Processing of materials and components used only in the ELSA-type ESS for 10 years	-	-	-	-	0.02	0.02
(5) Extraction from the vehicle and shipping of components used first in the vehicle for 10 years and later in an ELSA-type ESS for 5 years	-	-	-	-	0.00	0.00
(6) Use phase of the ELSA-type ESS (provision of services for 10 years): impact of generation, transport and distribution of electricity compensating losses during ESS charging and discharging, and impact made through changes in power generation and flows in the overall electricity supply system	-	-	-	-84.97	-0.10	-4.44
(7) Recycling, final disposal or incineration of materials and components used first in the vehicle and later in an ELSA-type ESS	-	-	-	-	-	-
(8) Recycling, final disposal or incineration of materials and components used only in the ELSA-type ESS	-	-	-	-	-	-
Sum	0.00	-0.01	0.00	-84.97	-0.09	-4.42

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