Reuse of electric vehicle batteries in buildings: an integrated load match analysis and life cycle assessment approach

Maria Anna Cusenza[a*], Francesco Guarino[a], Sonia Longo[a], Marina Mistretta[b], Maurizio Cellura[a]

[a]University of Palermo, Department of Energy, Information Engineering and Mathematical Models (DEIM), Viale delle Scienze Building. 9, Palermo, Italy

[b]University Mediterranea of Reggio Calabria, Department of Heritage, Architecture, Urbanism, Salita Melissari - Feo di Vito, Reggio Calabria, Italy.

*Corresponding author, E-mail address: mariaanna.cusenza@unipa.it

Abstract

The increasing use of renewable energy technologies for electricity generation in buildings will require a growing number of battery energy storage systems (BESS) to enhance the reliability of electricity supply. The increasing number of retired electric vehicle (EV) batteries, expected from the automotive sector, can match this demand as EV batteries can be used as BESS, considering that they have about 80% of their original energy capacity.

In this context, the study aims at examining the system, consisting of a BESS made by retired Li-ion EV batteries, a photovoltaic plant (20 kW) and the electricity grid, that provides the electricity required by an existing nearly net zero residential building (25.000 kWh/year). The goal is to identify the optimal BESS size, expressed as energy capacity, for load match optimization and environmental impacts in a life cycle perspective.

A BESS of around 46 kWh of energy capacity allows achieving significant results in terms of load match increase and environmental sustainability.

The study includes an environmental assessment combining the load match analysis and the life cycle approach. It highlights the potential synergy inspired to the principles of the circular economy and of the industrial symbiosis, between the building and the automotive sector.

Keywords: Electric vehicle battery, second life application, load match, battery storage system, life cycle assessment

Nomenclature	
Abiotic Depletion Potential	ADP
Acidification potential	AP
Allocation factor for the second life application	α_{fII}
Battery efficiency	η_B
Battery energy capacity	B_c
Battery Energy Storage System	BESS
Building Load	BL
Configuration	C
Cumulative Energy Demand	CED
Electric Vehicle	EVB
Electric Vehicle Battery	EVB
Electricity adsorbed from the electrical grid to feed the building load	$El_{grid \rightarrow BL}$
Electricity delivered from the BESS to feed the building load	$El_{BESS \rightarrow ZBL}$
Electricity losses due to the battery efficiency	$El_{\eta loss}$
Electricity generation from photovoltaic plant	El_{PV}
End of Life	EoL
European Energy Agency	EEA
European Union	EU
Freshwater ecotoxicity	EF_w
Freshwater eutrophication	EU_F
Functional unit	FU
Global warming potential	GWP
Greenhouse house	GHG
Human toxicity, cancer effects	HT-ce
Human toxicity, non-cancer effects	HT-nce
International Energy Agency	IEA
Ionizing radiation - human health	IR-hh
Leaf House	LH
Life Cycle Assessment	LCA
Life Cycle Impact Assessment	LCIA
Lithium manganese oxide - nickel manganese cobalt	LMO - NMC
Lithium-ion	Li-ion
Load cover factor	γ_{load}
Marine eutrophication	EU_M
Maximum battery state of charge	SoC_{max}
Maximum energy discharge from the BESS,	E_{BDmax}
Minimum battery state of charge	SoC_{min}
Nearly Zero-Energy Buildings	nZEB
Net exported electricity	ne
Ozone depletion potential	ODP
Particulate matter	PM
Photochemical ozone formation potential	POFP
Photovoltaic	PV
Product environmental footprint	PEF
Photovoltaic electricity generated on-site and directly consumed by the building	$El_{PV \rightarrow BL}$
Photovoltaic electricity injected into the electrical grid	$EL_{PV \rightarrow grid}$
Photovoltaic electricity used to charge the BESS	$El_{PV \rightarrow BESS}$
Renewable energy source	RES
State of charge	SoC
Terrestrial eutrophication	EU_T

1 Introduction

In 2015, the building and the transport sectors was responsible of 58.5% of the final energy consumption in the European Union (EU) [1]. According to European Energy Agency (EEA), in 2015, the transport sector contributed to 25.8% of total EU greenhouse gas (GHG) emissions [2], while the building sector was responsible for approximately 36% of all CO_2 emissions [3].

Electrification and renewable energy sources (RES) emerge as two of the major low-carbon pathways in both building and transportation sectors.

In building sector, the reduction of energy use and the production of energy from RES are important measures needed to reduce the European Union's energy dependency and GHG emissions [5]. This is addressed in the EU directives on the energy performance of buildings [6,7]. In particular, the Directive 2018/844/EU [7] states the need towards decarbonized pathways through the deployment of nearly zero energy buildings (nZEBs). In this kind of building, thermal and electricity energy storage systems are useful in order to increase the energy flexibility and to optimize the interactions between users and the energy grids. About electricity, the presence of self-generation in the residential sector can become an issue in terms of electricity grid management [8]. The main challenge of the self – generation/consumption is the difficulty in reliably providing power on a desired schedule due to the intermittency of RESs [9–11]. In order to balance supply and demand of electricity and to reduce the stress on the grid, one of the main choices for residential buildings is the use of distributed local battery energy storage systems (BESS). However, one of the most relevant drawback to more widespread use of BESS is the cost [12].

At the same time in the automotive sector, according to the International Energy Agency (IEA), the number of EVs will increase from 2 million units in 2016 to 56 million by 2030 [13] and this can be translated in a significant growing of the EV batteries waste stream in the next years. Currently, the Directives on the end-of-life (EoL) of vehicles [14] and on batteries and accumulators [15] support the recycling as EoL management for batteries.

The preferred technology for EV batteries is the lithium-ion (Li-ion) chemistry [16–21]. According to several previous studies [12,22–24] the EV Li-ion batteries usually retain as much as 70-80% of their original storage capacity at the point of retirement. Then, they may have enough capacity to be used in secondary less demanding energy applications, and, as a fully very circular – economy measure to supply the demand of BESSs of the building sector.

Coupling renewable energy generation on site with electricity storage can reduce wasted energy and transmission losses on the grid side, increase the consumption of the on-site electricity generated from The RES – BESS system will also lead to an improvement of the environmental performance of the building use phase. In fact, the reduction of energy waste and transmission losses and the increase of the consumption of the on-site electricity generation from RESs can allow lower energy and environmental impacts and can accelerate the decarbonisation of the energy generation system.

However, it is paramount to understand the system-wide potential environmental benefits of employing retired electric vehicles (EVs) batteries as BESSs through a life cycle perspective.

In this context, the authors propose the simulation of the installation of a BESS made of retired EV batteries to a residential nZEB, the Leaf House (LH), a case study analysed in [9]., equipped with a photovoltaic (PV) power plant.

The goal of the study is to identify the best trade-off between the BESS sizing and the associated environmental impacts in a life cycle perspective.

In line with this goal, the detailed analysis of the operational phase in terms of load – match and grid interaction is combined with the Life Cycle Assessment (LCA) of the energy system. The load match refers to how the local energy generation compares with the building load and is closely related with grid interaction (i.e. energy exchange between the building and the power grid). The LCA is a standardized methodology (ISO 14040) widely adopted by the scientific community to assess the environmental impacts of products and services from a life cycle perspective (i.e. including extraction of raw materials, transports, manufacturing processes, use and end-of-life) [25,26].

The approach proposed is one of the first that integrates the load match analysis and the life cycle perspective in the design choices of an electrical storage, based on the second life of batteries from the automotive sector.. This allows an environmental sustainability oriented design, that takes into account the repercussions of the design choices not only to the operational phase performances but also to the whole life cycle environmental impacts of system, in order to avoid the shifting of environmental and energy burdens from the operation phase to others life cycle phases [27].

The battery second life proposed in the paper is a synergy between the building and the automotive sector, which can further enhance their individual sustainability propositions; this strategy is in line with circular economy and industrial symbiosis principles [28] and the waste management hierarchy in which reuse is preferable to recycling [29].

2 State-of-the-art

Several LCAs are available in the literature on the EV batteries reuse for energy storage system in stationary applications [22] [23] [24] [30] [31] [32] [33] [34]. An extensive literature analysis carried out by Bobba et al. [22] highlighted that the available LCAs are characterized by significant differences: a) methodological assumptions (functional unit (FU)); b) life cycle phases included in the assessment (system boundaries); c) scope (e.g. different second-use applications, different product systems analysed); d) life-cycle inventory (LCI) data used for the life-cycle stages (e.g. energy flow of the use stage and battery degradation patterns).

Some aspects are further investigated in the presented study. About the BESS sizing, most of the studies examined simply consider the use of one battery pack without exploring the effective improvement in the system operational phase and if the installation of a higher energy capacity could result in an improvement of both operational phase and life cycle environmental sustainability. Concerning the methodological aspect of the allocation[1], five different options were identified ì. In Faria et al. [34] no environmental impacts are allocated to the second life application as, according to the authors, the primary function of the battery pack was to be used in the EV; in Richa et al. [32] the allocation is based on three different rules: market price, energy storage and equally divided. In Ahmadi et al. [23] and Casals et al. [33] the system investigated included both the first and the second life of the EV battery, then allocation was not necessary; in Bobba et al. [22] two different options are investigated: 0% and 25% of the environmental impacts related to battery production and EoL treatment allocated to the second life application. Concerning the operational phase, according to Bobba et al. [22], in the literature the modelling is often based on average data or previous studies [23,32–34]. Moreover, based on author knowledge, only Bobba et al. [22] proposes a detailed energy model of the system investigated including both the battery capacity and efficiency degradation in a time-step modelling of 15 minutes, however, only primary data on the PV generation are used, while data on the building load were generated through the ResLoadSIM tool[2].

In this paper, the authors simulate the installation of BESSs characterized by an increasing installed energy storage capacity, corresponding to the employment of a different number of retired EV batteries. The aim is to assess how the operational phase, in terms of load match, and the environmental life cycle impacts are affected by the installation of an increasing energy storage capacity. Moreover, the authors model the energy systems based on monitored data on PV generation and building load profiles considering both the battery capacity and efficiency degradation. The allocation of the environmental impacts between the first and the second life are based on the energy delivered during each application, allowing their partitioning based on the real function provided in both applications.

3 Description of the system examined

“The system examined is made of a PV plant with an overall efficiency of roughly 14%, a BESS and the electrical grid (PV plant + BESS + electrical grid). Its function is to provide electricity. The PV plant is a grid-connected system with a peak power of 20 kW. The yearly PV electricity generation is about 25 MWh. The BESS is based on a commercial Lithium-ion (Li-ion) EV battery used in a Plug-in hybrid EV [23,38]. At the end of the battery first life, the EV had driven about 140,000 km and had a residual capacity equal to 81.31% of the nominal capacity of the fresh battery [22][35]

The technical characteristics of the examined battery are in Table 1.

Further detail about the considered EV battery pack are available in Bobba et al. [22].

[1] Rule for partitioning the impact of the battery production and EoL phases between the first and the second battery application
[2] https://ses.jrc.ec.europa.eu/power-system-modelling.

Table 1. Technical characteristics of the reused battery [22]

Characteristics	Battery pack
Chemistry	Li-ion LMO-NMC
Nominal capacity [kWh]	9.27
Battery charging/discharging efficiency [%]	95
Weight of the battery pack [kg]	175

The system was simulated as installed in an Italian building nearly zero energy building called “Leaf House” (LH) [36]: a single house located in S. Angeli di Rosora (Marche, Italy). The electricity requirements of the building are supplied by the grid-connected PV system installed on the south-facing roof. The average yearly electricity consumption of the building is about 25 MWh. The highest contribution to the electricity use is from the heat pump, approximately 35%, and lighting and plug loads, 35%, while the pumps, auxiliary loads, and the air handling unit account for the remaining 30% of the total consumption.

The battery pack under investigation was disassembled from a Mitsubishi Outlander PHEV. It is one LMO–NMC battery pack with a nominal capacity of 11.4 kWh, which guarantees 136,877 km of driving for a passenger car weighing 1860 kg before the battery capacity reduced about 81.31% [22][35]. System efficiency modelling was performed by starting from monitoring and laboratory testing activities.

Aged and fresh LMO – NMC cells were purchased and tested by the Joint Research Centre (JRC) in order to evaluate the performance of the cells after the first use in the EV compared to the fresh cells. The rated capacity of the fresh battery cell is 38 Ah. Concerning the aged battery cell, the capacity recorded by the BMS after the first use in the EV, and then available for the stationary second life applications, is 30.91 Ah. Thus, the residual capacity of the aged cells results equal to 81.31% of the nominal capacity of the fresh battery cells.

The capacity of the aged and fresh battery cells under investigation are illustrated in Table 2.

Table 2. Capacity of the fresh and aged Li-ion battery cells investigated.

Characteristics	Aged battery cell	Fresh battery cell
Battery cell capacity [Ah]	30.91	38

During the use phase, in both stationary or mobile applications, battery cells undergo in a degradation mechanism that can contribute to either capacity fading or power fading, or both of them [38]. The aging of a battery cell occurs due to the electrochemical degradation processes that take place during the operation phase, called cycling aging, and also to processes that lead to a degradation of a battery cell independent of charge-discharge cycling, called calendar aging [39] [34]. The aging process leads to an increase of the internal resistance and a reduction of the battery cell performance.

The performance of the battery cells were assessed through an experimental campaign designed for the both fresh and aged cells in order to evaluate the calendar and cycling aging under different conditions and duty cycles, for first EV life and the potential stationary second use in utility grid applications.

The experimental campaign was performed within the SASLAB (Sustainability Assessment of Second Life Application of Automotive Batteries) project[3].

Table 3 illustrates the planned experimental and their status of achievement at the end of SASLAB project.

Table 3. Planned experimental test for the LMO-NMC battery cells in the context of SASLAB project [35].

Type of test	Scope of the test	Chemistry and number of samples	Conditions	Expected duration	Situation (July 2018)
Calendar ageing	Assess the degradation of cells without charging or discharging	6 aged and 6 fresh LMO-NMC/graphite cells	Temperature: 25°C and 45°C; SoC: 100% and 50%	As long as possible	Completed as planned. Still running for long term assessment
Cycle ageing (charge/discharge at CC-CV/CC)	Assess degradation of cells with 100% DoD at C/5 and 1C rate	2 aged and 2 fresh LMO-NMC/graphite cells	Temperature: 25°C and 45°C	6 months	The C/5 series is not completed as planned, 3 month performed. The 1C series not running
Automotive use cycle ageing (WLTC driving duty cycle)	Assess the degradation of cells for automotive applications	2 aged and 2 fresh LMO-NMC/graphite cells	Temperature: 25°C	3 months	Not running. Possibly to be cancelled
Second use cycle ageing (duty cycles: PV firming; PV smoothing; primary frequency regulation; peak shaving)	Assess the degradation of cells for second use applications	28 aged LMO-NMC/graphite cells	Temperature: 25°C, 45°C and 5°	6-9 months	Almost 2 months performed and still running (since November 2017) for 25°C and 45°C (23 samples). Not running the 5°C (5 samples)

With reference to the calendar aging, LMO-NMC aged and fresh Mitsubishi cells were kept under different conditions to assess the calendar ageing process: at a temperature of 25°C or 45°C and at 100% or 50% SOC following the standard of the International Electro-technical Commission (IEC) 62660-1:2010, 2011 [40].

Results that are relevant inputs to the environmental assessment model are the average energy capacity degradation for the cells calendar aged at temperature of 45°C and 100% SOC resulted of - 0.11 Wh/day [35] and the Round Trip Efficiency (RTE) at the beginning of the second life: around 95%.

[3] SASLAB is an exploratory project led by JRC under its own initiative in 2016-2017, aims at assessing the sustainability of repurposing EV batteries to be used in energy storage applications from technical, environmental and social perspectives

In order to characterize the building load profile respect to the PV generation, Table 4 reports the monthly peak-power and the monthly electricity consumption for each month, while Fig. 1 shows the building mean daily electricity consumption and PV electricity generation trends in particular days:

- 24th January (Cloudy cold);
- 6th March (Sunny cold);
- 24th July (Sunny hot);
- 4th August (Cloudy hot).

Table 4. Parameters describing the building load.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Monthly peak-power [kW]	7.47	6.97	7.09	6.89	5.24	5.01	9.02	7.97	5.42	6.47	7.47	8.57
Monthly electricity consumption [kWh]	2700	2286	2371	1736	1363	1521	3051	2271	1618	1496	1748	2897

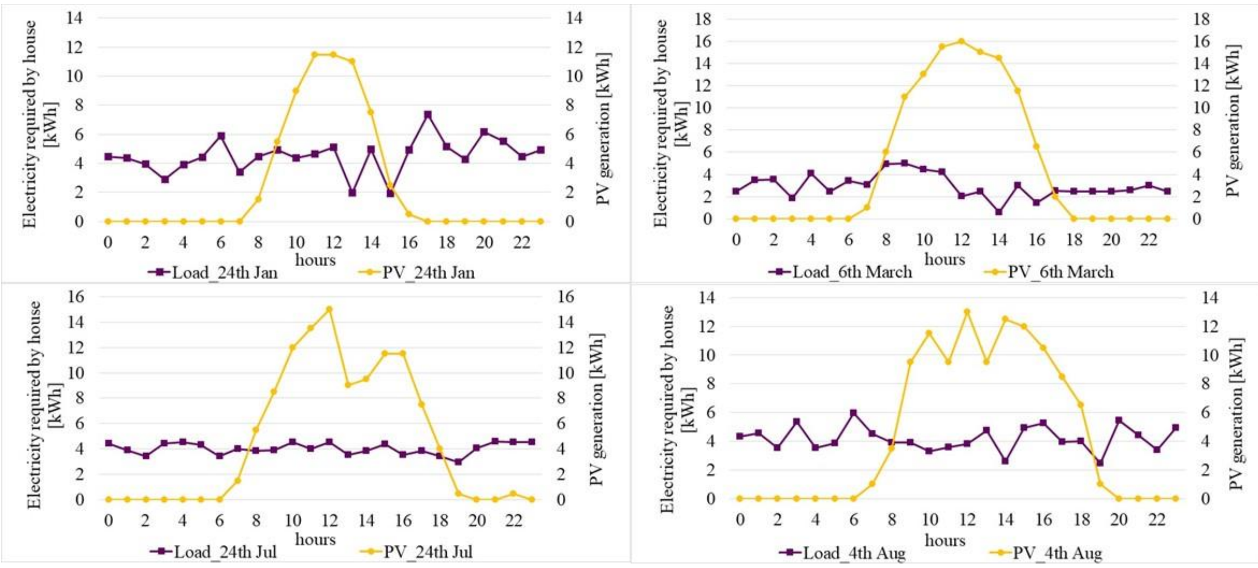

Fig. 1. Mean daily electricity consumption and PV production of the examined case study for four selected particular days.

4 Method

The BESS was simulated in order to quantify the potential improvement in load match between the on-site electricity generation from PV plant and the building load. Moreover, the life cycle energy and environmental impacts of the system (PV plant + BESS + electricity grid) was assessed. Thus, the methodology can be recapped in the following four steps:

1. step 1 – Simulation of the energy system, including the PV, the BESS and their mutual interactions with the energy grid. The BESS is made of retired EV batteries having a residual energy capacity of 9 kWh. A different number of batteries were simulated ranging from 1 to 10 (9 to 90 kWh);

2. step 2 – Identification of the load match and grid integration level for the examined system corresponding to the simulated configurations in step 1;
3. step 3 – Assessment of the life cycle energy and environmental impacts of the examined system through the LCA methodology;
4. step 4 – Identification of the best design solution/s in terms of system efficiency and environmental sustainability based on the results obtained in steps 2 and 3.

4.1 Step 1: Simulation of the energy system

The PV – BESS – Electrical grid system is modelled following the procedure described in Ciocia et al. [41] in which it is assumed that: (1) the PV system always feeds first the load and then, if a surplus is available, the BESS and at the end the grid; and 2) the batteries cannot be used to feed the grid and vice versa. In addition, a battery capacity fade model and a linear decrease of battery efficiency (5 percentage points in 5 years) were introduced according to Bobba et al. [22].

At each time step, the model, starting from the comparison among the on – site electricity production from PV (El_{PV}), the building load (BL) and the state of charge (SoC) of the BESS, allows for calculating the following energy flows:

- PV electricity generated on-site and directly consumed by the building ($El_{PV \rightarrow BL}$);
- PV electricity used to charge the BESS ($El_{PV \rightarrow BESS}$);
- PV electricity injected into the electrical grid ($EL_{PV \rightarrow grid}$);
- Electricity delivered from the BESS to feed the building load ($El_{BESS \rightarrow BL}$);
- Electricity adsorbed from the electrical grid to feed the building load ($El_{grid \rightarrow BL}$);
- Electricity losses due to the battery efficiency ($El_{\eta loss}$).

The diagram of the system analysed and the modelled energy flows are shown in Fig. 2.

The model uses a simplified battery state of charge estimator, which takes in consideration all energy flows reported in Fig. 2. The battery model works on the assumptions of variable efficiencies for charging and discharging due to battery ageing. The model is based on energy balance for every time step: whereas a surplus of electricity generation occurs, the state of charge is increased by a factor proportional to it, reduced by charging efficiencies and vice versa. Moreover, the model includes a linear reduction of the overall capacity based on pure ageing and on charge-discharge cycling.

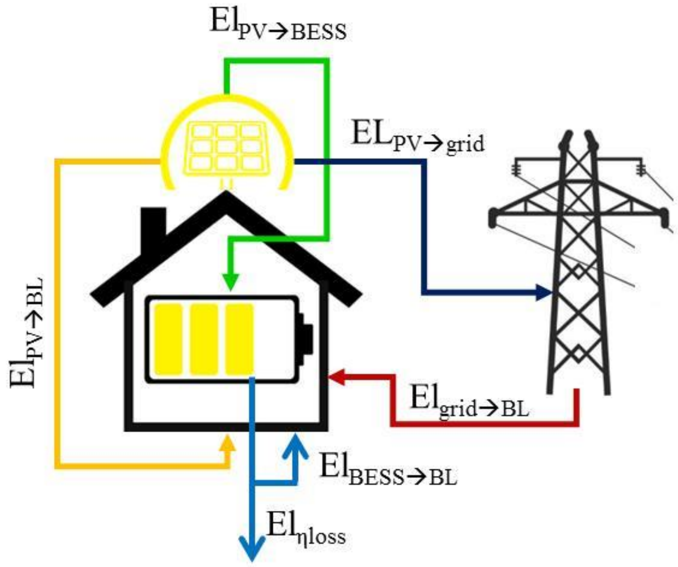

Fig. 2. Diagram of the PV – BESS – Electrical grid system and of the energy flows.

In detail, the maximum energy flow from the BESS (E_{BDmax}) was calculated, at each time step, according to its SoC, considering the following equation:

$$E_{BDmax}(t) = SoC(t) * B_C(t) \tag{1}$$

The SoC (t) is instead calculated with the Equation 2 if the El_{PV} (t-1) < BL and the SoC (t-1) of the BESS was sufficient to provide an energy flow ($El_{BESS→BL}$) able to match fully or partially the BL:

$$SoC(t) = SoC(t-1) - \left(\frac{E_{BESS\rightarrow BL}(t-1)}{B_C(t)}\right) \tag{2}$$

where:

B_c (t) is the capacity of the storage at the time step t. The capacity fade was calculated according to [22,34] taking into consideration both the cycling ageing and calendar ageing, i.e. the aging due to the operation and due to the basic material degradation over the life, respectively.

Alternatively the SoC is calculated with Equation 3 if El_{PV} (t-1) > BL and then EL_{PV} is available to charge the BESS ($E_{PV→BESS}$) and the SoC(t-1) < SoC_{max}:

$$SoC(t) = SoC(t-1) + \left(\frac{E_{PV\rightarrow BESS}(t-1) * \eta_B(t)}{B_C(t)}\right) \tag{3}$$

where:

η_B (t) is the battery efficiency corresponding at the time step (t).

The BESS model interrupts the electricity discharge when the battery SoC reaches the 20% (SoC_{min}) of energy capacity in order to limit battery degradation and aging [22,30,41]. Moreover, each battery is replaced as it reaches 60% of its nominal capacity. In fact, When the battery capacity falls below 60% of its initial capacity, the BESS is no longer able to satisfy the system requirements [33,42]. Moreover, based on previous studies on battery second life application [33,43], it is assumed a maximum BESS lifetime of 20 years. Therefore, considering that in a EVs the BESS has a service life of about 8 years [23,32] a maximum lifetime of 12 years is available in a potential second life application, i.e. after 12 years of second use the BESS reaches the EoL even if its energy capacity is not below the 60% of its initial nominal capacity.

The energy simulation is carried out for each of the following scenarios, differing for the number of batteries simulated being deployed in the building at the same time.

The configurations, corresponding to the employment of a number of retired batteries ranging from 1 (Configuration 1 – C1) to 10 (Configuration 10 – C10), are illustrated in Table 5.

Table 5. Energy storage capacity of each examined configuration.

Parameters	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Installed energy capacity [kWh]	9	19	28	37	46	56	65	74	83	93
Numbers of retired EV batteries employed	1	2	3	4	5	6	7	8	9	10

4.2 Step 2: evaluation of load matching and grid interaction indicators

To quantify the load-matching levels for the case study, the load cover factor (γ_{load}) index, defined in [44] was used. It represents the percentage of the electrical demand covered by on-site electricity generation and was calculated as in Equation 4:

$$\gamma_{load} = \frac{\int_{t1}^{t2} min[g(t) - S(t) - \xi(t), l(t)]dt}{\int_{t1}^{t2} l(t)dt} \tag{4}$$

where g(t) is the on-site generation (kW), S(t) is the storage balance (kW), ξ(t) are losses (kW), l(t) is the building load (kW), *t* is the time, τ_1 and τ_2 are the start and the end of the evaluation period, respectively.

Moreover, to quantify the energy exchange between the building and the electrical grid to which it is connected, the net exported electricity (kWh), ne, was calculated as in (5):

$$\mathrm{ne} = \int_{t1}^{t2} \mathrm{e(t)dt} - \int_{ti}^{t2} \mathrm{i(t)dt} \tag{5}$$

where e(t) and i(t) are the mean exported power (kW) and mean imported power (kW).

4.3 Step 3: LCA methodology – modelling and assumptions

The goal of the LCA is to estimate, for each configuration examined, the potential life cycle energy and environmental impacts connected to the PV – BESS – electrical grid system and to assess the contribution of each system component to the whole life cycle impacts.

The authors applied an attributional LCA approach according to the international standards of series ISO 14040 [25,26]. The functional unit (FU), selected as reference for the LCA, is the electricity required by the building in a time scale of 12 years. As previously explained, this time scale is selected considering a maximum service life of 20 years for the battery (first and second life), a service life in the EV of about 8 years and a potential maximum residual lifetime[4] of about 12 years for a less demanding stationary application [32,45].

The reference flow includes all components that provide the function described by the FU:

1. the PV – system installed in the LH, described in Section 3;
2. the BESS, described in Section 3;
3. the electrical grid.

The energy and environmental impacts associated to each component of the energy system are assessed following a "from cradle to consumer" approach.

The selection of the impact categories has been mainly based on the European Product Environmental Footprint (PEF) [46], as it provides a wide set of environmental indicators consistent with the sustainability objective of avoiding burden-shifting among impact categories [47]. Since the high relevance of the energy consumption in the evaluation of the studied system, the PEF categories have been complemented by the Cumulative Energy Demand (CED) method for the energy impacts estimation [48]. Moreover, according to Bobba et al. [49] and Latunussa et al. [50], the land use and the water resource depletion impact categories have been excluded, even if they are part of the PEF categories, due to the low availability and high uncertainty of life cycle inventory data. In order to avoid overlapping with the CED impact category, the Abiotic Depletion Potential (ADP) has been calculated only for the mineral resources.

The environmental impact categories investigated are listed in the following:

- Cumulative energy demand (CED) (MJ);
- Abiotic depletion potential (ADP) ($kgSb_{eq}$);
- Global warming potential (GWP) ($kgCO_{2eq}$);
- Ozone depletion potential (ODP) ($kgCFC\text{-}11_{eq}$);
- Human toxicity, non-cancer effects (HT-nce) (CTUh);
- Human toxicity, cancer effects (HT-ce) (CTUh);

[4] The residual lifetime depends on both batteries applications in first and second uses.

- Particulate matter (PM) (kgPM2.5$_{eq}$);
- Ionizing radiation – human health (IR-hh) (kBqU$^{235}_{eq}$);
- Photochemical ozone formation potential (POFP) (kgNMVOC$_{eq}$);
- Acidification potential (AP) (molcH$^{+}_{eq}$);
- Terrestrial eutrophication (EU$_T$) (molN$_{eq}$);
- Freshwater eutrophication (EU$_F$) (kgP$_{eq}$);
- Marine eutrophication (EU$_M$) (kgN$_{eq}$);
- Freshwater ecotoxicity (EF$_w$) (CTUe).

For each energy system component, the most relevant modelling assumptions and data needed are included in the following. The eco – profiles of materials and energy sources used to produce the battery components were based on Ecoinvent 3 database [51].

PV system

The life cycle energy and environmental impacts for this component are calculated as:

$$I_{PVsystem,i} = El_{PV \rightarrow BL} \cdot i_{PV,i} \quad (6)$$

where

$I_{PVsystem,i}$ = overall impact on impact category "i" associated to the electricity produced by the PV system and directly consumed in the building. This impact includes the PV manufacturing and EoL disposal [unit[5]].

$El_{PV \rightarrow BL}$ = PV electricity generated on-site and directly consumed by the building [kWh].

$i_{PV,i}$ = specific impact on the impact category "i" of electricity generated by the PV system in each examined impact category. The impact related to battery production and EoL disposal is quantified per kWh of electricity generated [unit/kWh]

i = examined impact category.

BESS

The BESS accounts for the energy and environmental impacts associated to the EV battery pack production, to the preparation of the battery pack for reuse (repurposing), to the battery pack EoL treatment, to the electricity produced by the PV system and provided to the building through the BESS and to the electricity loss due to the battery efficiency.

The battery production and the battery EoL are modelled according to Cusenza et al. [52], in which the life cycle inventory for battery production is obtained by combining primary data from laboratory test and secondary data from literature. About the end-of-life, Cusenza et al. [52] assumed that the battery components were dismantled and treated for recycling; the battery cell recycling was modelled according to recent Product Environmental Footprint Category

[5] Unit: unit of measure of each investigated impact category.

Rules on rechargeable batteries [53] while the recycling of the other battery components was modelled through processes specifically created for the examined battery pack.

As the EV traction battery provided two functions, one in the EV and another in the stationary energy storage system, a multi-functionality [54] problem occurs and the energy and environmental impacts of the battery manufacturing and EoL affect both the first and the second application [22]. It was assumed that both the impacts related to the recycling and the environmental credits were entirely attributed to the battery. In order to quantify the impacts of the battery manufacturing and EoL treatment for each function, the authors chose the allocation approach. In detail, the authors allocated the impacts between the co-functions considering a quality – based allocation factor, calculated considering the electricity delivered during the first life in the EV and the electricity delivered during the second life in the building.

The electricity needed to provide the first function (El_{EV}) is calculated as:

$$El_{EV} = D_{dr} \cdot El_{drm} \cdot CEl_{drm}$$

where:

D_{dr} = kilometres driven during the first life (km);

El_{drm} = kilometres driven in electric mode (%);

CEl_{drm} = electricity delivered by the EV traction battery per km driven in “electric mode” (kWh/km).

The El_{EV} was equal to 26,280 kWh.

The electricity delivered during the stationary second life application, $El_{BESS \rightarrow Bl}$, was calculated through the energy balance model described in Section 4.1.

The allocation factor for the second life application (α_{fII}) was calculated for each configuration as in Equation 7:

$$\alpha_{fII} = \frac{El_{BESS \rightarrow Bl}}{(El_{EV} + El_{BESS \rightarrow Bl})} \quad (7)$$

According to Richa et al. [32] and to Bobba et al. [22], for allocating impacts of EV battery manufacturing and EoL treatments, only the component considered for reuse (i.e. battery cells, BMS, cooling system and module casing) are accounted for in the paper. The impacts of the components recycled or landfilled after the first service life (i.e. battery casing) are not allocated to the second service life.

The life cycle energy and environmental impacts of the battery production and recycling and potential benefits related to material recycling (in terms of “avoided primary materials”) attributable to the stationary second life application are calculated as in Equations 8, 9 and 10:

$$I_{BP,i^*} = a_{fII} \cdot n_B \cdot i_{BP,i} \quad (8)$$

$$I_{BR,i^*} = a_{fII} \cdot n_B \cdot i_{BR,i} \quad (9)$$

$$EC_{BR,i^*} = a_{fII} \cdot n_B \cdot ec_{BR,i} \quad (10)$$

where:

$I_{BP,i}^{*}$ = overall impact on the impact category "i" of the battery manufacturing, allocated to the stationary second life application [unit];

$I_{BR,i}^{*}$ = overall impact on the impact category "i" of the battery recycling, allocated to the stationary second life application [unit];

$EC_{BR,i,j}^{*}$ = overall environmental credit on the impact category "i" related to the avoided primary materials [unit];

n_B = number of batteries employed in the examined configuration;

$i_{BP,i}$ = specific impact on the impact category "i" of the battery manufacturing process [unit/kWh] [52];

$i_{BR,i}$ = specific impact on the impact category "i" of the battery recycling process [unit/kWh] [52];

$ec_{BR,I}$ = specific environmental credit on the impact category "i" related to the avoided primary materials [unit/kWh] [52].

The impacts due to the repurposing (I_{BRep}) phase are modelled according to Bobba et al. [22]. The repurposing phase involves:

- battery pack disassembly up to modules as a deeper disassembly is not technically/economically feasible [55] [33]. A manually disassembly of the battery pack is assumed. No impacts are considered for the battery disassembling process;
- energy consumption for battery testing to evaluate the state of the battery pack [55] (electricity consumption for 1 cycle of charge/discharge);
- manufacture of new casing for the battery pack in order to guarantee safety conditions.

The impacts related to the manufacture and EoL of casing are fully allocated to the second life application.

The life cycle energy and environmental impacts related to the repurposing phase are calculated with the following Equation 11:

$$I_{BRep,i} = n_B \cdot i_{BRep,i} \quad (11)$$

where:

$I_{BRep,i}$ = overall impact on the impact category "i" of the battery repurposing phase [unit];

$I_{BRep,i}$ = specif impact on the impact category "i" of the battery repurposing phase [unit/kWh] [22].

The electricity produced by the PV and provided to the building through the BESS and electricity loss due to battery efficiency are calculate as explained in Section 4.1; the impacts associated are calculated with the following Equations 12 and 13, respectively:

$$I_{El_{BESS\rightarrow Bl},i} = El_{BESS\rightarrow BL} \cdot i_{PV,i} \quad (12)$$

$$I_{El_{\eta loss},i} = El_{\eta loss} \cdot i_{PV,i} \quad (13)$$

Electrical grid

The electrical grid includes the environmental impacts associated to the electricity imported from the national electrical grid. The imported electricity was calculated as explained in Section 4.1. The impacts for this component are calculated as:

$$I_{Elgrid,i} = El_{grid \rightarrow BL} \cdot i_{Elgrid,i} \quad (14)$$

where:

$I_{Elgrid,i}$ = overall impact on the impact category "i" associated to the electricity imported from the national electrical grid [unit];

$El_{grid \rightarrow BL}$ = amount of electricity imported from the national electrical grid [kWh];

$i_{Elgrid,i}$ = specific impact on the impact category "i" associated to the electricity imported from the national electrical grid [unit/kWh].

Finally, the potential benefits related to the PV electricity fed into the grid (in terms of "avoided electricity from the grid") are calculated as in Equation 15:

$$EC_{EL_{PV \rightarrow grid,i}} = -\left(El_{PV \rightarrow grid} \cdot i_{Elgrid,i}\right) \quad (15)$$

where:

$EC_{EL_{PV \rightarrow grid,i}}$ = overall environmental credit on the impact category "i" related to the avoided electricity taken from the national electrical grid;

$i_{Elgrid,i}$ = specific environmental impact on the impact category "i" of the electricity imported from the national electrical grid [51].

4.4 Step 4: Identification of the best design solution/s

In this step, the main outcomes obtained in the steps 2 and 3 are integrated to identify the most efficient design solution/s for the BESS in terms of load match and environmental sustainability.

5 Results and discussion

5.1 PV – BESS – electrical grid system balance, load match and net exported

The energy simulation of the PV – BESS – Electrical grid system is performed for each configuration (from C1 to C10). In configurations 1 (9 kWh), 2 (19 kWh) and 3 (28 kWh) the BESS is not able to perform its function for the entire period analysed and a BESS replacement during the examined time - frame is required. Starting from C4 (37 kWh), the BESS is not replaced. In fact, in C1, C2 and C3 the lower energy capacity installed causes a fast degradation of the BESS. In C1, four batteries are used to cover the time frame. Each battery works for 3 years before reaching the EoL. In configurations C2 and C3 the increased installed capacity allowed a lower stress for the BESS compared with C1 and a slightly energy capacity degradation resulted in an increased BESS lifetime. The yearly energy capacity degradation trend corresponding to the configurations 1, 2 and 3 is reported in Fig. 3, where the line with higher slope represents the battery capacity degradation in C1.

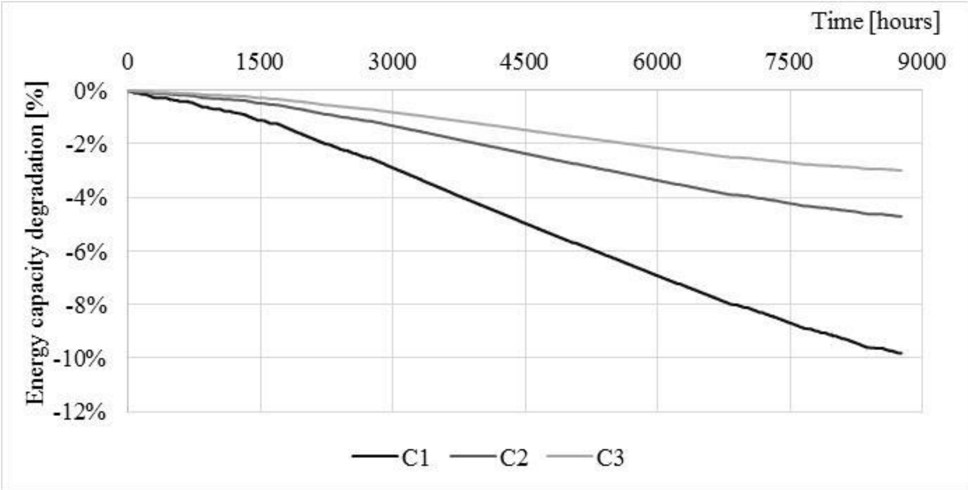

Fig. 3. Energy capacity degradation trend corresponding to a different installed BESS capacity.

In C2, the BESS reaches the EoL after six years, with four batteries being used, two for the first six years and two more for the following six years. In C3, the installed BESS worked for a lifetime of ten years before reaching the EoL. Then, after ten years a new BESS is installed with the same energy capacity (corresponding to the employment of 3 EV batteries). The new BESS has the same degradation pattern and then the same service life (10 years). However, only the first two years are analysed in order to cover the examined timeframe of 12 years. The BESS lifetime and the number of replacement required in each examined configuration are recapped in Table 6. The installation of a higher energy storage capacity allows for a longer battery lifetime.

Table 6. BESS lifetime and number of replacement in the configurations examined.

Parameters	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
Energy capacity of the BESS [kWh]	9	19	28	37	46	56	65	74	83	93
BESS lifetime [years]	3	6	10	12	12	12	12	12	12	12
Number of battery replacement [-]	3	1	1	0	0	0	0	0	0	0

The energy analysis of the PV – BESS – electrical grid system highlights that the installation of an increasing energy storage capacity allows to increase the consumption of the electricity locally produced by PV and, consequently, to reduce the electricity imported from the grid. In particular, the last decrease of a percentage ranging from 12% (C1) to 53% (C10) with respect to the scenario without BESS.

Fig. 4 shows the coloured contour graphs of the γ_{load} (A) and ne (B) for the scenario without BESS (C0). The x-axis reports the hours of the day (24) and the y-axis indicates the days of the year (1-365). In Fig. 4, the bars on the left associate the colours in the graph with the values assumed by the indicators in the whole period examined.

As shown in Fig. 4 – A the instantaneous γ_{load} strictly follows the on-site PV generation. In particular, it reaches the value of 1 during the day as PV generation reaches its peak, decreases during low solar radiation hours while during the night it is equal to zero. The yearly mean value of γ_{load} is equal to 0.37. The analysis of Fig. 4 – B highlights that also the *ne* indicator follows the on – site PV generation. The ne was higher than zero (export > import) when the PV generation reaches its peak and lower during the night.

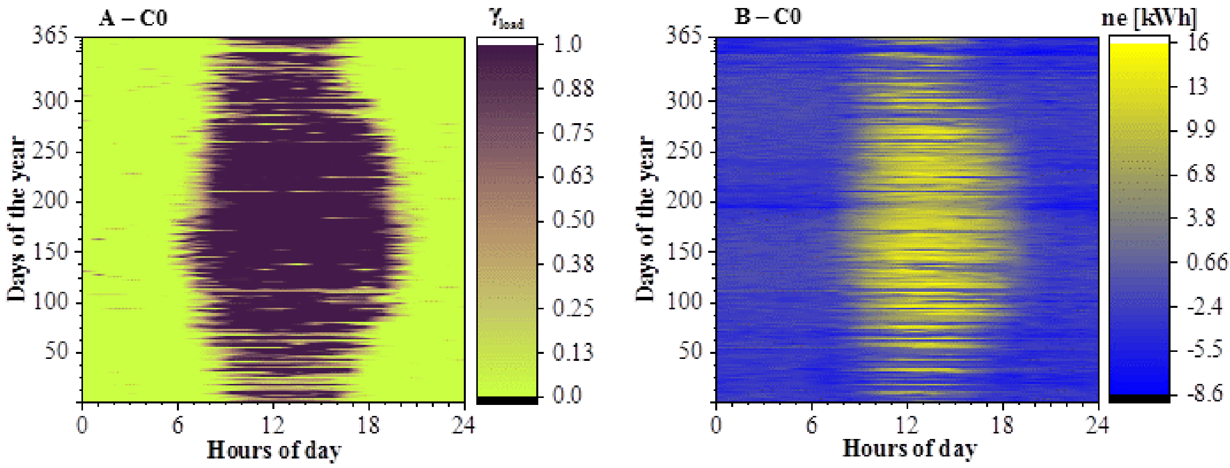

Fig. 4. Coloured contour graph of the γ_{load} (A) and ne (B) for the first year in the C0.

Fig. 5 and Fig. 6 show, respectively, the coloured contour graph of the γ_{load} and ne corresponding to the configurations 1, 2, 3, 4, 5 and 10, taken as example, since the other configurations would report similar results.

The installation of a 9 kWh BESS (C1) allows to increase the self-consumption of the building examined. However, also in this configuration, the γ_{load} follows the on-site PV generation for the most part of the year. In C2 the electricity stored in the BESS during periods with high PV generation and low load is able to supply electricity during the night for the greatest part of the year and in the summer season during the early morning hours. Starting from C5, the γ_{load} is equal to or close to 1 for a large part of the day during the whole year. The analysis of the coloured contour graph of the γ_{load} shows that starting from C5 (46 kWh) any further increase in the storage energy capacity would yield only limited benefit.

With reference to the *ne* indicator, the analysis highlights that the amount of electricity exported into the grid is reduced as the BESS size increases, as it was able to store a larger amount of electricity. Also for the *ne* indicator, the improvement became negligible as the BESS energy capacity reaches the threshold of 46 kWh.

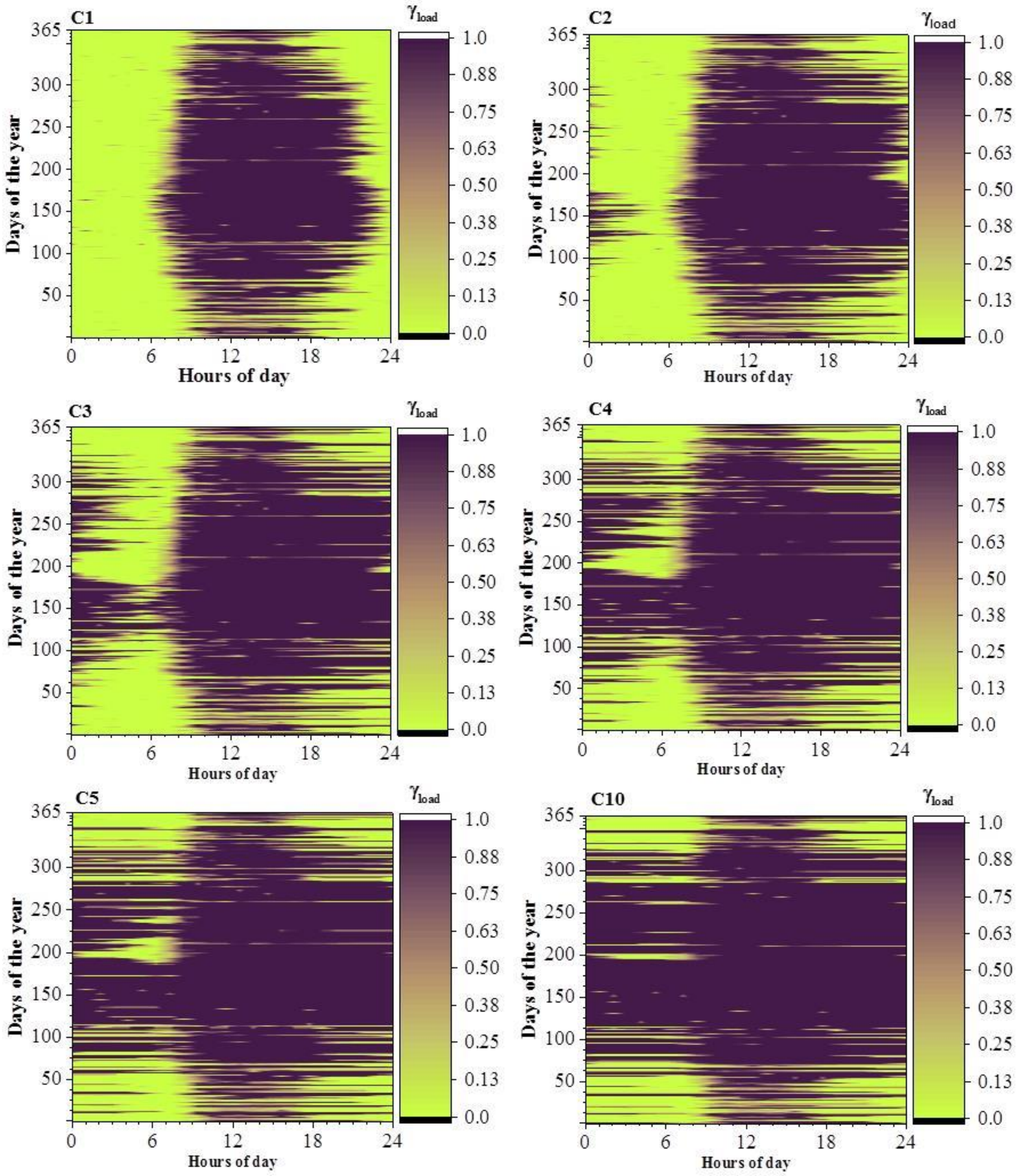

Fig. 5. Coloured contour graph of the γ_{load} for the first year of each investigated scenario.

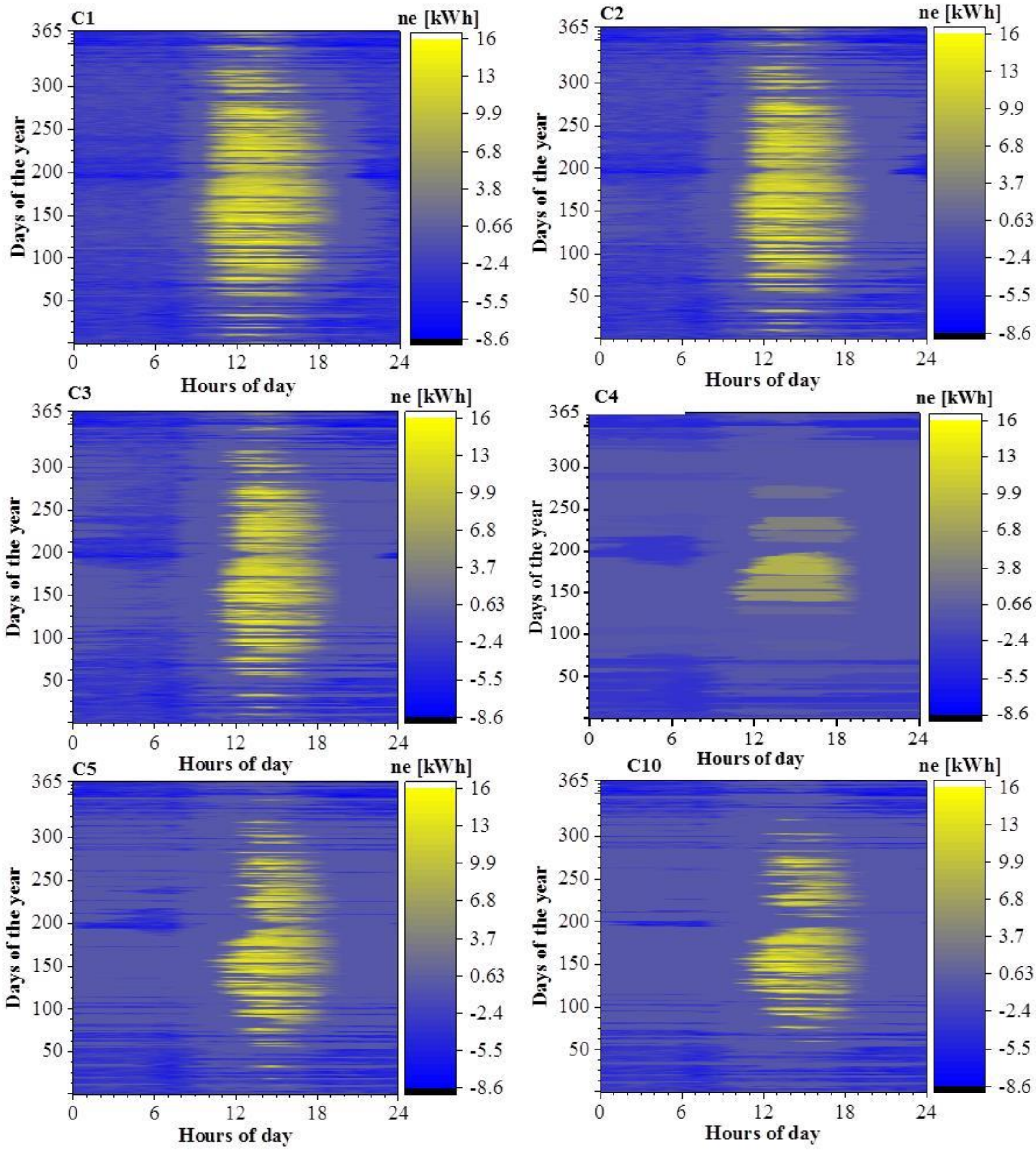

Fig. 6. Coloured contour graph of the *ne* for the first year of each investigated scenario.

The results of Fig. 5 are also following in Table 7, which recaps the first (γ_{Q1}), the second (γ_{Q2}) and the third (γ_{Q3}) quartile and the minimum (γ_{Min}) and maximum (γ_{Max}) values of the hourly γ_{load} values averaged on annual basis, over the whole examined period (12 years). The γ_{load} grows together with the storage but after reaching the storage threshold of 46 kWh (corresponding to 5 retired EV batteries), the effect of the storage on the γ_{load} is very limited [9].

The numerical results of the PV – BESS – electrical grid system simulation are illustrated in Table 8. The $El_{PV \rightarrow BL}$ is the same in all the examined configurations since this amount of electricity is not affected by the BESS. The $El_{BESS \rightarrow BL}$ increases with the BESS size. The $El_{grid \rightarrow BL}$ and the $EL_{PV \rightarrow grid}$ decreases, respectively, by 54% and 63% compared with scenario without BESS.

Table 7. Load match indicators - γ_{Q1}, γ_{Q2} and γ_{Q3} and the γ_{Max} and γ_{Min} values of the hourly γ_{load} values averaged on annual basis, over the whole examined period.

Statistic parameters	Installed energy capacity [kWh]									
	9	19	28	37	46	56	65	74	83	93
γ_{Max}	0.454	0.533	0.616	0.680	0.715	0.734	0.745	0.752	0.757	0.762
γ_{Q3}	0.450	0.523	0.600	0.667	0.707	0.728	0.740	0.747	0.752	0.757
γ_{Q2}	0.447	0.515	0.584	0.653	0.699	0.723	0.737	0.744	0.749	0.754
γ_{Q1}	0.443	0.506	0.569	0.639	0.692	0.719	0.733	0.742	0.746	0.752
γ_{Min}	0.440	0.498	0.554	0.624	0.683	0.713	0.730	0.739	0.743	0.749

Table 8. PV – BESS – electrical grid system energy simulation results.

Parameters	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
$El_{PV\rightarrow BL}$ [kWh]	99,582	99,582	99,582	99,582	99,582	99,582	99,582	99,582	99,582	99,582	99,582
$El_{BESS\rightarrow BL}$ [kWh]	-	23,240	43,820	63,002	78,613	91,517	99,051	103,348	105,764	107,482	108,955
$El_{\eta loss}$ [kWh]	-	1555	3579	5980	8929	10,483	11,391	11,909	12,194	12,393	12,564
$El_{grid\rightarrow BL}$ [kWh]	201,140	177,901	157,320	138,139	122,527	109,624	102,089	97,792	95,377	93,658	92,185
$EL_{PV\rightarrow grid}$ [kWh]	194,197	169,428	146,831	125,258	106,683	92,234	83,801	78,994	76,302	74,393	72,758

In order to strengthen the results of the simplified modelling proposed for the SoC, authors developed a comparison with the outputs of a more solid battery state of charge modelling tools available in literature for Li-Ion batteries. The model by Tremblay & Dessaint [56] – modifying a previous iteration of the Sheperd model for Li-Ion batteries – was used in the implementation of the RENEWIT green data centre library for TRNSYS (http://www.renewit-project.eu/green-data-centre-library/). Results have been compared throughout a year of simulation.

Since the Tremblay model does not account for the capacitance variation during the years, the simplified model outputs for the first year were used. This allowed to include very limited variations (below 3%) of the available capacitance due to ageing compared with the starting one.

Fig. **7** reports simulation data for ten consecutive days in December (thus with the lowest generation and highest consumption for heating) including state of charge according to the simplified model and the Sheperd/Tremblay model [56].

Although some differences between the two outputs exist, limited in specific hours that can reach up to 20% between the two models, they are deemed acceptable by authors.

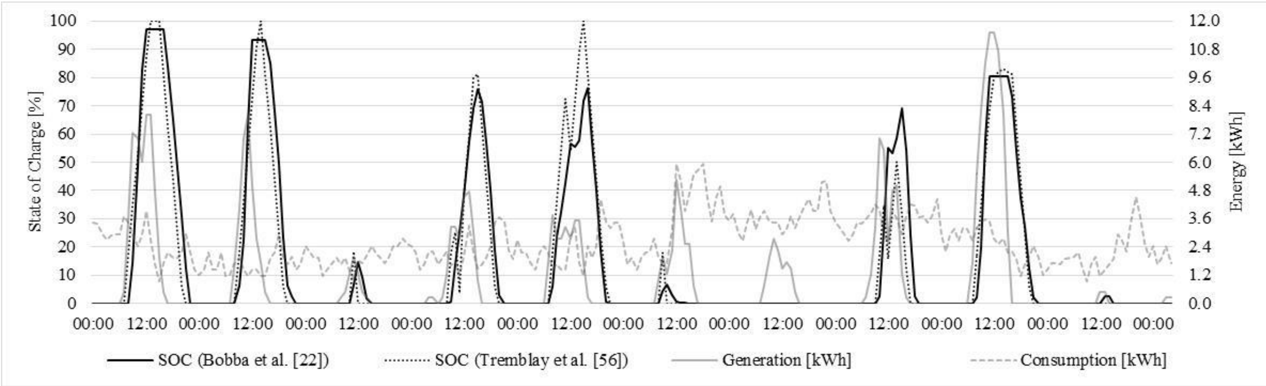

Fig. 7 Sample comparison between the simplified model proposed and Tremblay & Dessaint model [56].

Based on the results illustrated in Table 8 and the amount of electricity delivered by the EV batteries during the first life, the allocation factor for the second life application α_{fII} for each configuration is calculated, with the results being shown in Table 9. In C3, where the three-EV batteries are substituted once, there were 2 values of α_{fII}: the first one is referred to the battery group installed during the first year that worked for 10 years (C3 lifetime); the second one deal with the 3-EV batteries installed at the 11th year of the examined time-frame, in substitution to the first one. To take into account that three-EV batteries installed at the 11th year are used only for 2 years to cover the examined timeframe a specific α_{fII} is calculated.

Table 9. Allocation factor for the configurations examined

Parameters	**C1**	**C2**	**C3**		**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
α_{fII}	0.181	0.357	0.466	0.162	0.499	0.481	0.456	0.428	0.401	0.377	0.356

5.2 Life cycle impact assessment and interpretation

The life cycle impacts assessment (LCIA) results referred to the FU are illustrated in Table 10. The environmental credits for avoiding production of primary materials and avoided electricity from national grid were separated from the life cycle impacts according to the UNI EN 15978: 2011 standard [57].

The impacts related to the PV system are the same in all the examined configurations as the electricity generated on-site and directly consumed remained unchanged (Table 8). The installation of an increasing energy storage capacity caused an improvement of the energy system environmental performance in almost all the examined impact categories with the exception of the abiotic depletion potential, human toxicity – cancer and no cancer effect and freshwater ecotoxicity. In general, the reduction of the electricity imported from the grid, due to the increasing size of the energy storage capacity, is mainly responsible for the impacts reduction. However, in general the environmental benefits are partially offset by the increasing impacts associated to the production and recycling of larger BESS and to the electricity loss due to the battery efficiency, and, for some impact categories, also by the increasing consumption of the PV electricity generated on-site.

The impact categories can be grouped in three clusters depending on three different trends traceable with the increasing installed capacity in order to generalize the results and draw some more general results.

The first cluster, composed of the global warming potential, ozone depletion potential and ionizing radiation, shows a continuous decrease from C1 to C10. In detail, they decreased on average of 30% in C10 compared with C1. However, the marginal benefits obtainable within the scenarios become negligible (lower than 3%) past the threshold of 46 kWh of installed capacity (C5). The reduction in these impact categories is mainly due to the increase of the consumption of on-site PV electricity generation and, consequently, to the corresponding decrease of the electricity imported from the electrical grid. The increase in impacts due to battery production, recycling and repurposing caused by a growing installed capacity has not enough relative weight to offset the obtained environmental improvements.

The second cluster, composed by the abiotic depletion potential, human toxicity – cancer effect and no cancer effect and freshwater ecotoxicity, shows an increasing trend from configuration 1 to 10. In these cases, the increase of the impacts is mainly due to the increased share of the electricity generated from the PV plant in building load supply but also to the EV batteries production and recycling. These impacts surpassed the benefits arose by the reduced electricity imported from the electrical grid. In detail, the impact on the abiotic depletion potential increases by 82% in C10 compared to C1; the impact on human toxicity – cancer effect and no cancer effect by 14% and 30%, respectively; finally, freshwater ecotoxicity increases by 6.7%.

Table 10. Life cycle environmental impacts – referred to the FU (electricity required by the building in a time scale of 12 years).

	C1		C2		C3		C4		C5	
Impact categories	**Life cycle impacts**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***
CED (MJ)	2.236E+06	-67.7	-2.1	-60.0	-4.6	-52.6	-6.1	-45.6	-7.4	-40.1
ADP ($kgSb_{eq}$)	5.128E-01	-24.1	19.5	-18.9	31.9	-15.4	44.4	-12.8	56.4	-11.2
GWP ($kgCO_{2eq}$)	1.017E+05	-85.4	-7.5	-80.1	-15.2	-74.6	-21.1	-68.5	-25.7	-63.1
ODP ($kgCFC\text{-}11_{eq}$)	1.154E-02	-82.0	-6.5	-76.1	-13.2	-70.0	-18.3	-63.5	-22.4	-57.8
HT-ce (CTUh)	2.642E-02	-52.4	6.8	-43.7	9.8	-36.9	13.8	-31.3	18.2	-27.1
HT-nce (CTUh)	4.887E-03	-64.8	2.1	-56.2	1.0	-49.1	1.9	-42.7	4.0	-37.8
PM (kg $PM2.5_{eq}$)	4.452E+01	-71.6	-1.8	-63.8	-5.1	-56.7	-7.0	-49.7	-8.0	-44.1
IR-hh ($kBqU^{235}{}_{eq}$)	1.414E+04	-86.5	-7.0	-80.8	-14.9	-75.3	-20.8	-69.1	-25.2	-63.4
POFP ($kgNMVOC_{eq}$)	2.248E+02	-78.9	-4.8	-72.2	-10.4	-65.7	-14.5	-58.9	-17.4	-53.1
AP ($molH^{+}{}_{eq}$)	5.471E+02	-80.7	-4.8	-74.2	-10.7	-67.9	-15.0	-61.3	-18.0	-55.7
EUT ($molN_{eq}$)	7.120E+02	-80.3	-5.2	-73.8	-11.3	-67.5	-15.6	-60.8	-18.9	-55.0
EUF (kgP_{eq})	3.509E+01	-69.5	-0.2	-61.1	-2.7	-53.8	-3.7	-46.8	-3.8	-41.2
EUM (kgN_{eq})	7.358E+01	-77.9	-2.0	-70.6	-6.5	-64.2	-9.1	-57.6	-10.4	-52.2
EFw (CTUe)	2.863E+06	-60.2	1.4	-51.8	1.4	-44.3	2.2	-37.7	3.1	-32.6

	C6		C7		C8		C9		C10	
Impact categories	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***	**Life cycle impacts** ****** **(%)**	**Environmental credits (%)***
CED (MJ)	-7.9	-36.7	-8.1	-34.8	-8.0	-33.6	-7.9	-32.8	-7.8	-32.1
ADP ($kgSb_{eq}$)	64.8	-10.4	70.8	-10.1	75.2	-9.9	78.8	-9.8	82.0	-9.8
GWP ($kgCO_{2eq}$)	-28.2	-59.5	-29.5	-57.2	-30.0	-55.8	-30.3	-54.7	-30.6	-53.8
ODP ($kgCFC\text{-}11_{eq}$)	-24.6	-54.2	-25.7	-51.9	-26.2	-50.6	-26.5	-49.5	-26.7	-48.7
HT-ce (CTUh)	21.5	-24.9	24.1	-23.6	26.3	-23.0	28.1	-22.5	29.8	-22.2
HT-nce (CTUh)	6.3	-35.0	8.5	-33.6	10.6	-32.8	12.5	-32.4	14.4	-32.0
PM (kg $PM2.5_{eq}$)	-8.2	-40.7	-7.9	-38.7	-7.4	-37.5	-6.9	-36.6	-6.4	-35.9
IR-hh ($kBqU^{235}{}_{eq}$)	-27.5	-59.6	-28.5	-57.1	-28.9	-55.5	-29.0	-54.3	-29.1	-53.2
POFP ($kgNMVOC_{eq}$)	-18.8	-49.5	-19.4	-47.2	-19.4	-45.9	-19.3	-44.9	-19.2	-44.0
AP ($molH^{+}{}_{eq}$)	-19.4	-52.1	-19.9	-49.9	-19.9	-48.6	-19.7	-47.6	-19.6	-46.8
EUT ($molN_{eq}$)	-20.4	-51.3	-21.1	-49.0	-21.2	-47.7	-21.1	-46.6	-21.0	-45.7
EUF (kgP_{eq})	-3.3	-37.8	-2.5	-35.8	-1.7	-34.6	-0.8	-33.7	-0.1	-33.0
EUM (kgN_{eq})	-10.6	-48.9	-10.1	-46.9	-9.4	-45.7	-8.6	-44.8	-7.9	-44.1
EFw (CTUe)	4.0	-29.7	4.8	-27.9	5.5	-27.0	6.1	-26.3	6.7	-25.7

*Expressed as percentage of the "Life cycle impacts" including the impacts associated to the "PV system", "BESS" and "Electrical grid"; **Expressed as a percentage variation with respect to the previous configuration.

A detailed analysis of each environmental category belonging to the second cluster highlights that the impact on the abiotic depletion potential shows a negligible increase after the threshold of 46 kWh (C5). In fact, although, the configurations from C6 to C10 involve the use of a growing number of repurposed EV batteries, a reduced share of the impacts related to the battery production and recycling is allocated to the second life application because the α_{fII} (Table 9) decrease starting from C5. The increases in the human toxicity cancer and no-cancer effect and in the freshwater ecotoxicity are negligible starting from C3.

Finally, the third cluster of impact categories presents a mixed trend. The impacts on global energy requirement and acidification potential decrease until C7 (65 kWh of installed capacity); those on particulate matter and marine eutrophication until C6 (56 kWh of installed capacity); those on photochemical ozone formation and terrestrial eutrophication until C8 (74 kWh of installed capacity); those on freshwater eutrophication until C5 (46 kWh of installed capacity). After these values of capacity installed the impact increased: for these specifics values of energy capacity the impact reduction due to the lower electricity import is offset by the increasing contribution of the batteries life-cycle (manufacturing, recycling and repurposing).

The environmental credits arising from the potential production of secondary raw materials from the recycling process are negligible, being in each configuration, a percentage lower than 3% of the life cycle impact in all the environmental categories.

The environmental credits related to the avoided electricity from the grid are particularly relevant in impact categories such as global warming potential, ozone depletion potential, acidification potential, ionizing radiation in which the electricity from national grid presents a significant impact compared to the electricity from PV. These environmental credits are higher for the configurations with a lower BESS size since the electricity fed into the grid is higher Table 8.

The contribution of each component (PV + BESS + electrical grid) of the energy system examined to the total impacts in all the examined configurations is following, respectively, in Table 11, Table 12 and Table 13.

The results show that the contribution of the PV system remains unchanged in all the configurations examined in almost all the impact categories with the exception of the abiotic depletion potential and human toxicity – cancer effect. The contribution of the BESS increased in all the impact categories in all the examined configurations due to the increased impacts related to battery production and EoL treatment and to the higher electricity provided to the building through the BESS. Consequently, the contribution to the total impacts of the electrical grid decreases in all the examined impact categories and configurations due to the reduced import of electricity from the grid.

Table 11. Life cycle environmental impacts – contribution of the PV system.

Impact categories	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)	C6 (%)	C7 (%)	C8 (%)	C9 (%)	C10 (%)
CED	22.1	22.6	23.2	23.6	23.9	24.0	24.1	24.1	24.1	24.0
ADP	52.3	43.8	39.7	36.2	33.5	31.7	30.6	29.9	29.3	28.8
GWP	7.1	7.7	8.4	9.0	9.6	9.9	10.1	10.2	10.2	10.2
ODP	10.1	10.8	11.6	12.4	13.0	13.4	13.6	13.7	13.7	13.8
HT-nce	32.0	30.0	29.1	28.1	27.1	26.3	25.8	25.4	25.0	24.7
HT-ce	21.3	20.9	21.1	21.0	20.5	20.1	19.7	19.3	19.0	18.7
PM	17.7	18.0	18.6	19.0	19.2	19.3	19.2	19.1	19.0	18.9
IR-hh	5.5	5.9	6.4	6.9	7.3	7.5	7.6	7.7	7.7	7.7
POFP	12.0	12.6	13.4	14.1	14.6	14.8	14.9	14.9	14.9	14.9
AP	10.4	11.0	11.7	12.3	12.7	13.0	13.0	13.0	13.0	13.0
EU_T	10.8	11.4	12.2	12.9	13.4	13.6	13.7	13.8	13.7	13.7
EU_F	18.6	18.6	19.1	19.3	19.3	19.2	19.1	18.9	18.8	18.6
EU_M	11.8	12.1	12.6	13.0	13.2	13.2	13.1	13.0	12.9	12.8
E_{fw}	27.6	27.2	27.2	27.0	26.7	26.5	26.3	26.1	26.0	25.8

Table 12. Life cycle environmental impacts – contribution of the BESS.

Impact categories	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)	C6 (%)	C7 (%)	C8 (%)	C9 (%)	C10 (%)
CED	6.9	13.3	19.1	24.4	28.9	31.7	33.5	34.6	35.4	36.1
ADP	24.2	38.9	46.5	52.6	57.3	60.1	61.8	62.9	63.8	64.6
GWP	3.4	6.8	9.7	12.9	16.2	18.6	20.2	21.3	22.2	23.0
ODP	3.9	7.8	11.4	15.1	18.7	21.2	22.8	23.8	24.7	25.4
HT-nce	14.8	26.0	33.3	39.7	45.2	48.6	50.7	52.1	53.2	54.1
HT-ce	14.0	23.1	29.2	35.4	41.2	45.0	47.6	49.4	50.8	52.1
PM	8.0	15.0	20.5	25.9	31.0	34.3	36.4	37.9	39.0	40.0
IR-hh	3.9	7.9	10.9	14.3	18.0	20.7	22.6	24.0	25.1	26.1
POFP	5.6	10.8	15.1	19.6	24.0	26.9	28.9	30.3	31.3	32.3
AP	5.6	11.0	15.2	19.7	24.2	27.3	29.4	30.8	31.9	32.9
EU_T	5.3	10.3	14.4	18.6	22.9	25.9	27.8	29.2	30.3	31.2
EU_F	9.3	17.4	23.3	29.1	34.5	38.0	40.2	41.8	42.9	44.0
EU_M	8.1	15.7	20.9	26.3	31.7	35.4	37.9	39.6	41.0	42.1
E_{fw}	9.6	18.1	24.8	30.7	35.8	38.9	40.8	42.0	42.9	43.7

Table 13. Life cycle environmental impacts – contribution of the electrical grid.

Impact categories	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)	C6 (%)	C7 (%)	C8 (%)	C9 (%)	C10 (%)
CED	70.9	64.1	57.7	52.1	47.2	44.2	42.4	41.4	40.6	39.9
ADP	23.4	17.3	13.8	11.2	9.2	8.2	7.5	7.2	6.9	6.7
GWP	89.5	85.5	81.9	78.1	74.2	71.5	69.7	68.5	67.6	66.8
ODP	86.0	81.4	77.0	72.5	68.3	65.5	63.6	62.5	61.6	60.8
HT-nce	53.1	44.0	37.6	32.2	27.7	25.1	23.5	22.6	21.8	21.2
HT-ce	64.6	56.0	49.7	43.7	38.3	34.9	32.8	31.3	30.2	29.3
PM	74.3	67.0	60.8	55.1	49.8	46.5	44.4	43.1	42.0	41.2
IR-hh	90.7	86.2	82.7	78.8	74.7	71.8	69.7	68.3	67.2	66.2
POFP	82.4	76.5	71.4	66.3	61.5	58.2	56.2	54.8	53.8	52.8
AP	84.0	78.0	73.1	68.0	63.1	59.8	57.6	56.2	55.1	54.1
EU_T	83.9	78.3	73.4	68.5	63.7	60.5	58.4	57.1	56.0	55.1
EU_F	72.1	63.9	57.5	51.6	46.2	42.8	40.7	39.3	38.3	37.4
EU_M	80.1	72.2	66.5	60.7	55.1	51.4	49.0	47.4	46.1	45.0
E_{fw}	62.8	54.7	48.0	42.3	37.5	34.6	32.9	31.9	31.1	30.5

The detailed contribution analysis of the BESS components highlights that the battery production phase accounts in average for 30% of the BESS impacts in all environmental impact categories investigated in each configuration. This outcome confirms that this phase is highly impacting [52] and highlights the need to improve the sustainability of the battery production process in perspective of its key role towards low carbon transportation and buildings.

5.3 Identification of the best configuration/s in terms of load match and life cycle environmental impacts

According to the LCIA results, the impact categories can be grouped into three different clusters depending on their trend in correspondence of the increasing capacity. For each cluster, the different impact categories follow comparable trends with the increasing installed capacity. Thus, it is possible to examine each cluster by analysing only one impact category, assumed as representative.

Since all impacts categories within each cluster have comparable trends, for the first cluster, global warming potential is selected because of its relevance to society and policy [58]. For the second cluster, abiotic depletion potential is selected because of the relevance of natural resource availability to economic development and also because of increasing political interest in resource consumption [59,60]. For the third cluster, freshwater eutrophication is selected since this is the impacts category that presents the most variable trend with the increasing installed capacity within the third cluster.

Fig. 8 shows the comparison of γ_{load}, global warming potential, abiotic depletion potential and freshwater eutrophication with the installed capacity. The analysis highlighted that C5 could represent the best BESS size in terms of load matching and environmental sustainability for 3 reasons:

- The employment of an additional repurposed EV battery (C6) causes a negligible improvement of γ_{load} (+3.5%) and of the impact categories represented by global warming potential (-3.4%) respect to the previous configurations;
- Freshwater eutrophication shows a decrease until C5 and an increase starting from C6.
- C5 performs better than the previous configurations in 10 out of 14 environmental impact categories investigated. While, for example, configuration 7 performs better than C6 only in 7 out of 14.

Moreover, if a market for retired EV battery will develop in the future, also economic considerations will favour configurations with a lower number of batteries, less expensive.

In order to provide a quantification of the environmental sustainability of the configuration C5 identified through the integrated sizing procedure proposed, in Table 14 the percentage variations of the corresponding life cycle impacts (I_{C5}) with respect to those of the configuration without BESS (I_{C0}) are reported.

The data shows that the installation of a BESS made of retired EV batteries in support to the renewable energy technologies increases the environmental benefits arising by these technologies in residential buildings in almost all the impact categories examined, with the exception of abiotic depletion potential, human toxicity cancer and no-cancer effect and freshwater ecotoxicity.

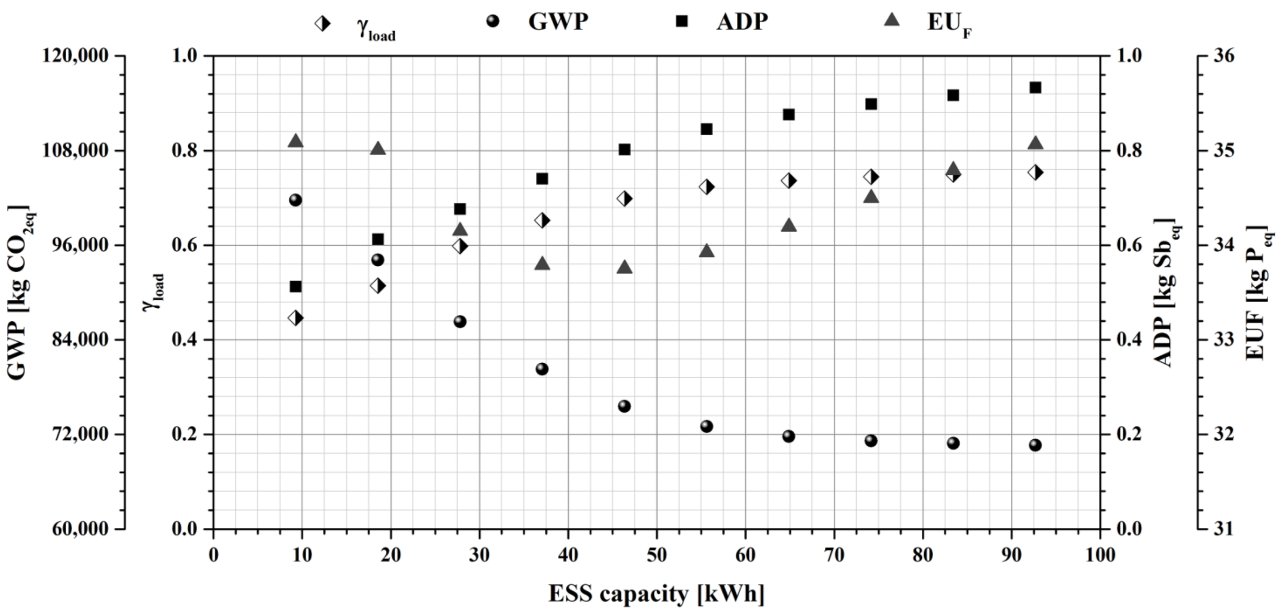

Fig. 8. Comparison of γ_{load}, global warming potential, abiotic depletion potential and freshwater eutrophication with the installed capacity.

Table 14. Percentage variation of the impact in C5 compared to C0.

Impact categories	I_{C0}	$(I_{C5}-I_{C0})/I_{C0}$ (%)
CED (MJ)	2.288E+06	-9.5
ADP ($kgSb_{eq}$)	4.043E-01	98.4
GWP ($kgCO_{2eq}$)	1.101E+05	-31.4
ODP ($kgCFC\text{-}11_{eq}$)	1.239E-02	-27.7
HT-nce (CTUh)	2.433E-02	28.3
HT-ce (CTUh)	4.614E-03	10.2
PM (kg $PM2.5_{eq}$)	4.529E+01	-9.6
IR-hh ($kBqU^{235}{}_{eq}$)	1.526E+04	-30.7
POFP ($kgNMVOC_{eq}$)	2.365E+02	-21.5
AP ($molH^{+}{}_{eq}$)	5.766E+02	-22.2
EUT ($molN_{eq}$)	7.525E+02	-23.2
EUF (kgP_{eq})	3.514E+01	-3.9
EUM (kgN_{eq})	7.529E+01	-12.5
EFw (CTUe)	2.822E+06	4.7

6 Conclusions

The growing waste battery flows expected from the automotive sector in the next years could be the response to the increasing demand of storage systems in buildings equipped with RESs, since at their second life these batteries could retain around 80% of their initial energy capacity.

In this framework, the authors examine an energy system made of retired batteries and used as storage for a PV system installed in a nZEB, also connected to the grid.

The study is carried out by combining the load match analysis for quantifying the load cover factor and the LCA methodology for assessing the life-cycle energy and environmental impacts of the system investigated.

The installation of different BESS size was analysed and the optimal energy capacity of the BESS is identified in order to find the best trade-off for reducing the mismatch in the building and the associated environmental impacts in a life cycle perspective. The environmental analysis performed through the LCA methodology highlights that the installation of the BESS allows to reduce the impact in almost all the environmental categories examined, with the exception of the abiotic depletion potential, human toxicity cancer and non-cancer effect and freshwater ecotoxicity. These are the impact categories mainly affected by the PV electricity generation and by battery production and EoL treatment. These results suggest that although the integration of storage systems allows the improvement of the environmental sustainability of the electricity supply in a residential building equipped with RESs in almost all the impact categories examined, it is necessary to improve the technologies currently available in order to obtain better performance in a wide range of environmental impact categories. In particular, it is relevant to improve the design of the PV system, in terms of resources efficiency and the chemical toxicity control and the battery production process in order to increase the environmental performance both in the automotive (first life application) and in the building sector (second life application).

Considering that RESs can play a key role in the decarbonisation of the building sector and that storage systems are needed to increase the reliability of the electricity supply, the approach proposed can be useful during the preliminary design of BESS made with retired EV batteries or with fresh batteries in buildings.

The study is an application of the principles of the circular economy and industrial symbiosis. Moreover, it contributes to the literature of the environmental analysis of the second life applications of retired EV batteries with one of the first study combining the load-match analysis with the LCA methodology.

References

[1] Eurostat, Statistics explained - Consumption of energy. ISSN 2443-8219, (2017). http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy (accessed July 12, 2018).

[2] Eurostat, Greenhouse gas emissions from transport, (2009). doi:tsdtr410.

[3] European Union, Directive (EU) 2018/ of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, Off. J. Eur. Union. 2018 (2018) 75–91.

[4] M. Beccali, M. Cellura, M. Mistretta, Environmental effects of energy policy in sicily: The role of renewable energy, Renew. Sustain. Energy Rev. (2007). doi:10.1016/j.rser.2005.02.001.

[5] M. Cellura, A. Di Gangi, S. Longo, A. Orioli, An Italian input-output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings, Energy Build. 62 (2013) 97–106. doi:10.1016/j.enbuild.2013.02.056.

[6] E. Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur. Union. (2010) 13–35. doi:doi:10.3000/17252555.L_2010.153.eng.

[7] EU, Directive (EU) 2018/ of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, Off. J. Eur. Union. 2018 (2018) 75–91.

[8] J.M. Santos, P.S. Moura, A.T. de Almeida, Technical and economic impact of residential electricity storage at local and grid level for Portugal, Appl. Energy. 128 (2014) 254–264. doi:10.1016/j.apenergy.2014.04.054.

[9] F. Guarino, P. Cassarà, S. Longo, M. Cellura, E. Ferro, Load match optimisation of a residential building case study: A cross-entropy based electricity storage sizing algorithm, Appl. Energy. 154 (2015) 380–391. doi:10.1016/j.apenergy.2015.04.116.

[10] F. Guarino, S. Longo, G. Tumminia, M. Cellura, M. Ferraro, Ventilative cooling application in Mediterranean buildings: impacts on grid interaction and load match, Int. J. Vent. (2017). doi:10.1080/14733315.2016.1214389.

[11] M. Ferraro, F. Sergi, V. Antonucci, F. Guarino, G. Tumminia, M. Cellura, Load match and grid interaction optimization of a net zero energy building through electricity storage: An Italian case-study, in: EEEIC 2016 - Int. Conf. Environ. Electr. Eng., 2016. doi:10.1109/EEEIC.2016.7555812.

[12] B. Gohla-Neudecker, M. Bowler, S. Mohr, Battery 2nd life: Leveraging the sustainability potential of EVs and renewable energy grid integration, in: 5th Int. Conf. Clean Electr. Power Renew. Energy Resour. Impact,

ICCEP 2015, 2015: pp. 311–318. doi:10.1109/ICCEP.2015.7177641.

[13] International Energy Agency - IEA, Energy Technology Perspectives 2017 - Executive Summary, Iea. (2017) 371. doi:10.1787/energy_tech-2014-en.

[14] E. Union, DIRECTIVE 2000/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 September2000 on end-of life vehicles, Off. J. Eur. Union. L (2000) 34–42. doi:10.1016/j.jclepro.2010.02.014.

[15] EU, Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, OJ L 266, 2006.

[16] S.M. Schexnayder, S. Das, R. Dhingra, J.G. Overly, B.E. Tonn, J.H. Peretz, G. Waidley, G.A. Davis, Environmental evaluation of new generation vehicles and vehicle components, 2001. http://www-cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2001_266.pdf.

[17] P. Van den Bossche, F. Vergels, J. Van Mierlo, J. Matheys, W. Van Autenboer, SUBAT: An assessment of sustainable battery technology, J. Power Sources. 162 (2006) 913–919. doi:10.1016/j.jpowsour.2005.07.039.

[18] S. Vazquez, S.M. Lukic, E. Galvan, L.G. Franquelo, J.M. Carrasco, Energy Storage Systems for Transport and Grid Applications, IEEE Trans. Ind. Electron. 57 (2010) 3881–3895. doi:10.1109/TIE.2010.2076414.

[19] L.A.W. Ellingsen, G. Majeau-Bettez, B. Singh, A.K. Srivastava, L.O. Valøen, A.H. Strømman, Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack, J. Ind. Ecol. 18 (2014) 113–124. doi:10.1111/jiec.12072.

[20] European Energy Agency, Electric Vehicles in Europe., 2016. doi:10.2800/100230.

[21] K.W. Nam, W.S. Yoon, H. Shin, K.Y. Chung, S. Choi, X.Q. Yang, In situ X-ray diffraction studies of mixed LiMn2O4-LiNi1/3Co1/3Mn1 /3O2 composite cathode in Li-ion cells during charge-discharge cycling, J. Power Sources. 192 (2009) 652–659. doi:10.1016/j.jpowsour.2009.02.088.

[22] S. Bobba, F. Mathieux, F. Ardente, G.A. Blengini, M.A. Cusenza, A. Podias, A. Pfrang, Life Cycle Assessment of repurposed electric vehicles batteries : an adapted method based on modelling of energy flows, J. Energy Storage. 19 (2018) 213–225. doi:10.1016/j.est.2018.07.008.

[23] L. Ahmadi, S.B. Young, M. Fowler, R.A. Fraser, M.A. Achachlouei, A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems, Int. J. Life Cycle Assess. 22 (2017) 111–124. doi:10.1007/s11367-015-0959-7.

[24] A. Assunção, P.S. Moura, A.T. de Almeida, Technical and economic assessment of the secondary use of repurposed electric vehicle batteries in the residential sector to support solar energy, Appl. Energy. 181 (2016) 120–131. doi:10.1016/j.apenergy.2016.08.056.

[25] ISO, ISO 14040: Environmental management — Life Cycle Assessment — Principles and Framework, 2006. doi:10.1002/jtr.

[26] ISO, ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines, 2006. doi:10.1136/bmj.332.7555.1418.

[27] M. Cellura, M.A. Cusenza, S. Longo, Energy-related GHG emissions balances: IPCC versus LCA, Sci. Total Environ. 628–629 (2018) 1328–1339. doi:10.1016/j.scitotenv.2018.02.145.

[28] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A European Strategy for Plastics in a Circular Economy, Eur. Comm. Website. SWD(2018) (2018) 1–18. doi:10.1021/acs.est.7b02368.

[29] US EPA (U.S. Environmental Protection Agency), Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy. www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy., 2017. (n.d.).

[30] L. Ahmadi, A. Yip, M. Fowler, S.B. Young, R.A. Fraser, Environmental feasibility of re-use of electric vehicle batteries, Sustain. Energy Technol. Assessments. 6 (2014) 64–74. doi:10.1016/j.seta.2014.01.006.

[31] K. Richa, C.W. Babbitt, G. Gaustad, Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy, J. Ind. Ecol. 21 (2017) 715–730. doi:10.1111/jiec.12607.

[32] K. Richa, C.W. Babbitt, N.G. Nenadic, G. Gaustad, Environmental trade-offs across cascading lithium-ion battery life cycles, Int. J. Life Cycle Assess. 22 (2015) 66–81. doi:10.1007/s11367-015-0942-3.

[33] L.C. Casals, B.A. García, F. Aguesse, A. Iturrondobeitia, Second life of electric vehicle batteries: relation between materials degradation and environmental impact, Int. J. Life Cycle Assess. 22 (2017) 82–93. doi:10.1007/s11367-015-0918-3.

[34] R. Faria, P. Marques, R. Garcia, P. Moura, F. Freire, J. Delgado, A.T. De Almeida, Primary and secondary use of electric mobility batteries from a life cycle perspective, J. Power Sources. 262 (2014) 169–177. doi:10.1016/j.jpowsour.2014.03.092.

[35] S. Bobba, A. Podias, F. Di Persio, M. Messagie, P. Tecchio, M.A. Cusenza, U. Eynard, F. Mathieux, A. Pfrang, Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB): JRC Exploratory Research (2016-2017): Final technical report: August 2018; EUR 29321 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-928, 2018. doi:10.2760/53624.

[36] M. Cellura, F. Guarino, S. Longo, M. Mistretta, Different energy balances for the redesign of nearly net zero energy buildings: An Italian case study, Renew. Sustain. Energy Rev. 45 (2015) 100–112. doi:10.1016/j.rser.2015.01.048.

[37] S. Bobba, A. Podias, F. Di Persio, M. Messagie, P. Tecchio, M.A. Cusenza, U. Eynard, F. Mathieux, A. Pfrang, Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB): JRC Exploratory

Research (2016-2017): Final technical report: August 2018; EUR 29321 EN, Publications Office of the European Union, Luxembourg, 2018, JRC112543, 2018. doi:10.2760/53624.

[38] M.M. Kabir, D.E. Demirocak, Degradation mechanisms in Li-ion batteries : a state-of- the-art review, (2017) 1963–1986. doi:10.1002/er.

[39] P. Keil, S.F. Schuster, J. Wilhelm, J. Travi, A. Hauser, R.C. Karl, A. Jossen, Calendar Aging of Lithium-Ion Batteries, J. Electrochem. Soc. (2016). doi:10.1149/2.0411609jes.

[40] International Electrotechnical Commission (IEC)., IEC 62660-1:2010. International Standard IEC 62660-1:2010, Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing, (2011).

[41] A. Ciocia, J. Ahmad, G. Chicco, P. Di Leo, F. Spertino, Optimal size of photovoltaic systems with storage for office and residential loads in the Italian net-billing scheme, in: Proc. - 2016 51st Int. Univ. Power Eng. Conf. UPEC 2016, 2017: pp. 1–6. doi:10.1109/UPEC.2016.8114082.

[42] G. Lacey, G. Putrus, A. Salim, The use of second life electric vehicle batteries for grid support, IEEE EuroCon 2013. (2013) 1255–1261. doi:10.1109/EUROCON.2013.6625141.

[43] L. Ahmadi, S.B. Young, M. Fowler, R.A. Fraser, M.A. Achachlouei, A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems, Int. J. Life Cycle Assess. 22 (2017) 111–124. doi:10.1007/s11367-015-0959-7.

[44] J. Salom, A.J. Marszal, J. Candanedo, J. Widén, K. Byskov Lindberg, I. Sartori, Analysis of Load Match and Grid Integration Indicators in Net Zero Energy Buildings with High-Resolution Data. A report of Subtask A IEA Task 40/Annex 52 Towards Net Zero Energy Solar Buildings., (2014) 102.

[45] R. Hein, P.R. Kleindorfer, S. Spinler, Valuation of electric vehicle batteries in vehicle-to-grid and battery-to-grid systems, Technol. Forecast. Soc. Change. 79 (2012) 1654–1671. doi:10.1016/j.techfore.2012.06.002.

[46] European Commission, Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations, Off. J. Eur. Union. (2013) 210. doi:doi:10.3000/19770677.L_2013.124.eng.

[47] M. Hauschild, R.K. Rosenbaum, S.I. Olsen, E. Al., Life Cycle Assessment - Theory and Practice, 2017. doi:10.1007/978-3-319-56475-3.

[48] R. Frischknecht, N. Jungbluth, H. Althaus, C. Bauer, G. Doka, R. Dones, R. Hischier, S. Hellweg, T. Köllner, Y. Loerincik, M. Margni, Implementation of Life Cycle Impact Assessment Methods, Am. Midl. Nat. 150 (2007) 1–151. http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf.

[49] S. Bobba, F. Ardente, F. Mathieux, Environmental and economic assessment of durability of energy-using

products: Method and application to a case-study vacuum cleaner, J. Clean. Prod. 137 (2016) 762–776. doi:10.1016/j.jclepro.2016.07.093.

[50] C.E.L. Latunussa, F. Ardente, G.A. Blengini, L. Mancini, Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels, Sol. Energy Mater. Sol. Cells. 156 (2016) 101–111. doi:10.1016/j.solmat.2016.03.020.

[51] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (2016) 1218–1230. doi:10.1007/s11367-016-1087-8.

[52] M.A. Cusenza, S. Bobba, F. Ardente, M. Cellura, F. Di Persio, Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles, Under Rev. J. Clean. Prod. (Ref. No. JCLEPRO-D-18-04856). (2018).

[53] Recharge, The Advanced Rechargeable & Lithium Batteries Association PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications Version : H Time of validity : 31 December 2020. (http://ec.europa.eu/, (2018) 1–98.

[54] European Commission - Joint Research Centre - Institute for Environment and Sustainability, General guide for Life Cycle Assessment - Detailed guidance, 2010. doi:10.2788/38479.

[55] L. Ahmadi, M. Fowler, S.B. Young, R.A. Fraser, B. Gaffney, S.B. Walker, Energy efficiency of Li-ion battery packs re-used in stationary power applications, Sustain. Energy Technol. Assessments. 8 (2014) 9–17. doi:10.1016/j.seta.2014.06.006.

[56] O. Tremblay, L.A. Dessaint, Experimental validation of a battery dynamic model for EV applications, World Electr. Veh. J. 3 (2009) 289–298. doi:10.3390/wevj3020289.

[57] International Organization for Standardization, UNI EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, Sustain. Constr. Work. - Assess. Environ. Perform. Build. - Calc. Method. (2011).

[58] UNFCCC, Paris Agreement, Conf. Parties Its Twenty-First Sess. 21932 (2015) 32. doi:FCCC/CP/2015/L.9/Rev.1.

[59] E. Crenna, S. Sozzo, S. Sala, Natural biotic resources in LCA: Towards an impact assessment model for sustainable supply chain management, J. Clean. Prod. (2017). doi:10.1016/j.jclepro.2017.07.208.

[60] J. Dewulf, L. Benini, L. Mancini, S. Sala, G.A. Blengini, F. Ardente, M. Recchioni, J. Maes, R. Pant, D. Pennington, Rethinking the area of protection “natural resources” in life cycle assessment, Environ. Sci. Technol. 49 (2015) 5310–5317. doi:10.1021/acs.est.5b00734.