ASSOCIAZIONE
RETE ITALIANA LCA

ATTI

X Convegno dell'Associazione Rete Italiana LCA
XV Convegno della Rete Italiana LCA

INNOVAZIONE E CIRCOLARITÀ

Il contributo del *Life Cycle Thinking* nel Green Deal per la neutralità climatica

22-24 settembre 2021

Università Mediterranea
di Reggio Calabria
Via dell'Università, 25
Reggio Calabria

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PROGRAMMA
22 settembre 2021
mercoledì

14.00 — 15.00 **Registrazione dei partecipanti**

15.00 — 15.30 **Apertura dei lavori e saluti istituzionali**

Chair: Marina Mistretta, Università Mediterranea di Reggio Calabria, Associazione Rete Italiana LCA

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Magnifico Rettore Università Mediterranea di Reggio Calabria

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Presidente Associazione Fisica Tecnica Italiana

Bruno Notarnicola
Presidente Associazione Rete Italiana LCA, Università degli Studi Aldo Moro

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15.30 — 16.15 **SESSIONE I**
IL LIFE CYCLE THINKING NELLA TRANSIZIONE ECOLOGICA
Chair: Bruno Notarnicola, Associazione Rete Italiana LCA

Il Life Cycle Thinking applicato alle strategie di crescita dell'idrogeno: sfide e prospettive
- **Maurizio Cellura,** Università degli Studi di Palermo

Green Deal e Sustainable Development Goals: Il ruolo del settore edile
- **Marina Mistretta**, Università Mediterranea di Reggio Calabria

Il contributo della metodologia PEF nelle politiche europee per il Green Deal
- **Fulvio Ardente,** Commissione Europea, Joint Research Centre Ispra

Il Life Cycle Thinking a supporto dello sviluppo di tecnologie per l'accumulo elettrochimico di energia elettrica
- **Marco Ferraro,** Consiglio Nazionale delle Ricerche - Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano (CNR-ITAE), Messina

16.15 — 18.00 **SESSIONE II**
LCT E CIRCOLARITÀ
Chair: Monica Lavagna – Associazione Rete Italiana LCA
Roberta Salomone – Università degli Studi di Messina

Circular Bioeconomy metrics and Life Cycle Assessment.
Answers from literature review
- **Federico Gallo,** Università degli Studi di Padova

Implementing the Circular Transition Indicators in a global packaging company
- **Anna Walker,** Università degli Studi di Chieti-Pescara

"Toward carbon neutral urban regeneration: the use of LCA to support competition for innovative, carbon-free and circular architectural projects"
- Anna Dalla Valle, Politecnico di Milano

Strumenti con approccio di ciclo di vita di supporto alle aziende per la scelta di soluzioni circolari: la matrice di valutazione multicriterio
- **Benedetta Bellotti**, Ecoinnovazione srl

LCA on Carbon Dots: a state-of-the-art evaluation
- **Virginia Lama,** Università di Bologna

La banca dati italiana LCA BDI-LCA
- **Caterina Rinaldi,** ENEA

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Chair: Pietro Alexander Renzulli, Università degli Studi di Bari "Aldo Moro"
Anna Irene De Luca, Università Mediterranea di Reggio Calabria

Life Cycle Assessment applied to Carbon Dioxide Removal processes: a literature review
- **Francesco Pietro Campo,** Politecnico di Milano

Analisi delle strategie di riuso e riciclo dei nuovi "critical raw materials"
- **Angela Malara,** Università Mediterranea di Reggio Calabria

Life Cycle Assessment di batterie stazionarie a ioni-litio nello scenario italiano
- **Andrea Temporelli,** RSE Ricerca Sistema Energetico, Milano

Riuso del fresato e modificanti: due parametri per la misura della sostenibilità ambientale delle pavimentazioni stradali
- **Lucia Capuano,** Università degli Studi di Milano Bicocca

Il piano nazionale di ripresa e resilienza in ottica LCA: una valutazione preliminare per sviluppi futuri
- **Daniela Camano,** Università degli Studi di Padova

Blockchain Technology in Life Cycle Assessment: Opportunities and Current Challenges
- **Davide Accordini,** Politecnico di Milano

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PROGRAMMA
23 settembre 2021
giovedì

8.30 – 9.00	**Registrazione dei partecipanti**
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11.15 – 12.45	**SESSIONE IV** **EDILIZIA** *Chair: Marina Mistretta, Associazione Rete Italiana LCA* *Patrizia Frontera, Università Mediterranea di Reggio Calabria* The environmental footprint of buildings at city level: a new assessment tool • **Jacopo Famiglietti**, Politecnico di Milano Materiali isolanti per l'edilizia: uno studio di LCA • **Sonia Longo**, Università degli Studi di Palermo End of Life tool for building product development: the Solar Window Block case study • **Martino Gubert**, Eurac Research Bolzano Reuse in the construction sector: Life Cycle Assessment as a driver tool • **Serena Giorgi**, Politecnico di Milano Sustainability of disruptive innovation – cradle-to-gate LCA of Carbon Reinforced Concrete • **Jane Backes**, RWTH Aachen University LCA in building sector policies • **Monica Lavagna**, Politecnico di Milano

12.45 — 13.15 **SESSIONE POSTER II**

Chair: Laura Cutaia, Associazione Rete Italiana LCA
Sonia Longo, Università degli Studi di Palermo

State-of-the-art analysis of environmental assessment studies on Concentrated Solar Power systems
- **Federico Rossi**, Università degli Studi di Siena

Timber and concrete in the building sector: a review of Life Cycle Assessment studies
- **Sofia Pastori**, Politecnico di Milano

Carbon Footprint di un Ateneo: confronto metodologico tra ISO 14064-1 e linee guida RUS
- **Alessandro Marson**, Università degli Studi di Padova

L'approccio parametrico basato su LCA per l'eco-progettazione di involucri edilizi
- **Francesca Thiebat**, Politecnico di Torino

Moving A/E practices towards life cycle design
- **Anna Dalla Valle**, Politecnico di Milano

Recupero del fosforo da ceneri di fanghi di depurazione: modellazione del processo e analisi del ciclo di vita
- **Serena Righi**, Università di Bologna

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Chair: Maurizio Cellura, Associazione Rete Italiana LCA
Matilde Pietrafesa, Università Mediterranea di Reggio Calabria

Life cycle assessment (LCA) of an innovative compact hybrid electrical-thermal storage system for residential buildings in Mediterranean climate
- **Valeria Palomba**, Consiglio Nazionale delle Ricerche - Istituto di tecnologie avanzate per l'energia "Nicola Giordano (CNR-ITAE), Messina

Supporting life-cycle conscious decisions in household energy requalification
- **Nicolò Golinucci,** Politecnico di Milano

Primary vs secondary data in LCA: the case of an electronic product
- **Giovanni Mondello,** Università degli Studi di Messina

L'Italia e l'Europa verso la transizione energetica. Situazione attuale e scenari a confronto
- **Benedetta Marmiroli,** RSE Ricerca Sistema Energetico, Milano

Environmental Impact Evaluations of automotive Lithium-ion Batteries' first and second life
- **Silvia Colnago,** Politecnico di Milano

Life Cycle Assessment of Sustainable Aviation Fuels: a review
- **Simone Maranghi,** Ecoinnovazione srl

EV LIBs towards circular economy: literature review of electric vehicle lithium-ion batteries LCA for a circular economy implementation
- **Matteo Fervorari,** Politecnico di Milano

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Chair: Paolo Masoni, Ecoinnovazione srl
Serena Righi, Università degli Studi di Bologna

Towards sustainable freight transportation: an LCA review
- **Marta Negri,** Politecnico di Milano

Applicazione del Life Cycle Assessment al servizio di erogazione di acqua potabile in Romagna
- **Francesco Arfelli**, Università di Bologna

Qual è il reale interesse delle imprese verso l'economia circolare? Risposte da una survey
- **Elena Battiston,** Università degli Studi di Padova

Life Cycle Assessment Overview on Polyhydroxyalkanoates
- **Loïc Ronin,** Politecnico di Milano

Resource pressure of woven carpets: guide to their circular design
- **Virginia Lama,** Università di Bologna

Impatti ambientali delle perforazioni petrolifere: il contributo della "scarpa di cementazione"
- **Raffaella Taddeo,** Università degli Studi "G. d'Annunzio" Chieti – Pescara

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16.30 — 17.00 **Coffee Break**

17.00 — 17.45 **PREMIO GIOVANI RICERCATORI**
Chair: Andrea Raggi, Associazione Rete Italiana LCA

Un framework esteso di Life Cycle Sustainability Assessment applicato ai sistemi energetici
- **Francesco Guarino,** Università degli Studi di Palermo

La Cereal Unit come metrica per allocazione e unità funzionale appropriate nel settore agroalimentare: Metodologia, limiti e prospettive discussi attraverso il caso dei seminativi in Italia
- **Giuseppe Costantini,** Università degli Studi di Milano

17.45 — 18.15 **ASSEMBLEA ASSOCIAZIONE RETE ITALIANA LCA**

20.30 **Cena sociale – L'A L'Accademia gourmet**
Via Largo Cristoforo Colombo 6, Reggio Calabria
(Solo per i partecipanti già registrati a questo evento)

PROGRAMMA
24 settembre 2021
venerdì

9:15 — 11:00

SESSIONE VI
ESPERIENZE E CASI STUDIO NEL SETTORE AGRO-ALIMENTARE

Chair: Bruno Notarnicola, Associazione Rete Italiana LCA
Giacomo Falcone, Università Mediterranea di Reggio Calabria

Life Cycle Methodologies and Social Agrarian Metabolism Approach to assess Agroecology Practices in Mediterranean Olive Growing: A Methodological Framework in the International "Sustain olive" Project
- **Anna De Luca,** Università Mediterranea di Reggio Calabria

Assessing Climate Change impacts of typical Sardinian sheep cheese production: The Pecorino Sardo and Fiore Sardo case study
- **Delia Cossu,** Consiglio Nazionale delle Ricerche, Istituto per la Bioeconomia, Sassari

Social Life Cycle Assessment degli Allevamenti Suinicoli intensivi in Italia: Indicatori e Scale di Valutazione
- **Giuseppe Coppola,** Università degli Studi di Milano

A proposal of customized Life Cycle model to circularity challenges in the olive-oil supply chain
- **Teodora Stillitano,** Università Mediterranea di Reggio Calabria

LCA e Emergy come strumenti di individuazione e valorizzazione di pratiche agricole circolari: un caso studio in Toscana
- **Gaia Esposito,** Università degli Studi di Siena

Environmental life cycle assessment of typical organic carrot in central Italy
- **Francesco Pacchera,** Università degli Studi della Tuscia

Messa a punto di un protocollo di gestione della sommersione per una risicoltura più sostenibile
- **Michele Zoli,** Università degli Studi di Milano

11.00 — 11.30 **Coffee Break**

11.30 — 12.00 **SESSIONE POSTER IV**

Chair: Antonio Scipioni, Università degli Studi di Padova
Filippo Praticò, Università Mediterranea di Reggio Calabria

A Comparative Life Cycle Assessment of Conventional and Organic Hazelnuts Production systems in Centre Italy
- **Giuseppe Coppola,** Università degli Studi di Milano

The role of users in addressing environmental impacts in LCA: a literature review
- **Alice Paola Pomè,** Politecnico di Milano

Applicazione metodologia mista LCA e UI/UX al contesto autoproduzione per la creazione di green skills
- **Claudia Morea,** Università degli Studi di Firenze

Life Cycle Assessment of Composite Materials: a literature review
- **Pietro Ballarin,** Politecnico di Milano

Simplified Life Cycle Assessment (LCA) of a semi-finished aluminium product
- **Ioannis Arzoumanidis**, Università degli Studi "G. d'Annunzio" Chieti – Pescara

Abbattimento delle emissioni dalle porcilaie attraverso scrubber con soluzione di acido citrico
- **Jacopo Bacenetti,** Università degli Studi di Milano

12.00 — 12.45 **TAVOLA ROTONDA**
"PNRR E TRANSIZIONE ECOLOGICA: OBIETTIVI E PROSPETTIVE DELLA GREEN REVOLUTION"

Chair: Marina Mistretta

Partecipano:
- **Maurizio Cellura,** Associazione Rete Italiana LCA
- **Patty L'Abbate,** Senato della Repubblica
- **Maurizio Melis,** Radio 24 - Il Sole 24 ore
- **Bruno Notarnicola,** Associazione Rete Italiana LCA

12.45 — 13.00 **CHIUSURA CONVEGNO**
- **Bruno Notarnicola**
- **Marina Mistretta**
- **Maurizio Cellura**

13.00 - 14.00 **Pranzo**

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ESPERIENZE E CASI STUDIO NEL SETTORE AGRO-ALIMENTARE

SESSIONE POSTER IV

PREFAZIONE

Il X Convegno dell’Associazione Rete Italiana LCA (XV Convegno della Rete Italiana LCA) si è svolto a Reggio Calabria nei giorni 22, 23 e 24 settembre 2021, sul tema “Innovazione e Circolarità: il contributo del Life Cycle Thinking nel Green Deal per la neutralità climatica”. Il Convegno ha ricevuto il patrocinio del Ministero dell’Ambiente e della Tutela del Territorio e del Mare (MATTM), dell’Associazione Condizionamento dell’Aria Riscaldamento e Refrigerazione (AICARR), SETAC Italia, Città Metropolitana di Reggio Calabria, ARPA Calabria, Confindustria Reggio Calabria, Camera di Commercio di Reggio Calabria, e con il sostegno di CNR-ITAE di Messina.

In linea con gli obiettivi dell’Agenda 2030, che si pongono alla base delle politiche di ripresa post-Covid, il Green Deal europeo rappresenta la nuova roadmap della strategia di crescita sostenibile per raggiungere una giusta transizione energetica e la neutralità climatica entro il 2050. In tale contesto, l’approccio del Life Cycle Thinking (LCT), diventato uno dei pilastri principali delle politiche strategiche europee orientate alla decarbonizzazione dell’economia, rappresenta un supporto metodologico efficace nell’innovazione, coerente con la transizione ecologica, non solo di cicli produttivi e modelli di consumo, ma anche di approcci culturali e stili di vita.

Il X Convegno dell’Associazione Rete Italiana LCA (XV Convegno della Rete Italiana LCA) si è focalizzato sul ruolo dell’LCT come approccio integrato: 1) nella valutazione della sostenibilità che le complesse sfide della transizione verso la neutralità climatica e l’uso efficiente delle risorse impongono; 2) nella definizione di strategie per il raggiungimento degli obiettivi di sviluppo sostenibile nelle sue varie dimensioni ambientali, economiche e sociali, stimolando la creazione di valore e la resilienza dei sistemi economici.

I contributi scientifici, presentati durante le sessioni tematiche orali e le sessioni poster, testimoniano il grande interesse della comunità scientifica nazionale verso tali tematiche, ponendo anche grande attenzione all’impiego dell’LCT per il raggiungimento dei SDG, all’integrazione con altri strumenti per la sostenibilità, e alla crucialità della metodologia LCA nel supportare le imprese nell’intraprendere un percorso più green, come metrica delle proprie prestazioni energetiche e ambientali.

Il volume raccoglie i contributi scientifici, presentati a seguito di un processo di double peer review gestito dal Comitato Scientifico. I suddetti contributi sono stati inviati sui seguenti temi:

- Metodi e strumenti LCT – based nelle politiche ambientali.
- Impiego del LCT nelle strategie di mitigazione e adattamento ai cambiamenti climatici.
- Sviluppi metodologici di LCA, LCC e SLCA e integrazione con altri strumenti per studi di sostenibilità
- Impiego del LCT per il raggiungimento dei Sustainable Development Goals
- LCT ed Economia Circolare: casi studio di eco-design e di produzione e consumo sostenibili
- Impiego della LCA e degli strumenti LCT - based nei settori alimentare e agroindustriale, energetico, chimico, edilizio, turistico, gestione dei rifiuti, infrastrutture viarie e trasporti.

Un'ultima sezione riporta i contributi presentati dai primi due classificati della dodicesima edizione del Premio Giovani Ricercatori LCA, rivolto ai giovani ricercatori, che operano nel campo dell'analisi del ciclo di vita al fine di promuovere la ricerca e divulgare le loro attività.

Il Chair del Convegno

Marina Mistretta

Marina Mistretta

Il Presidente dell'Associazione Rete Italiana LCA

Bruno Notarnicola

EV LIBs towards circular economy: literature review of electric vehicle lithium-ion batteries LCA for a circular economy implementation

Matteo Fervorari*[1], Marcello Colledani[1,2], Giovanni Dotelli[3]

Abstract: The electric vehicle lithium-ion batteries are strategic products and wide literature on environmental assessment is available in the field. This papers review aims to provide an overlook of the recent studies on EV LIB LCA applications, giving priority to product systems including circular economy treatments such as remanufacturing, repurpose and recycling. From the literature analysis it emerged that most of the environmental assessments considered repurpose and recycling strategies and only in one case the remanufacturing process. Different functional units, LCA approaches, and impact categories were investigated by the practitioners. Some authors highlighted lack of primary data and LCA guidelines for remanufacturing and repurpose. In one case a non-intuitive correlation between circularity and environmental sustainability was detected. Therefore, further investigation in these directions is encouraged.

1. Introduction

In the last decade, the automotive industry has faced an increasing transition from the internal combustion engine vehicles (ICEVs) to the Electric (EVs) and Hybrid (HEVs) vehicles. In 2018 the global electric car fleet exceeded 5.1 million and from market forecasts it could reach between 23 to 43 million unit sales by 2030 (Virta, 2019).

The electric vehicles are mainly composed by the battery pack (which accounts for around 30% – 50% of the total car value (Lebedeva et al., 2016), the motor, the generator, the inverter, the AC/DC converter and the transmission (Masias, 2018). The structure of the EV battery packs is similar: battery cells are assembled in parallel and series into a module and more modules are connected in series to form the whole pack together with other units, such as heating/cooling system, battery management system and power electronics (Gentilini et al., 2020; Wegener et al., 2014). Three types of Li-Ion battery (LIB) cells exist: cylindrical, prismatic and pouch.

The battery disposal nowadays is becoming a concrete issue due to the product complexity and inner value, and the market trend and average lifespan of an electric car (estimated between 10 and 20 years with a batteries warranty around 8 years or 160,000 km) (batteryuniversity, 2020; Canals Casals et al., 2017). Circular Economy (CE) strategies such are repair, remanufacture, repurpose and recycle, has been proposed as possible solutions to reduce the product impact and

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[3] Politecnico di Milano, Chemical department
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recover its value (Canals Casals et al., 2017; Colledani, 2019; Gentilini et al., 2020; Mossali et al., 2020b) and product redesign is under investigation (Mossali et al., 2020a).

Consumers and public institutions are demanding for a clearer understanding of the battery environmental impact. The Life Cycle Assessment (LCA) can be a decision support tool for designer and industrial companies to address the optimal decisions, from the best raw materials choice at the design phase, to the legislation certification requirement accomplishment of hazardous substances, and to the identification of more environmentally friendly circular solutions at the end-of-life (EoL) stage, not only in terms of material recovery but also in terms of impact of the end-of-life operations themself.

2. Scope of the research and methods

The aim of this paper is to give a comprehensive overview of the recent LCA application for the electric vehicles lithium-ion batteries, with a focus on CE treatment implementation.

From the available studies between 2017 and 2020 performing LCA on batteries and electric vehicles, 10 paper including circular economy treatments in the assessment (such as recycling, repurpose, remanufacturing and direct reuse) has been identified and analysed (Ahmadi et al., 2017; Bobba et al., 2018; Casals et al., 2017; Cusenza et al., 2019a, 2019b, 2019c; Hao et al., 2017; Raugei and Winfield, 2019; Richa et al., 2017; Xiong et al., 2020). The lifecycle analysis of the selected papers has been discussed in Chapter 3 according to the LCA methodological steps and overall conclusions on literature review were drawn in Chapter 4.

3. LCA literature review results

3.1. Goal and Scope Definition

In Richa et al. (2017) a CE-inspired waste hierarchy for end-of-life EV lithium-ion batteries was proposed and assessed under environmental and economical perspective, considering the management of 1,000 end-of-life EV battery packs in the United States.

Hao et al. (2017), Raugei and Winfield (2019) and Cusenza et al. (2019a) measured the energy and environmental impact of traction lithium-ion battery pack considering only the recycling EoL treatment. The impact of secondary use strategies such as EV repurposing in energy storage system (ESS) for building has been analysed by Casals et al. (2017), Ahmadi et al. (2017), Bobba et al. (2018), Cusenza et al. (2019b) and Cusenza et al. (2019c). Among them, Casals et al. (2017) and Cusenza et al. (2019b) included also the impact of the recycling into the assessment. Xiong et al. (2020), instead, analysed the environmental effect at cell level of a lithium-ion battery remanufacturing and compared it with a cell manufactured using virgin materials.

3.1.1. Functional Unit

For the assessment of the LIB waste hierarchy, Richa et al. (2017) considered a FU of 1,000 end-of-life EV battery packs. An EoL-oriented unit was adopted also by Hao et al. (2017), for the analysis of a single EoL vehicle impact (FU = 1 EoL EV).

The other LCA studies focused on recycling opted for a kWh functional unit: a 17kWh battery pack by Raugei and Winfield (2019) and 11.4 kWh pack for the energy and environmental assessment of Cusenza et al. (2019a). Unitary kWh has been chosen by Casals et al. (2017) and Ahmadi et al. (2017) for their second-used battery assessment.

The remaining papers on EV LIB repurpose considered the Average yearly energy balance in the building and in the transportation sector (Bobba et al., 2018; Cusenza et al., 2019b), and the electricity required by the building in a time scale of 12 years (Cusenza et al., 2019c). For the remanufacturing impact Xiong et al. (2020) selected 1kg of produced cell.

3.1.2. System Boundaries and Multi-functionality

The waste hierarchy analysed by Richa et al. (2017) consisted in a multiple interacting routes system of spent battery packs (grave stage) flowing in series or parallel through different pathways: closed-loop direct reuse (in EV); open-loop cascaded use for secondary stationary storage applications; recycling, and landfill disposal of materials not reused or recycled. Keeping as a starting point the EoL stage, Hao et al., (2017) proposed a grave-to-gate approach including in the system: vehicle recycling (subdivided in vehicle dismantling, vehicle recycling without tires and batteries, tire recycling and battery recycling); material recovery; and vehicle production (with material production, components manufacturing and assembling). Grave-to-gate has been adopted also by Xiong et al. (2020), who divided the remanufacturing process into three phases: hydrometallurgical recycling, cathode remanufacturing, and cell remanufacturing.

The systems of the remaining LCA papers began instead from the traditional cradle stage. Raugei and Winfield (2019) measured the impact of a novel EV Li-ion battery considering its production, EoL recycling, and assigning the energy and emission credits from recovered metals according to a substitution logic (i.e. cradle-to-gate + EoL + recycling credits). Different decision was made by Cusenza et al. (2019a), that analysed the impact of traction lithium-ion battery pack for plug-in hybrid electric vehicles taking into account the whole lifecycle, from cradle to cradle. The system comprised: battery pack production; battery primary use in the EV; recycling at the end-of-life considering the recovery of material fractions. The material recycling potential benefits were credited to the EoL stage in terms of avoided primary materials.

EV battery secondary applications in different scenario were compared by Casals et al. (2017) with a cradle-to-cradle expanded system, including the car production, both the battery usage phases (i.e. primary use in EV and second use as ESS), and the recycling.

Cusenza et al. (2019c) analysed with a cradle-to-consumer approach the case of battery reuse as ESS for a building connected to the grid, equipped with an energy system composed by a PV (photovoltaic) plant and five EV batteries, comparing it to the scenario without storage systems. The multifunctionality generated by the battery repurpose was handled by an attributional approach with physical relationships allocation (energy delivered by the ESS).

Further analysis on battery secondary application was performed in Cusenza et al. (2019b), where the authors compared two different scenarios: a Reuse battery scenario (RBS) employing used batteries, designed in a previous work (Cusenza et al., 2019c), and a New battery scenario (NBS) with new batteries. Even in this case an allocation procedure with physical relationships (energy delivered by the ESS) was implemented to solve the multifunctionality.

A scenario comparison was also applied by Bobba et al. (2018), with a cradle-to-grave approach. The considered repurpose scenario system included a grid-connected or stand-alone house, with a repurposed EV pack storing PV energy. The associated impact was compared to three reference configurations: grid-connected house with a fresh LIB storing the PV energy; grid-connected house and no ESS; stand-alone house with diesel-electric energy generator complementary to the PV energy generation (in this last case the repurpose scenario was the stand-alone house). All the reference and repurpose scenarios included a PV installation. 0% and 25% market-based allocation factors have been considered to allocate the environmental impacts related to first-life battery production and EoL treatment to the second-life application.

Cradle-to-grave system expansion was implemented by Ahmadi et al. (2017) to compare the "cascaded" system of the battery EV use and repurpose in ESS, to a "conventional" system of ICEV and a stationary power with natural gas.

3.1.3. Impact categories

While Casals et al. (2017) focused the assessment only on the Global Warming Potential (GWP), all the other LCA studies analysed more impact categories, including always an energy-related impact. Energy consumption and Greenhouse Gases (GHG) emissions has been measured by Xiong et al. (2020) and Hao et al. (2017), who also included effects on material consumption. Richa et al. (2017) assessed the environmental impact of the waste stream calculating the cumulative energy demand (CED), the eco-toxicity and the material input. Raugei and Winfield (2019) focused on CED and GHG emissions. Four impact categories has been measured by Bobba et al. (2018): CED, ADP-res (abiotic depletion potential, mineral resources), GWP, and HTc (Human toxicity, cancer effects). CED and 6 ReCiPe indicator categories measurements (GWP, POFP-photochemical oxidation formation potential, PMFP-particulate matter formation potential, FEP-freshwater eutrophication potential, MDP-metal depletion potential, FDP-fossil resource depletion potential) were analysed in Ahmadi et al. (2017), while Cusenza et al. (2019a), Cusenza et al. (2019b) and Cusenza et al. 2019c) measured the CED and the PEF (product environmental footprint) impact categories.

3.2. Life Cycle Inventory

In all the analysed LCA studies at least secondary data source has been consulted. Casals et al. (2017) obtained information from secondary data source, Xiong et al. (2020) used data models such as BatPac and GREET. Richa et al. (2017) measured the environmental impact of the hierarchical waste stream relying on previous LCA studies data, information from bill of material of LIB cell and pack components, SimaPro CED calculation methodology, USEtox method and Ecoinvent database. Hao et al. (2017) calculated the impact assessment with data from literatures and reports, GREET, BatPac and Automie models, and calculus from IPCC. Bobba et al. (2018) gathered primary data from the PV plant monitoring and secondary data for the building with ResLoadSIM tool. Cusenza et al. (2019c) modelled the energy system based on data monitored from PV installation, from building load profiles, literature and Ecoinvent database for battery production, previous LCA studies for the battery EV primary use. A mix of primary and secondary data has been used by the remaining LCA papers. For example, Ahmadi et al. (2017) gathered real-time primary data during usage phase, and secondary data from Ecoinvent and EPA databases. In Raugei and Winfield (2019), Cusenza et al. (2019a), Cusenza et al. (2019b) primary data has been measured for battery manufacturing while secondary information were picked up from literatures, BacPac and Ecoinvent.

3.3. Life Cycle Impact Assessment and Interpretation

The impact assessment of the CE waste hierarchy (Richa et al., 2017) demonstrated the possibility to recoup 77% of CED and 30% of eco-toxicity impact coming from the battery original production. Metal input impact can be reduced by 1.6 times net mass used in LIB production, mainly due to replacement by the cascaded pathway of much larger PbA battery systems. 200,000MJ of cumulative energy demand can be therefore saved, corresponding to a production of 11 new EV battery packs of 18 kWh each. This effect could be tenfold if lead-acid batteries would be replaced by cascaded retired EV LIBs. The authors highlighted that direct reuse of the retired EV batteries for within the primary scope was less desirable than cascading them into a secondary application (ESS). In the sensitivity analysis, the waste hierarchy results were tested by comparing the adopted cathodes battery technologies with previous studies choices.

The GWP impact assessment of Casals et al. (2017) for different second-use scenarios pointed out that battery reuse in ESS is advisable only if coupled with renewable energy sources, otherwise losses from ESS should be added as a multiplier factor to the emissions from pollutant energy source. Regardless the adopted storage technology (reused EV battery or new lead-acid one), the battery use with energy arbitrage (battery used during the day and recharged with low fare rate energy bought during the night) induced more than 30% GWP increase respect to the base case (i.e. no battery use after EV EoL and energy gathered from the grid). EV batteries re-use in island installations (system connected to renewable energy sources (RES), charging batteries when energy production excessed the system demand) instead reduced the GWP impact of 32% respect to the base case.

The EV manufacturing product system assessed by Hao et al. (2017) emitted 9.8 tCO2eq. and 14.9 tCO2eq, respectively with and without EV recycling adoption. The obtained 34% impact reduction primarily came from recycled steel, aluminium and cathode material of traction battery, which contributed to 61%, 13% and 20% of total reduction.

In the repurpose system of Ahmadi et al. (2017), usage (in EV) and reuse (as ESS) phases were the most demanding in terms of CED, while, from greater to smaller, battery manufacturing, refurbishing for reuse, and recycling represented the minor impacts. Battery manufacturing generated the greatest contribution for GWP, POFP, PMFP, FEP and MDP, and the third higher impact for the FDP (preceded by use and reuse stages). In all the six impact categories, refurbishing and recycling had the lowest impact. If compared to the conventional case with ICEVs, the cascaded system was significantly beneficial for all the ReCiPe impact categories except the MDP. Sensitivity tests on electricity mix and battery degradation has been performed.

According to the Bobba et al. (2018) analysis, the repurposed battery scenario of grid-connected house allowed to reduce all the four impact categories respect to the reference scenario of grid-connected house and fresh battery (-62% for CED, -93% for ADP-res, -58% for GWP and -55% for HTc), but increasing them in comparison to the reference scenario of grid-connected house with no battery (+47% for CED, +143% for ADP-res, +46% for GWP and +225% for HTc) mainly due to EV battery repurposing, request of new battery components and energy losses for battery's efficiency. Impact reduction is also achieved by the repurposed battery scenario of stand-alone house compared to the stand-alone house with diesel-electric generator (-48% for CED, -44% for ADP-res, -49% for GWP and -33% for HTc). Some relevant parameters, such as residual capacity and allocation factor, were tested in the sensitivity analysis.

The majority of the CED required by the LPC EV battery pack product system (Raugei and Winfield, 2019) came from cathode production (more than 60%), while the lowest contribution was due to anode production and battery pack assembly. EoL treatment and recycling credits generated only 2% reduction of the total CED. Cathode represented the greatest contribution (around 70% of total CO2eq emissions) also for GWP, while anode, electrolyte, and pack assembly the minor one. The EoL treatment and credits decreased the total GWP impact by 8%. As in Richa et al. (2017), result sensitivity has been checked by comparing the battery chemistry with previous literature choices.

In the cradle-to-cradle system of composite cathode active material battery pack (Cusenza et al., 2019a) the pack manufacturing affected each impact category for more than 60% and cell assembly represented the greatest contribution for CED, GWP and ozone depletion. Recycling caused less than 11% the lifecycle impact in all the categories, except for freshwater ecotoxicity where it accounted around 60%. Environmental credits associated with materials recovered through battery recycling were particularly relevant due to impact reduction of marine eutrophication (-27%), human toxicity (-40% for cancer effect and -20% for no cancer effect), particulate matter (-17%) and abiotic resource depletion (-16.4%). A scenario-based sensitivity analysis tested the amount of solvent and the electricity required for cell assembly. The sensitivity confirmed that more renewable energy mix could significantly improve the impact of battery use phase.

Sustainability of the EV battery repurpose has been confirmed by Cusenza et al. (2019c), according to which the installation of retired batteries in a grid-connected buildings with PV plant could reduce the majority of the analysed environmental categories impacts, except for cancer and no-cancer human toxicity and freshwater ecotoxicity. These two were mostly affected by effects of PV plant, battery production and EoL treatment. The battery production was responsible, on average, for the 30% of the ESS impact in all the analysed categories.

The comparison of Cusenza et al. (2019b) between the EV LIB reuse in residential building (RBS) and the adoption of new battery storage systems (NBS) suggested that the overall sustainability convenience of the repurpose scenario is not so higher than the virgin ESSs solution. The RBS reduced the abiotic depletion by 17%, EU_M and HT_{nce} by 12%, HT_{ce} by 11% and CED by 4% respect to the NBS. The reason of this slight difference was due to the fact that five used batteries provided the same system function of four new batteries: the benefit of the EV battery usage extension and environmental impact partitioning between the first (EV) and the second (ESS) usages were not so effective in overcoming the better charge/discharge efficiency and higher lifetime of the new batteries.

The overall battery cells remanufacturing process analysed by Xiong et al. (2020) consumed 149.80 MJ for each kg of energy and emitted 10.53 kg per kg of GHG emissions, compared to 163.81 MJ/kg and 11.28 kg/kg, for energy and GHG emissions respectively, of the cell production with virgin materials, meaning an 8.55% energy reduction and 6.62% decrease in GHG emissions. The recycling accounted for around 20% of the overall energy consumption, cathode remanufacturing the 17.62% and the cell remanufacturing the 62.62%. Environmental benefits were attributed to reuse of materials such as cobalt, nickel and manganese, aluminium, and copper. The quantitative analysis therefore demonstrated the potential benefit of the EV LIB remanufacturing.

The LCA main characteristics and results of the analysed research papers are summarized in the table below (Table 1):

Table 1: Main characteristics of the reviewed LCA studies

Authors	***CE treatments***	***System boundary***	***FU***	***Impact category***	***Data source***	***LCA results***
Richa et al. (2017)	Reuse, Repurpose, Recycling	grave-to-cradle	1,000 EoL LIB packs	CED, eco-toxicity, material input	Secondary	CE waste hierarchy can recoup 77% of CED and 30% of eco-toxicity impact coming from the battery original production. Metal input impact can be reduced by 1.6 times net mass used in LIB production. Direct reuse of retired EV batteries within the primary scope is less desirable than cascading them into ESS.
Casals et al. (2017)	Repurpose, Recycling	cradle-to-cradle	1 kWh from Batt Pack	GWP	Secondary	EV battery reuse as ESS coupled with energy arbitrage increases GWP by 30% respect to base case of no battery use after EV EoL and energy gathered from the grid. Battery reuse as ESS is suggested only if coupled with RES (GWP reduction of 32% respect to the base case).
Hao et al. (2017)	Recycling	grave-to-gate	1 EoL EV	GHG, Energy/ material consumption	Secondary	The EV recycling allows to reduce by 34% the CO2 emissions of EV manufacturing product system (20% of total reduction is due to traction battery cathode material recycling).
Ahmadi et al. (2017)	Repurpose	cradle-to-grave	1 kWh from Batt Pack	CED + 6 ReCiPe indicators	Primary & Secondary	CED highest impacts of the cascaded system are related to battery primary use in EV and reuse for ESS. Cascaded system significantly beneficial for most of the ReCiPe indicators compared to conventional system.
Bobba et al. (2018)	Repurpose	cradle-to-grave	average yearly energy balance	CED, ADP-res, GWP, HTc	Primary & Secondary	Impact indicators reduction when repurpose scenario is compared to a grid-connected house with PV installation and fresh battery or a stand-alone house with PV installation and complementary diesel-electric generator. Impact worsening for all the indicators if repurpose scenario is compared to stand-alone house with PV installation and no ESS.
Raugei and Winfield (2019)	Recycling	cradle-to-gate + EoL + recycling credits	17 kWh battery pack	CED, GHG	Primary & Secondary	EoL treatment and recycling credits decreased the total GWP impact of the product system by 8% and total CED impact by 2%.
Cusenza et al. (2019a)	Recycling	cradle-to-cradle	11.4 kWh battery pack	CED + PEF impact categories	Primary & Secondary	Recycling generated less than 11% impact in all the categories, except for freshwater ecotoxicity (around 60% of lifecycle impact). Relevant environmental credits thanks to materials recovery: EU_M(-27%), HT-ce(-40%), HT-ce(-20%), PM(-17%) and ADP(-16.4%).

(continued on the next page)

Table 1: (continued from previous page)

Authors	***CE treatments***	***System boundary***	***FU***	***Impact category***	***Data source***	***LCA results***
Cusenza et al. (2019c)	Repurpose	cradle-to-consumer	Electric energy for a building along 12 years	CED + PEF impact categories	Primary & Secondary	EV battery repurpose in buildings with PV plants reduces most of the impact categories (-9.5% CED, -31.4% GWP, -27.7% ODP, -9.6% PM, -30.7% IR-hh, -21.5% POFP, -22.2% AP, -23.2 EUT, -3.9% EUF, -12.5% EUM) except cancer human toxicity (+10.2%), no-cancer human toxicity (+28.3%) and freshwater ecotoxicity (+4.7%).
Cusenza et al. (2019b)	Repurpose, Recycling	cradle-to-cradle	average yearly energy balance	CED + PEF impact categories	Primary & Secondary	RBS generates positive impact respect to NBS (reduction of abiotic depletion by 17%, EU_M and HT_{nce} by 12%, HT_{ce} by 11% and CED by 4%).
Xiong et al. (2020)	Remanuf.	grave-to-gate	1 kg of produced cell	GHG, Energy consumption	Secondary	8.55% energy reduction and 6.62% GHG emissions decrease for battery cells remanufacturing process respect to cell production with virgin materials.

4. Summary of results and conclusion

The literature analysis aimed to give an overlook of the LCA methodology applied to the electric vehicle lithium-ion batteries, focusing the research on recent studies addressing product systems including circular economy strategies such as remanufacturing, repurpose and recycling.

From the review it has emerged that most of the papers adopted an energy-oriented FU. The majority gathered information from secondary data, or a mix with primary sources. Some authors highlighted lack of primary data availability in the field.

The analysis of the product life cycle mainly started from the traditional grave stage, and in some cases from the gate stage, which is nothing less than the starting point of the CE treatment implementation.

All the repurpose-focus life cycle assessments proposed stationary storage system as a second-use applications, even if it is not the only possible secondary scope (Canals Casals et al., 2017). Among all the ten LCA papers only one, the most recent, addressed a remanufacturing treatment, and only at cell level. This could be due to the novelty and critical issues of the strategy respect to the more diffused and consolidated recycling and repurpose techniques (Canals Casals et al., 2017; Colledani, 2019; Gentilini et al., 2020; Mossali et al., 2020b). Moreover, some experts pointed out lack of LCA guidelines for repurpose and remanufacturing (Peters, 2016; Schulz, 2020), so more research is encouraged in these directions.

Generally, all the impact assessments confirmed the environmental benefit of the circular treatment implementation in the product system, but the correlation between circularity and environmental sustainability is not necessarily always granted, as stated by Richa et al. (2017) in the case of direct reuse of the EV battery packs within the primary EV scope.

Given the high strategical value of the EV LIB pack (Gentilini et al., 2020; Wegener et al., 2014), and the goal of gaining environmental benefit when applying CE solutions (MacArthur, 2015), it is therefore important to further investigate the relationship between the CE treatments and the environmental impacts.

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