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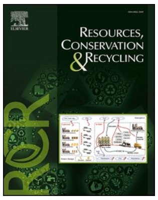

The environmental benefits and burdens of RFID systems in Li-ion battery supply chains – An ex-ante LCA approach

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ABSTRACT

This article explores the current and future technological pathways of RFID components and quantifies their environmental impacts through life cycle assessment (LCA), and also covering the critical materials and energy use of tags, readers, and backend servers. We assess RFID-enabled lithium-ion battery supply chains with different cathode chemistries – lithium nickel cobalt aluminum oxide (NCA), nickel cobalt manganese oxide (NCM) as case applications. The results indicate that miniaturization and novel antenna materials can reduce the current environmental impacts of tags and readers by 60 % and 4 %, respectively. Direct energy consumption and antennas are the main contributors for tags, while microcontrollers and transceivers are the main contributors for readers. Furthermore, the overall environmental improvements of RFID system outweigh their additional environmental impacts. The use of RFID systems in optimizing battery supply process gives higher reductions in climate change and abiotic resource depletion impacts than switching to low-carbon battery chemistries (i.e. using NCM instead of NCA).

1. Introduction

1.1. Importance to assess RFID systems through LCA

In recent years, with the increasing complexity of supply systems, stringency of environmental policies and environmental awareness all sectors of electronic device manufacturing have been subject to influence (Das and He, 2019). Enterprises tend to adopt products enabling the Internet of Things (IoT), which include, for example, radio frequency identification (RFID) systems to create innovative designs and services that break the information barriers between supply nodes, thus increasing productivity, efficiency and supporting sustainable development (Kanth et al., 2012). IoT has become an important contributor to low-carbon electronic supply chains (Coe et al., 2008; Mastos et al., 2020; Ding et al., 2023a). However, the growing demand for IoT related products, such as printed electronics and radio frequency (RF)-based products, also raise concerns related to possible increased environmental impacts, such as greenhouse gas emissions during their manufacturing and use-phase.

As one important IoT supply chains facilitator, RFID systems play a significant role in monitoring and tracking products in supply chain management (Ding et al., 2023b). A typical RFID system consists of tags (attached to the objects), readers (with antenna) and backend servers (management system to store and evaluate database). While the advantages of RFID systems are well-documented, a comprehensively evaluation of their environmental impacts, both in terms of costs and benefits is still missing (Ding et al., 2023c). Due to the foreseeable increase in usage of RFID tags for accurate asset management, a transition to RFID tags with low critical raw materials usage, low environmental burden, and high capability is a key leverage in building IoT-enabled sustainable supply chains (Yang et al., 2023). RFID tags with different substrates, such as paper or polyethylene terephthalate (PET), and integrated circuit (IC) designs, such as printed or silicon-based, impact differently in environmental categories (Liu et al., 2014; Gehring et al., 2019). Although in total numbers the demand for RFID readers is quite small compared to tags to build up a RFID system, their environmental impacts across the full life-cycle of RFID systems (e.g. the energy consumption in operating RFID reader and the management system) cannot be ignored (Mouattah and Hachemi, 2020).

Life cycle assessment (LCA) allows exploring the environmental impacts of IoT-enabled supply systems and hardware components (e.g., RFID tags) across their full life-cycle, from raw materials extraction, via

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production and use, to end-of-life treatment (Finnveden et al., 2009). For instance, Gehring et al. (2019) assessed the environmental impacts of all life-cycle stages of RFID tags developed under the EU-funded project NECOMADA (**N**ano-**E**nabled **Co**nducting **M**aterials **A**ccelerating **D**evice **A**pplicability) on four packaging applications (food boxes, aluminum can, plastic detergent bottle, and medical blister). Their research used an LCA approach to innovatively quantify the additional environmental impacts of RFID tags under different applications. However, it did not consider entire RFID system including readers and backend servers. Additionally, it did not evaluate the indirect potential for environmental benefits enabled by optimizing supply chain operations through using RFIDs. Ding et al. (2023c) designed a hybrid system dynamic and agent-based model to quantitatively investigate IoT-enabled and conventional battery supply chain performance in emissions, profits, and market penetration. The model reveals the IoT's potential of decreasing carbon emissions by at least 50 % in the supplying process (incl. storage and shipment). However, the additional environmental impacts of creating IoT equipment (e.g., RFID tags and readers) are missing in this simulation.

In this respect, to further assess the overall perspective for small and medium-sized enterprises that might be interested in IoT application also as a means to improve environmental performance (Awan et al., 2022), a study quantifying both the environmental benefits and costs of the RFID system is required. LCA has been established as a commonly accepted approach for assessing environmental impacts, but it typically uses static systems as a point of departure. In practice, products and processes form dynamic networks with changing and evolving relations over time (McAvoy et al., 2021). The use of systems thinking and group model-building processes can identify critical variables that attributional LCA may not consider, thereby strengthening the LCA approach (McCabe and Halog, 2018; Laurenti et al., 2014). Importing system simulation results into LCA frameworks helps to more comprehensively understand the additional environmental impacts and potentials of RFID system (or IoT technology in the supply chain) (Ding et al., 2023c).

1.2. Selecting Li-ion EV batteries as application scenarios

The widespread adoption of Electric Vehicles (EV) and the associated growth of EV battery production have significantly influenced the automotive industry's sustainability agenda. Li-ion batteries are highly demanded by the global electric vehicle industry. This demand stream alone is projected to reach 1.8 to 3.0 TWh of batteries before 2030 (IEA, 2022), which requires a rapid scale-up of battery production capacities with related supply chains. Challenges include ensuring available and affordable raw materials (Schade et al., 2022), as well as minimizing environmental emissions in production and supply (Mancini and Nuss, 2020). One solution is to focus on emerging EV battery chemistries to reduce environmental impacts in the production phase. For instance, major battery roadmaps by the US, EU, and China anticipate lithium nickel cobalt aluminum oxide (NCA) and nickel cobalt manganese oxide (NCM) based chemistries as likely widely used cathode materials (USDRIVE, 2017; Edström et al., 2023; Chen et al., 2019). NCA, NCM111 (nickel: cobalt: manganese = 1:1:1), and NCM811 (nickel: cobalt: manganese = 8:1:1) are expected to dominate the market in the next decade (Xu et al., 2020).

The implementation of RFID system also holds a great promise for enhancing supplying efficiency, decreasing associated environmental emissions. In view of technical and scientific progress, RFID technology is also one alternative to QR codes helping to realize a digital battery passport (DBP) considering that DBP will be mandatory for all EV batteries in EU from 2027 (European Parliament, 2023). There is a pressing need to assess implication by incorporating RFID systems into EV battery supply chains. Hence, this study introduces RFID systems for battery supply chains (incl. management system, reader and RFID tags) and analyzes the related environmental impacts. Thereafter the emerging RFID system (consists of emerging tags, readers and backend servers) is considered to show potential environmental benefits from technological innovation. Finally, we compare the environmental performance of three Li-ion battery supply chains: NCA, NCM111, NCM811 with and without RFID systems.

This study aims to answer the following research questions:

RQ 1. What are the environmental impacts of current and prospective RFID components?

RQ 2. What are the environmental impacts of three battery supply chains supported by RFID systems?

RQ 3. Which technical processes of RFID systems are decisive to minimize across impact categories?

The paper proceeds as follows: Section 2 introduces the research goals and system boundaries. Section 3 lists the critical material usages and technical routes of current and emerging RFID systems, and builds up different demand and battery application scenarios for battery supply chain. Section 4 calculates the influence of each RFID elements on environment dimensions through LCA, thereafter compares the differences of overall environmental impacts across the three alternative RFID-enabled battery supply chains under different demand scenarios, and reveals the key contributing processes. Finally, Section 5 reflects on the key findings, lists the limitations and proposes the future steps.

2. Goal and scope

2.1. Goal definition

Considering the current insufficient research exploring the environmental impacts of RFID systems as well as RFID's potentials on optimizing Li-ion battery supply chain operations, this research focuses on two major goals:

2.1.1. RFID components assessment

The first goal is to evaluate and compare the environmental impacts of current and emerging RFID components, considering different material technological routes. This analysis encompasses passive tags, readers, and the management system (backend servers) in line with the definition of RFID systems in previous studies (Yan et al., 2023), see Supplementary Figure 1.

2.1.2. RFID-enabled Li-ion battery supply chains assessment

The second goal is to investigate the environmental impacts of incorporating RFID technology into three Li-ion battery (including NCA, NCM111, and NCM811) application scenarios and two demand scenarios: high- and low- demand. The low demand scenario gradually forms a buyer's market in which factories are operating far from full capacity. Conversely, the high demand scenario reflects the opposite trend. The demand driven supply chains are modelled by Ding et al. (2023c). This will help to clarify the environmental potentials of RFID applications in the evolving landscape of Li-ion battery technologies.

2.2. Scope definition

Technologies reflect a different technology readiness level (TRL) according to their different implementations (Olechowski et al., 2015). IoT has shown a TRL 4–6 level in aircraft manufacturing (Zutin et al., 2022). While preliminary research by the European Association of Research and Technology Organizations (EARTO, 2014) identified a TRL 6–7 level in a printed intelligence pilot factory. However, the data derived from these laboratory and pilot scale implementations cannot be applied in the environmental assessment of a technology operated at full scale. Therefore, we follow the ex-ante LCA approach developed by Delpierre et al. (2021), and follow Cucurachi et al. (2018) and Tsoy et al. (2020) for aspects related to upscaling. As shown in Fig. 1, we structure

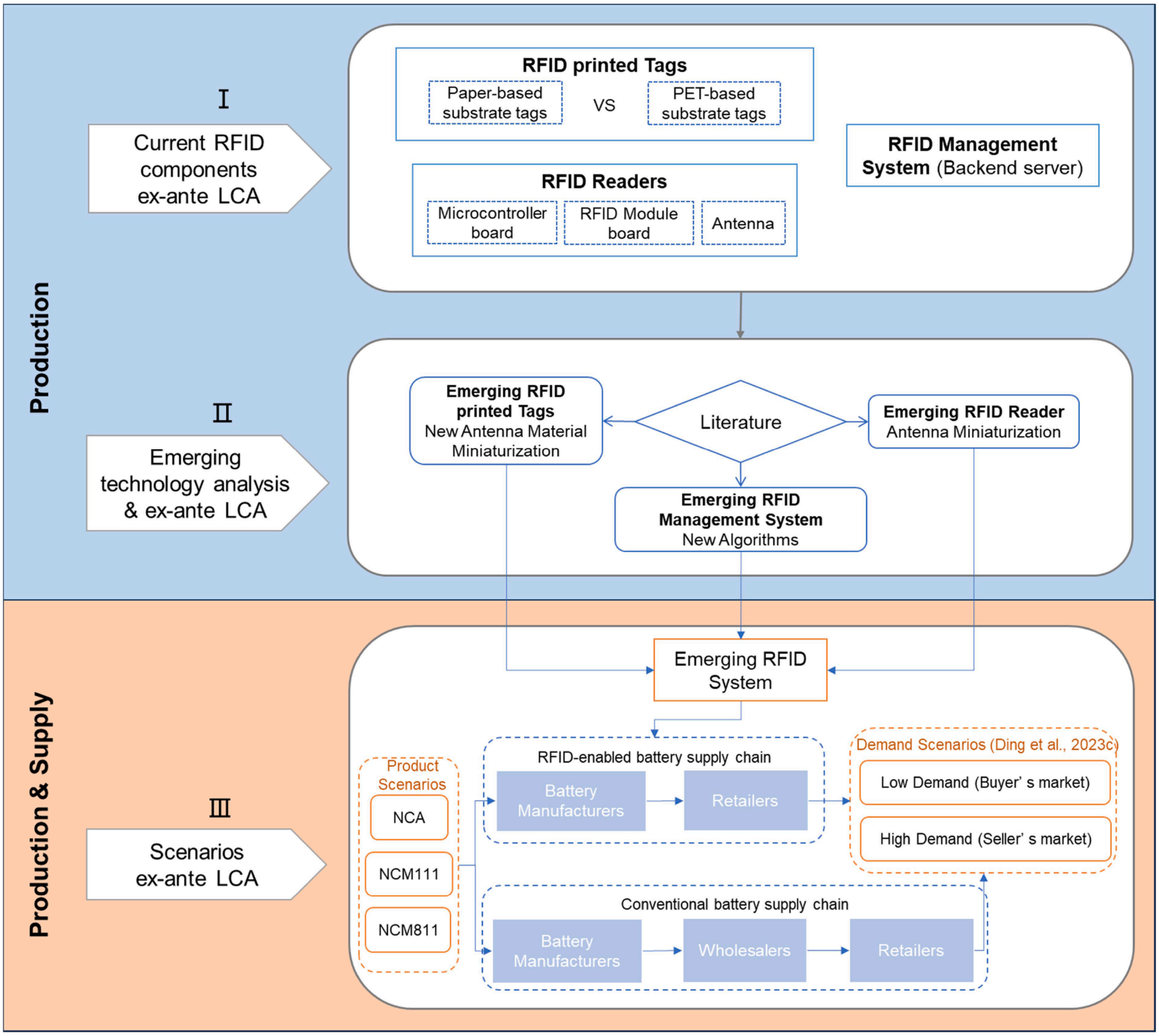

Fig. 1. Methodology diagram.

the assessment in three phases, which are as follows.

In phase I, an ex-ante LCA study of the current RFID tags (paper- and PET- based), readers and management system are deployed, respectively. In phase II, technology analyzes are conducted to explore potential evolutions and developments of the selected technologies (substrate and conductive materials for tags, miniaturization for readers, and new algorithm designs for management system). The functional unit in these two phases (I and II) are so-called technical functional unit, thus defined as “producing 1 unit of tag” for LCA calculation of current and emerging tags, “producing 1 unit of reader” for LCA calculation of current and emerging readers. They are only comparable within the same type of RFID components (e.g., in between different types of tags).

Finally, in Phase III these analyzes are fed into three implemented scenarios (NCA, NCM111, and NCM 811) and two demand scenarios (high- and low- demand) to perform the ex-ante LCA of alternative battery setups. Simulation work that we conducted in previous published work supports the projected data estimation and demand scenarios definition in upscaling (Ding et al., 2023c). The functional unit in this phase is defined as “1 kg of battery module produced and delivered to users”, thus considering that the whole RFID system (incl. tags, readers and backend servers) work together to support the battery supply chain.

This ex-ante LCA study applies cradle-to-gate approaches in the first two phases (tags or readers are produced from raw materials and stored in local warehouses) and a cradle-to-site approach in the third phase (the packaged batteries together with RFID tags are produced from raw materials and finally delivered to consumers). The background processes for three Li-ion batteries were modelled using the Ecoinvent 3.8 database (Wernet et al., 2016), while the foreground processes for RFID systems and RFID-optimized supply chains come from relevant peer reviewed literature and reports (Peng et al., 2020; Su et al., 2020; Avery Dennison, 2023; Ding et al., 2023c) (see Supplementary Table 1–5 for inventory data). The LCA followed the ISO 14,044 framework (International Organization for Standardization, 2020). The Activity Browser software (AB) was used for the LCA calculations (Steubing et al., 2020).

This paper uses the International Reference Life Cycle Data System (ILCD) 2.0 2018 impact assessment method that translates thousands of LCI entries to 16 mid-point impact categories using a variety of environmental mechanisms (Junne et al., 2021) (see Supplementary Table 1). The characterization factors were adapted for the Ecoinvent 3.8 database used. We focus in the main body of the article on i) Climate change (CC) – due to the relevance of greenhouse gas emissions and the climate goals of the EU. ii) Abiotic resource depletion (ARD) – due to relevance of raw materials and energy used for printed electronics and components and to reduce the demand of critical metals and minerals along the entire life cycle. iii) Freshwater & terrestrial acidification (FTA) – due to high demand of acids and other chemicals for printed electronics and pre-products. iv) Photochemical ozone creation (POC) – due to the general interest in reducing its impacts to the environment (Gehring et al., 2019).

3. Inventory and scenario analysis

3.1. Inventory analysis of current RFID passive tags (Phase I)

The definition of current technologies in an ex-ante LCA approach depends on identifying technologies at a later stage of the technological development curve, i.e. those that have already passed the pilot stage, or have achieved a considerable level of market penetration. The current (incumbent) technology should reveal advantages in comparison with available alternatives (e.g. being cheaper, more efficient, or have lower environmental impacts) (Cucurachi et al., 2018). The traditional etching approach for tag production consumes a large amount of metal materials, and needs to go through a series of complex processing steps, resulting in a large amount of waste liquid. In contrast, printing as an alternative approach is an additive manufacturing process that has a high utilization rate of metal materials at lower costs (Yang et al., 2023). Therefore, the mature printed tags (printed antennas and integration of conventionally manufactured surface-mount devices, TRL6–7) are selected to be the current technological pathways.

The passive tags being used to record and locate certain cargos do not require separate batteries for power supply and hence have longer lifespans compared with active tags (Shariq et al., 2022). To do so the tags are powered through electromagnetic waves of the reader. This process is called radiative coupling or backscatter coupling.

To produce a passive printed RFID tag, materials like substrate, conductive and dielectric ink are required for printing and curing, see Supplementary Figure 2. The process involves depositing and curing the inks, then attaching small devices like integrated circuits (ICs) to the printed antenna. Chemical-free methods like printing are increasingly used in antenna manufacturing (Gehring et al., 2019), where silver particle is prevalent conductive material as antenna (Bottani et al., 2014; Fernandes et al., 2020). Silver-based inks enable fabrication on flexible and environmental-friendly substrates like PET film and paper using inkjet printing (Yang et al., 2023). We therefore select it as the current antenna material for both PET and paper-based printed tags in this research.

Silicon ICs are manufactured by etching pure silicon into wafers with multiple individual ICs, which are then cut apart. Each RFID tag typically contains one IC attached with epoxy or polyurethane based materials (e.g., silver nano particles) as conductive adhesives (Bottani et al., 2014). The tag is then protected with a conversion layer using glue like methyl acrylate for physical and chemical protection (Liu et al., 2014), ensuring durability.

The example PET-based RFID tag details are from Smartrac company provided by Bottani et al. (2014), while paper-based tag weight is estimated based on substrate density and electrically conductive adhesive (ECA) (see Supplementary Table 2 and 3). Due to the lack of specific LCI dataset for tag composition, we assume the polyurethane- (or epoxy) based materials (ECA binder) to be pure polyurethane (or epoxy), and silver particle-based ink (Antenna) as silver ingot in LCA calculation.

3.2. Inventory analysis of current readers and backend server (Phase I)

RFID readers transmit and receive radio waves to communicate with tags, computers, or smart devices (Seol et al., 2017). Ultra-high frequency (UHF) handheld readers, particularly useful for locating items or taking inventory, include an integrated antenna (generate radio waves to communicate over long distances), RF module, and controller. RF modules ensure that i) tags are provided a radio wave for energy supply, ii) modulation of the transmitter signal for the transmission of data to the tag and iii) the demodulation of data received from the tag (Shokouhifar, 2021). The controller manages communications with the host, executes commands, and facilitates signal encoding and decoding. Readers can utilize tag contents to access a backend database linking product information or tracking logs (Williams et al., 2019). While the backend server is to manage the gathered information from different RFID readers.

Manufacturing RFID readers involves assembling processor chips, interfaces, LEDs, and other components on PCBs. It comprises three main parts: a microcontroller board, RFID module board, and antenna. The Arduino Mega 2560, a widely used microcontroller board, offers various pins, inputs, serial ports, and connectivity options (Meje et al., 2021).

RFID modules typically integrate RF encoder and decoder IC functions alongside other components on a PCB, forming the RFID module board. Connecting the microcontroller board, RFID module board, and antenna completes the basic RFID reader assembly (see Supplementary Figure 3).

While critical material data for RFID readers is lacking, inventory analysis of RFID reader can be estimated using sub-component datasheets combined with Ecoinvent database (for printed wiring board), see Supplementary Table 4. The information of critical raw materials usage is based on one functional unit (one reader).

The backend servers (hosts) rely on hardware devices like workstations and relative software to manage the dataset transferred from RFID readers. Unlike hardware items such as tags and readers, PCs or workstations are not only used for RFID systems, therefore we considered only their energy consumption in operating and managing RFID system rather than the material use of supported hardware. In an ordinary RFID system, the energy consumption for reading and writing one tag once is 3.605 W (Mouattah and Hachemi, 2020).

3.3. Inventory analysis of emerging RFID technology (Phase II)

3.3.1. Emerging RFID tags

Fully printed tags (printed antennas and ICs) are another emerging technological option to build RFID systems, while their IC performance in computation and signal communication may not yet match the silicon-based IC (Khan et al., 2020). However, printed ICs can hardly meet the requirement for providing enough information and supporting battery supply chain operations. Therefore, we still focus on hybrid printed tags with emerging materials and designs.

In hybrid printed RFID tags, minimizing antenna size for integration with compact devices while maintaining performance parameters (e.g., antenna gain, radiation efficiency and bandwidth) requires a trade-off. Metal-based conductive materials, particularly silver or copper inks, are still choices. Inui et al. (2015) fabricated a miniaturized flexible antenna on a high dielectric constant paper. The silver antenna printed on this paper was downsized by about a half, compared with the antenna printed on the conventional plastic film, and it retained its sensitivity to specific radio frequencies. Hong et al. (2022) demonstrated an effective method to fabricate an antioxidant high-conductivity copper paste for printed RFID tag antenna. The utilization of formate anions and organic thiols improved the antioxidation properties of the flake-like copper powder as well as the electrical conductivity of the as-prepared copper paste. The antioxidant copper paste can be printed on different substrates with appealing electrical and mechanical properties, which allowed the achievement of outstanding performances in stability, flexibility, and cost for printed RFID antennas. The optimized copper paste was composed of copper powder (processed by formate ions and dodecyl mercaptan to form a protective layer), phenolic resin (PR), triethanolamine (TEA), and aminomethyl propanol (AP) as both solvents and curing agents, dimethyl carbonate (DC) as an additive agent to enhance flexibility (Peng et al., 2020). The optimum mass ratio is

50:22:15:11:2.

As for substrate materials, the polymers are more stable and have better flexibility and scalability and a lower price. Compared with paper-based materials, it is resistant to moisture and corrosion (Yang et al., 2023). Therefore, polymer substrates will be widely used in the field of flexible printed RFID antennas. The optimized designs have decreased the size of RFID antenna, and the material use of polymer substrate will also drop significantly. Some cases proved a 40 % of substrate material use can be saved to achieve similar impedance matching performance (Xuan et al., 2016; Ahmar et al., 2022).

Therefore, considering these main potential improvement directions, we assume two emerging RFID tags (expressed as New_A and New_B) with the same mass, consisting of silver particles and optimized copper paste-based antenna materials respectively. Both tags have smaller size of substrates and antennas compared with current tags, see Supplementary Table 5.

3.3.2. *Emerging RFID readers and management system*

Similar to RFID tags, the major requirement of the RFID reader is minimizing antenna size with circularly polarized (CP) characteristics. There are two directions of UHF RFID CP antenna designs: one is multilayer stacking (Lin et al., 2013) and the other is single-layer printed planar microstrip antennas (Raviteja et al., 2014). The impedance bandwidth of the multilayer stacked type is larger but they have bulky structures. While the single-layer planar antenna has advantages over these antennas such as relatively low-cost to manufacture and light weight. Both of these two structures are optimized to have compact size and offer larger bandwidth with good quality of circular polarization. According to data compiled by Farswan et al. (2016), antennas (with similar performance) have reduced their size by about 10 % in three years, so we assume that the size (material usage) of antennas in emerging readers can be reduced by at least 30 % before 2040.

Compared with tags and readers, new algorithms or protocols are the main solution to improve the energy efficiency of RFID systems, especially in reader-tag interaction domains. For instance, a time and energy saving based frame adjustment strategy (TES-FAS) algorithm is proposed to improve the time and energy efficiency by optimizing parameters that is not leveraged by the prior algorithms including MAP and Q-algorithm (Su et al., 2020). Their proposed TES-FAS algorithm can achieve 3 % higher energy efficiency compared with prior state-of-the-art solutions. We here use it as the referenced energy consumption (3.497 W) of emerging RFID systems compared with conventional ones.

3.4. *Scenario explanation (Phase III)*

We set up application scenarios of RFID systems based on the system dynamic structure of Lithium-ion battery supply chains (Ding et al., 2023c), see Fig. 2. It mainly shows how RFID systems work in the battery supply chain under proposed scenarios. We assume that the battery and logistics companies directly buy these RFID components from market (usually one-time purchases in bulk) and build up their RFID system. The operation of this supply chain is not continuous and not influenced heavily by market dynamics. Therefore, we simplify the details of RFID supply chain dynamics. Since all RFID components work together as a system in Phase III and they play the role in optimizing the battery supply chain, they use the consistent functional unit – “1 kg of battery module produced and delivered to users”. The flowchart for the production of the RFID-enabled Li-ion batteries using NCM811 as an example, is shown in Supplementary Figure 4.

The IoT-enabled battery supply chain mainly includes manufacturers and retailers. The Li-ion cell modules from the producing factories are being sold to users (e.g., electric vehicles users), and the demands of potential users drive the production arrangement of Li-ion modules of the supply chains. Since the demand-supply relationship is a significant factor shaping the relative environmental improvements of IoT-enabled sustainable supply chains compared with conventional ones, here two representative demand scenarios: High-demand and Low-demand are

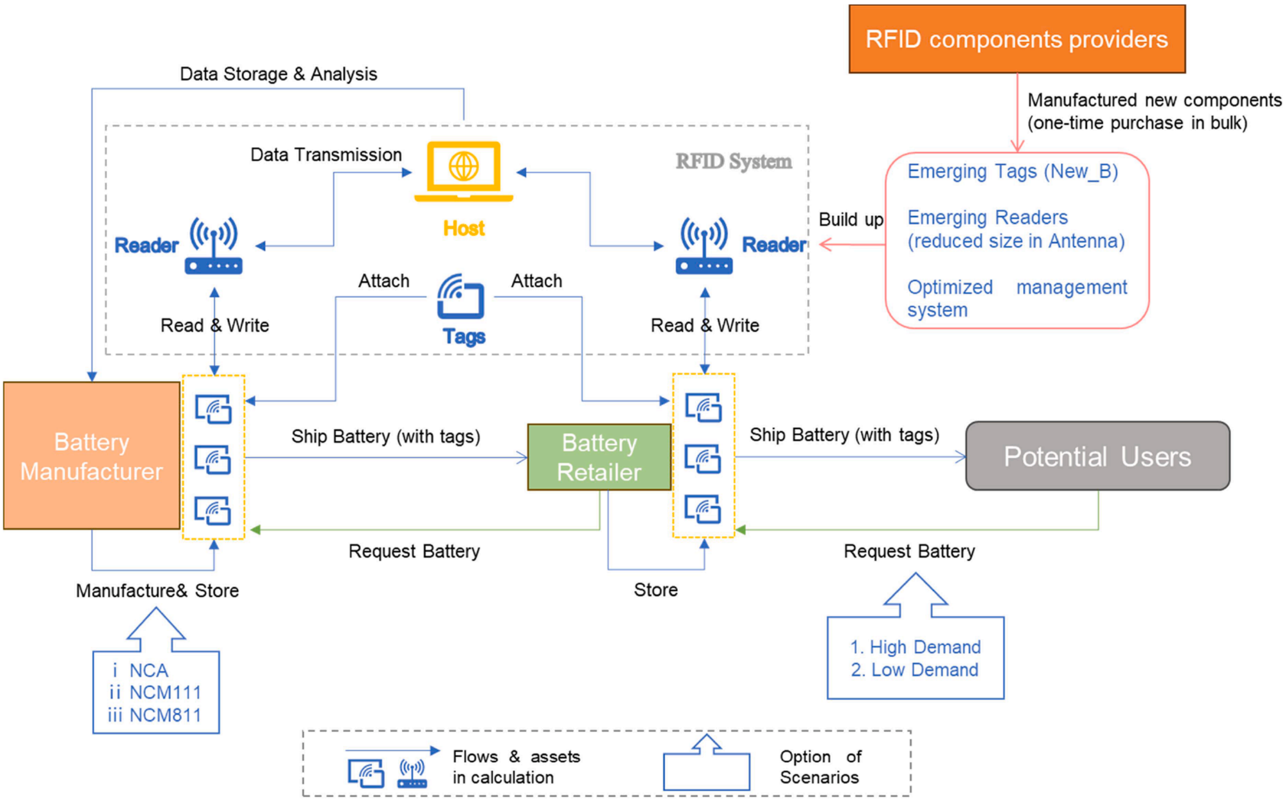

Fig. 2. RFID system applied in Lithium-ion batteries supply chain scenarios.

settled up to reflect market situation. See e.g., Ding et al. (2023c) for more details of this SD-AB model. Furthermore, in this example structure host, readers and tags work as a complete RFID system to support this supply chain. Tags are attached on the surface of each produced battery cells to record their key information (e.g., Production Date, Type, Location). Each supply node has a reader to read and write products (batteries) information once they are flowing in (being stored after produced) or flowing out (being transported to downstream nodes) of warehouse. Therefore, an RFID reader should read each tag two times (when entering and exiting the warehouse) at one supply node. All the recorded information is managed and analyzed by the host with a certain software. This collected information is also used to locate and monitor every battery cell to optimize shipment and storage strategy in supply dynamics.

This proposed structure is used to assess three representative IoT-enabled Lithium-ion batteries (NCA, NCM111, NCM811) scenarios, their life cycle inventory can be acquired directly from Ecoinvent 3.8 database. Other global significant parameter settings in these scenarios are shown in Supplementary Table 6.

4. Results

4.1. LCA study of the RFID tags and readers (Phase I and II)

We used the Activity-Browser software developed by Steubing et al. (2020) to model and analyze our LCA results. The selected environmental impacts of four RFID tag types as described in Sections 3.1 and 3.3 see Fig. 3. The others are in Supplementary Figures 5a and b.

We do not observe a significant difference between the existing representative current Paper and PET-based RFID tags under the four environmental indicators, however the new miniaturized tags can significantly reduce their negative impacts on the environment, especially tags using emerging antenna materials (e.g., in RFID_NewB). The only exception occurs in the ozone layer depletion category, where paper-based tags cause less environmental impact (see Supplementary Figure 5a).

For the contribution of each component, the direct energy consumption of three tags (Paper-based, PET-based and NewA) in the manufacturing process contributes more than half for CC and ARD, followed by the antenna. While the antenna contributes larger in FTA and POC compared with direct energy consumption. However, the improved material significantly reduces the environmental emissions of the antenna in NewB, making energy consumption the largest contributor factor for all four environmental dimensions. Other components or processes have little impact (less 10 % even summed up). Therefore, the emerging RFID tags should mainly focus on the development of less environmental impacts materials, miniaturization for antennas, as well as low energy consumption printing and sintering methods. Also, more cleaner energy supply would be another way to shrink environmental impact.

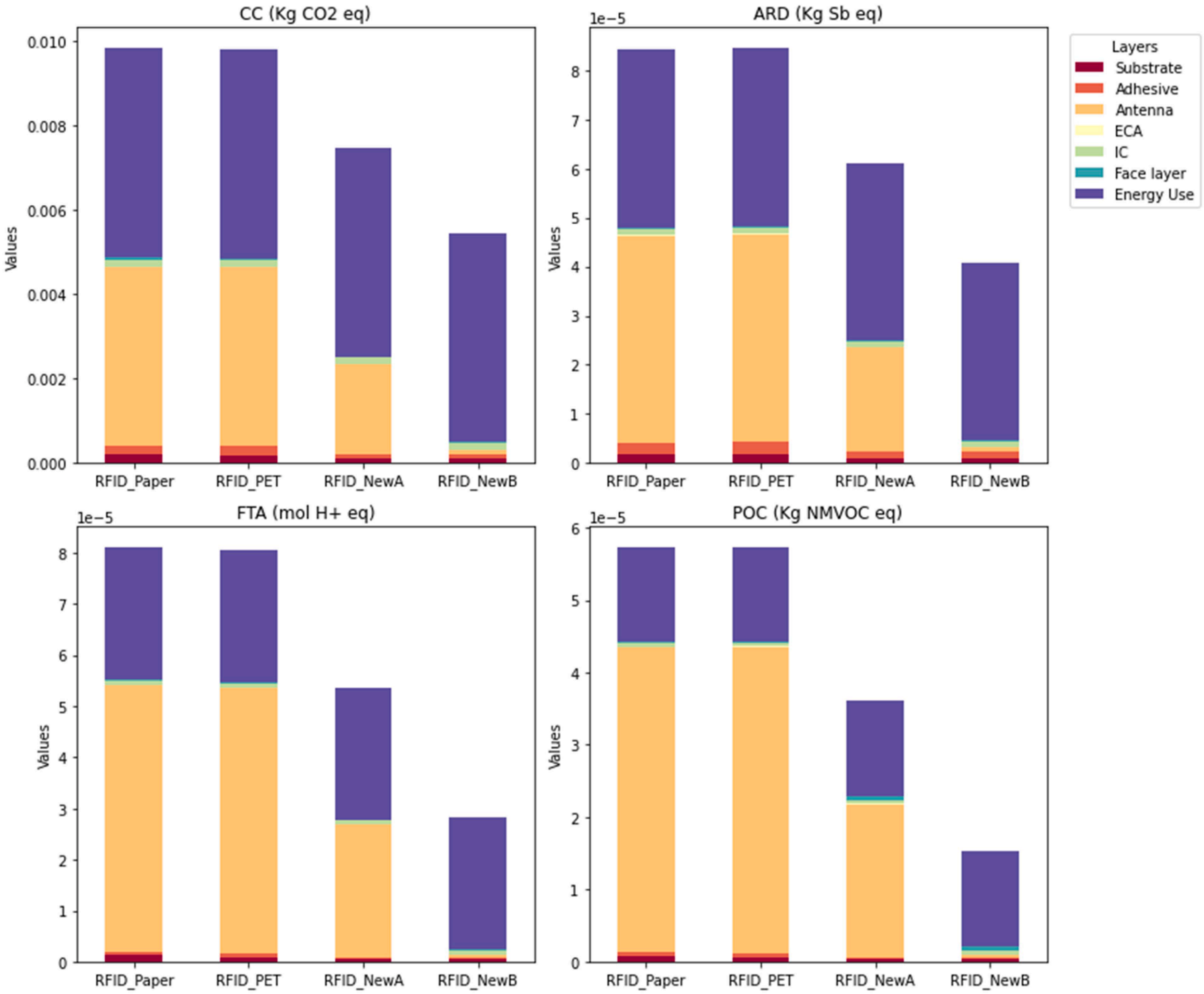

Fig. 3. Environmental impacts of producing 1 unit of current or emerging (new) RFID tags (from selected categories of ILCD 2.0).

We then measured the selected environmental impacts of the current and emerging (reduced size in antennas) RFID reader, see Fig. 4. The other categories are shown in Supplementary Figure 6a and 6b.

Due to its larger weight and extensive use of metal in integrated circuits and antennas, the absolute environmental impact value of RFID reader is much greater than that of tags. For instance, the environmental impact of an emerging reader is 5420 times greater than that of the tag (NewB) in terms of climate change impact. The module board and microcontroller board are particularly influential in this regard.

The reader improvement mainly relies on technical performance potential through increasing the reader's antenna frequency band and enhancing the signal range. Miniaturization of antennas plays a limited role in environmental improvements, as the antenna accounts for only 10 % to 15 % of the total environmental impact of each reader across various impact categories. Therefore, the proposed improvement to the RFID reader should not only consider minimizing the antenna size, but also optimizing the design of the microcontroller and transceiver (Module) circuit and using a better integration of electronic components to reduce the required circuit board area.

4.2. LCA study under three battery chemistry and two demand scenarios (Phase III)

LCA calculations in phase III are performed based on different battery chemistry and market demand scenarios, as explained in Section 3.4. Fig. 5 depicts nine groups of relative environmental impacts of battery supply chains with and without the application of RFID system (based on New_B Tag, emerging Reader and optimized Management System in Fig. 2). The contribution of RFID systems to more sustainable supply chains is assessed through simulating results for the high (Decrease 50 % emissions in transportation and storage, D-50 % in figure) and low (Decrease 70 % emissions in transportation and storage, D-70 % in figure) market demands scenarios in Ding et al. (2023c) respectively. This is because in low demand scenarios, the accurate scheduling of orders and storage becomes quite significant. In conventional supply chains low demand scenarios easily lead to a high level of storage on average. While the more accurate scheduling for a "zero inventory" enabled by IoT will lead to a relative higher reduction of carbon emissions compared with conventional ones (Ding et al., 2023c). The performances within the four environmental impact categories for NCA battery production and delivery process without RFID implementation were set as baseline values (100 %). The other categories are shown in Supplementary Figures 7a and b.

The advancement of battery chemistry technology itself will contribute to reducing negative environmental impacts. For example, NCM811 reduces impacts by an average of 2 % compared to NCA. In contrast, NCM111, due to its higher cobalt content, exhibits increased environmental impacts in terms of CC and ARD compared to NCA.

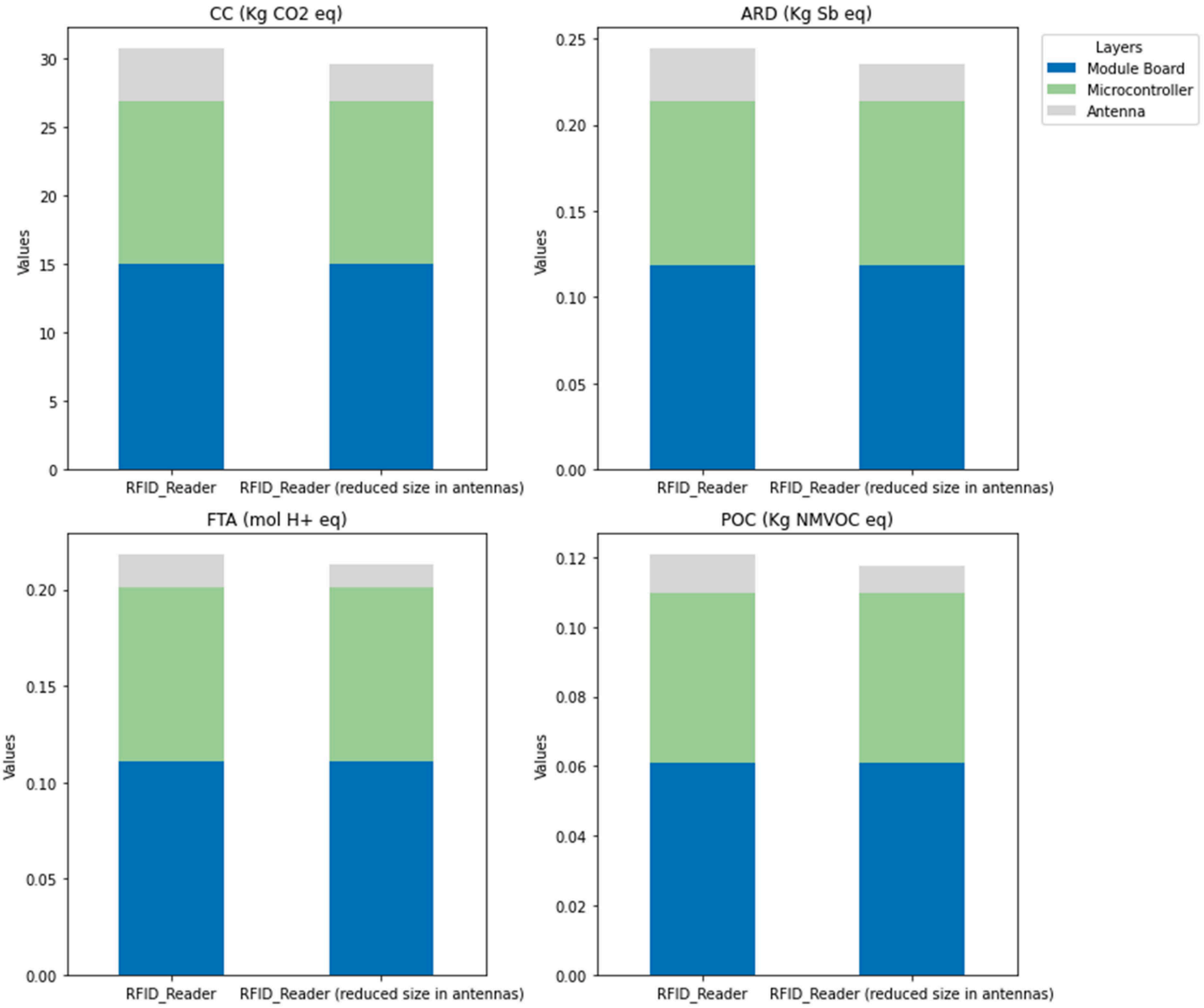

Fig. 4. Environmental impact of producing 1 unit of current or emerging (reduced size by 30 % in antennas) RFID readers (from selected categories of ILCD 2.0).

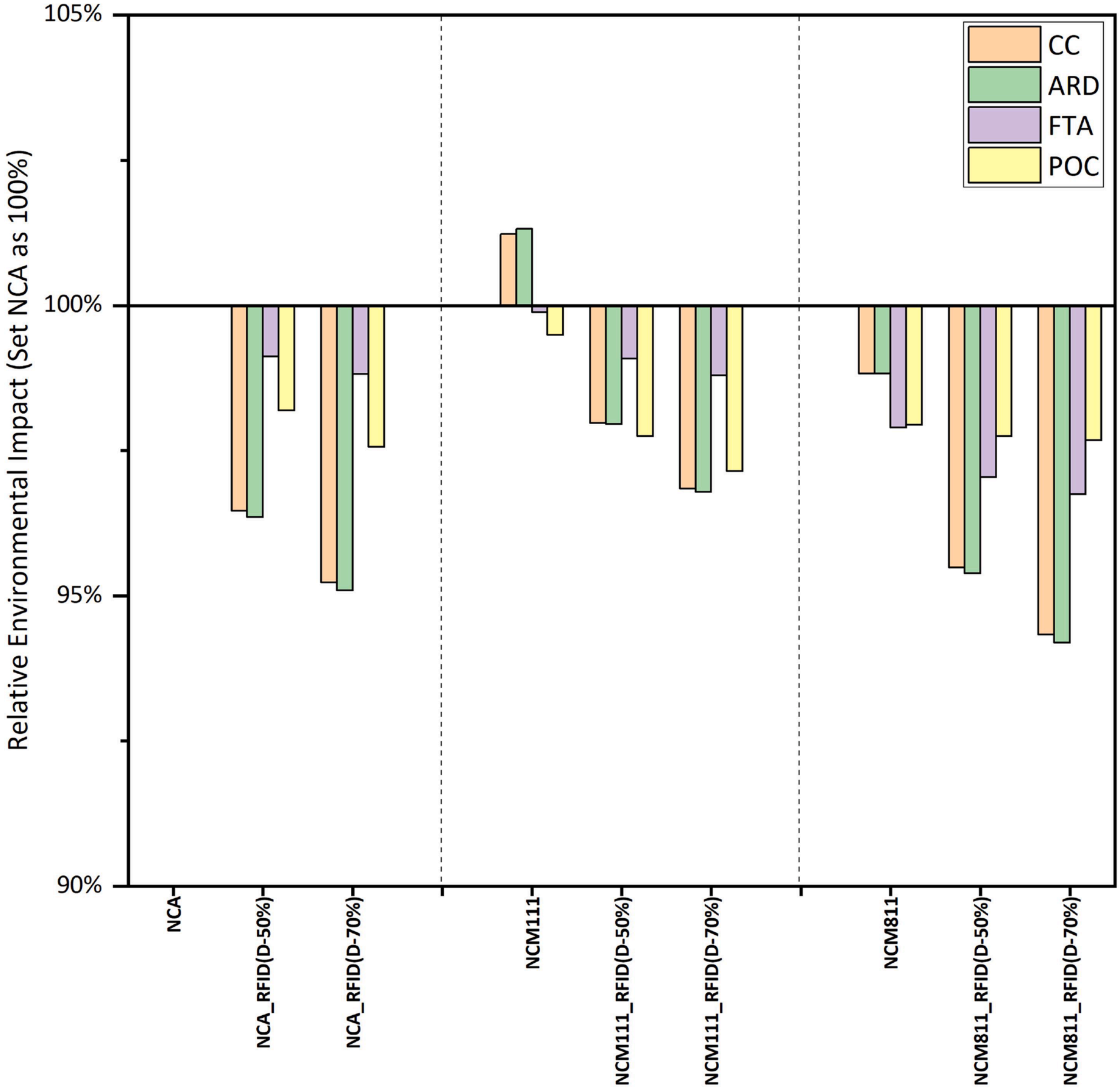

Fig. 5. Relative environmental impacts of producing and delivering 1 kg of Li-ion batteries under different batteries and demand scenarios (based on conventional and RFID-enabled battery supply chains).

However, RFID systems can achieve additional improvements in some indicators through optimizing the supply chain. In high-demand scenarios (D-50 %), the RFID-enabled NCA battery supply chain has a better environmental performance in CC and ARD compared with the new battery (NCM811). In low-demand scenarios (D-70 %), an RFID system reveals advantages through supporting supply chains in the two previously mentioned impact dimensions. Impacts further decline for the POC indicator compared with new batteries without RFID system support.

4.3. Contribution analysis of RFID under different demand scenarios (Phase III)

Further zooming into the LCA results reveals the individual contribution of additional environmental impacts of RFID system in a battery supply chain (producing and supplying 1 kg NCM811 as a case), see Fig. 6. The average environmental impact of building the RFID system itself is extremely low compared to its supported battery supply chain. It accounts for less than 0.1 % of the impact under 4 environmental indicators. Overall, the extensive consumption of tags constitutes the primary source of environmental impacts within RFID systems. Despite the fact that the environmental impact of an individual reader is substantially greater than that of a single tag, a reader is capable of supporting the reading and writing of hundreds of thousands of tags (500,000 in this study) throughout its lifespan. Consequently, two readers in this study contribute to only 2 % of environmental impacts of whole RFID system, as illustrated in Supplementary Figure 8.

However, the contribution of RFID optimized supplying operations to environmental emission reduction is substantial. Supplementary Figure 9 depicts the contribution of RFID system and battery chemistry improvements to environmental impact reductions switching from NCA supply chains to RFID-enabled NCM811 alternatives. The use of RFID systems in optimizing battery supply processes results in larger reductions in CC and ARD than switching to low-carbon battery chemistries (using NCM811 instead of NCA). Considering the negligible

Fig. 6. Environmental contribution of RFID components in producing and delivering 1 kg of NCM811 batteries.

additional environmental impacts of whole RFID systems, the environmental benefits of investing in an RFID system in battery supply chains seems to be highly worthwhile.

5. Conclusion

This study uses an ex-ante LCA approach combined with a technology analysis and pre-scenario development determined through SD-AB models. It explores the environmental impact of RFID system for three Lithium-ion battery supply chains (from production to users of EV batteries). Furthermore, emerging technologies for RFID systems are considered.

As for environmental impacts of current and prospective RFID components (RQ1), adopting IoT/RFID systems creates additional environmental burdens whenever tags are the major contributors to environmental impacts, primarily because of the large number of tags used to monitor and track products flowing in and out of warehouses. Emerging new tags (new antenna materials and miniaturization) and readers (antenna miniaturization) hold the potential to reduce 25–70 % and 3–10 % for most of the environmental impact categories, respectively in comparison with currently applied technologies.

The overall environmental impacts of all three battery supply chains supported by RFID systems are positive (RQ2), even when taking the additional environmental impacts of the current IoT/RIFD systems into account. The resulting, more efficient logistics for the illustrative Li-ion battery supply chains lead to a net life-cycle (cradle-to-site) reduction for most environmental impact categories (around 3 %–5 %). This reduction is most prominent for low-demand scenarios. Efficient and accurate scheduling of RFID systems can minimize required storage levels, resulting in significant emissions savings. A contribution analysis shows that the use of RFID systems in optimizing battery supply processes increases the reductions in CC and ARD in comparison to switching to low-carbon battery chemistries (e.g. using NCM811 instead of NCA).

The results also reveal that using emerging materials and miniaturization in key RFID components such as antennas can significantly reduce associated negative environmental impacts (RQ3). However, because of a missing system-perspective technicians may overlook linked processes that account for a considerable proportion of environmental impact when pushing for further improvements of certain technical performance of RFID components. Ignored processes include direct energy consumption within RFID tags production, miniaturization and simplification of reader's transceiver and microcontroller. Focusing on the latter could be a focus of future research.

This research also has constraints. Firstly, this paper focuses on product flows which are at the supply chain intersection of production and use, we do not consider the RFID's capability in recycling or reusing processes of batteries as well as the reuse and recycle phase of RFID components. Secondly, although ex-ante LCA approaches could help to calculate the critical raw material requirements and additional environmental impacts of the RFID systems, current LCI data on RFID systems are far from sufficient. Since the available data are mostly from literature with high innovation dynamics, we use simplified assumption for mass and composition of RFID materials. The calculation results may slightly deviate from refined assessments. It is hence recommended to embark on a program of primary data acquisition for a solid assessment of impacts. Availability of comprehensive first-hand RFID product composition data combined with an up-to-date LCI database would be of great significance for improving and expanding this research.

CRediT authorship contribution statement

Suiting Ding: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stefano Cucurachi:** Writing – review & editing, Supervision. **Arnold Tukker:** Writing – review & editing, Supervision. **Hauke Ward:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Suiting Ding reports financial support was provided by China Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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