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Review

Material Sustainability of Low-Energy Housing Electric Components: A Systematic Literature Review and Outlook †

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† This paper is an extended version of our conference paper from the 4th LA SDEWES Conference, Viña del Mar, Chile, 14–17 January 2024 and WSED 2024, Wels, Austria, 5-8 March 2024.

Abstract: As part of the energy transition, near-Zero-Energy-Buildings use electric systems that reduce emissions and consumption. Nevertheless, the increased use of such systems comes with the E-waste challenge. Circular Economy concepts try to make more efficient use of these materials, but sustainable evaluations mainly focus on energy and emissions. The developed automated text analysis tool quantifies the appearance of circularity concepts in open-access literature about different stages of production, use, and end-of-life for heat pumps, Lithium-Ion batteries, photovoltaic modules, and inverters. The energy focus is corroborated in different amounts depending on the component and stage, and when circularity concepts appear, they are centred on waste and recycling. Numerical variables to model environmental impact available in open-access literature are limited, generalised, or present in a wide range. Access to product environmental specifications should be encouraged to ensure that energy transition is sustainable in all its dimensions.

Keywords: Circular Economy; sustainable energy; photovoltaic systems; heat pumps; sustainable evaluation

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Academic Editors: Oz Sahin and Russell Richards

Received: 11 November 2024
Revised: 9 January 2025
Accepted: 20 January 2025
Published: 22 January 2025

Citation: Carrasco, F.A.; May, J.F. Material Sustainability of Low-Energy Housing Electric Components: A Systematic Literature Review and Outlook. *Sustainability* **2025**, *17*, 852. https://doi.org/10.3390/su17030852

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1. Introduction

Buildings have a significant potential to fight climate change, as worldwide, they account for around 38% of energy-related CO_2 emissions [1]. Consequently, the EU required that all new buildings should be 'Nearly Zero Energy Buildings' (nZEB) by 2020 [2]. These use a set of energy strategies that frequently include renewable energy, usually photovoltaic (PV), efficient heating/cooling, as well as forced ventilation [3] or automation [4]. Examples of sustainable houses in different contexts, Australia [3], Japan [5], and the United States of America [6], are concluded to be environmentally and financially advantageous while also improving living conditions.

Nevertheless, overcomplicating systems could lead to efficiency loss [7], and high resource use and reliability should be considered as there can be simpler vernacular alternatives to high-tech automation [4]. Critiques can also be made as when modelling and optimizing PV [8] and heating [9], focus is given to cost and CO_2 emissions. However, in sustainability, there are many other factors to consider, as shown in Life Cycle Assessment (LCA). This approach shows different environmental indicators, which may include End-of-Life (EoL) challenges for Lithium-Ion Batteries (LIB) [10], overall higher impacts excepting emissions for heat pumps (HP) [11,12], or land use, emission, and water use challenges for PV [13].

Material use and its implications are generally neglected, but they are especially interesting for these electrical components due to their potential role in the development model [14]. As the electrification of building energy systems and E-waste continues to increase, it is of interest to study how Circular Economy (CE) concepts are incorporated into sustainable evaluations of energy systems of the energy transition.

Individual components of these systems and specific CE strategies are extensively treated in the literature, but their evaluation as a whole, including all possible combinations of strategy/component and their implications, is not well documented. Review papers try to gather and summarise the literature, but they tend to fall into the same component specificity problem. Accordingly, a systematic evaluation would be beneficial to assess and prioritise possible measures.

Therefore, the challenge is to holistically assess the current research focus, identifying trends and gaps in an automated manner and representing them quantitatively, such that comparing different technologies is more accessible. Thus, the objective is to evaluate sustainability and CE concepts in qualitative and quantitative trends in research papers about electrical systems used in nZEBs. For this, qualitative trend analysis should be conducted in a systematic and automated way, and corresponding quantitative values needed to model such systems should be manually identified.

2. Methods

Qualitative and quantitative trends have different approaches, as they have different focuses. These are described in the following points.

2.1. Qualitative Trends

Qualitative trends in a research topic can be monitored by the frequency of appearance of specific keywords or indexes. This does not refer to the result of the evaluation but only if the subject is being addressed. Examining words that are present in a text and then relating them to a research topic is difficult, as separation from contextual and thematic words needs to be achieved manually or by advanced classification methods. Topic detection tools are available, but they require the use of external servers or processing algorithms that cannot always be customised. Alternatively, a common and locally feasible approach are Wordclouds, which present words by frequency after cleaning a text from connectors. Applying this to 241 open-access research papers shows results that are more general than expected, as shown in Figure 1.

Therefore, a second option is to look for specific representative words that characterise a particular research topic and then find them in the text. These representative keywords can be selected from a set of sustainability evaluation methods defined by the literature. Sustainability keywords can be taken from LCA, as it is a methodology to evaluate a project through its complete life. A set of elements to consider is stated by the German Institute for Standardisation [15] and the European Commission [16]. For CE, keywords can be obtained from one of its many definitions, e.g., "...a design for repairing, remanufacturing, refurbishing, or recycling to keep products, components, or materials circulating in and contributing to the economy..." [17] or 10 R definition [18]. Also, in the Ellen Macarthur Foundation butterfly diagram, maintaining, prolonging, refurbishing, remanufacturing, and recycling are important cycle subloops [19].

Finally, evaluated technologies used as active strategies in nZEBs are heat pumps, Lithium-Ion batteries, PV inverters, PV modules, and PV systems. Evaluated methods are 'life cycle assessment', 'circular economy', 'manufacturing', 'degradation', 'reliability', and 'end-of-life'. Each search consists of all possible combinations of methods and technologies.

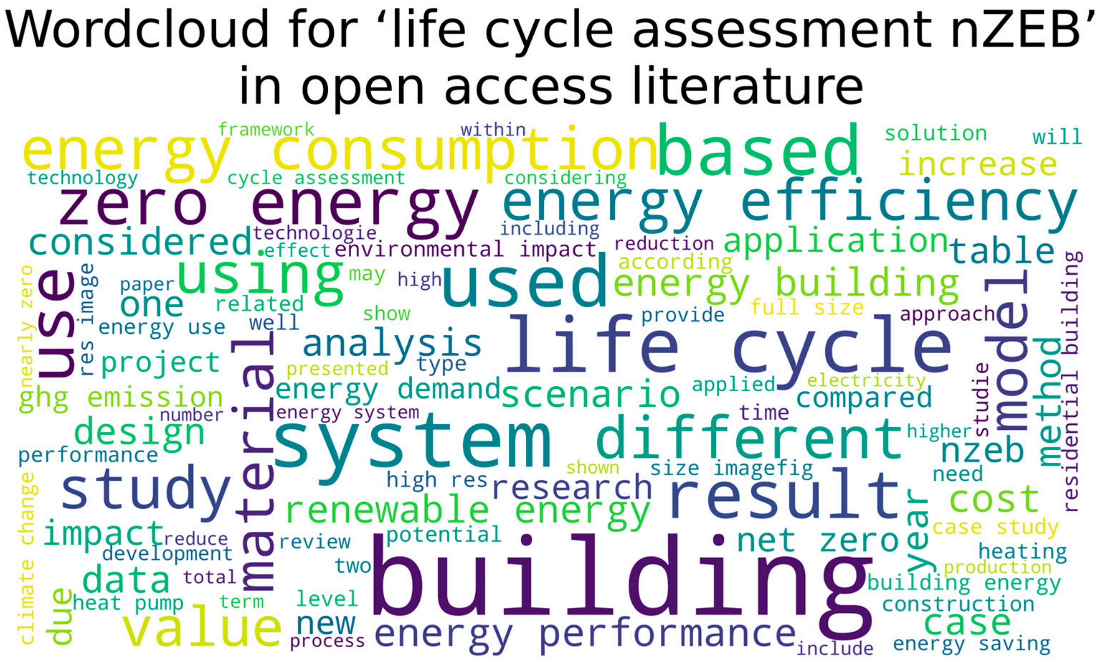

Figure 1. Wordcloud for "life cycle assessment nZEB", mostly generic words are identified.

2.2. Text Processing

Processing was performed with Python. To have a good article corpus, systematic separation by topic needs to be conducted over a vast number of available open-access candidate articles. To achieve this, article filtering is conducted by searching for words' frequency of appearance in the text. Trends can later be identified by counting input indexes obtained from previously mentioned concepts. The process workflow can be summarised in Figure 2.

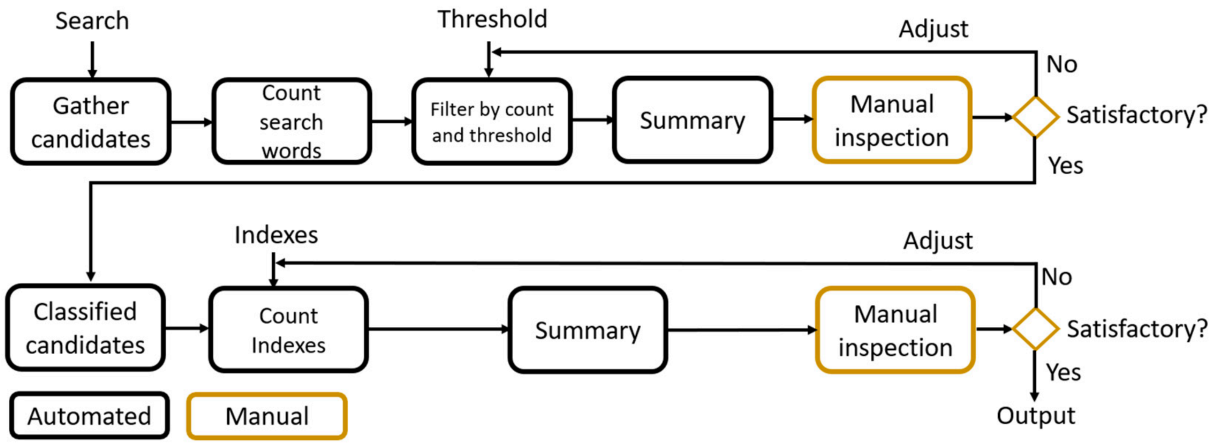

Figure 2. Workflow of article processing and manual intervention reduced to the minimum possible.

To obtain better text classification, shorter texts were prioritised; therefore, long "institutional reports" and theses were ignored. This also helps to reduce the number of possible article sources into better sources, thus helping systematisation. Accordingly, the three sources of papers for this research were ResearchGate, ScienceDirect, and MDPI. Open-access papers are downloaded by search, with each search acquiring between 200 and 230 raw candidates. Taking "Life cycle assessment heat pump" as an example yielded five candidates from MDPI, ResearchGate (twenty-two candidates), and ScienceDirect (two hundred candidates), with a total of 219 candidates after removing duplicates.

Once the text of the papers is extracted (images are ignored), a count of search keywords is used to determine if the paper is on the right topic. Following the example, for each paper, a count of 'life', a count of 'cycle', a count of 'assessment', a count of 'heat', and a count of 'pump' would be completed. This count is in lowercase and eliminates special characters, thus reducing the number of possible combinations. This search count is then divided by the total paper word count in order to compare papers with different lengths. This is presented as appearances per 10,000 words; hence, the numbers are not too small. If all input search words are above a certain threshold (30 for LCA, 20 for degradation, and 15 for CE; manufacturing, EoL, and reliability, appearances per 10,000 words), then the paper is considered acceptable for the analysis. Finetuning the threshold requires a quick manual review of paper titles and keyword appearances. Taking the paper "Environmental Life Cycle Assessment scenarios for a district heating network. An Italian case study" [20], the search word 'life' appears 79.7 times per 10^4 words, 'cycle' 70.24, 'assessment' 54.03, 'heat' 229.64 and 'pump' 81.05. Thus, this paper would pass the filter.

The same counting procedure is applied for indicator keywords, but no further action is taken. In the given paper example, results for 'climate change' were 18.91 appearances per 10^4 words, 'ozone depletion' 4.05, 'ionizing radiation' 6.75, 'photochemical ozone formation' 4.05, 'particulate matter' 4.05. The output of the process is a table where each paper is a row, and each index is a column. Each cell is a count per 10^4 words of the index on that paper.

This search is attained with "find in text" on a text striped from spaces, special characters, and break lines, and not with "word is", as some words can be deformed by the pdf formatting-extraction. This finding modality implies that searching for acronyms can lead to many false positives; therefore, they are avoided. Another challenge is that word conjugation, alternative spelling, or synonyms are not directly recognised. Nevertheless, this can be manually corrected by adding words to the "keyword list" but using the word root to include plurals and conjugations, also known as stem (recycl: recycle, recycling, recycled) or by including alternative wording of the search (end-of-life: decommissioning, . . .).

2.3. Quantitative Parameters

To complement this, quantitative values to model such systems are researched. These values would potentially be used to calculate material and energy inventories required to predict economic outputs and environmental impacts.

Material inventories mostly relate to the material needed to manufacture, operate, and decommission systems. Examples of operation and maintenance could also be lubricants, refrigerants, or cleaning fluids while repairing soldering or sealants. Replacements of complete components are also needed due to the EoL of cables, batteries, or modules; therefore, the lifetimes of components are also considered. After EoL, treatment options and efficiencies need to be accounted for. This could be in the form of repurposing, remanufacturing, upgrading, or recycling, but most commonly by disposal. This point is also associated with production energy per constituent part or by material mass.

Energy inventories refer to the amount of energy these systems generate/consume. Besides design capacities, degradation and operational times are required. Therefore, failure and repair times are again needed.

As the desired output of each component is different, each variable can be expected to be found and normalised in different units besides time, with thermal output and electric input in HPs, electric output and area for PV modules, electric output power and weight for inverters, or storage capacity and weight for LIBs.

Values for these parameters are manually searched by exploring accelerated ageing tests, manufacturer technical sheets, and "statistical" logs literature of specific components. Finally, for each technology, the following values are searched: Manufacturing: Material and Energy; Ageing: Lifetime, Degradation; Reliability: Failure, Repairability; Decommissioning: Recycle, Waste, Energy.

3. Results

Applying the aforementioned methods, the following results were obtained.

3.1. Qualitative Trend Results

Results are obtained with available papers until June 2023. The final number of articles after filtering can be summarised in Figure 3. It can be directly noted that some methods and technologies have more available matches. This is also noted as concepts such as decommissioning and ageing were originally tested with unsuccessful results. PV inverters show a low quantity of matches, while batteries have the most. EoL has the least number of matches by analysis mode, while degradation is significantly higher, especially for LIBs and PV modules. Additionally, 'life cycle assessment nZEB' was also searched with 13 total matches.

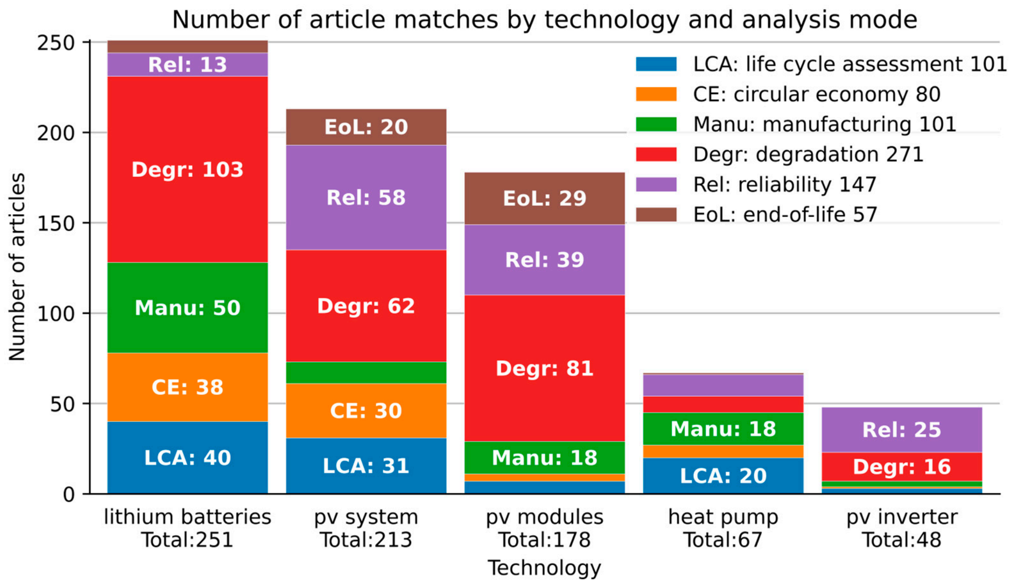

Figure 3. The number of article matches by technology and analysis mode. Lithium batteries have an overall number of papers addressing them, while inverters are the least. End-of-Life is the least frequent analysis mode.

Life cycle assessment: Technology average word count from original LCA indexes indicates a focus on 'climate change' with 5.4 per 104 words, followed by 'acidification' (1.6), 'land use' (1.1), and 'ozone depletion' (0.9) as the main topics of interest. Overall, 'Heat pump' addresses more indexes and more often. Oppositely, 'PV inverter' addresses fewer indexes, with only significant 'climate change' and 'land use'. Technology disaggregation can be seen in Figure 4.

Using the six most frequent synonyms and alternative wording found, average numbers across technologies improve for the 'material' group, increasing to 11.9, but 'emission' still triples it with 43.5. One noticeable exception (besides the 'material' concept) is 'recycle', especially for LIBs. Other concepts tested with limited success were specific materials and metals, LCA midpoints and methodologies, or indicator units. This is visualised in Figure 5.

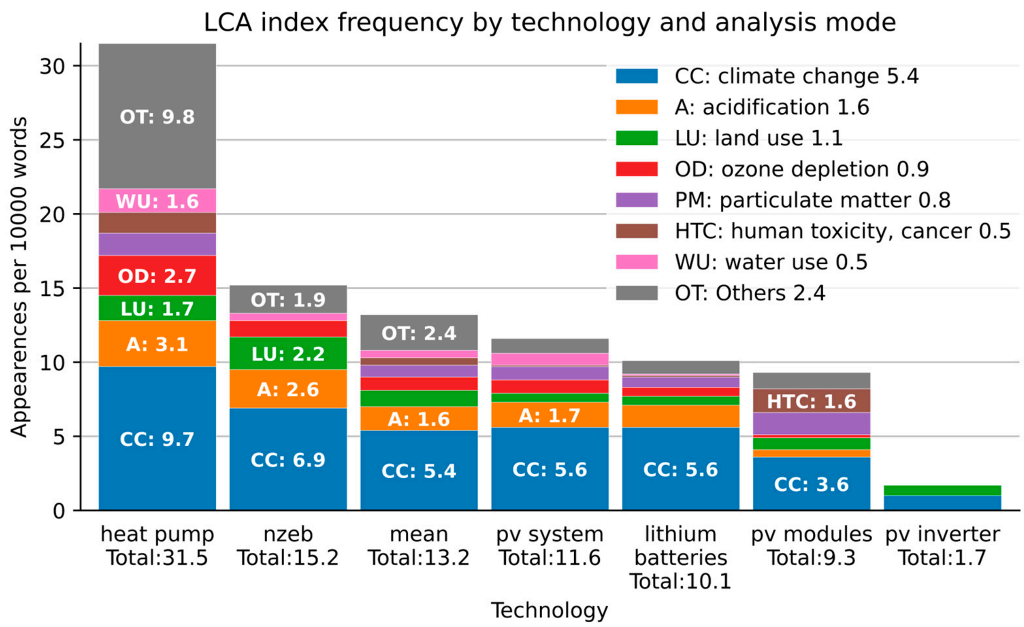

Figure 4. LCA index frequency by technology and analysis mode. Heat pumps treat more environmental impact categories, and more often, the opposite happens to inverters. Climate change is the most common impact category.

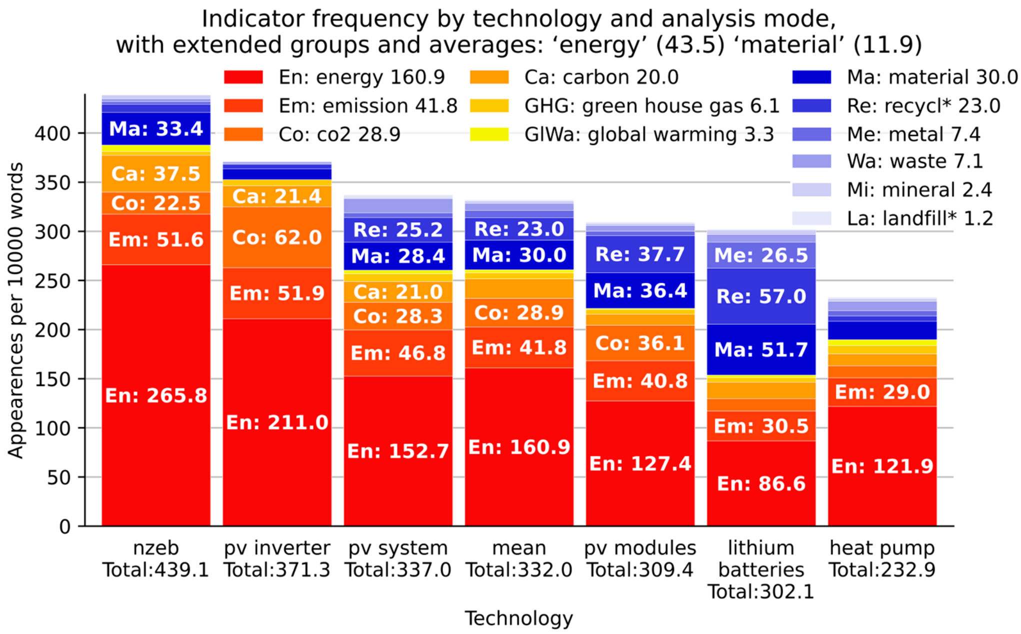

Figure 5. Indicator frequency for extended 'material' and 'energy' concepts by technology and analysis mode, with group average. The 'energy' group is higher than the 'material' group by around 4 times, with the exception of Lithium-Ion batteries. Stemmed words marked with *, representing multiple possible endings.

Circular Economy: Ignoring 'PV inverter' due to low count, 'heat pump' reaches overall less frequency. As summarised in Figure 6, 'recycle' (63.3) has the most appearances for technology average, followed by 'design' (42.7) and 'material' (26.0). These three already accumulate 53% of the overall matches. In technology, disaggregated values such as 'recycling' and 'material' gain specific importance for LIBs and PV modules. The category 'others' includes concepts of maintaining, prolonging, redistributing, refurbishing, remanufacturing, and adapting.

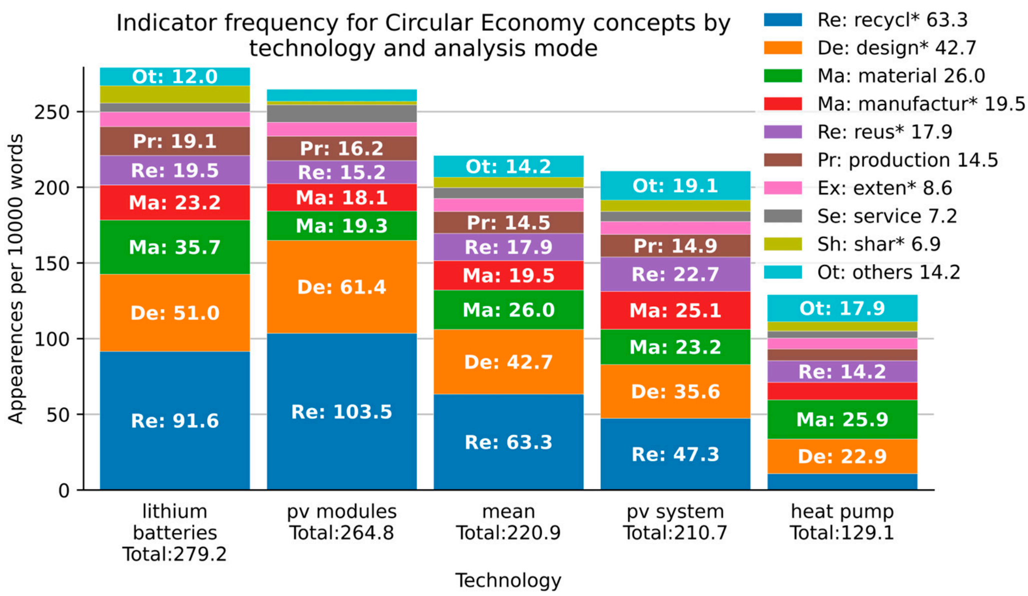

Figure 6. Indicator frequency for Circular Economy concepts by technology and analysis mode. Recycling is the most quoted term except in heat pumps. Stemmed words marked with *, representing multiple possible endings.

Using alternative wording for 'waste', 'regulation', and 'business' groups, 'waste' as a group and word maintains its importance, especially for PV modules. 'Regulation' and 'business' together account for roughly 50% of the average findings. Further concepts tested were 'legal', 'legislate', 'politics', and 'norm' for regulation, while for business, 'driver', 'enabler', 'profit', 'investment', 'job', and 'uncertainty'. Finally, this is shown in Figure 7.

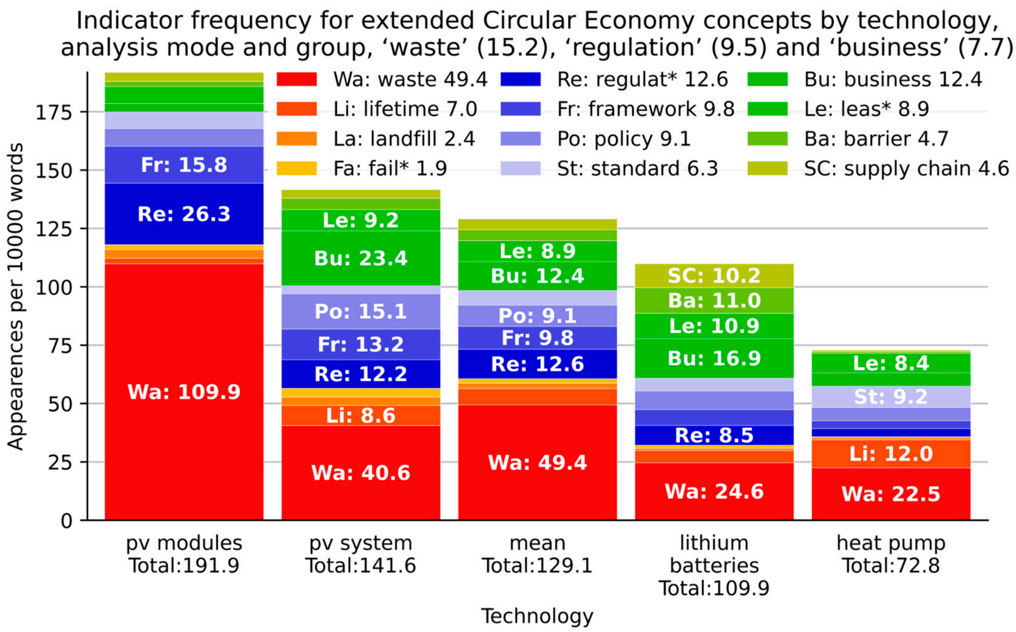

Figure 7. Indicator frequency for extended Circular Economy concepts, 'waste', 'regulation', and 'business' top four more frequent concepts by technology and analysis mode, with the group average. Waste the most quoted concepts across all technologies. Stemmed words marked with *, representing multiple possible endings.

Manufacturing: Figure 8 presents the five most frequent manufacturing concepts grouped in 'energy', 'manufacturing', and 'material', showing an overall focus on energy, whereas a group accounts for around half of the appearances. Nevertheless, material concepts gain importance in 'PV modules' and 'LIBs'. 'Manufacturing' as a word appears more often than 'material', but specific manufacturing processes do not appear frequently enough to be influential. Other tested concepts were specific materials contained in components, manufacturing processes, and machinery.

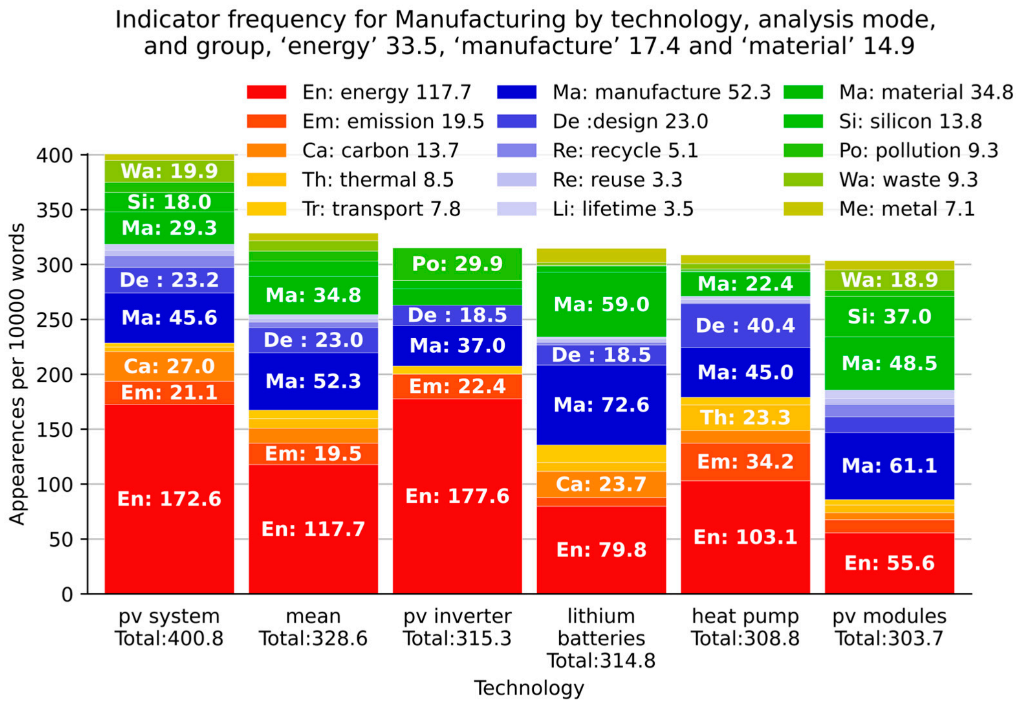

Figure 8. Indicator frequency for manufacturing: The top five most frequent concepts by technology and analysis mode, with group average. The 'energy' group presents most of the occurrences.

Degradation: Most degradation-related concepts focus on 'efficiency', especially for heat pumps. Specific modes of fail/deterioration only appear after 'fail' and 'lifetime', with 'cracking' and 'corrosion' for 'PV modules' and 'resistance' for LIBs. LIBs in literature present more specific chemical modes of degradation and failure, which are not represented under these indicators (see Figure 9).

Reliability: For reliability analysis, the words 'fail' and 'lifetime' gain particular importance as they represent 56% of all average matches. This is especially noticeable for 'PV inverters'. Only one specific failure mode is significant, with 'cracking' for PV modules (see Figure 10).

End-of-life: Heat pumps and inverters are excluded from the analysis due to low count. 'Recycle', 'waste', and 'recover' account for 75% of all matches. LIBs are especially centred towards 'recycling' with 46% of their matches. Other tested concepts were alternative CE EoL options such as 'repair', 'upgrade', 'downgrade', 'repurpose', 'remanufacture', and 'refurbish', as well as 'incinerate', 'collect', and 'landfill' (see Figure 11).

3.2. Quantitative Trend Results

For precise modelling and calculation of the life cycle impacts and circularity potentials of nZEBs as a system, numerical variables for the aforementioned elements need to be identified. Repairability numbers in open data were scarce; therefore, they were omitted. Other inconclusive points are also skipped. Obtained values are commented on.

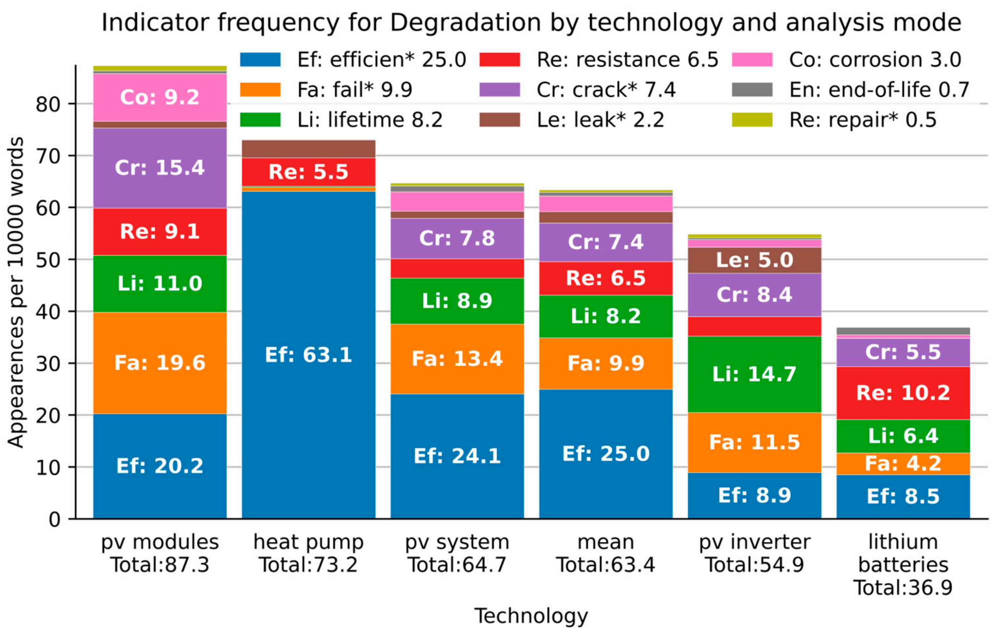

Figure 9. Indicator frequency for degradation by technology and analysis mode. Efficiency is the most important topic, especially for heat pumps. Stemmed words marked with *, representing multiple possible endings.

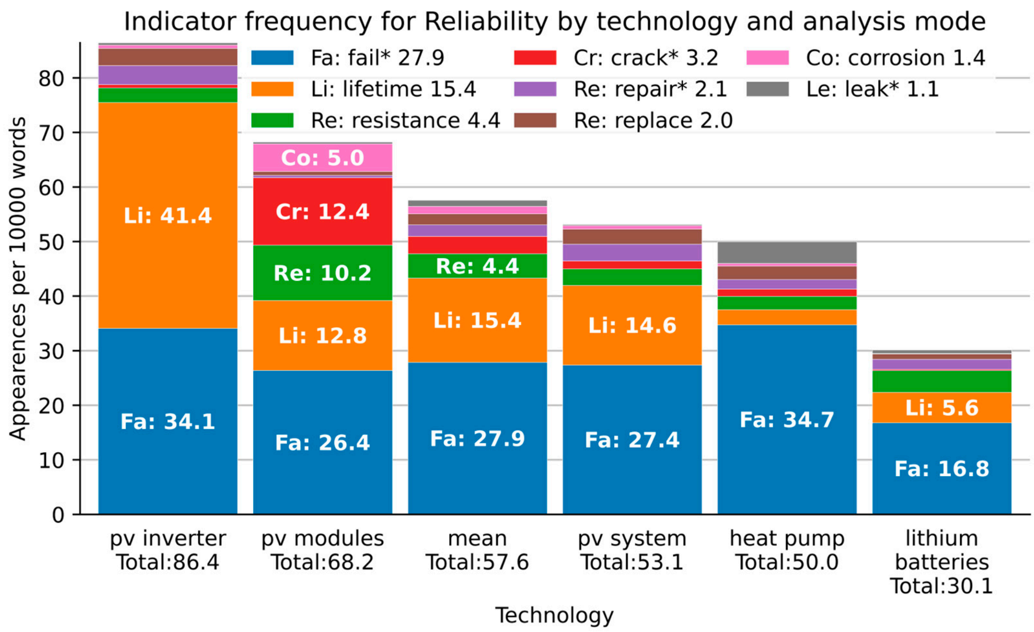

Figure 10. Indicator frequency for reliability by technology and analysis mode. 'Fail' and 'lifetime' are the most common concepts. Stemmed words marked with *, representing multiple possible endings.

3.2.1. PV Module

Manufacturing Material: These are needed to calculate energy input and possible recycling rates. The material depends on technology, but a common distribution by weight is glass 68–85% and aluminium 10–14%, followed by plastic and copper, with sources for Silicon (Si) [21], Si and Cadmium-telluride (CdTe) [22], while [23] gives even up to 95% glass to CdTe panels.

Manufacturing Energy: mainly relates to emissions, where manufacturing step and place of production play a significant role. Production is dominated by electric energy with some traits of natural gas and coal [22], but as most cells are produced in China, where a higher emission rate needs to be taken into account [24]. Transportation should also be added to these values. An average of 3392 MJ/m^2 in a range between 2513 and 5253 MJ/m^2 is calculated for different module technologies and years [25] (2017), [26] (2006), [27] mono and polycrystalline Si (2014). Others also state per Wp or by module.

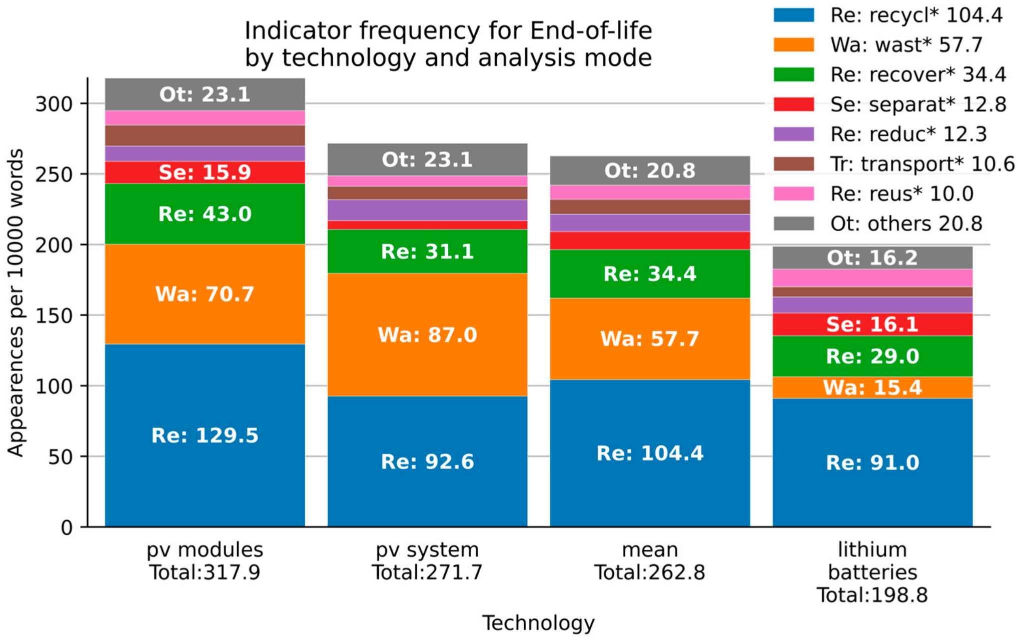

Figure 11. Indicator frequency for End-of-Life by technology and analysis mode. 'Recycle' and 'waste' are the most common concepts. Alternative CE EoL modes are not relevant in the literature. Stemmed words marked with *, representing multiple possible endings.

Lifetime: Most projects consider a lifespan of 25–30 years [22], with [28] considering up to 35, but [29] suggests that real values corrected by economic or practical reasons can be between 15 and 20 or even 7 years [21]. Climatic conditions and sociocultural conditions are not always explicitly addressed for lifetime selection.

Degradation: A degradation rate of around 0.8% per year is often used [30], as it is the mean rate of a skewed distribution for different technologies [31]. An updated version [32] also includes weather categories for Si modules with a range for upper and lower bounds of the interquartile range between 0.2 and 1.5%/year. Additionally, ref. [33] gives distributions by climatic zone and degradation mode.

Failure: Failure distributions for complete PV systems are presented by [34] with a range of 0.0046–26 (10^{-6} failures/year) for different system components, while [35] gives distributions. More detailed causes and comments on failure sources and climatic conditions are presented in [36], ranging between 0.0152 and 0.065 (10^{-6} failures/unit-h).

EoL waste and recycling: Most elements can be highly recovered in PV modules with a yield of over 80%, except plastic [37]. To this, ref. [38] adds tin with 60% recycling yield but neglectable mass share (0.12%). The EU targets 65% of the weight of products on the market or 85% of waste, with 80% of it recycled or ready for reuse [23], but worldwide, only 10% is recycled [38].

PV technology is a quickly evolving field, visualised by the rapid cost decrease and growing global production capacity [22]. A disadvantage of this is that constant changes in technological capabilities make the use of precise historical indicators challenging. Even though there are studies on specific topics for more accurate modelling and values, it is common to use average numbers. These are commonly abstracted from their usage conditions, climatic zones, or cultural environment.

3.2.2. Inverter

Manufacturing Material: Weight material distribution is given in [39], with different power capacities having different weights. Table 1 summarises this per kg/kW.

Table 1. Material distribution of PV inverters kg/kW.

Kg/kW	Min	Mean	Max
Total weight	2.31	4.15	7.48
Copper	0.39	0.89	2.20
Aluminium	0.56	1.29	2.00
Steel	0.18	0.99	3.92
Other individual components	0.12	0.55	0.88
Printed board assembly	0.25	0.42	0.68
Printed wiring board	0.07	0.13	0.28

Manufacturing Energy: The same authors [39] also give energetic manufacturing needs for different power sizes and fuels, with total values normalised to kW range between 10.4 and 20.5 MJ/kW, with an average of 15.1.

Lifetime: 15 years are estimated, but these are highly dependent on weather, PV module degradation, and installation location (indoor vs. outdoor) [40], while [41] gives time-to-fail probabilities with rough ranges depending on survival probability and manufacturer, ranging between 6 and 18 years. The effect of load ratios and temperatures on lifetime is also considered in [42].

Failure: In [43], inverters present the most prominent failing rates among PV components, with [34] giving failure rates between 11 and 180 (10^{-6} failures/year), with an average of 44. Accordingly, ref. [42] states that inverter failures accounted for 36% of lost energy, while modules only 5%.

Analysis for inverters tends to be focused on failure and reliability as it is one of the most failing components of the system. Other topics of interest are difficult to find.

3.2.3. Lithium-Ion Battery

Manufacturing material: For a 7 kg battery with a 1.4 kWh capacity, the primary material used as weight percentage [44] is 25% NMC111 powder (Lithium-nickel-manganese-cobalt Li-Ni-Mn-Co oxides), 15% graphite/carbon, 11% copper and 25% aluminium. A range between 40.5 and 50.1 kWh/kg is given by [45] for a different battery.

Manufacturing energy: for the same battery [44], the total energy is 1126 MJ or 44.6 kWh/kg, and CO_2e emissions (72.9 kg) have a very similar distribution, with 38% coming from NMC111, 17% aluminium, and 19% from cell production.

Lifetime and degradation: EoL of a battery is defined as reaching 80% of original capacity due to degradation without catastrophic failure. Up to 20 years can be expected [46], but the actual degradation could reach 8 years [30] and vary over technologies [47]. There are calendar [46], cycle [48], and varied approaches [49] degradation models, where the most influential variables are:

Full Equivalent Cycle (FEC): It can be understood as the amount of energy that the battery has given compared to its nominal capacity. As most of the degradation methods are caused by cyclical charge and discharge, an overall more used battery will have a reduced capacity. State of Charge (SOC): Refers to the amount of energy stored at a moment in the battery. If this is high, it means there is a high potential between the anode and cathode, accelerating cell degradation. For operational use, a medium average SOC is preferred. Depth of Discharge or Cycle (DOD or DOC): Similarly, when SOC levels are too low (the depth of the discharge is high), there is a tendency for capacity loss; thus, high DOD is avoided. C-rates: A high C-rate, or speed of charge/discharge relative to the capacity, will reduce capacity and increase resistance, even for the same FEC with a low C-rate. Temperature: Working temperatures are expected to range between 15 and 35 °C, as high temperatures due to charging or the ambient can degrade the battery. Low operating temperatures can also reduce cell capacity and efficiency. Therefore, real lifetimes will depend on usage conditions.

Failure: According to [34], a range of 9–11 (10^{-6} failure/year) is documented for general batteries.

EoL waste and recycling: Following [50], recovering rates can be summarised by material as (min-mean-max): Li 60-89-100, Co 64-89-100, Mn 91-95-99, Ni 94-98-100. Nevertheless, collection rates reached 5% in 2016 in the United Kingdom and 45% in 2015 for 12 countries in the European Economic Area [51].

The use of Lithium-Ion batteries in e-mobility offers a broader range of studies. Degradation studies are present, but average values are still used for a PV project's lifetime. The main sustainable treatment by EoL is recycling, although real access to service is not clear or widespread.

3.2.4. Heat Pump

Manufacturing Material: Total manufacturing materials depend on the type of heat pump exchange type (Air, water, ground), assuming a capacity of 10 kW [52], summarised in Table 2.

Table 2. Material needs (Kg) of Heat Pumps according to exchange medium.

Part	Material	Air	Water	Ground
HP	Steel	152	95	95
	Copper	37	22	22
	Elastomere	16	10	10
	Refrigerant	5	3	3
Underfloor heating system	Sand	4600		
	Cement	900		
	Aluminium	126		
	LDPE	101		
	Polystyrene	66		
Collector	Ethylene glycol		274	267
	Brass		7	7
	Cast Iron		43	
	Cement		1	19
	Steel		33	33

Lifetime: A report from 2014 suggests that the most used value is 20 years, but values between 25 and 30 would be more realistic [53].

Failure: Most common and costlier failures are shown in [54], but not dependent on other variables (time, cumulative output, etc.). For degradation, between 0.25 and 1 are identified [55].

EoL waste and recycling: Recycling-to-landfill ratios are given in [54], where steel gets 61.7% recycled, aluminium 90%, copper 41%, refrigerant 80% reused, and ethylene glycol 100% to wastewater treatment. Meanwhile, plastics, sand, brass, and cement are 100% landfilled.

Heat pump material use and recycling potentials are clear, but lifetimes and failures are not clear or often assumed.

Finally, ranges for desired search combinations, with commented limitations, can be summarised in Table 3, where '*' are inconclusive values and empty for not found.

Table 3. Search combination results (min, average (or mode), max).

Component	1 Manufacturing Material Energy	2 Ageing Lifetime Degradation	3 Reliability Failure	4 Decommissioning Recycle and Waste Energy
Module	Mass distribution given. (68-*-95) % mass is glass, (2.5-3.4-5.3) GJ/m^2 for different technologies and years	(7-20-30) years, (0.2-0.8-1.5) %/year. Bigger ratios found, but unusual	(0.0046-*-26) 10^{-6} failures/year	(*-80-*) % mass, ()
Inverter	kg/kW ratios per material given, aluminium is the most intensive one, ranging (0.56-1.29-2.00), (10.4-15.1-20.5) MJ/kW	(6-15-18) years, ()	(11-*-180) 10^{-6} failures/year	(), ()
Battery	For a 1.3 kWh 7 kg LIB (25% NMC111 powder, 25% aluminium) % mass, (40-*-50) kWh/kg	(8-*-20) years, (degradation models)	(9-*-11) 10^{-6} failures/year	(60-*-100) % mass recovering rate for different materials with collection (5-*-45) %, ()
Heat pump	(95-*-152) kg steel without a heating system and collector ()	(20-20-30) years, (0.25-*-1) %/year	()	Recycling ratios per material given (41-*-90) % of mass recyclable, ()

3.3. Environmental Impacts

Environmental impacts in LCA results are presented according to a Fundamental Unit (FU), which for energy systems usually is energy generated or consumed. This means that the same product, under different usage or weather conditions, could report EIs varying significantly even if manufacturing and EoL are the same.

For PV systems, manufacturing accounts for the most important share [13]. During the use stage, land use could be an issue, but considering domestic and roof-top installations, this could be ignored.

Most of the energy and material required for PV modules are related to high-quality glass and aluminium. Additionally, other impacts can also be found in part due to the use of critical raw materials such as Ga, Ge, In, and Sb, among other raw materials [13,22]. From a CE point of view, materials gain special relevance depending on the definition; this can be represented by "resource use, mineral and metals" or "abiotic resource depletion", which relates production rates to reserves [56]. Materials are also important, considering supply chain bottlenecks and competing final uses [14]. Thus, even if recycling may not always be percentage-wise significant for EI reduction [28,57], it is still important to diversify sources and reduce waste. Water use is another resource required in the chemical processing and recycling processes of raw materials. Nonetheless, PV is still one of the least water-consuming sources of energy [13].

Lithium batteries have many combinations of materials for anode, cathode, and electrolyte materials [50]. Acknowledging this, commonly used materials with environmental significance are cobalt, lithium, and nickel. Cobalt is mainly produced in DR Congo, where illegal, artisanal, or small mining is considerable. Its real impacts are unknown, but their release of heavy metals causes health issues. Lithium extraction causes water issues in the high plains of Argentina, Bolivia, and Chile, where it is extracted from brine. In Australia and China, it is extracted from hard rock, which also requires water and energy and generates waste rock. Nickel production is related to acid rain, heavy metal contamination, particulate matter, and water pollution. To all of these EIs, the social implications of raw material mining and illegal E-waste treatment should also be considered [58].

In the case of HPs, the major source of EIs is the use stage [59]; therefore, consumption patterns and electricity mix play an important role, unlike manufacturing and EoL. Refrigerant leaks in the use stage also generate global warming potential and ozone depletion challenges [60].

3.4. Selection of Relevant Literature

Considering the previous methods, values, and limitations, literature on the direction of addressing identified gaps is presented in Table 4. These should work as examples of modelling trade-offs, statistical research, identification of keywords, or general CE inspiration.

Table 4. Selection of relevant literature that partially addresses identified gaps.

Title	Year	Method	Analysis	Main Takeaway
Economic Lifetimes of Solar Panels [21].	2022	Modelling	Module lifetime	Real lifetime can be shorter than technical values due to economic reasons
Compendium of Photovoltaic Degradation Rates [32].	2016	Statistical description	Module degradation	Real degradation rates depend on the use conditions
Reliability, Availability and Maintainability Analysis for Grid-Connected Solar Photovoltaic Systems [34].	2019	Modelling/Statistical description	System failing	Failing distribution of components in PV systems
Failure Rates in Photovoltaic Systems: A Careful Selection of Quantitative Data Available in the Literature [36].	2020	Statistical description	System failing	Failing distribution of components in PV systems, inverter most failing.
Life Expectancy of PV Inverters and Optimizers in Residential PV Systems [41].	2022	Statistical description	Inverter lifetime	The survival probability of inverters depends on using conditions
PV System Component Fault and Failure Compilation and Analysis [43].	2018	Statistical description	System failing	Failing distribution of components in PV systems, inverter most failing
Aging Aware Operation of Lithium-Ion Battery Energy storage Systems: A Review [49].	2022	Modelling	LIB degradation	Degradation factors and models for LIBs
The Common and Costly Faults in Heat Pump Systems [54].	2014	Statistical description	HP failing	The most common faults in HPs are in compressors
Environmental Life Cycle Assessment of Heating Systems in the UK: Comparative Assessment of Hybrid Heat Pumps vs. Condensing Gas Boilers [11].	2021	Modelling/LCA	HP LCA	HP is better in emission but worse in other EI categories

Table 4. *Cont.*

Title	Year	Method	Analysis	Main Takeaway
A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK [12].	2021	Modelling/LCA	HP LCA	HP is better in emission but worse in other EI categories
Circular economy priorities for photovoltaics in the energy transition [61].	2022	Modelling	Module CE variables	The long life of modules is concluded as the best alternative to reduce virgin material demands under a PV modules model with CE variables
PV in the circular economy, a dynamic framework analysing technology evolution and reliability impacts [62].	2022	Modelling	Module CE variables	Present open-source tool to model CE variables of modules
A critical review of the circular economy for lithium-ion batteries and photovoltaic modules-status, challenges, and opportunities [63].	2022	Literature review	Module and LIB CE variables	An extensive literature review of modules and LIBs shows a focus on recycling. Other CE strategies are commented
When to replace products with which (circular) strategy? An optimization approach and lifespan indicator [64].	2021	Modelling/LCA	Heating CE variables	Long lifetimes are not always better, calculated for HPs with CE variables and alternatives

4. Discussion

4.1. Qualitative Method Limitations

The advantages of the proposed method are that qualitative trends are represented numerically, therefore reducing human bias and allowing for automated and repeatable processes.

Limitations of this approach are that the tool only considers papers and ignores "institutional reports" or theses. Many of these research papers have closed access; therefore, there may be different trends that are not represented by this approach. Similarly, the selected paper sources are general and standardised, therefore suited for comparing different technologies and analysis modes with the same procedure. Nevertheless, it is possible that specific paper sources with a heavy focus and better results are available by sacrificing standardization. This bias can be solved by increasing and generalising the obtention of papers (more sources of paper, closed access).

Furthermore, processing errors such as failures to download, extract, and store caused by internet connection, website construction, PDF structure, or type of content may lead to a reduction in candidates or content. An example is that only text is processed, and images are ignored. Using the proper wording is fundamental, as word similarities are not recognised; plural-singular or synonyms must be actively and manually considered on the list of indicators. The search was performed by trying representative words and discarding low-frequency ones as they did not make an impact. When a concept does not show a unique clear indicator, groups are presented. To compare concept groups, the same quantity of indicators is needed to have a fair comparison between groups. Searches are conducted over "text find", not "word is in", which means that text is analysed as a whole, not as a list of words; therefore, using acronyms could lead to many false positives. Alternatively, more advanced word search options (capitalization, acronyms, adjective detection, position of word in text) are possible and would make for richer future development of the tool.

Additionally, some searches present a low quantity of matches; therefore, not much can be concluded from them. Finally, even if a topic is addressed, this does not indicate if a positive or negative evaluation is made of it.

4.2. Quantitative Method Limitations

Available values in product datasheets face varied challenges, such as a lack of standardisation of values, names, and units, as well as future estimations for operation and degradation. Additionally, values of environmental impacts and ageing are arduous to measure and, therefore, hard to control. On the other hand, historical and statistical descriptions are difficult to perform due to quick technological evolution and the long time needed to assess life cycle results.

As recognised by other sources, data gathering is a challenging process where the use of proprietary software and databases is needed, industrial secrecy is present, and details are not always explicitly given, such as system boundaries, type and quantity of materials and parts, material loss during production, origin country and transportation of raw material, among others.

4.3. Qualitative Trends and Gaps

While analysing sustainability, some research topics receive more focus than others. This is represented by the number of papers or the appearance of specific words in those papers. PV inverters are highly neglected, representing 6% of the matches, mainly with reliability analysis playing a role, while interest in End-of-life is only substantially present in PV modules. Meanwhile, LIBs research is more abundant at 33%, as the automotive industry has even more restrictive conditions than PV use; therefore, there is some "research intersection". Sustainability analysis focuses primarily on energy and emissions, as the most frequent concepts are words such as 'climate change', 'energy', 'emission', or 'co2'. Proportions change depending on analysis mode and wording, but energy topics represented 40% of matches in LCA original concepts, 79% in LCA extended concepts, and 50% for manufacturing under the aforementioned conditions. When material concepts are present, they are mostly related to 'recycling' and 'waste', with matches representing 28% of CE original concepts, 38% of CE extended concepts, and 62% for EoL under the mentioned conditions. Specific modes to apply Circular Economy beyond recycling have infrequent appearances. Exact materials and modes of failure can appear, especially for LIBs and PV panels, but not as often as energy concepts.

Generally, incentives in the CE still need to be clarified. A tendency towards energy and emissions is understandable as these can be more or less directly correlated with costs. Even if less clear, the importance of raw materials, recycling, and waste still appears, as they can also be linked to costs. Other variables appear more diluted in cost estimation, as middle CE strategies as maintain, prolong, reuse, redistribute, refurbish, remanufacture. A disadvantage for them is also that they are much more component/model dependent, reducing scalability. Reinterpreting less-treated topics as advantages (e.g., cost saved) would more clearly present their importance for a person not immersed in the topic.

4.4. Quantitative Trends and Gaps

Previous trends are similarly present in quantitative variables. To model life cycle impacts from a circular economy perspective, production and operation factors are easier to find than EoL or repairability variables. Again, PV modules and LIBs have more information available, but values are presented in a general manner as there are many possible technologies and operation modes. Usually, 'standard' average values are used, while papers can present a broader range according to technological, economic, or user conditions. Most values are obtained from statistical reports, as technical sheets only offer variables for initial system dimensioning and generalised degradation. Better estimation of life impacts could be achieved with the standardisation of product datasheets, environmental indexes, and units. Acknowledging this, wide ranges for some variables are also found, where differences between minimum and maximum are significant for the lifetime of modules with 4.3 times, 2.7 times for inverter, 2.5 for batteries, in failure rates of 5600 for modules, and 16.4 times for inverters. The exact effect of these uncertainties on environmental impacts and costs should be calculated for each use case, but final results must include sensitivities and uncertainty ranges to account for them.

From the manufacturer's side, different types of datasheets and datasets are available but with limited access and standardisation. Encouraging open access to component reports with agreed variables, names, and units would be imperative. When industrial secrets are at risk, the material composition could be replaced by impact categories as presented in environmental declarations, but again, under a single standard. Operational measurements to identify degradation and failure should be published as raw data, even if this is not for the complete lifecycle. This would allow us to assess the effects of other variables not considered when focusing on a single point of study. With the increased application of these energy systems in the public sector, installation in public buildings could serve as an example of data openness. Claims made by manufacturers should be tested under these operational conditions.

5. Conclusions

Circular Economy is a strategy that fights climate change and E-waste simultaneously, as it offers strategies to increase the efficiency of used material at the design, use, and End-of-Life stages both for producers and users. From an automated analysis of electrical energy components in a 'near Zero Energy Building' combined with circular strategies, the key observations are:

Automated review:

- Allows for reduction in time, bias, and error through automation. Anyhow, manual validation and calibration are still needed;
- Literature sources themselves present biases through access type and scope;
- The presented tool and methodology do not replace the expert's knowledge but allow for a more efficient way to find specific information.

Qualitative concepts:

- High representativity of Lithium batteries is present due to automotive research;
- Relegation PV inverters;
- Favouritism for CO_2 and Global Warming Potential and energy consumption over other environmental impacts;
- Favouritism for recycling over other Circular Economy strategies;
- Recognizing all possible combinations of components and strategies allows for easier identification of priorities, but incentives for each still need to be studied case by case;
- Expressing less treated CE strategies and components in terms of gains or losses avoided can make these studies more attractive.

Quantitative values:

- Lack of many key indicators (e.g., repairability or recycling energy) or average values used;
- Wide range degradation models for LIBs, but no equivalents for other components;

- The potential for recycling given by technology and material differs significantly from onsite real rates. Developing markets for this will correlate with increased waste as old components phase out;
- For available values, wide ranges and different units are found depending on the technology of each component. The difference between min and max could reach up to 5600 times in the worst case;
- Due to quick technological evolution and the time needed for statistical measurements, available values are old or estimated;
- Climatic conditions or user patterns are not always stated for calculations;
- Standardization of metrics and units delivered with products is a must to ensure comparability.

Author Contributions: Conceptualization, F.A.C. and J.F.M.; methodology, F.A.C.; software, F.C; validation, F.A.C. and J.F.M.; formal analysis, F.A.C.; data curation, F.A.C.; writing—original draft preparation, F.A.C. and J.F.M.; writing—review and editing, J.F.M.; visualization, F.A.C. and J.F.M.; supervision, J.F.M.; project administration, J.F.M.; funding acquisition, J.F.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia, Germany, by funding the project "Circularity of electrical building energy systems" ("Zirkularität elektrischer Gebäudeenergiesysteme (Zensys)").

Data Availability Statement: The data presented in this study are available at https://zenodo.org/records/14050352 (published on 7 November 2024) "Frequency of sustainability indicators in open access literature of house energy components". These data were derived from the following resources available in the public domain: MDPI, ScienceDirect, and ResearchGate.

Acknowledgments: The research is connected to the LivingLab NRW, the North Rhine-Westphalia research, education and communication platform for sustainable building, managed by the Faculty of Architecture and Civil Engineering of the University of Wuppertal.

Conflicts of Interest: The authors declare no conflicts of interest.

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