IEEE Power Electronics Magazine, Vol. 11, No. 1, March 2024

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This article has been accepted for publication in IEEE Power Electronics Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MPEL.2024.3354013

Energy Efficiency is Not Enough!

Environmental Impacts as New Dimensions in Multi-Objective Optimization of Power Electronic Systems

by Jonas Huber, Luc Imperiali, David Menzi, Franz Musil, and Johann W. Kolar

I. Introduction

In its latest report, the Intergovernmental Panel on Climate Change (IPCC) concludes that any further increase of global temperatures aggravates climate-related risks like species losses, extreme heat and humidity with significant consequences for human health, or negative impacts on food production and water availability; the projected negative outcomes escalate with higher temperature increases [1]. Therefore, worldwide efforts and international policymaking (i.e., The Paris Agreement from 2015) aim at limiting global warming by the end of the 21st century to well below +2 °C above pre-industrial levels, preferably to not more than +1.5 °C.

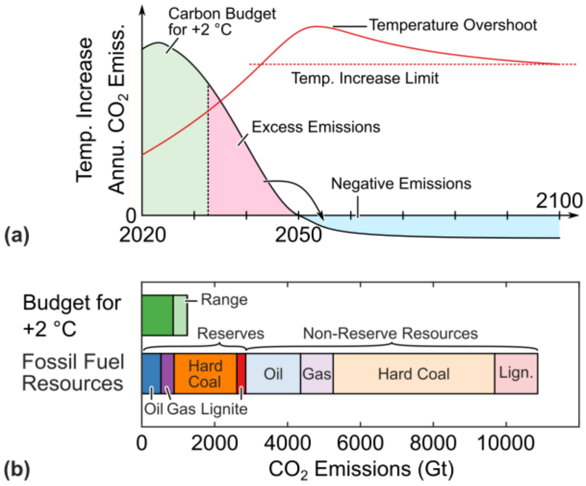

FIG. 1. (a) Even with ambitious pathways for achieving net-zero CO_2 emissions by 2050, global temperatures are expected to overshoot the limit of +2 °C targeted for the end of the century, and large-scale deployment of negative emission technologies is thus required (conceptual representation based on [2], [3]). (b) Limits to fossil fuel consumption: only a fraction of fossil fuel reserves and resources can be burned until 2050 without compromising the +2-°C global warming limit [4].

FIG. **1**(a) indicates that also the most optimistic scenarios which reach net-zero carbon dioxide (CO_2) emissions by 2050 still result in a temporary temperature overshoot beyond these limits and hence imply the need for a large-scale deployment of negative-emission technologies like direct air capture of CO_2 [2]. As the feasibility of scaling-up such technologies is uncertain, avoiding CO_2 emissions in the first place is of paramount importance. FIG. **1**(b) compares the CO_2 emission budget (between 2011 and 2050) that is compatible with a temperature increase of +2 °C to the CO_2 emissions that would result from burning the world's fossil fuel reserves and resources [4]; the authors of that *nature* article conclude that "globally, a third of oil reserves, half of gas reserves and over 80% of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C." Or, as a Shell manager put it in 1999: "The stone age did not end because the world ran out of stones, and the oil age will not end because we run out of oil" [5]. Instead, a net-zero-emissions energy system is needed [6]: While employing multiple non-electric energy carriers like hydrogen or ammonia for difficult-to-decarbonize energy applications like long-haul transport, electricity dominates such a future multi-carrier energy system, and virtually all energy used originates from emissions-free electricity generation. In particular, a massive expansion of solar photovoltaics (PV) and wind power generation (possibly combined with concentrating solar power [7], [8]) is necessary, with projections [9], [10] indicating a tenfold increase between 2020 and 2050, as depicted in FIG 2.

Power electronics is a key enabling technology for such a future power distribution system [11], which, according to early visions [12]-[14], might feature high-voltage dc (HVDC) lines spanning the entire globe, and which essentially is a hierarchical and hybrid mix of ac and dc sub-grids [15], interconnected by power electronic interfaces. Based on rough assumptions, we estimate the installed power converter capacity in such a power-electronics-dominated system: The United Nations expects an increase of the world population to almost 10^9 humans by 2050. Covering an estimated[1] per-capita energy

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[1] Based on a world total final energy demand of 398 EJ in 2050 as projected by DNV's ambitious pathway-to-net-zero scenario [2]: with a world population of 10 bn people, an energy usage rate of 1.26 kW per capita results.

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demand of 2.5 kW requires a renewable generation capacity of 25,000 GW. By further assuming typically four conversion stages between source and load, a total installed power electronic conversion capacity in the order of 100,000 GW results in 2050.

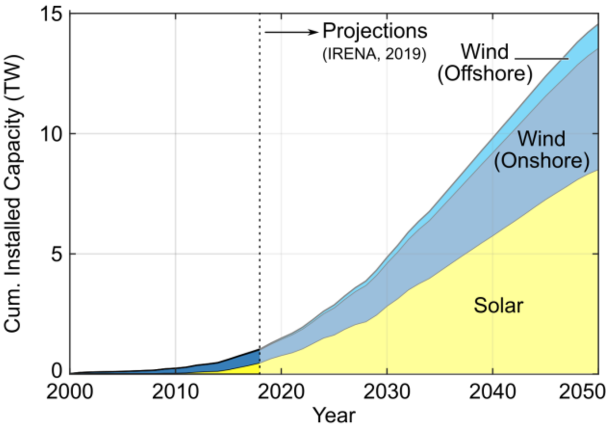

FIG 2 Projected expansion of solar (60% utility-scale and 40% rooftop in 2050) [10] and wind (onshore and offshore) [9] generation capacities.

Even though a fully renewable energy system (which comes with significant challenges on its own like possibly low energy return on energy investment (EROI) [17], and the need for short-term and seasonal storage [18]) is necessary for achieving the targets limiting global warming, there are further important aspects that must be considered. The limited lifetime of power converters of typically around 20 years [19], [20], implies, first, that the systems installed now must be replaced even before 2050, and, second, about 5,000 GW/yr of electronic waste (e-waste) that comes on top of e-waste from non-energy sectors like IT or white goods. FIG 3(a) shows past and projected global e-waste generation (without considering the discussed massive restructuring and expansion of the electric power system) and highlights the huge improvement potential of current recycling rates [21]. Generating that much waste is expensive ([21] estimates the value of raw materials in the global e-waste generated in 2019 at 57 billion USD), risky (the supply of critical minerals is limited and often geographically and/or geopolitically more constrained—more so than in case of fossil fuels [22]), and clearly not sustainable. There is thus a need to transition from the traditional “linear economy” and its “take-make-dispose” approach to a circular economy with its three foundational principles [23] of (1) eliminating waste and pollution, (2) circulating products and materials at their highest values, and (3) regenerate nature, i.e., a circular economy aims at a perpetual flow of resources as illustrated in FIG 3(b) and thus achieves a high material efficiency. Governmental organizations on all levels push in this direction, e.g., the United Nations’ Sustainable Development Goal No. 12 or the European Union’s Green Deal, its Circular Economy Action Plan, and its Ecodesign Directive. Similarly, standardization regarding Ecodesign and material efficiency has started (e.g., EN 4555x series targeting energy-related products [24], [25]).

Since recently, Ecodesign principles, or “Design for Circularity” [23], [26], [27] with a focus on facilitating repairs, reuse of assemblies, and recycling, are also discussed for power electronic systems, e.g., [28]-[30] with [31] providing an overview. Ecodesign relies in part on the quantification of a power electronic system’s environmental impact in multiple dimensions, e.g., carbon footprint or global warming potential (GWP), damage to human health or ecosystems, etc., over its entire life cycle (FIG 3b). A life-cycle assessment (LCA) as, e.g., defined in ISO 14040 [32] and ISO 14044 [33], must thus be employed. Note that it is beyond the scope of this article to give a generic and comprehensive description of LCA methodology, frameworks, databases, and standards like ISO 1404x; the following discussion should be considered an overview example tailored to power electronics and an entry point for interested readers.

An LCA can be applied to processes, products, or individual sub-components, and contains two major steps: first, a life-cycle inventory (LCI) of all relevant inputs (energy, material) and outputs (pollutants released into the environment) is compiled. Then the associated environmental impacts are quantified in a so-called life-cycle impact assessment (LCIA), whereby various methods can be employed

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With an (optimistic) capacity factor of about 0.5, an installed generation capacity of 2.5 kW per capita follows. Note that DNV’s baseline (i.e., most likely) scenario projects a higher final energy demand of 489 EJ [16] or 1.55 kW per capita in 2050.

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(an example is discussed in **Section II**). During recent years, the number of published power-electronics-related LCAs and similar studies has steadily increased [19], [20], [34]-[48], and industry associations like the European Center for Power Electronics (ECPE) are starting initiatives focusing on sustainable power electronics [49].

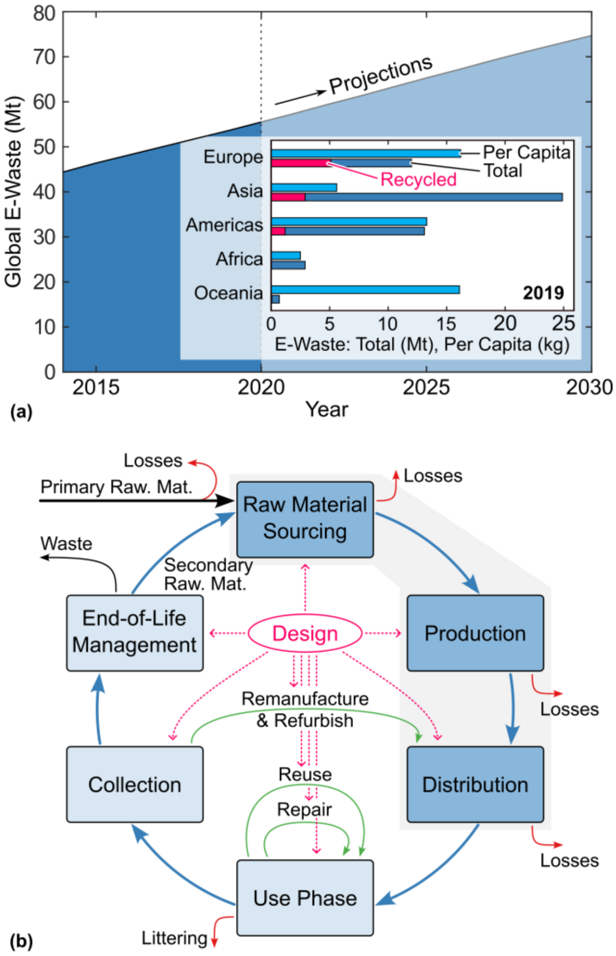

FIG 3 (a) Global electronic waste (e-waste); the inset shows the geographic distribution in 2019, highlighting, first, the very unequal amount of e-waste per capita, and, second, that only a tiny fraction of e-waste is properly recycled (data source with further details: [21]). (b) Circular economy concept (graphical representation inspired by [50]) with an emphasis on how *all* life-cycle phases are influenced by design decisions. In contrast, today's design procedures typically only consider a subset of the life cycle (see gray shading).

LCAs are typically applied to existing products, i.e., *a posteriori.* However, as indicated in FIG 3(b), decisions taken during the design phase of a converter influence all life-cycle stages and ultimately the LCA result, i.e., according to [51], typically up to 80% of a product's environmental impact is determined at the design stage. Even though power converter efficiencies beyond 99% are feasible today and enable remarkably high energy efficiencies during the use phase, there might still be potential to design power converters with improved material efficiency and in general a minimized environmental impact. Therefore, we propose to extend the multi-objective Pareto optimization of power electronic converter systems, which today typically only considers efficiency, power density and sometimes cost [52], by further dimensions representing LCA results. This enables an *a-priori* assessment and/or comparative evaluation of the environmental impacts of converter topologies and other engineering choices already in the early design stages.

In the following, **Section II** first presents a comparative evaluation of the environmental impacts of two built 12.5-kW PV inverter demonstrators with equal CEC efficiencies of 99.1% but very different circuit topologies, which also supports the explanation of key concepts. In addition, the main results of the LCA of an industrial PV inverter are summarized in the **Sidebar. Section III** first reviews the concept of multi-objective Pareto optimization and then, using an exemplary three-phase ac-dc converter building block, shows how environmental impacts can be included in a trade-off analysis covering not only the production but also the use phase. Finally, **Section IV** proposes a roadmap towards circular-economy-compatible power electronics and concludes the article.

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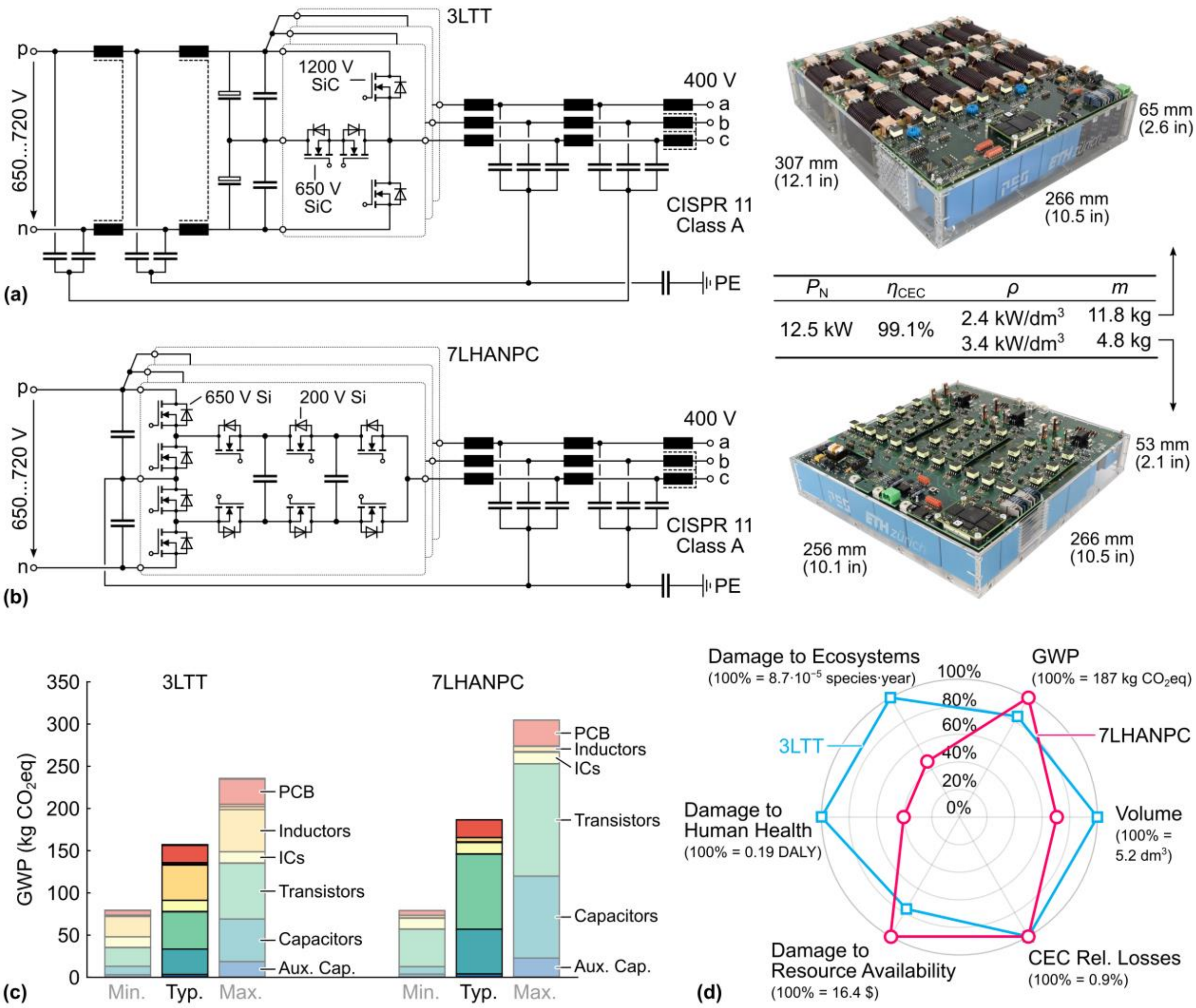

FIG 4 Power circuits, photos, and key data of (a) an all-SiC three-level T-type (3LTT) three-phase inverter [53] and (b) an all-Si seven-level hybrid active-neutral-point-clamped (7L-HANPC) three-phase inverter [54]. (c) Global warming potential (GWP) breakdown by components for the two systems, where "min.", "typ.", and "max." indicate a wide spread between the component-level data sources considered. (d) Multi-dimensional comparison that includes an environmental profile obtained with the ReCiPe 2016 framework [55], [56] (egalitarian perspective, ecoinvent database [57]), which characterizes damages to human health, to ecosystems, and to resource availability. Note that these results refer only to the converter as sum of its components, i.e., do not include assembly (which, however, is not expected to contribute significantly, see the inset on p. 5) and, in particular, not the use phase (where, however, the identical CEC efficiencies imply identical environmental performance).

II. A-Posteriori LCA of Two PV Inverter Demonstrators

To illustrate some key concepts and challenges, it is useful to first discuss a-posteriori LCAs of built systems. Therefore, the **Sidebar** presents an a-posteriori LCA of an industrial PV inverter product. Furthermore, FIG 4(a) and FIG 4(b) show two ultra-efficient but conceptually very different 12.5-kW PV inverter demonstrators that interface a 650-V…720-V dc input to a 400-V (line-to-line rms) three-phase mains. The demonstrator from FIG 4(a) employs 1200-V and 650-V SiC transistors in three-level T-type (3LTT) bridge legs and a dc-side common-mode filter [53]. In contrast, FIG 4(b) shows an all-silicon (650-V and 200-V transistors) realization using seven-level hybrid active-neutral-point-clamped (7LHANPC) bridge legs [54]. Interestingly, even though the two converters show different efficiency characteristics, the resulting weighted CEC efficiencies are equal and with 99.1% very high [53], i.e., the two converters accrue equal energy losses during the use phase (under standardized operating conditions). The 7LHANPC achieves a higher volumetric power density and weighs significantly less, because the seven-level structure minimizes the use of heavy inductive components.

Nevertheless, despite employing fundamentally different concepts, the two system show equal performance in one of the conventionally considered performance dimensions (CEC efficiency or, equivalently, use-phase energy losses), which illustrates a form of the design space diversity discussed below in **Section III**. As the different concepts dictate the use or dominant role of different component types (e.g., SiC vs. Si transistors, inductors vs. capacitors), it is interesting to investigate whether the environmental footprints (not including the use phase) of the two demonstrators differ.

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This can be investigated by an LCIA, where we first focus on the climate impact of the components used in the two converters in terms of the 100-year GWP measured in kilograms (kg) of CO_2 equivalents (kgCO_2eq), which is shown in FIG 4(c). The figure also illustrates a key challenge faced when performing LCAs for power electronic systems: data quality. Usually, component-level data regarding GWP (and other indicators) is obtained from LCA databases like ecoinvent [57], collected from the literature, or obtained as primary data by breaking down components and tracing the sub-components or materials used (see also the **Sidebar**). The results might further differ between manufacturers of second-source components, and in general depend strongly on the specific supply chain (i.e., suppliers' energy mixes, transport routes, etc.). Such specific aspects, however, cannot be considered in the targeted a-priori analyses (see **Section III**) by definition, i.e., databases and literature must be relied upon. Unfortunately, there are significant variations between available data sources (details are discussed in [58] and not repeated here for the sake of brevity), which leads to the “min.”, “typ.”, and “max.” results shown in FIG 4(c). Due to the overlapping “min.”/ “max.” results of the 3LTT and the 7LHANPC, it is not possible to clearly identify the topology resulting in a lower GWP. Therefore, for any meaningful comparison, especially between studies carried out by different actors, there is a need for a single agreed-upon data source (see also **Section IV**).

In addition to the GWP, there are other environmental impact indicators that can/should be considered in an LCIA to establish an environmental profile. Such indicators characterize, e.g., land or water use, human toxicity, terrestrial or marine ecotoxicity, etc. There are various methods for aggregating these indicators into areas of protection; here, we consider ReCiPe 2016 [55], [56], which defines human health, ecosystem quality, and resource scarcity as areas of protection. The framework ultimately maps the LCI, i.e., a list of all resources used and emissions released, to three values that characterize damage to human health (measured in disability-adjusted life years, DALY), to ecosystem quality (measured in species loss integrated over time, species·yr), and to resource availability (measured in dollars, $), whereby different value perspectives (individualistic, hierarchist, and egalitarian) can be taken to consider different time frames during which the environmental impacts are evaluated. FIG 4(d) includes the ReCiPe 2016 indicators in the comparison of the two converter concepts, which results in environmental profiles that differ significantly in at least two dimensions. It is interesting to observe that even though the 7LHANPC is more compact and weighs less than half of the 3LTT, its environmental footprint is worse in terms of GWP. This illustrates that different components have very different mass-related impact profiles depending on the employed materials, processes, etc. (see also [58]). Specifically, the 7LHANPC employs more transistors that are characterized by an energy-intensive production. On the other hand, the smaller size and the lower weight of the 7LHANPC imply a smaller housing and less sturdy mechanical construction, whose impact on the environmental profile is not considered here.

This exemplary a-posteriori LCA illustrates how different converter concepts feature different environmental impact profiles; the same is true for different implementations of the same topology, which motivates including these aspects already in the early design phases, i.e., a priori, as additional dimensions of a multi-objective optimization, e.g., for the comparative evaluation of concepts.

[Sidebar]

LCA of an Industrial PV Inverter System

The two highly efficient PV inverters discussed in **Section II** are demonstrator systems but not industrial products, which consist of more subsystems. Therefore, the key results of an ISO 14040/44 [32], [33] LCA of a Fronius GEN24 10-kW PV inverter are summarized here; details are given in [19], [42]. **SidebarFIG 1(a)** shows the power circuit that comprises a silicon-IGBT-based three-level neutral-point-clamped (NPC) inverter stage with an LCL-type EMI filter, and SiC-MOSFET-based two-level bridge legs for the dc-bus balancer and two unidirectional and one bidirectional boost converters as maximum-power-point (MPP) trackers and battery interface, respectively. Further, there are electromechanical components like the grid-side relays and the three-pole dc isolator switch, and, as shown in**SidebarFIG 1(b)**, an intricate mechanical assembly with heat sink and housing.

Consulting LCA databases and the literature has given widely varying results for certain components. Significant effort has thus been put into gathering accurate primary data, e.g., via full-material declarations (FMDs) provided by some manufacturers and then using LCA databases on the material and processing step level. As of now, many component manufacturers do not or cannot provide relevant characterization data (e.g., regarding their components' carbon footprints). Therefore, several components

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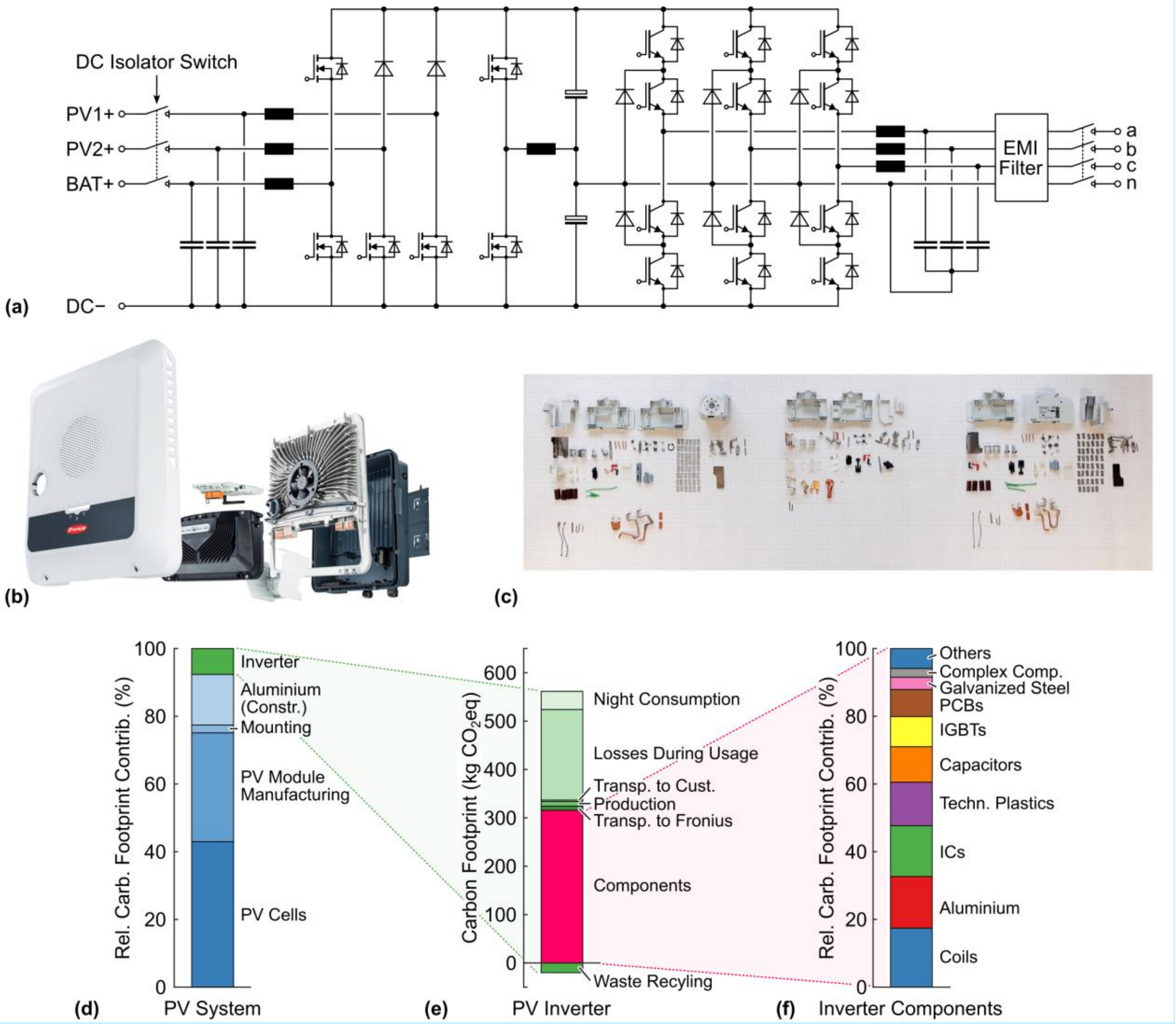
have been diligently disassembled to obtain primary data by weighing individual parts; **SidebarFIG 1**(**c**) shows the dc isolator switch as an example.



SidebarFIG 1 (a) Power circuit and **(b)** exploded view of a Fronius GEN24 10-kW PV inverter. A fully detailed LCA might require gathering of primary data through disassembling components: **(c)** shows the individual parts of an exemplary dc isolator switch. **(d)-(f)** LCA results, i.e., **(d)** relative contributions to the carbon footprint of a PV system, **(e)** carbon footprint of the PV inverter over its lifetime (including losses and night consumption during use phase; green electricity mix in Germany with 43.4 g CO_2eq/kWh [57]), and **(f)** relative contributions of the inverter's main components. Further details are given in the text and in [19], [42].

SidebarSidebarFIG 1(**d-f**) show the key LCA results in terms of carbon footprint of the complete PV system (panels, structural elements, inverter), the full life cycle of the inverter (including the use phase), and of the individual inverter components, respectively. The scenario assumes 20 years of operation in Germany and a 97% efficiency of the PV inverter. Then, the inverter itself contributes less than 10% to the entire PV system's carbon footprint. The inverter's carbon footprint is dominated by the components (about 60%) and the electrical losses during the use phase (about 35%; the losses are covered by the electricity generated by the PV system itself, which, however, still has a non-zero carbon footprint of 30.2 g CO_2eq/kWh, which results from the embodied CO_2 footprint form the manufacturing of the PV panels etc. and a typical lifetime energy production). On the other hand, the production at Fronius' factory in Austria, which is supplied by green energy, and transports are minor contributors. Interestingly, the night consumption (i.e., energy taken from the power grid to supply the control electronics at night) is not negligible, even though green electricity contracting in Germany with 43.4 g CO_2eq/kWh [57] is assumed. Note further that the end-of-life management considers thermal waste treatment with subsequent metal recycling, which leads to a corresponding credit (negative contribution to the carbon footprint). Regarding the components, the technical plastics and the aluminum used for the housing, heat sink, frame and in general the mechanical assembly together account for almost 30%

of the carbon footprint. The ICs are another interesting case, as they account only a few grams of the converter's mass but are responsible for 15% of the carbon footprint due to their energy-intense production; a similar observation holds for the Si IGBT and SiC MOSFET power modules.

Even though a PV system has a non-zero carbon footprint, in today's Germany it is used to substitute an electricity mix that is dominated by fossil power plants (519 g CO_2eq/kWh [57]), and hence the CO_2 payback time is only a little longer than one year (then, the avoided CO_2 emissions offset the carbon footprint of the PV system). However, with the necessary transition to a fully renewable energy system discussed in **Section I**, the importance of the PV systems' carbon footprint increases accordingly.

Finally, carrying out full LCAs to gain a clear understanding of a product's environmental impact implies a significant effort, i.e., Fronius employs a dedicated expert team. Whereas there is a trend towards customers requiring information on environmental footprints, and upcoming regulations point the way, a key challenge lies in the comparability of results reported by different actors. The underlying reason is the lack of commonly available primary data from component manufacturers in the upstream supply chain, i.e., there is a need for all manufacturers to provide more and accurate primary data and/or a clear need for standardization.

III. Multi-Objective Optimization Including Environmental Impacts

The commonly employed a-posteriori LCAs as described above are important tools for, e.g., reporting the environmental footprint of a product, and for gaining insights regarding possible improvement vectors. However, designing power electronic converters for low environmental impacts by systematically investigating trade-offs between various targets requires a-priori LCAs as part of a comprehensive multi-objective Pareto optimization procedure, which we outline in the following.

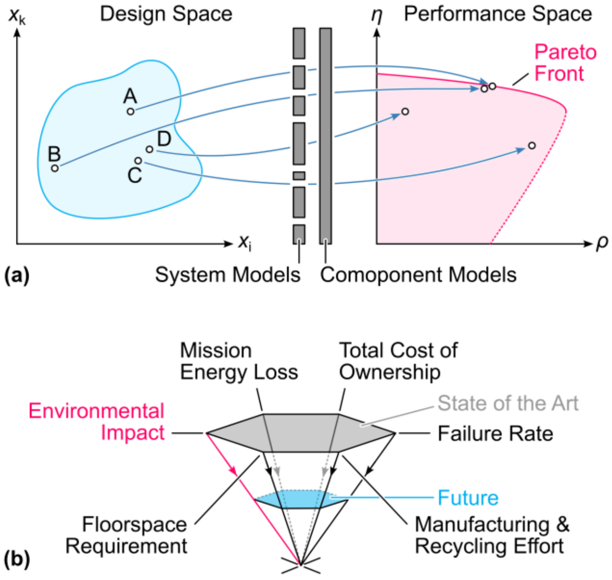


FIG 5 (a) Conceptual representation of a multi-objective converter optimization as a mapping of designs from the design space via system and component models into the performance space [59], here represented by the two dimensions efficiency, η and power density, ρ. Note that very different designs (i.e., with a large distance in-between in the design space) can show very similar performances at least in certain dimensions, see designs A and B. This *design-space diversity* opens up degrees of freedom to optimize further dimensions without compromising efficiency or power density; (b) lists further performance indicators of interest, including, in particular, environmental impacts [60].

FIG 5(a) illustrates how the optimization of power converters can be understood as a mapping from a multi-dimensional design space via component and system models into a multi-dimensional performance space [59]. The dimensions of the design space comprise all possible degrees of freedoms for converter realizations for given specifications and boundary conditions, e.g., a range of switching frequencies, inductor core materials, but also different converter topologies. The most common dimensions of the performance space are (weighted mission-profile) efficiency, η, (volumetric and/or gravimetric) power density, ρ, and sometimes (life-cycle) costs, σ [52]. Thus, component and system models are needed to calculate these performance indicators for each possible design. The boundary of the reachable subset of the performance space is the Pareto front; different subsets of the design space (e.g., different converter topologies) result in different Pareto fronts in the performance space, which facilitates a direct and comprehensive comparison along multiple dimensions. Note that designs that are located far apart in the design space (example designs A and B in FIG 5(a) can end up very close to each other in the shown $\eta\rho$-subset of the performance space (i.e., the projection of the multi-dimensional Pareto surface onto the $\eta\rho$-plane). This phenomenon is known as *design space diversity* [61], [62] and opens up a path for optimizing further dimensions (see the examples in FIG 5(b) without significantly affecting η and ρ.

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Using the 10-kW three-phase ac-dc power electronic building block (PEBB) shown in FIG 6(a) as an example, we outline including environmental impacts as further performance space dimensions in the following. The PEBB interfaces a 400-V three-phase ac system via a single-stage full-sinewave (i.e., differential-mode and common-mode) LC filter to an 800-V dc bus and could thus serve as a core building block (extended by, e.g., additional EMI filters) for power-factor-correction (PFC) rectifiers or, with the opposite power flow direction, for variable speed drives (VSDs). The PEBB employs two-level (2L) bridge legs with 1200-V SiC transistors (note that later also a three-level realization is considered) and a forced-air cooling system (cooling system performance index of $CSPI = 25$ W/(K dm^3) [63] and ambient temperature of 40 °C). FIG 6(b) shows a rendering of one exemplary realization and highlights the main components that are considered in the optimization, whereby component losses and volumes are modelled as in [58], [64]. The considered design space dimensions are the switching frequency, the inductor current ripple, and the transistor chip area, which are varied over wide ranges to obtain a high number of designs. FIG 6(c) shows the results in the $\eta\rho$-plane with the corresponding Pareto front. Note that for the sake of clarity, we only consider the full-load efficiency η, but a mission-profile efficiency could be included likewise. Further, each design in FIG 6(c) is colored according to its inductor current ripple, and the zoomed inset illustrates the design space diversity (i.e., there are designs with very different current ripples but almost equal performances in the η and ρ dimensions).

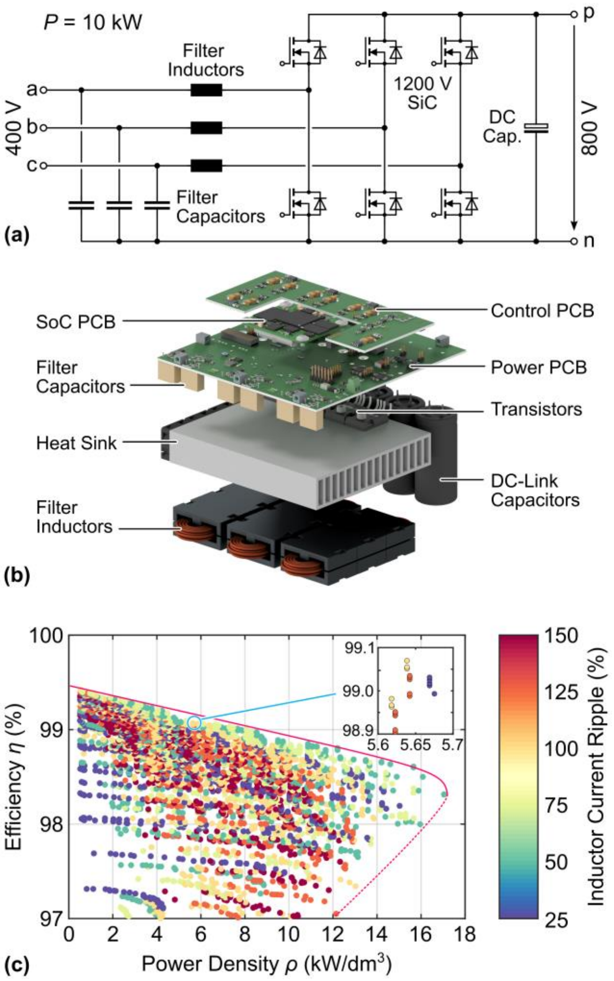

FIG 6 Three-phase ac-dc converter power-electronic building block (PEBB) considered for the multi-objective optimization. (a) Power circuit and (b) CAD rendering of an exemplary realization, highlighting the main components. (c) Efficiency vs. power density Pareto front with the filter inductor current ripple selection indicated by the marker colors; the inset illustrates the design space diversity, i.e., very similar efficiencies and power densities are achieved with a wide range of different current ripples, see also FIG 5(b).

In a next step, the environmental impacts caused by each component used in a specific design are aggregated to obtain an environmental footprint of that design. Note that the components account for the major share of a power converter's environmental footprint (similar to the system detailed in the **Sidebar**). The focus is on the main components highlighted in FIG 6(b), whereby the power components are design-dependent, but the control hardware is modeled as an offset (based on comparable built systems). The corresponding LCA data is mostly taken from the ecoinvent database [57]; more details are given in [58] and not reiterated here for the sake of brevity. It is important to highlight that such an a-priori LCA is inherently less precise than an a-posteriori LCA, because (at least as of now, see also

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Section IV) per-component-class environmental footprints are used that, for example, cannot account for differences between specific component models and/or manufacturers.

FIG 7(a) shows the optimization results in the same $\eta\rho$-plane as FIG 6(c), but the color scale indicates each design's GWP (without yet including the use phase, as shown in FIG 3(b). There is a trend indicating that more power-dense designs also feature a smaller GWP. However, during the use phase, a converter operates and wastes electricity as losses because $\eta < 100\%$. The wasted electricity, though, has an environmental footprint on its own, e.g., regarding GWP, 112 g CO_2eq / kWh for the Swiss household electricity consumption mix (2022, [65]), or, if only renewable electricity production in Switzerland is considered, about 21 g CO_2eq / kWh [57]. Over time, the overall environmental impact of a design increases depending on its efficiency characteristic, the mission profile, and the electricity mix. FIG 7(b) illustrates this for the two exemplary designs highlighted in FIG 7(a) with $\eta_A = 99.25\%$ and $\eta_B = 98.5\%$ (and hence different converter GWP footprints of 51 kg CO_2eq and 27 kg CO_2eq, respectively), considering a simplified scenario of 8 h/d operation at full-load over ten years. After a certain number of years, and depending on the electricity mix, the overall environmental impact in terms of GWP is lower for the more efficient converter design despite its higher initial GWP.

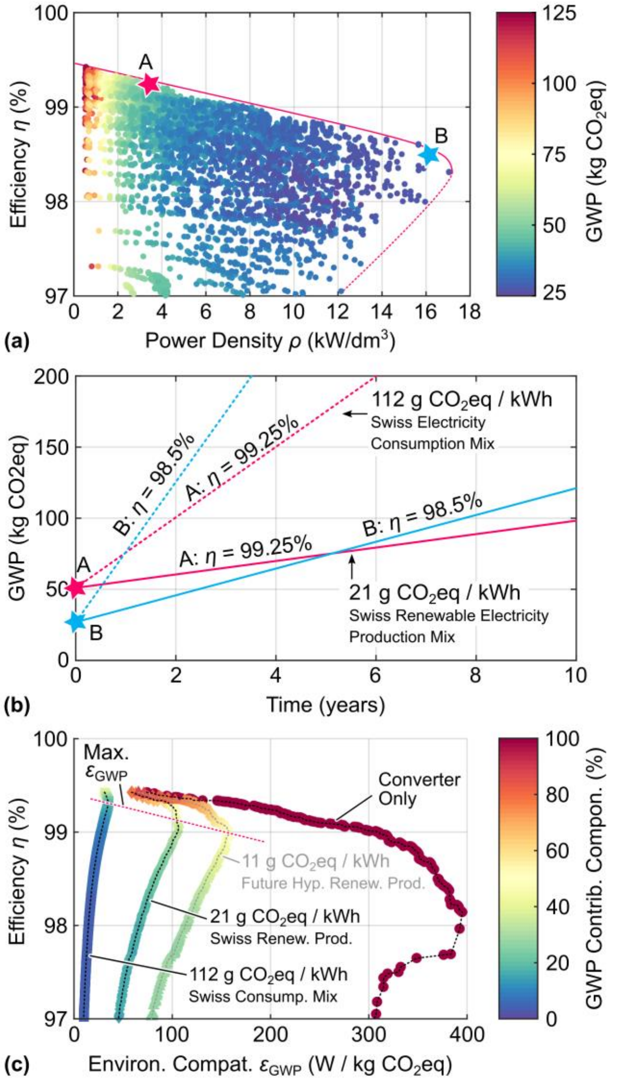

FIG 7 (a) Efficiency vs. power density Pareto front of the PEBB from FIG 6 with the marker colors indicating the GWP of each design. (b) During the use phase (assuming 8 h/d operation at rated power over 10 years), the energy losses contribute to the overall GWP depending on the electricity mix, and hence, over time, a more efficient design (A) with a higher initial GWP of the converter itself can outperform a less efficient design (B) with a lower initial GWP. (c) Considering the use phase contributions to the GWP of each design, different Pareto fronts representing the trade-offs between efficiency and the environmental compatibility indicator for GWP expressed as $\varepsilon_{GWP} = P / GWP$ (note that large values on this axis imply a low GWP, i.e., the scaling is such that on both axes, higher values are more advantageous) for different electricity mixes result. For greener electricity mixes it is less advantageous to design for maximum efficiency; the actual mission profiles (e.g., daily hours of operation) has a similar influence.

The operating scenario can be included in the multi-objective optimization, and FIG 7(c) shows the trade-off between efficiency and the environmental compatibility indicator (ECI) $\varepsilon_{GWP} = P / GWP$ with $[\varepsilon_{GWP}]$ = W / (kg CO2eq) and P referring to the rated power of here 10 kW. This indicator is introduced such that in the projections of the designs in the performance space on any pair of axes, larger values imply better performance. Comparing the $\eta\varepsilon_{GWP}$-Pareto fronts clearly indicates that an electricity mix with a lower environmental footprint, which is expected in the future, increases the importance of a low initial converter GWP footprint, i.e., motivates designs that are not aiming for maximum efficiency, to

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achieve highest environmental compatibility over the life cycle. The same applies to scenarios with less usage of the power converter, e.g., for cell phone chargers that typically operate less than 1 h/d.

The PEBB's bridge legs could alternatively be realized with three-level (3L) flying-capacitor structures employing 650-V transistors instead of the 1200-V transistors of the 2L solution. As expected, FIG 8(a) shows that 3L solutions can achieve better performance in terms of efficiency and power density. However, the trade-off between efficiency and the ECI $\varepsilon_{\mathrm{GWP}}$ shown in FIG 8(b) indicates that a PEBB with 3L bridge legs cannot achieve as high an $\varepsilon_{\mathrm{GWP}}$ (i.e., as low a GWP; note the colors) as the original 2L PEBB. This is because the 3L PEBB employs more power semiconductors, which are characterized by a relatively high GWP due to the energy-intense manufacturing processes. Note that the 3L PEBB can be built with a smaller volume, which would be beneficial once the housing and mechanical construction are considered.

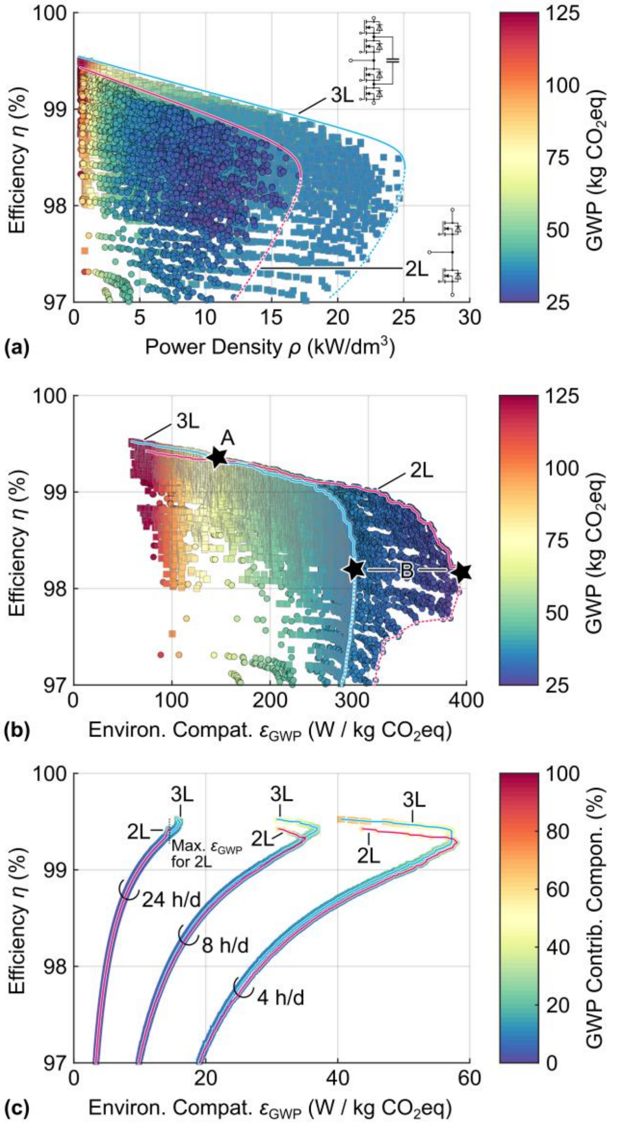

FIG 8 The bridge legs of the PEBB from FIG 6 can alternatively be realized as 3L flying-capacitor structures with 650-V SiC transistors. (a) and (b) compare these solutions on the converter level whereas (c) considers the use phase, too. **(a)** Shows the expected performance improvement of the 3L over the 2L solution regarding efficiency and power density. However, **(b)** indicates that a 3L PEBB inevitably features a larger initial GWP compared to the 2L baseline (again, the x-axis shows the environmental compatibility indicator for GWP expressed as $\varepsilon_{\mathrm{GWP}} = P\,/\,GWP$, i.e., large values on this axis imply a low GWP). The designs indicated by A and B are further evaluated in FIG 9. On the other hand, 3L PEBBs can be built with higher efficiencies, which influences the comparison once the use phase is taken into account. Therefore, **(c)** shows the resulting GWP for different use-phase scenarios (10 years, Swiss household electricity consumption mix with 112 g CO_2eq/kW (2022, [65])), and full-load operation during four, eight, and 24 hours per day, respectively). More intense use justifies a more efficient converter with a higher initial GWP. Note that due to the use phase's contribution to the overall GWP, lower $\varepsilon_{\mathrm{GWP}}$ values result in (c) than in (b).

Furthermore, the 3L PEBB can be built with higher efficiency, which is advantageous once the use phase is taken into account. FIG 8(c) shows the resulting trade-off for three different use phase scenarios that differ regarding the hours of daily operation (again a 10-yr lifetime and the Swiss household electricity consumption mix are considered). For a low usage intensity of 4 h/d, the 2L PEBB offers the best environmental compatibility, whereas at 8 h/d or 24 h/d, the 3L solution outperforms the 2L PEBB. Note the similarity to total-cost-of-ownership (TCO) considerations, where a more efficient and thus typically more expensive converter may pay off over time via lower energy costs [52].

So far, the discussion of environmental impacts has been limited to the GWP. However, a comprehensive LCIA should consider further dimensions as discussed previously in **Section II**. Again using the ReCiPe 2016 method [55], [56], we characterize these additional environmental impact dimensions

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in the following for exemplary 2L and 3L PEBBs. The marker "A" in FIG 8(b) indicates the intersection of the $\eta\varepsilon_{\mathrm{GWP}}$-Pareto fronts of the 2L and the 3L PEBB, i.e., two designs that have equal efficiencies of $\eta \approx 99.3\%$ (and hence equal impact from the use phase, which is therefore not considered here in the interest of brevity) and equal GWPs. This is visible in the radar plot from FIG 9(a), which also includes the remaining dimensions of the performance space, i.e., volume and the three ReCiPe areas of protection. The 3L PEBB is, as expected, much smaller. Despite having the same GWP and similar impact on resource availability than the 2L PEBB, the 3L PEBB's impact on ecosystems and human health is considerably lower than the 2L PEBB's. To attain $\eta \approx 99.3\%$, the 2L PEBB requires a low switching frequency and hence larger filter inductors, whereas the 3L PEBB uses comparably more power semiconductors and generates more losses there, i.e., requires a larger heat sink. These components have different environmental profiles (i.e., GWP vs. ReCiPe indicators, see also [58]), which leads to the observed differences between the 2L and the 3L PEBB. Note further that the more detailed a-posteriori LCAs of the 3LTT and the 7LHANPC PV inverters from **Section II** give comparable results.

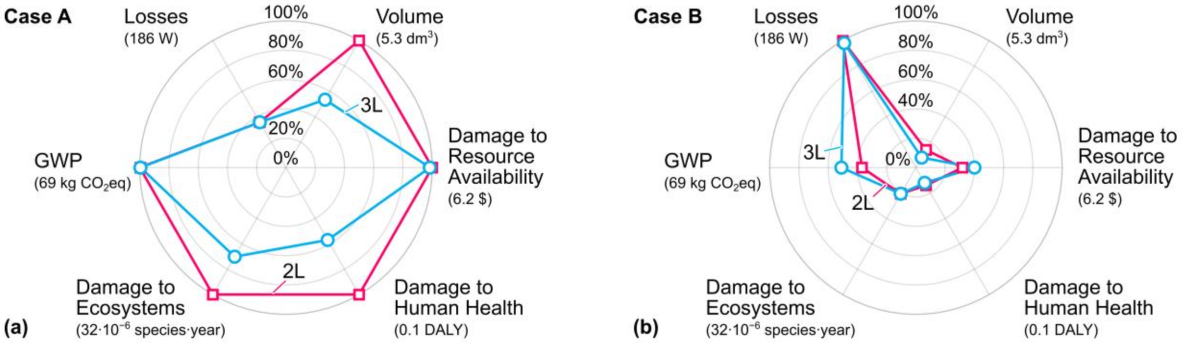

FIG 9 Comparison of the exemplary 2L and 3L (flying-capacitor) PEBB designs indicated in FIG 8(b) regarding the six performance space dimensions considered here. (a) 2L and 3L PEBB designs at the intersection of the respective $\eta\varepsilon_{\mathrm{GWP}}$-Pareto fronts (A in FIG 8(b) and (b) at the respective maximum $\varepsilon_{\mathrm{GWP}}$ (B in FIG 8(b)).

FIG 9(b) shows a like comparison for the two designs marked with "B" in FIG 8(b)**,** which are characterized by the respective highest $\varepsilon_{\mathrm{GWP}}$ (lowest GWP) and still approximately equal efficiency of $\eta \approx 98.2\%$ (therefore, the use phase again contributes approximately equally for both designs). The corresponding 2L and the 3L PEBB designs are more similar, i.e., have about the same size and, except for the GWP, similar environmental impacts, because the component distribution is more similar between the two realization options.

These examples illustrate that even though the environmental impact indicators are usually specified per weight of a material or component, power density is not necessarily a good proxy; here, and also in the PV inverter example from Section II, the smaller design performs worse regarding GWP but better regarding the three ReCiPe dimensions. Therefore, a careful and comprehensive, multidimensional / multi-objective analysis is needed. The environmental impact of a converter itself matters most if (a) there is a very good electricity mix (as expected in a future net-zero-emissions energy system) and/or (b) if the system is only rarely used (mission profile); both lower the relevance of the use phase compared to the production of the converter. Therefore, the mission profile and the application environment are very important aspects that modify the optimum concept for and then design of a power electronic converter system.

Further research should therefore extend the initial findings reported here by more detailed mission profiles (e.g., standardized in analogy to "driving cycles" in the automotive industry), consider housings and mechanical assembly, and electromechanical components found in a complete system. Further performance indicators like cost should be included, too: note that there is trade-off between environmental impact and cost regarding the converter itself but also regarding the use phase, given the widespread implementation of taxes on CO$_2$ emissions. In doing so, obtaining reliable and representative environmental impact data for components typically employed in power electronic converters is a major challenge. A second set of key research questions relates to including aspects such as reliability (e.g., a larger heat sink might have a higher initial environmental footprint but allow operation with lower temperatures and hence facilitate a longer lifetime), repairability, reuse, and recycling in a-priori LCAs that are part of a future comprehensive multi-objective optimization frameworks for power electronic converters.

IV. Conclusion and Outlook

All in all, the time horizon for achieving the net-zero-emission targets required for limiting global warming is relatively short—too short for relying on the hope for a disruptive technology emerging as a panacea: the lead times for technology development and scaling are long [61], [66], as are the lifetimes of energy infrastructures once installed [61], [6]. Power converters with highest efficiencies of 99% and beyond have been demonstrated for various applications, i.e., there is little room for improvement. This can be seen as a consequence of the fact that until recently, converter optimizations mostly considered efficiency, power density, and sometimes (life-cycle) costs. However, future power converters can and should be improved regarding their environmental footprint and their compatibility with a circular economy, i.e., Ecodesign [29]–[31] or "Design for Circularity" [23], [26], [27] concepts must be applied.

This implies that environmental performance indicators, i.e., LCIA results, must be considered as early in the design phase as possible: rendering the consequences of design choices visible allows engineers to influence a desirable outcome. Therefore, in this article, we have described a first step on a proposed roadmap (see FIG 10) towards circular-economy-compatible power electronics by including environmental compatibility in a multi-objective optimization framework. Ultimately, this facilitates a careful balancing of design trade-offs, which, in the future, should also consider cost and other business aspects like customer acceptance/satisfaction.

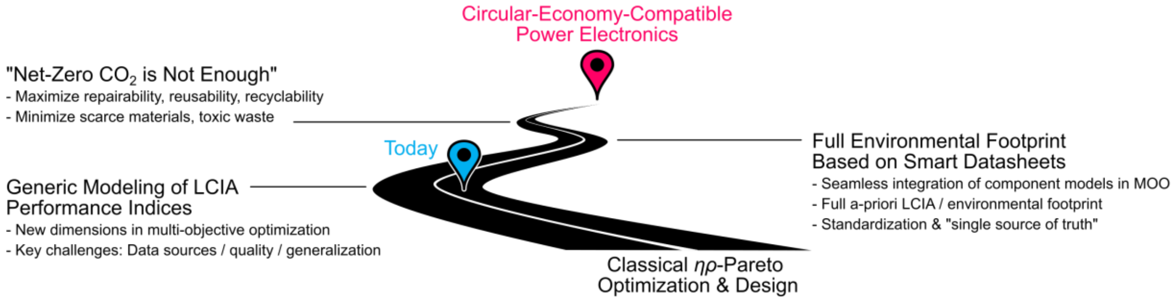

FIG 10 Proposed roadmap towards circular-economy-compatible power electronics.

Key challenges lie, first, in obtaining reliable and representative environmental impact data of components commonly used in power electronic converters, and second, in the need for a certain generalization to obtain scalable environmental impact models for key components. Similarly, an agreed-upon set of data sources and methods is necessary to facilitate comparisons between LCIA results obtained by different actors. In an ideal future, smart datasheets provided by component manufacturers would not only contain data on electric or magnetic device characteristics dependent on operating conditions, etc., but also on the component's environmental footprint. Then, future optimization frameworks could operate with vast numbers or real components (computing power being ubiquitously available) and generate accurate a-priori LCIA results of specific converter designs. Note that there is a strong link to general efforts towards further design automation; furthermore, artificial intelligence (AI) will support the handling and evaluation of the correspondingly large sets of results with multiple performance dimensions.

Finally, especially in a future fully renewably powered net-zero-emissions world, where the use-phase contributions to a converter's environmental impact will be correspondingly low, there is a need to carefully consider all life-cycle phases, in particular repair (also in the view of upcoming right-to-repair legislation, e.g., in the European Union [67]) and reuse to maximize the lifetime, and the end-of-life management (recycling), with the goal of minimizing toxic waste and depletion of scarce resources. In doing so, further challenging trade-offs must be expected, e.g., between integration and reusability/recyclability, or between repairability and reliability (long lifetime).

As indicated by FIG 11, past development cycles of power electronics have been triggered by advancements in power semiconductor technology [68] and/or by disruptive technologies. A next cycle, i.e., Power Electronics 5.0, is driven by the need for minimizing the environmental impact of the future power-electronics-dominated energy system, and the need for future power converters to be compatible with a circular economy. As the engineering talent gap widens with an aging society [69], AI-assisted tools will be instrumental, e.g., for designing but also for prognostics and intelligent maintenance [70], which are key to achieving long product lifetimes. A second consequence, in addition to the general need for attracting more students to STEM subjects, is therefore that an awareness for environmental impacts and/or LCA methodology should be included in engineering curricula [71].

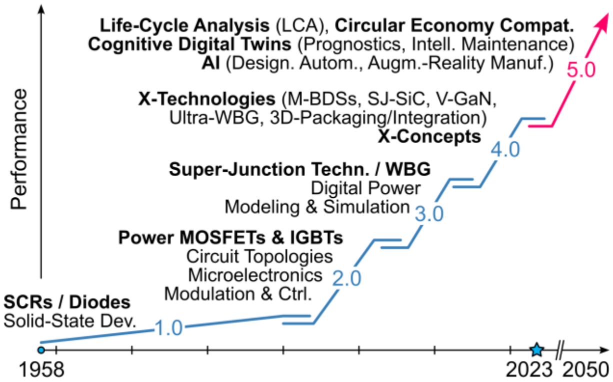

FIG 11 Technology S-curves of subsequent power electronics development cycles, which have been triggered by advances in power semiconductor technology and then by disruptive replacement technologies with factor-of-*X* improvements (X-Technologies and X-Concepts [72]). Power electronics 5.0, on the other hand, will be driven by new key performance indicators characterizing the compatibility with the environment and a future circular economy, with AI-supported design methods and intelligent maintenance as key enablers.

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References

[1] IPCC, "Summary for policymakers," in Climate change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [Core Writing Team, H. Lee and J. Romero (eds.)], Geneva, Switzerland, 2023. [Online]. Available: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

[2] DNV, "Pathway to net-zero emissions," 2023. [Online]. Available: https://www.dnv.com/publications/pathway-to-net-zero-emissions-report-2023-249543

[3] World Meteorological Organization (WMO), "Understanding the IPCC special report on 1.5°C," 2018. [Online]. Available: https://library.wmo.int/idurl/4/56268

[4] C. McGlade and P. Ekins, "The geographical distribution of fossil fuels unused when limiting global warming to 2 °C," *Nature,* vol. 517, no. 7533, pp. 187–190, Jan. 2015. doi: 10.1038/nature14016

[5] Quote Investigator, 2018. [Online]. Available: https://quoteinvestigator.com/2018/01/07/stone-age/

[6] S. J. Davis et al., "Net-zero emissions energy systems," *Science,* vol. 360, no. 6396, Jun. 2018, doi: 10.1126/science.aas9793.

[7] R. I. Dunn, P. J. Hearps, and M. N. Wright, "Molten-salt power towers: Newly commercial concentrating solar storage," *Proc. IEEE,* vol. 100, no. 2, pp. 504–515, Feb. 2012, doi: 10.1109/JPROC.2011.2163739.

[8] R. Sioshansi and P. Denholm, "Benefits of colocating concentrating solar power and wind," *IEEE Trans. Sust. Energy,* vol. 4, no. 4, pp. 877–885, Oct. 2013, doi: 10.1109/TSTE.2013.2253619.

[9] IRENA, "Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects," International Renewable Energy Agency, Abu Dhabi, Oct. 2019. [Online]. Available: https://www.irena.org/publications/2019/Oct/Future-of-wind

[10] IRENA, “Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects,” International Renewable Energy Agency, Abu Dhabi, Nov. 2019. [Online]. Available: https://www.irena.org/Publications/2019/Nov/Future-of-Solar-Photovoltaic

[11] R. Singh, P. Paniyil, and Z. Zhang, “Transformative role of power electronics in solving climate emergency,” *IEEE Power Electron. Mag.,* vol. 9, no. 2, pp. 39–47, Jun. 2022. doi: 10.1109/MPEL.2022.3169317

[12] Y. Kuwano, “The PV era is coming — the way to GENESIS,” *Solar Energy Mat. Solar Cells,* vol. 34, no. 1, pp. 27–39, Sep. 1994. doi: 10.1016/0927-0248(94)90021-3

[13] R. Hata and S. Isojima, “GENESIS project and use of sustainable energy,” *SEI Tech. Rev.,* vol. 69, Oct. 2009.

[14] S. Chatzivasileiadis, D. Ernst, and G. Andersson, “The global grid,” *Renewable Energy,* vol. 57, pp. 372–383, Sep. 2013. doi: 10.1016/j.renene.2013.01.032

[15] D. Boroyevich, I. Cvetković, D. Dong, R. Burgos, F. Wang, and F. C. Lee, “Future electronic power distribution systems – A contemplative view,” in *Proc. 12th Int. Optim. Electric. Electronic Equipment Conf. (OPTIM),* Brasov, Romania, May 2010, pp. 1369–1380. doi: 10.1109/OPTIM.2010.5510477

[16] DNV, “Energy transition outlook 2023,” 2023. [Online]. Available: https://www.dnv.com/energy-transition-outlook/

[17] I. Capellán-Pérez, C. de Castro, and L. J. Miguel González, “Dynamic energy return on energy investment (EROI) and material requirements in scenarios of global transition to renewable energies,” *Energy Strategy Reviews,* vol. 26, p. 100399, Nov. 2019. doi: 10.1016/j.esr.2019.100399

[18] IEA, “Net zero by 2050: A roadmap for the global energy sector.” [Online]. Available: https://www.iea.org/reports/net-zero-by-2050

[19] Fronius International GmbH, “GEN24 Plus – A benefit for the environment: Life cycle assessment,” 2023. [Online]. Available: https://www.fronius.com/~/downloads/Solar%20Energy/Whitepaper/SE_WP_LCA_GEN24_Plus_EN.pdf

[20] SMA Solar Technology AG, “Sunny Highpower PEAK3 life cycle assessment (LCA),” 2023. [Online]. Available: https://files.sma.de/assets/280662.pdf

[21] V. Forti, C. P. Balde, R. Kuehr, and G. Bel, “The global E-waste monitor 2020: Quantities, flows and the circular economy potential.” Bonn/Geneva/Rotterdam: United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU), and International Solid Waste Association, 2020. [Online]. Available: https://collections.unu.edu/view/UNU:7737

[22] IEA, “The role of critical minerals in clean energy transitions.” May 2021. Accessed: Jan. 09, 2024. [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[23] Ellen MacArthur Foundation, “Circular economy introduction,” 2023. [Online]. Available: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

[24] M. Patra, “European ecodesign material efficiency standardization overview for circular economy aspects in motor and power drive systems,” in *Proc. 11th Int. Conf. Energy Efficiency in Motor Driven Syst. (EEMODS),* Tokyo, Japan, Sep. 2021, pp. 231–242. doi: 10.1007/978-3-030-69799-0_18

[25] M. Patra, T. Cormenier, A. Louise, and P. Mourlon, “European ecodesign material efficiency standardization supporting circular economy aspects of power drive systems for sustainability,” in *Proc. 12th Int. Conf. Energy Efficiency Motor Driven Syst. (EEMODS),* Stuttgart, Germany, May 2022.

[26] A. Berwald et al., “Design for circularity guidelines for the EEE sector,” *Sustainability,* vol. 13, no. 7, Art. no. 7, Jan. 2021. doi: 10.3390/su13073923

[27] S. Suppipat and A. H. Hu, “A scoping review of design for circularity in the electrical and electronics industry,” *Resources, Conservation & Recycling Advances,* vol. 13, p. 200064, May 2022. doi: 10.1016/j.rcradv.2022.200064

[28] B. Rahmani, Y. Lembeye, M. Rio, and J.-C. Crebier, “Analysis of passive power components reuse,” in *Proc. Power Convers. Intelligent Motion Conf. (PCIM Europe),* Nuremberg, Germany, May 2021.

[29] G. Parise and M. Lombardi, “Ethics and eco-design for complex uses of energy: What we need for a sustainable future,” *IEEE Ind. Appl. Mag.,* vol. 28, no. 5, pp. 74–79, Sep. 2022, doi: 10.1109/MIAS.2022.3160998.

[30] L. Fang, P. Lefranc, and M. Rio, “Barriers for eco-designing circular power electronics converters,” *Procedia CIRP,* vol. 116, pp. 287–292, Jan. 2023. doi: 10.1016/j.procir.2023.02.049

[31] L. Fang et al., “Eco-design implementation in power electronics: A literature review,” in Proc. *Int. Symp. Advanced Techn. Electr. Syst. (SATES),* Arras, France, Mar. 2023.

[32] *Environmental management – Life cycle assessment – Principles and framework*, EN ISO Std. 14040, 2021.

[33] *Environmental management – Life cycle assessment – Requirements and guidelines*, EN ISO Std. 14044, 2021.

[34] N. Jungbluth, C. Bauer, R. Dones, and R. Frischknecht, “Life cycle assessment for emerging technologies: Case studies for photovoltaic and wind power,” *Int. J. Life Cycle Assess.,* vol. 10, no. 1, pp. 24–34, Jan. 2005. doi: 10.1065/lca2004.11.181.3

[35] J. Popović-Gerber, J. A. Ferreira, and J. D. van Wyk, “Quantifying the value of power electronics in sustainable electrical energy systems,” *IEEE Trans. Power Electron.,* vol. 26, no. 12, pp. 3534–3544, Dec. 2011. doi: 10.1109/TPEL.2011.2166088

[36] J. Auer and A. Meincke, “Comparative life cycle assessment of electric motors with different efficiency classes: A deep dive into the trade-offs between the life cycle stages in ecodesign context,” *Int. J. Life Cycle Assess.,* vol. 23, no. 8, pp. 1590–1608, Aug. 2018. doi: 10.1007/s11367-017-1378-8

[37] W. Bulach et al., “Electric vehicle recycling 2020: Key component power electronics,” *Waste Manag. Res.,* vol. 36, no. 4, pp. 311–320, Apr. 2018. doi: 10.1177/0734242X18759191

[38] N. André and M. Hajek, “Robust environmental life cycle assessment of electric VTOL concepts for urban air mobility,” in *Proc. AIAA Aviation Forum,* Dallas, TX, USA, Jun. 2019. doi: 10.2514/6.2019-3473

[39] G. A. Quintana-Pedraza, S. C. Vieira-Agudelo, and N. Muñoz-Galeano, “A cradle-to-grave multi-pronged methodology to obtain the carbon footprint of electro-intensive power electronic products,” *Energies,* vol. 12, no. 17, Art. no. 17, Jan. 2019. doi: 10.3390/en12173347

[40] A. Nordelöf, M. Alatalo, and M. L. Söderman, “A scalable life cycle inventory of an automotive power electronic inverter unit—Part I: Design and composition,” *Int. J. Life Cycle Assess.,* vol. 24, no. 1, pp. 78–92, Jan. 2019. doi: 10.1007/s11367-018-1503-3

[41] A. Nordelöf, “A scalable life cycle inventory of an automotive power electronic inverter unit—Part II: Manufacturing processes,” *Int. J. Life Cycle Assess.,* vol. 24, no. 4, pp. 694–711, Apr. 2019. doi: 10.1007/s11367-018-1491-3

[42] F. Musil, C. Harringer, A. Hiesmayr, and D. Schönmayr, “How life cycle analyses are influencing power electronics converter design,” in *Proc. Power Convers. Intelligent Motion Conf. (PCIM Europe),* Nuremberg, Germany, May 2023.

[43] A. Schiro, “Sustainability benefits of GaNFast power ICs,” presented at *IEEE Appl. Power Electron. Conf. (APEC),* Orlando, FL, USA, Mar. 2023.

[44] A. Díaz, S. Schmidt, S. Glaser, and M. Makoschitz, “A ‘life cycle thinking’ approach to assess differences in the energy use of SiC vs. Si power semiconductors,” in *Proc. e·nova Int. Conf.,* Pinkafeld, Austria, Jun. 2021.

[45] S. Glaser, A. Díaz, and M. Makoschitz, “Design aspects and environmental impacts of wide band gap based semiconductor technology in chargers for electronic devices,” in *Proc. Going Green Care Innov. Conf.,* Vienna, Austria, May 2023.

[46] L. B. Spejo, I. Akor, M. Rahimo, and R. A. Minamisawa, “Life-cycle energy demand comparison of medium voltage silicon IGBT and silicon carbide MOSFET power semiconductor modules in railway traction applications,” *Power Electron. Dev. Comp.,* vol. 6, p. 100050, Oct. 2023. doi: 10.1016/j.pedc.2023.100050

[47] S. Glaser, P. Feuchter, and A. Diaz, “Looking beyond energy efficiency – Environmental aspects and impacts of WBG devices and applications over their life cycle,” in *Proc. Europ. Power Electron. Conf. (EPE),* Aalborg, Denmark, Sep. 2023.

[48] P. Zacharias, “Impact of power electronics on resource efficiency of electric energy conversion,” presented at *IEEE Southern Power Electron. Conf.,* Florianopolis, Brazil, Nov. 2023.

[49] J. W. Kolar, J. Huber, L. Imperiali, and D. Menzi, “Net-zero CO_2 by 2050 is NOT enough (!),” presented at *ECPE Expert Discussion Sustainability in Power Electron.,* Zurich, Switzerland, Jul. 12, 2023. [Online]. Available: https://u.ethz.ch/rHBjy

[50] “CCPE Self-check of the Circular Readiness Level®.” [Online]. Available: https://ccpe.iml.fraunhofer.de/selfcheck/ (accessed Aug. 21, 2023).

[51] J. Thackara, *In the bubble: Designing in a complex world.* Cambridge, MA, USA: The MIT Press, 2006.

[52] R. M. Burkart and J. W. Kolar, “Comparative life cycle cost analysis of Si and SiC PV converter systems based on advanced η-ρ-σ multiobjective optimization techniques,” *IEEE Trans. Power Electron.,* vol. 32, no. 6, pp. 4344–4358, Jun. 2017. doi: 10.1109/TPEL.2016.2599818

[53] J. A. Anderson, D. Marciano, J. Huber, G. Deboy, G. Busatto, and J. W. Kolar, “All-SiC 99.4%-efficient three-phase T-type inverter with DC-side common-mode filter,” *Electron. Lett.,* vol. 59, no. 12, p. e12821, 2023. doi: 10.1049/ell2.12821

[54] J. Anderson Azurza, E. J. Hanak, L. Schrittwieser, M. Guacci, J. W. Kolar, and G. Deboy, “All-silicon 99.35% efficient three-phase seven-level hybrid neutral point clamped/flying capacitor inverter,” *CPSS Trans. Power Electron. Appl.,* vol. 4, no. 1, pp. 50–61, Mar. 2019. doi: 10.24295/CPSSTPEA.2019.00006

[55] M. A. J. Huijbregts et al., “ReCiPe 2016 v1.1: A harmonized life cycle impact assessment method at midpoint and endpoint level, Report I: Characterization,” 2016. [Online]. Available: https://pre-sustainability.com/legacy/download/Report_ReCiPe_2017.pdf

[56] M. A. J. Huijbregts et al., “ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level,” *Int. J. Life Cycle Assess.,* vol. 22, no. 2, pp. 138–147, Feb. 2017. doi: 10.1007/s11367-016-1246-y

[57] ecoinvent, “Ecoinvent Database 3.9.1.” [Online]. Available: https://ecoinvent.org/

[58] L. Imperiali, D. Menzi, J. W. Kolar, and J. Huber, “Multi-objective minimization of life-cycle environmental impacts of three-phase AC-DC converter building blocks,” in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC),* Long Beach, CA, USA, Feb. 2024.

[59] J. W. Kolar, J. Biela, and J. Miniböck, “Exploring the Pareto front of multi-objective single-phase PFC rectifier design optimization - 99.2% efficiency vs. 7 kW/dm^3 power density,” in *Proc. 6th IEEE Int. Power Electron. Motion. Control Conf. (IPEMC),* Wuhan, China, May 2009. doi: 10.1109/IPEMC.2009.5289336

[60] J. W. Kolar, F. Krismer, and H. P. Nee, “What are the ‘BIG CHALLENGES’ in power electronics?,” presented at *8th Int. Conf. Integr. Power Electron. Syst. (CIPS),* Nuremberg, Germany, Feb. 2014.

[61] J. W. Kolar, J. Biela, S. Waffler, T. Friedli, and U. Badstuebner, “Performance trends and limitations of power electronic systems,” in *Proc. 6th Int. Integr. Power Electron. Syst. Conf. (CIPS),* Nuremberg, Germany, Mar. 2010.

[62] J. W. Kolar, D. Neumayr, D. Bortis, M. Guacci, and J. Anderson Azurza, “Google Little-Box reloaded,” presented at *10th Int. Conf. Integr. Power Electron. (CIPS),* Stuttgart, Germany, Mar. 2018.

[63] U. Drofenik, G. Laimer, and J. Kolar, “Theoretical converter power density limits for forced convection cooling,” in *Proc. Power Convers. Intelligent Motion Conf. (PCIM Europe),* Nuremberg, Germany, Jun. 2005, pp. 608–619.

[64] D. Menzi, Z. Yu, J. Huber, and J. W. Kolar, “Comparative evaluation of ultra-lightweight buck-boost DC-DC converter topologies for future eVTOL aircraft,” in *Proc. 23rd Workshop Control Modeling Power Electron. (COMPEL),* Tel Aviv, Israel, Jun. 2022. doi: 10.1109/COMPEL53829.2022.9830019.

[65] VSE, “Der CO_2-Gehalt im Schweizer Strom steigt (in German),” 2023. [Online]. Available: https://www.strom.ch/de/pressemitteilung/der-co2-gehalt-im-schweizer-strom-steigt

This article has been accepted for publication in IEEE Power Electronics Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MPEL.2024.3354013

[66] J. W. Kolar and J. Huber, "Power electronics enabling a net-negative-CO_2 integrated sustainable multi-carrier energy system," presented at *2nd Three Corners Power Electronics Extended Collaboration (3C-PEEC) Workshop "Moving Towards a Carbon-Free World by 2050",* Arlington, VA, USA, Apr. 2023. [Online]. Available: https://u.ethz.ch/q7dLf

[67] European Commission, "Right to repair: Making repair easier for consumers," Mar. 22, 2023. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1794

[68] R. V. White, "Which came first? Part I," *IEEE Power Electron. Mag.,* vol. 9, no. 3, pp. 96–94, Sep. 2022. doi: 10.1109/MPEL.2022.3193858

[69] Bain & Company, "Engineering and R&D report 2023," 2023. [Online]. Available: https://www.bain.com/globalassets/noindex/2023/bain_report_engineering_and_r_and_d_report_2023.pdf

[70] C. H. van der Broeck, S. Kalker, and R. W. De Doncker, "Intelligent monitoring and maintenance technology for next-generation power electronic systems," *IEEE Trans. Emerg. Sel. Topics Power Electron.,* vol. 11, no. 4, pp. 4403–4418, Aug. 2023. doi: 10.1109/JESTPE.2021.3119590

[71] D. Parsons, "The environmental impact of electronics and its incorporation into the curriculum," in *Proc. 17th Annu. Conf. Australasian Assoc. Engin. Edu. (AaeE),* Auckland, New Zealand, Dec. 2006.

[72] J. W. Kolar and J. Huber, "'X-Concepts'—The DNA of future high-performance power electronic systems," presented at *1st IEEE Int. Power Electron. Appl. Symp. (PEAS),* Shanghai, China, Nov. 2021.