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White Paper

Circular Economy Compatible Power Electronics and New Application Areas

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Executive Summary

Power electronics is a key technology for a future all-renewable energy system. In generation, transmission, distribution, and electrified end-use applications, technologies like wide-bandgap power semiconductors, single-stage and/or multilevel converter topologies, modularization, and digital control already enable highest performance of *Power Electronics 4.0* (see **Fig. A**). Further industrial scaling-up and hence the "slide down the learning curve" should be emphasized, while ensuring full compatibility with the circular economy paradigm to minimize life-cycle environmental impacts and the use of raw materials, i.e., *Power Electronics 5.0* (see **Fig. B**).

Furthermore, we expect significant opportunities for new applications of power electronics in concepts and new processes (chemical, metallurgical, etc.) for the direct electrification of hard-to-abate sectors such as the production of pig/crude iron and steel, cement, and chemicals, which contribute 25% of today's greenhouse gas emission. Corresponding research in power electronics in close collaboration with neighboring disciplines like metallurgy or chemistry should be prioritized. This broadening of application areas highlights the importance of the *Power Electronics 5.0* paradigm.

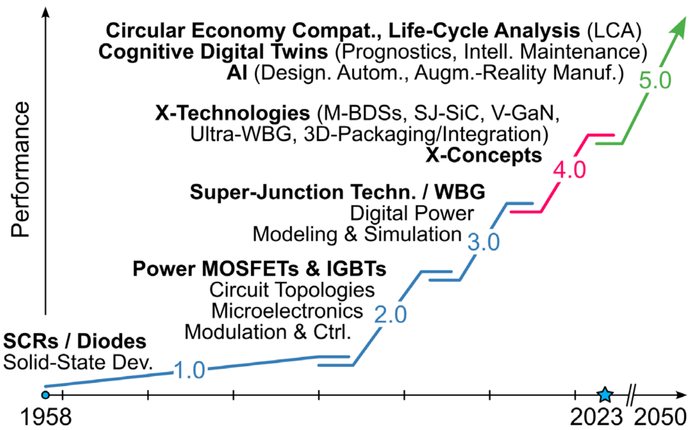

Fig. A: S-curves of power electronics technology development cycles (figure adapted from [1]).

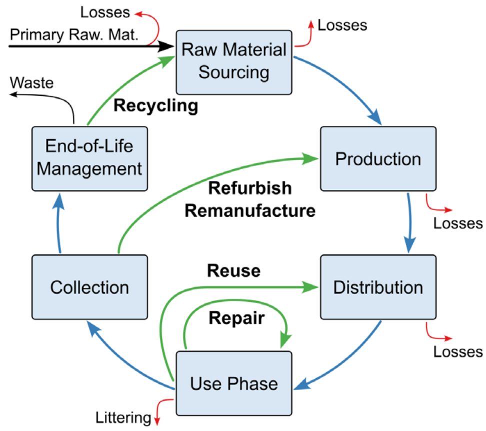

Fig. B: Circular economy paradigm at the core of *Power Electronics 5.0*.

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Global Context

Complex modern societies rely on the availability of sufficient cheap energy for agriculture, heating, transportation, industry (e.g., steel and concrete for infrastructure), and amenities of modern life like health care, education, and leisure. Thus, the per-capita energy consumption is proportional to the economic performance of societies in terms of GDP per capita [2]. Even though there is some decoupling observed for affluent countries [3], i.e., a reduction of the energy intensity of the economy, studies anticipate a 90% increase in global useful energy demand to around 500 EJ by 2050. Advantageously, gains in efficiency, e.g., through electrification, heat pumps, building isolation, recycling, etc., could limit the increase in final energy demand to only 10% [4].

Today, the energy mix is dominated by around 80% of fossil fuels [4], whose historically high energy returns on energy invested (EROI)[1] have enabled the unprecedented economic growth observed since the industrial revolution, and whose high energy densities and on-demand availability are advantageous in many applications like transportation or load-following electricity generation.

However, the negative consequences of burning fossil fuels are well understood and range from air pollution, causing around 9 million premature deaths per year globally alone from exposure to fine particulate matter (PM2.5) [5], to climate change, which will lead to rising sea levels, droughts, etc., and affect hundreds of millions of people [6], especially in regions of the world that did not (yet) benefit to the same degree from the economic development fueled by coal, oil and gas—a true "tragedy of the commons". Further, relying on the availability of fossil fuels comes with short-term risks in the form of geopolitical and global economic dependencies and long-term supply risks given progressively more difficult and hence expensive extraction and the ultimate finiteness of fossil resources [7]–[9].

Even so, given our reliance on fossil fuels not only for obvious uses such as transportation but also for many large-scale and essential industrial processes such as the production of steel and cement, chemicals, fertilizers, etc., phasing out fossil fuels entirely on a global scale to achieve net-zero carbon emissions by 2050, i.e., in just 25 years from now, is a monumental challenge—especially considering that today's energy system took 150 years to establish [10].

Renewable Energy

Clearly, a net-zero energy supply system relies almost exclusively[2] on renewable energy sources (see **Fig. 1**) like hydro, solar PV, concentrated solar power (CSP), and wind; and possibly nuclear power. These inherently provide electricity directly, which advantageously enables efficiency gains (avoiding, e.g., Carnot-cycle efficiency limits) in the overall energy system (e.g., electric vehicles, heat pumps, etc.) as mentioned above. However, direct electrification might not be applicable in important sectors like long-haul transportation (shipping, aviation), the production of steel, cement, and chemicals (plastics, fertilizers, etc.), which contribute around a quarter of today's greenhouse gas (GHG) emissions, see **Fig. 2**. This implies that a future energy system, even though almost exclusively supplied from renewable electricity, will be a multi-carrier energy system [11], in which Power-to-X technologies play a key role in providing synthetic fuels based on hydrogen (e.g., ammonia,

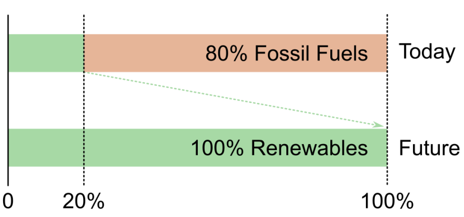

Fig. 1: Today, fossil fuels account for 80% of the energy mix [4], whereas a future net-zero energy system relies entirely on renewable sources.

[1] The EROI is the ratio of the energy obtained to the energy required to obtain that energy (e.g., to build the extraction infrastructure and then to run the pumps, etc.); an EROI of 10:1 means that for every 1 J of energy invested, 10 J are obtained and hence 9 J of net energy are supplied to society for discretionary economic activities.

[2] Assuming that carbon capture and storage (CCS) technologies won't scale sufficiently to have a significant impact [10].

methanol, ethanol, etc.) for industrial processes that can't be electrified, as well as for long-haul transportation and long-term/seasonal energy storage.

The theoretically available solar and wind energy exceeds the global energy needs by orders of magnitudes and, considering only the exploitable solar potential, around 0.2% of the continental area would suffice to supply an electrified world with energy [13]. However, employing renewables is not without challenges:

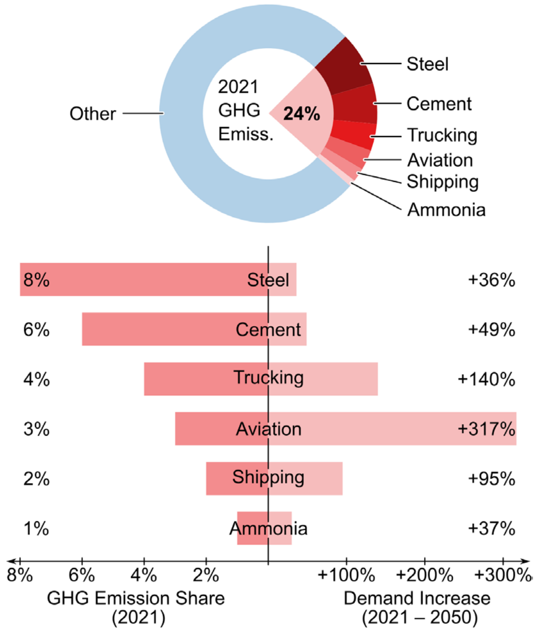

Fig. 2: "Hard-to-abate" industry sectors, their current greenhouse gas (GHG) emission shares (totaling to one fourth of all emissions), and projected demand increase until 2050. Data from [12].

- First, the power output of renewable energy sources fluctuates (e.g., day/night and seasonal cycles, weather conditions, etc.). The average annual power output is thus significantly lower than the nameplate power rating, resulting in global average capacity factors[3] of only around 0.15 for solar PV, 0.34 for onshore and 0.44 for offshore wind [14], with regional differences due to latitude, climatic conditions, etc.
- Second, the areal energy densities (global averages) of renewable power generation plants (PV: 0.04...0.09 TWh/km^2, wind onshore: 0.02 TWh/km^2) are around two orders of magnitude lower than those of conventional plants (nuclear: 6.7 TWh/km^2, natural gas: 3.3 TWh/km^2; including delivery and fuel extraction infrastructure) [14]. This implies relatively high land use, large collection grids, and, since large-scale renewable power plants are advantageously located in regions with high capacity factors, long-distance transmission to load centers like cities. Studies estimate an expansion of the global HV transmission line length from 3 million kilometers in 2016 to 7.5 million kilometers in 2050, resulting in significant raw material requirements (e.g., the annual copper and aluminum demand of the electricity sector could increase to around 30% of current annual global production) [15].
- Third, the fluctuating power output of renewables requires the installation of energy storage and overcapacities to guarantee a continuous supply. Studies find that even with an installation of 150% of the required annual energy generation capacity using an optimal combination of renewables and 12 h storage, more than 60% of the demand cannot be satisfied during several 100 h per year [16]; commonly, the term "Dunkelflaute" is used to describe an extended period of little sunshine and wind. Aggregating renewables over a larger region, e.g., a continent, via sufficiently capable transmission grids improves the reliability of supply but does not completely eliminate the need for energy storage [16]. Whereas short-term (in the order of several hours) storage can be provided by batteries, e.g., directly combined with PV plants, long-term (seasonal) storage is more challenging: suitable sites for highly efficient pumped hydro stations are scarce and storage in chemical form is inefficient (the Power-to-X-to-Power best-case roundtrip efficiency for 30 d storage is just around 25% for hydrogen and ammonia; ammonia outperforms hydrogen for longer storage durations) [17].

[3] The capacity factor is the ratio of the actual yearly energy production to the theoretical maximum (delivering rated power during 24 h on 365 days of the year).

CRITICAL RAW MATERIAL REQUIREMENTS

Consultancies put a price tag (cumulative spending on physical assets) of 275 trillion USD on a (hypothetical) net-zero-by-2050 scenario, which implies an increase in annual spending by 3.5 trillion USD compared to today [18]. However, it is not automatically clear that the required excess quantities of raw materials like copper are actually available in time [19]: 6 large new copper mines per year would be needed, but it takes 20+ years from discovery to mining operation and the frequency of significant copper discoveries is declining. In addition to long project development times and declining resource quality, also the geographical concentration of production and processing of critical minerals like cobalt and lithium (for EV batteries) poses geopolitical supply-chain risks [20]. Further, ore quality of newly discovered deposits of, e.g., copper is declining, which increases effort and energy consumption of the extraction [21].

Energy systems can be characterized by their EROI, generally defined as the ratio of the energy obtained to the energy required to obtain that energy (considering a power plant as an example, this includes, e.g., the construction, maintenance, and decommissioning of the power plant, the extraction of fuel, etc.). An EROI of 10:1 (or, shorter, 10) means that for every unit of energy invested, 10 units of energy are obtained and hence 9 units of “net energy” can be supplied to society for discretionary (not related to the provision of energy) purposes.

Thus, there are clear correlations between EROI and quality-of-life indicators (likewise, correlations between available energy per capita and quality-of-life indicators exist), with saturation observed above a certain level [7], [22]. **Fig. 3** shows the relationship between net energy and EROI, highlighting the so-called “Net-Energy Cliff”: For EROI values of less than about 5, the net energy available for discretionary purposes drops quickly.

The EROI of fossil fuels is declining since decades, as those deposits with lowest extraction efforts are depleted first and hence mining/extraction cost increase [8] [7]. Fossil fuels being dominant in today’s energy system leads to estimates of the overall global energy system EROI also declining [9]. EROI values for renewable energy sources other than large-scale hydropower are relatively low (see **Fig. 3**), e.g., due to low areal power densities, and reduce further once the extra effort for storage and/or the installation of overcapacities are considered [24] [26]. It is important to highlight that, when taking into account the quality of the energy output (electricity vs. oil, coal, or natural gas), i.e., moving the EROI consideration to an interface closer to the end-user (final-stage and useful-stage) EROI figures, the (declining) EROI of fossil fuels might be similar to that of renewables (including the need for energy storage) [8], [25], [27] as a consequence of, e.g., low conversion efficiencies of fossil-fuel-fired power plants or internal combustion engines.

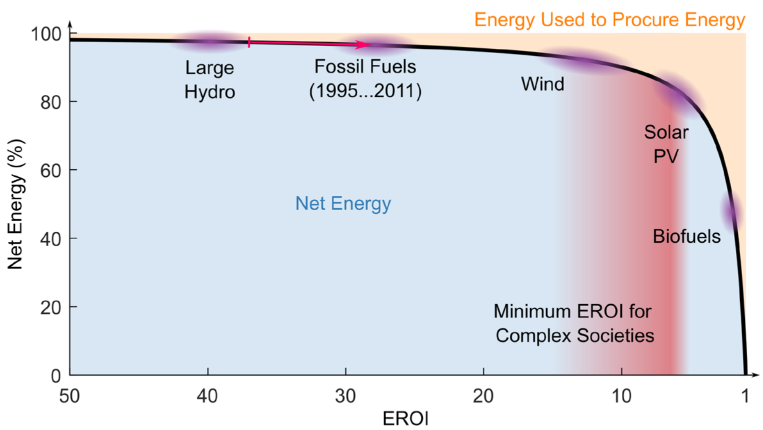

Fig. 3: The “Net-Energy Cliff”: Net energy supplied to society for discretionary purposes in dependence of the EROI, where for EROI < 5 the available net energy rapidly decreases. Commonly, EROI values of 5...15 are associated with a minimum level necessary for sustaining a complex modern society [22]. The exemplary EROI ranges for different fuels/technologies are based on [7], [8], [23], [24] and should be regarded as indicative only due to a wide range of values reported in the literature; further, the EROI of fossil fuels decreases once the system boundary is moved closer to the end-user, e.g., due to limited conversion efficiency of fossil power plants or internal combustion engines: at this final-stage and/or useful-stage, EROI figures of fossil fuels and renewables (including the need for energy storage) might be comparable [8], [25].

There is thus a risk that a quick change of the energy system to a fully renewable supply could lead to EROI values dropping below 5, at least temporarily, putting at risk the feasibility of our complex modern societies [22]. Hence, improvements in the energy efficiency and in the material

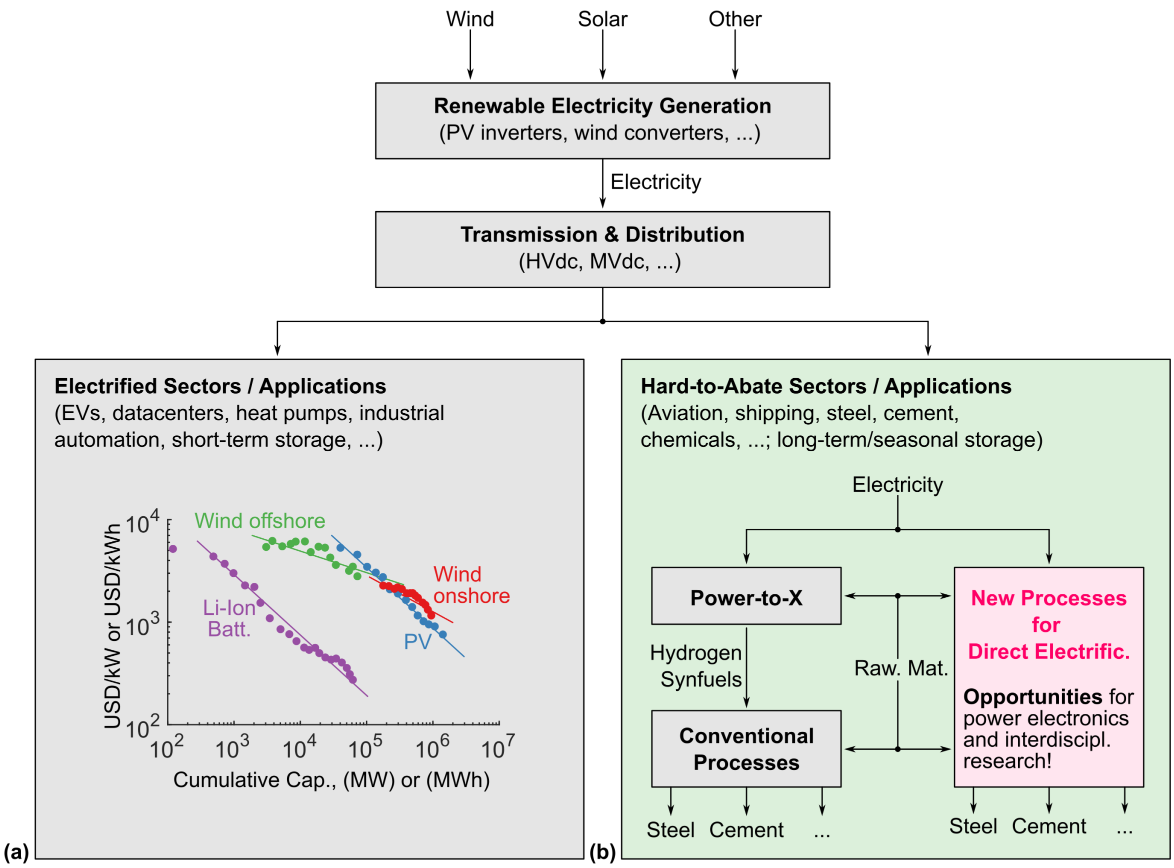

Fig. 4: Power electronics in a future net-zero energy system. **(a)** Power electronics for renewable generation and electrified applications (grey shading) is well understood, scaling, and "rides down the learning curve" (exemplary data for PV, wind, and batteries from [30], [31]). **(b)** Long-term energy storage and hard-to-abate sectors, which contribute a quarter if today's greenhouse gas emissions (see **Fig. 2**), require new (chemical, metallurgical, etc.) processes to enable direct electrification, which is a significant opportunity for new power electronics applications and interdisciplinary research.

efficiency of the economy are of high importance to facilitate a smooth reshaping of the energy system [7]. In the following, we outline the resulting implications for future power electronics research and development vectors.

Challenges and New Opportunities for Power Electronics

In an energy system solely supplied with renewable sources such as wind and solar as indicated in **Fig. 4**, power electronics is a key enabling technology for all aspects of generation, transmission, storage, conversion, and use of renewable electric energy. Correspondingly, we will see a massive expansion of the installed power electronic conversion capacity [1], first in the renewable energy generation, storage, transmission, and distribution sector itself as well as in electrified sectors of industry and society, e.g., electric mobility, heat pumps, industrial automation, IT and datacenters, etc. Power electronics for such applications is well understood and industrialized on a large scale. Technological advancements such as wide-bandgap power semiconductors, multilevel topologies, higher operating frequencies and/or motor speeds, integration of multi-stage converters into single-stage solutions, high-performance digital control, AI for design and condition monitoring, etc., i.e., *Power Electronics 4.0* as indicated in **Fig. 5**, facilitate continuous improvements regarding energy conversion efficiency (e.g., PV inverters with 99.1% mission-profile efficiency [28]), power density (e.g., highly integrated 30+ kW fixed-ratio dc-dc converters with power densities of 550 kW/dm^3 and 130 kW/kg [29]) and/or material efficiency, robustness, and lifetime at reduced costs, i.e., a "slide down the learning curve (experience curve)" (see **Fig. 4a**).

The need to maximize not only the energy conversion efficiency but also the material/resource efficiency in general as discussed above, concerns regarding power electronics' contribution to

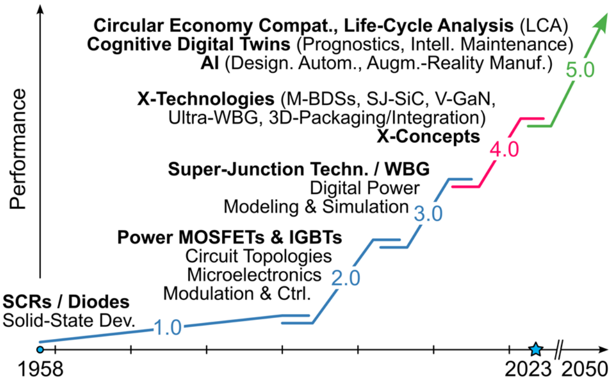

Fig. 5: S-curves of power electronics technology development cycles. *Power Electronics 5.0* is driven by the need to minimize life-cycle environmental impacts of power electronic converters (figure adapted from [1]).

the already gigantic quantities of electric and electronic waste (62'000'000 tons in 2022 globally [32], including power electronics;[4] and with estimates indicating that a fully renewable energy supply system could contribute in the order of 5'000 GW worth of end-of-life power electronics per year [1]), plus the reliance of many power-electronic components on a limited supply of critical raw materials, motivate *Power Electronics 5.0* (see **Fig. 5** and **Fig. 6**): Life-cycle environmental impacts (carbon footprint, but also further indicators characterizing, e.g., the impact on the health of humans or the ecosystem, etc.) should be considered in the design phase and eco-design paradigms be applied. An important pathway to minimize the environmental impacts of power electronics is to ensure compatibility with the circular economy paradigm [1], [33] as shown in **Fig. 6**: The useful lifetime should be maximized through reliability and the possibility for repair, and waste should be minimized through reuse of converters, refurbishing/remanufacturing of systems or subsystems, and finally recycling of raw materials. There is growing interest in academia, e.g., [34]–[38], and industry, e.g., [39]–[42], regarding ecodesign and circular economy compatibility of power electronics.

Care must be taken to take a holistic perspective: Replacing old, inefficient power converters with new, highly efficient ones might still be preferable to extending the legacy systems' lifetimes, because of the associated energy savings. For newly developed converter systems, which already today achieve efficiencies in the order of 99% and hence little further improvement can be expected, the circular economy paradigm should be applied. Thereby, in addition to applying concepts for repair/reuse/refurbishment, material mix choices that facilitate and benefit from recycling should be identified and preferred—e.g., recycled metals come with 70% (steel) to 95% (aluminum) energy savings compared to extraction from ore [43], recycled critical minerals like nickel, cobalt, lithium, etc.), in average, come with 80% lower greenhouse gas emissions [44].

Further, the so-called "hard-to-abate" (i.e., not easily electrifiable) sectors like steel, cement, chemicals, and long-haul transportation contribute about 25% of today's carbon emissions (see **Fig. 2**) and demand is expected to grow significantly. If all global energy needs should be provided from renewable sources in the form of electricity, close attention must be paid to these sectors, as no clear and scalable pathways for quickly cutting their reliance on fossil fuels, exist [10]. Of course, conventional processes could be used and the fossil fuel input substituted as far as possible by other molecular energy carriers like hydrogen or synthetic fuels, which can be obtained using known methods (electrolysis, Haber-Bosch process for ammonia synthesis) and renewable electricity (see **Fig. 4b**), but known Power-to-X processes show relatively low energy

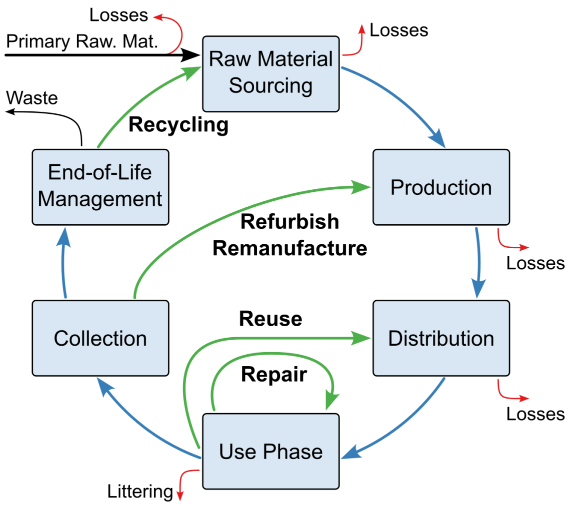

Fig. 6: *Power Electronics 5.0* ensures compatibility with the circular economy paradigm to minimize resource usage, waste, and environmental impacts.

[4] Note that electronic waste is a complex mix of materials, dominated by metals and plastics [32].

conversion efficiencies (which also affects long-term/seasonal storage based on chemical energy carriers).

New processes (chemical, metallurgical, etc.), ideally able to cope with high dynamics (with respect to chemical time constants) of fluctuating renewable energy inputs, and technologies for a *direct* electrification of hard-to-abate sectors are therefore of high interest (see **Fig. 4b**). Clearly, this is a huge opportunity for identifying new use cases of power electronics in industrial applications and constitutes a very important research vector in power electronics with a strong interdisciplinary component (e.g., plasma torches for steel furnaces [45], microwaves in chemical and materials processing [46], or plasma electrolysis for hydrogen generation [47]). This expansion of power electronics into new application areas highlights its ubiquitousness and hence the importance of the *Power Electronics 5.0* paradigm.

Conclusion and Next Steps

Power electronics is the key enabling technology of modern societies and for a future all-renewable multi-carrier energy system. Whereas many sectors of industry and of the daily life are already electrified and hence can immediately employ renewable electricity when available, we expect significant opportunities for new applications of power electronics in new concepts and processes for the direct electrification of hard-to-abate sectors such as the production of pig/crude iron and steel, cement, and chemicals. Thus, corresponding research in power electronics in close collaboration with neighboring disciplines like metallurgy or chemistry should be prioritized.

With the increasing spread of power electronics comes a responsibility to ensure that the life-cycle environmental impacts of power converters are minimized, i.e., an optimum balance between conversion efficiency and material efficiency/usage must be targeted, and hence energy flows *and* material flows must be considered. To balance the design trade-offs, new design methods that include life-cycle assessment (LCA) metrics are needed, relying on high-quality environmental impact data for components used in power electronics, which is not readily available today. Further, power electronics should be designed targeting compatibility with the circular economy paradigm, i.e., facilitate repair, reuse, refurbishment, remanufacturing, and recycling. Again, research on the system, component, and material level is needed, as well as regarding suitable business models.

- **Academia**, in addition to focusing on the research vectors outlined above, should ensure that the curricula of engineering students include concepts like LCA and circularity, equipping young engineers with these essential tools for a career in the fast-developing power electronics area.
- **Industry** should ensure that established power electronics continues to slide down the learning curve, fully leveraging the potential of wide-bandgap power semiconductors and *Power Electronics 4.0* key concepts for maximizing energy efficiency, while at the same time including circular economy compatibility as a main design paradigm, making *Power Electronics 5.0* a reality. This might include new business models, e.g., based on “X-as-a-service” approaches or exploring second-life markets. Clearly, there is a “first mover dilemma”, because doing so might reduce short-term profits. However, long-term economic advantages might be expected from preparing new technologies that ultimately must find application on a global scale.
- **Policymakers**, thus, should drive manufacturers to minimize environmental impacts through regulations (i.e., implementing specific measures for power electronics based on the European Union’s *Ecodesign Sustainability Product Regulation (ESPR)* framework in force since July 2024) or incentivization (e.g., declarations like an “embodied carbon footprint label” including methods for verification), whereby international coordination and worldwide adoption of like measures is highly important. Further, regulations fostering the availability of high-

quality data for LCA studies (e.g., mandatory inclusion in future digital datasheets of components) should be enacted, specific use-cases such as second-life applications evaluated together with industry, and research regarding the electrification of hard-to-abate sectors supported.

A "first mover dilemma" exists on a global scale, too: Regulations like those discussed above could put affected economies at a disadvantage now for a "benefit" (i.e., avoidance of adverse consequences of climate change) in the relatively far future—a prime example of delayed gratification. Unlike in the case of polluting industries, however, there is little incentive for outsourcing an advanced green technology industry to overseas, which might turn into economic and social advantages, not least regarding the availability of high-quality jobs. Finally, one can argue that affluent nations have an obligation to act now and prioritize the development and scaling-up (learning curve) of the technologies needed for a future renewable energy system, preventing modern societies from falling of the "Net-Energy Cliff".

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