Sustainability Considerations for Organic Electronic Products

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Abstract

The development of organic electronic applications has reached a critical point.. While markets, including the internet of things, transparent solar, and flexible displays gain momentum, OLED displays lead the way, with a current market size of over $25 billion, to help create the infrastructure and ecosystem for other applications to follow. It is imperative to design built-in sustainability into materials selection, processing and device architectures for all of these emerging applications, and close the loop for a circular approach. In this perspective, we evaluate the status of embedded carbon in organic electronics, options for more sustainable materials and manufacturing, including engineered recycling solutions that can be applied within the product architecture and at end-of-life. This emerging industry has a responsibility to ensure a "cradle-to-cradle" approach. We highlight that ease of dismantling and recycling needs to closely relate to the product lifetime, and that regeneration should be facilitated in product design. Materials choices should consider the environmental effects of synthesis, processing and end-product recycling as well as performance.

Embedded carbon

A major aspect in the circular carbon economy of organic electronics is the carbon footprint, and more specifically, the embedded carbon in organic electronic devices. Whether it is mining of materials from the earth or synthesis of organic semiconductors from petroleum and bio-derived products, all components within organic electronic devices comprise embedded carbon.

The overall weight fraction of the organic semiconductor in thin film electronic devices, such as organic light emitting diodes (OLED), organic thin film transistors (OTFT), organic photovoltaics (OPV), organic electrochemical transistors (OECT) and others, is extremely low compared to the substrate and other components. For example, the German OPV manufacturer Heliatek, which utilises a vacuum deposition process, estimate this to be about 0.02 weight %,[1] based on a layer thickness of sub 100 nm, a common thickness not only for OPV, but most other organic electronic applications. Indeed, less than 1 g of active material is required for the fabrication of a 1 m^2 solar panel.[1] However, this does not accurately reflect the relative share of embedded value inherent in active layer materials. The difference between embedded value and embedded carbon balances the weight of the material versus the complexity and the energy intensity during synthesis. Typical synthesis of a complex organic semiconductor involves multiple steps, repeated purifications, often involving column chromatography, high reagent and raw materials costs, including expensive transition metal catalysts, low yields and low volume production. The low solubility of aromatic organic compounds also contributes to a large solvent footprint. By contrast, production of commodity plastics such as PET requires only a single step, is solvent free, and both high yielding and high volume. A very rough estimation of the difference in embedded carbon per unit weight between the two components can be seen in their respective market prices, with roughly 5 orders of magnitude higher cost of organic semiconductors, albeit at pre-production scale, an indication that it cannot be discounted when considering relative contributions. For example, a state of the art electron acceptor in solution processed organic photovoltaics is the molecule Y6.[2] Analysis of the scalability of the synthesis of this compound[3] reveals a 14-step synthetic route, including low yielding annulation chemistry, and multiple purifications. Furthermore, halogenated solvents were repeatedly used for the synthesis, purification and deposition of this compound during OPV fabrication. Similarly, a state-of-the-art organic transistor charge transport polymer, IDT-BT, used in OTFT backplane prototypes, requires a 7-step sequential synthesis, with multiple purifications, a double ring closing acylation step, a relatively low yielding tetraalkylation, and an atom inefficient palladium catalysed Stille polymerisation. Some polymers however are amenable to more sustainable polymerisation routes including direct arylation and aldol condensation. Efforts addressing aspects like the synthetic complexity of organic electronic materials,[4] greener processing conditions – such as semiconductor deposition from water formulations,[5] and petroleum-versus biomass-derived materials,[6] are ongoing and vital in improving sustainability. While it is not feasible to address these aspects for all research materials, champion materials such as Y6 should be the subject of process optimisation and higher scientific value and recognition should be associated with such endeavours. Beyond the search for higher yielding reaction conditions, cheaper catalysts and improved purification and processing steps, the exploration of structural derivatives with, for instance, lower synthetic complexity or side chains that endow a different solubility, purification and processing profile should be encouraged. By far the largest volume of organic semiconducting materials is employed in OLED displays. Both the red and green emissive materials currently utilise phosphorescent molecules containing heavy metals such as iridium and platinum. Iridium in particular is one of the rarest of the elements with an abundance of only 0.0007 ppm in the earth's crust [7]. More sustainable all-organic materials will be required, especially if large volume lighting applications emerge, such as those which utilise thermally activated delayed fluorescence. [8]

Heliatek has estimated that their entire materials input represents a relatively large fraction (>50%) of the embedded carbon of a vacuum-deposited OPV module, with the manufacturing process (~27%) and end-of-life impact (~13%) contributing significantly as well. Although the active organic electronic materials in the device make up a very small fraction (0.02 wt% of the entire mass in Heliatek's case study), they can have a surprising impact in terms of total carbon footprint. Other OPV manufacturers, including ONINN, ARMOR and technology innovators such as InfinityPV and ZAE Bayern utilise a solution based fabrication approach. It is likely that a similarly large fraction of the embedded carbon will be attributed to materials. The continued development of active materials is therefore still a crucial component of organic electronics research and rightfully so. For instance, more efficient photoactive blends that lead to higher yielding solar panels will require a smaller footprint – and therefore less embedded carbon – to generate the same electricity as a less efficient system.[9] Similarly, research into active materials with greater ambient and operational stability could ultimately reduce the need for high-performance device encapsulation, which carries a significant proportion of the overall material input in an organic electronic device. In the case of Heliatek's evaporated solar panels, the encapsulation (mechanical and barrier encapsulation) accounts for 67% of the entire weight of the device. Organic electronic applications are typically benchmarked in performance parameters such as light emission (cd*h/€), power generated (Wh/€) or charge carrier mobility during product lifetime, whereas product costs are currently restricted to production costs. CO_2 can be taxed into these calculations in two different ways. Carbon pricing is one instrument. All external costs of greenhouse gas (GHG) emissions during the lifetime of an organic semiconductor can be expressed in costs of emissions through a price on the CO_2 emitted. Including the costs of GHG emissions into the productivity Figure of Merit (FoM) of organic electronics is one way to illustrate true costs. As we approach a future where CO_2 costs will dominate material prices, the introduction of FoMs based on performance per embedded CO_2 might become an interesting additional parameter to report. In that case, solar cells could be reported in terms of both Wh/€ and also Wh generated per kg CO_2 embedded. Indeed, a carbon evaluation of the Heliatek panels by TUV Rheinland certified that only 15kg of CO_2 was emitted over the full life cycle of OPV modules per kWh of electricity, roughly one third of that of a silicon module, and almost two orders of magnitude less than coal[10]. In the end, an OPV module will still generate over 100 times the input energy over their lifetime and disposal, despite limited lifetime and efficiency. [11]

Fortunately, strides are being made to implement new materials and technologies that directly or indirectly reduce the amount of embedded carbon throughout the device stack. For optoelectronic devices, one such consideration is the ongoing efforts to replace indium tin oxide as a transparent conductive electrode material. Owing to element scarcity, of indium in particular,[12] and costly extraction by mining and subsequent transport, many alternative transparent conductors to indium tin oxide are being researched. Despite also being considered an element of scarcity, highly transparent silver-based electrodes can be fabricated by creating an interconnected mesh of silver nanowires.[13] Lower carbon footprint processes are highlighted by the fact that these metal nanowires can be supplied as stable suspensions in green solvents such as ethanol to afford an ink formulation that is compatible with large-area printing techniques. One example of an approach to circumvent elements of low natural abundancy, is the deposition of ultra-thin graphene oxide layers which can be subsequently reduced to graphene. This offers a route to all-carbon-based transparent electrodes.[14] While this was initially demonstrated by solvent-mediated oxidation of graphite to graphene oxide, followed by thermally induced reduction to graphene, the direct and solvent-free exfoliation of graphite into graphene using a plasma spray technique offers an outlook towards lower carbon footprint electrodes that can be integrated with printable grid lines.[15]

Compared to the low contribution from the active material to the overall mass of an organic electronic device, the substrate makes up a considerably larger fraction of the mass, estimated at 11% of the total mass (substrate including the transparent electrode) for Heliatek's evaporated solar cell. The development of ultrathin and low-weight flexible substrates for organic electronic devices, within the constraints of specific application criteria, therefore appears to be a more direct route to reduce the carbon footprint of organic electronics. Such efforts must be within the product requirement constraints, elegantly illustrated when employing a 1.2 µm thick polyethylene naphthalate substrate to afford a lightweight, flexible organic electronic device with an overall thickness of only 2 µm including electrical contacts and an encapsulating parylene layer.[16] Applying such strategies to the fabrication of ultrathin solar cells have afforded prototype devices using a combination of solution-based deposition and metal evaporation,[17] while a fully inkjet-printed device less than 4 µm thick has been demonstrated.[18] Considering the energy output, these low-weight solar cells have power-per-weight values in the range 6-10 W/g, at least twice that achieved with Cu(In,Ga)Se_2 (CIGS) based solar cells on thin polyimide substrates,[19] and more than two orders of magnitude higher than corresponding Si- or CIGS-based solar panels. Whether it is feasible at high yield to manufacture and handle such thin films is certainly debatable, but the ultra weight-conscious James Webb space telescope relies on 50 micron thick layers in its critical solar shield, demonstrating that it is possible to make large-scale functional structures. These examples have focused on pushing the technology as far as possible in terms of low weight and high flexibility and conformability, which is not necessarily attractive or feasible for high-volume commercial applications, yet it clearly shows that there is ample room for further progress in minimising the contribution from substrate and encapsulation to overall weight and embedded carbon in an organic device stack. Another application space where thin, flexible and conformable devices show promise is organic bioelectronics. This rapidly emerging field aims to deliver new diagnostic tools, drug delivery systems and health monitoring devices such as wearable sensors.[20] While, for instance, on-skin bioelectronic patches could offer a paradigm shift in personalised healthcare, the advantages of such cheap, mass-produced and potentially single-use organic electronic devices must be carefully weighed against their embedded carbon and end-of-life considerations. In this context, it is worth mentioning the concept of transient electronics where a chemically designed degradability can facilitate break-down of the major components of the device into potentially harmless by-products after use.[21]

The device fabrication steps also carry a significant carbon footprint. The original vision inspiring the emergence of an organic electronic industry, was of a more sustainable future, with high throughput, additive processing,[22-24] [25] circumventing the costly and wasteful traditional electronic manufacturing processes involving steppers and photolithography. More recently however, the organic thin film transistor display backplane industry has increased its focus on a more pragmatic approach, in some cases involving a photolithographic patterning step of the semiconductor, with the semiconductor being area deposited by slit coating. This change in strategy perhaps arises from the technical complexities of merging demanding electronic product specifications with traditional printing processes. One positive, sustainable aspect arising, is the opportunity to prolong the productive lifetime of existing fabrication lines. In addition, there is the possibility to adapt existing equipment and processes to reduce environmental impact. For example, the reuse of a “carrier” glass substrate during low temperature processing, if widely adopted by the flexible display industry[26,27], has been estimated by Flexenable to save 1TWh of energy per year.[28]

While polymeric semiconductors lend themselves favourably to solution-deposition,[29] small-molecule organic semiconductors, on the other hand, are often optimised for vacuum-deposition, particularly in most current large scale manufacturing of OLED displays.[30] OPV fabrication development is currently following a similar path, with arguably the most advanced manufacturing status, at Heliatek, pursuing vapour deposition. In their recent case study, roughly 25% of the total carbon footprint was attributed to the energy consumption during the active layer vapour deposition fabrication processes.[1] Conversely, direct solution deposition methods, are often touted as being able to avoid energy-intensive high-vacuum and high-temperature techniques instead relying on cheap, scalable and high-throughput techniques such as roll-to-roll printing. One direction has been to deposit all electrical components via solution-based methods as exemplified by the silver nanowire inks and the ultrathin fully inkjet-printed solar cell discussed previously. Considering this continued reliance in the field on materials that are not solution-processable, seen also for certain metallic electrodes, the carbon footprint from their high-temperature processing remains an issue, and indeed these energy-intensive steps should be replaced with more sustainable alternatives.

Transition from Lab to Fab

The performance of organic semiconductors is strongly related to the device fabrication methods, based largely on optimising film formation and multilayer assembly. Large scale production is subsequently driven by methods that can deliver the optimum application performance achieved in the laboratory. In the most advanced organic electronic application, namely OLED displays, this has been achieved by vacuum deposition. Consequently, manufacturing infrastructure is more advanced for this deposition technique, which in turn often guides decisions regarding the adoption of future fabrication technology explored in laboratories, including some types of molecular solar cells. Nonetheless, there are still strong sustainability motivations for employing solvent-based printing processes, most recently fuelled by efforts for fully inkjet printed large scale TV panels.[27] Therefore developing solvent-efficient printing processes is needed whether using ink-jet printing for circuits/LEDs or large-area coating for solar cells. The use of green solvents that reduce the environmental footprint of the deposition equipment are of importance. The amount of solvent is much higher than the organic semiconductor, particularly if spin coating is used as a deposition process. A typical semiconductor ink for an efficient deposition method, such as inkjet printing or slit coating[31], comprises in excess of 95% solvent. To address large markets, there will be hundreds of tonnes of solvent required for semiconductor formulation. The development of functional materials that can be processed in solvent-lean formulations would have significant advantages even over green solvents.[32] Approaches to using water based deposition[33] are being explored in this context.

When considering device assembly, there is a significant question regarding designing the optimum product lifetime. Current electronics are built to be rugged and essentially last forever. For example, today´s silicon photovoltaic modules reliably operate in the field for decades[34] to maximize LCOE and minimize environmental impact. The scientific challenge of a closed cycle (C2C) organic electronics technology is to reconcile durability and separability. The immortality approach of using monolithically integrated modules to minimize exposure to the environment pits durability against separability and is the root cause of all challenges in product recycling. The stronger and more durable the package, the slower and more costly recycling becomes. A major contribution to extending product lifetimes has been improvements in the module adhesive. Strongly cross-linked and covalently bound EVOH glass-module adhesives increase module lifetimes. However, this strategy makes recycling via clean separation challenging. In fact, no process exists today which results in a conventional PV module deconstruction and reuse of the polymeric components.

Within defect tolerant semiconductor devices comprising organics or perovskites, interfaces are the most vulnerable location for failure, typically much more vulnerable than the bulk. Interface design must provide stability and robustness but should not hinder later separation. Finally, when recycling single components, retention of material quality and suitable purification are essential for the economic viability of recycling.

A prudent approach to streamlining the efficiency of a lab to fab transition is to adopt the governing design principles of the fabrication processes, particularly with respect to recycling, already in the laboratory. Engineering applications to last only as long as the required lifetime of organic devices will therefore have a major impact on the attraction of recycling. In the same context, a fundamental scientific challenge, that translates from the lab to manufacturing and ultimately recycling, is to reconcile product persistence and separability in a balanced way. Disposable organic electronic product lifetimes are significantly shorter, requiring built in methods to recycle components and materials. From the point of view of process development, low-temperature solution processing of multi-layers is an attractive process for eventual recycling. The orthogonality of solvents and solubility inherently introduces weakly Van-der-Waals bound interfaces between layers. In the absence of cross-linking strategies, such layers can be selectively removed by solvent processing, minimizing purification of extracted components. For example, a relatively simple layer by layer extraction with minimum intermixing can be envisaged for a generic organic opto-electronic product, where a layer sequence of ZnO/absorber (OPV) or emitter (OLED) /PEDOT can be dissolved selectively with water, organics and then mild acid, thus sequentially extracting each individual material from the used product. Minimising the large quantities of solvent required to achieve such an extraction and their subsequent recycling will also go hand in hand with such approaches. Building biocompatibility and biodegradability into the upstream materials selection, is an ambitious approach, utilising both naturally available or nature inspired benign semiconductors, dielectrics, electrodes and substrates[35,36].

Circular Organic Electronics

The key to achieving circularity lies in the choice of the materials, the design of interfaces and the development of releasable packaging. Following the design principles of C2C, future processes must be designed to only use materials that can be produced and processed in a closed-loop manner and which avoid toxicity and scarcity. Material and interface design has to be based on systems with orthogonal solubility and on material composites where cohesion exceeds adhesion.

In the landmark book "Cradle to Cradle: Remaking the Way We Make Things" the principles of green engineering are outlined.[37] The central aspect of green engineering compiles the design of applications that are compatible to multiple lifecycles, ideally at the same value of the application. Current organic electronic applications are not designed for future application generations. Embedding such design criteria into a material or an application is the first step to transform organic electronics into a cradle-to-cradle compatible technology.

While there are potential advantages for adoption of organic electronics, in practice this relies on establishing a beneficial combination of performance and economic cost. Some of the key challenges in the transition from the laboratory to commercialization include the scale-up of materials, process yield, integration with systems, and addressing the market need. Detailed process and techno-economic analysis will be required to determine the industrial economics of recycling, but a rule-of-thumb guiding criteria suggests that the flow of energy, mass and money into recycling has to be less than the BOM of fresh raw materials [adapted from Braungart´s rule number 3 for green engineering, saying that energy and mass flow for recycling have to be minimized].

The circular economy for electronic waste is hindered by the lack of a standardised recovery process. The disassembly of electronics to separate hazardous and non-hazardous components and their subsequent recovery is at an early stage. Many product designers are developing consumer electronics that are difficult to disassemble or service.[38] The flexibility of the form factor of printed organic electronics can provide advantages for product designers who consider recycling at the onset of design. For example, often packaging design is limited by the shape of the product, whereas designers have a wider scope if the product can be bent to fit the packaging.

Modern recycling strategies need a paradigm change. Rather than designing recycling strategies for existing modules, it is imperative to think about integrated design at the product development level for improved recycling. Moreover, down-recycling as well as thermal recycling should be avoided in favour of a closed loop process. A further challenge is adapting to the potentially receding value of recycled material in fast evolving technologies. For example, recycling triplet sensitizing active materials from an OLED display or fullerenes from an organic solar cell product fabricated 10 years ago, has reduced value as current modules no longer use these materials. Readapting these materials for emerging applications might be a solution, e.g., fullerenes may be attractive for UV/Vis photodetectors or in combination with scintillators for X-Ray detection. Finally, recycling has to happen at the speed of production. Organic solar cells or displays will be produced with printing lines that can process at up to 1 m/sec web speed. Slower recycling processes will cause unbalanced labour forces and additional investments, possibly raising the processing costs of recycling beyond those of production.

Even if efficient disassembly is achievable, most conventional electronic devices have significant packaging to ensure long lifetimes. Printed circuit boards, for example, comprise a complex mixture of materials that are difficult to recover.[39] If circuit designs and materials can be developed that are tolerant to environmental degradation then requirements of packaging become less stringent and the flexibility of printable electronics could help reduce the need for PCBs by tighter integration of relatively benign components on flexible substrates.

End-of-life

In addition to considering the scientific practicalities of low embedded carbon and circularity, it is also important to take an industry-level view of organic electronic devices. In that context, the end-of-life problems for organic electronics are no different to any other industry that has encountered rapid expansion. Perhaps most relevant is the textiles industry where the "fast fashion" concept has seen the mass adoption of a business model that has driven a significant increase in consumption across the world. This, in turn, has driven huge concerns about sustainability. The possibility that the electronics and textiles industries could combine to deliver on the promise of wearable electronics could also be perceived as posing an even greater threat to the planet by combining even more complex, hard to recycle components into short-lifetime products.

The model of designing long-lasting electronic devices was once dominant for clothing and textiles, where garments were also manufactured to last and even to be repaired. Like fast fashion, the emergence of organic electronics raises a significant risk that low manufacturing costs will lead to devices that are disposed of relatively quickly, which leads to large volumes of waste.

From a societal point of view, the larger issue for organic electronics may actually be dealing with the perception of waste. Consumers of, for example, flexible solar cells, will be highly sensitive to their environmental impact. Companies in this area will need a social licence to operate, particularly if they are targeting activities such as renewable energy. Issues such as metal waste,[40] microplastics and the impact of plastics on our oceans,[41] while small for organic electronics devices, could assume greater significance in the perception of an environmentally sensitive market. This perception of risk could therefore become a potential barrier to entry, as manufacturers may be reluctant to release products without a clear narrative around end-of-life. This raises the key question – are organic electronics devices sustainable?

Measuring overall sustainability is significantly more complicated than other device parameters. The key performance attributes of all electronics can be evaluated with respect to four criteria: power/energy efficiency, device lifetime, product aesthetics and cost. Each of these are fairly objective measures. By contrast, sustainability is more difficult to define. Figure 1 gives a qualitative assessment of photovoltaic technologies against a range of performance and sustainability parameters. For example, organic photovoltaics offer clear aesthetic benefits in comparison with silicon solar cells whereas the latter offer longer device lifetimes. In terms of embedded energy, silicon solar cells rate considerably less favorably than organic or perovskite devices but the latter rate lower with respect to toxicity. Embedded energy, recyclability, decomposability and toxicity are not necessarily correlated so bringing them all together into a single “sustainability” parameter is challenging. Energy payback times (EPBT) for OPVs of between 220 and 460 days have been reported.[42] This is around 50–60% lower than the amorphous silicon panels in the same study. This is significant with respect to manufacturing energy consumption but rating a product as highly sustainable on this single parameter fails to consider that the product still represents waste. A lot of very efficiently manufactured solar cells being transferred rapidly into waste is not necessarily a sustainable outcome.

Although the world can aspire to ideals of circularity through reuse, it is difficult to find evidence of this being taken up with respect to mass consumer items. The reuse of the current range of consumer electronics, such as mobile phones and laptops, is largely focused on transfer to lower socioeconomic groups. However, such is the reach of modern consumerism, even this is undermined by a strong desire to have the latest and greatest devices.

The widespread re-use of mass consumer items is unprecedented, so organic electronics waste strategies broadly fall into two categories – biodegradability and recycling. To date, the literature has largely addressed niche applications and the performance of devices comprising biodegradable components is far below technology benchmarks.[43] While the extremely robust oxygen and water barrier layer device requirements may present some challenges, recent research has identified approaches in breaking down complex plastics. For example, a two-step process has been reported that uses metal catalysed aerial oxidation and bacteria to break down mixtures of waste plastics in high yields.[44] The US Environmental Protection Agency reports that, in the US, only about 9% of plastics are recycled.[45] This has seen pyrolysis emerge as a potentially attractive breakdown technology. However, there are many environmental and technical concerns that need to be addressed before this technology can be relied upon.[45]

Interestingly, the low toxicity of carbon, in comparison to lead, may have contributed to the slower development of organic electronics recycling technologies compared to perovskites. Despite being the later discovery, recycling of perovskite solar cells has been more widely reported[46,47,48,48,49] than organic electronic products, with a focus on recovering lead, which encouragingly has reached a recycling efficiency of over 99 %. More recent studies have also included the recycling of the glass substrate and module encapsulants. A theoretical study was conducted, investigating the environmental impact of cradle-to-cradle recycling of perovskite solar cells which, assuming full recyclability, determined EPBTs of about one month and a reduction of greenhouse gas emissions by more than 70% to 13.4 g CO2 equivalent per kWh. Similar concerted efforts, going beyond pure life cycle analysis studies, are required for the full range of potential organic electronic applications.

Some device components will remain highly problematic with respect to degradation or decomposition. The environmental impacts of the broad area of printed electronics including use and waste of all component types has recently been discussed,[50,51] highlighting a particular issue with silver-containing devices. Not only are silver nanoparticles toxic,[52] but the potential environmental loss of silver if unrecovered, amplifies this risk. A report from the Ellen MacArthur Foundation, identified three key challenges that must be overcome with regards to recycling consumer electronics devices. These are incentives for users to return waste, the logistics of collecting waste and regulations around handling and transporting waste.[53] A key conclusion, clear from all of these reports is that further investment in recycling technologies is required to handle all components present in organic electronics devices. While organic electronics has the potential to have transformational impact, the real and perceived issues around transforming devices at end-of-life must be addressed.

Outlook

An assessment of the sustainability of emerging flexible electronics devices requires considering embedded carbon, manufacturing processes and end-of-life treatments, as summarised in Figure 2. The prospect of manufacturing ubiquitous organic electronic products and subsequent environmental impact, necessitates innovative solutions to ensure balanced sustainability. At the onset of upstream materials considerations, attention must be paid to elemental scarcity, toxicity and schemes with high atom efficiency and benign synthesis. For example, new synthetic routes in the polymerisation of organic semiconducting polymers have been developed to completely avoid transition metal catalysts,[54] while in the synthesis of state-of-the-art non-fullerene acceptors, detailed analyses of each low yielding step has led to more atom efficient routes to be demonstrated.[55]

Having a holistic view of the circular industrial perspective at this early stage will require taking green fabrication processes and ease of recyclability into account. Organic semiconductors and solution processing offer opportunities to integrate material recovery, device repair, self-healing, and regeneration, and specifically recyclability directly into the product design, far exceeding today's possibilities of established semiconductors. Inherently building-in recyclability into the design of applications can act as a game-changer but requires the development of suitable design rules. For instance, using materials with complementary solubility allows to establish 'subtractive manufacturing' extracting phase pure material from a device stack. Addition of such reversible device designs integrates end-of-life disassembly into device architectures. This integration will trigger a discussion how to balance operational lifetime with recycling yields and the economics of recycling - high yields and low costs can become a leverage to reduce otherwise requested long operational lifetimes. More effort is clearly needed as there is currently a disconnect between organic electronic materials performance optimisation and the necessity to minimise embedded carbon in their synthesis and utilisation in fabrication processes. Resolving this disconnection requires trans-disciplinary research concepts. One of the most promising pathways to overcome this bottleneck is the exploration of synthesis routes for high performance and ultrapure organic semiconductors by using feedstock CO_2. Using ultimately green CO from the electrocatalysis of CO_2 with H_2 as feedstock for C_2+ products[56] and further on e.g. to chirality pure single wall carbon nanotubes[57] would constitute a breakthrough for the green synthesis of high performance organic semiconductors.

Quantitative targets for embedded carbon should consider the specific application payback, which will differ for energy harvesting devices, including solar cells, and functional electronics, such as sensors. Both shelf life and in-operation stability of organic semiconductors to ambient oxygen and water require that the energy of excited electrons, holes or excitons is lower than any relevant chemical or electrochemical reactions. For example, it has recently been reported that high energy electrons in an organic semiconductor, catalysed by metallic impurities, can react with water to generate hydrogen in an electrochemical transistor. In an OLED device, the stability of the blue emitter and its host is often compromised by the high energy of the host charges and emitter excitons. The molecular nature of organic semiconductors lends itself to facile optimisation and control of these energy levels by molecular functional manipulations[58], which is helpful to reduce the stringent needs of encapsulants, and therefore prolong useful lifetimes.

Developing an understanding of environmental impacts of existing materials and processes will be a driver for new scientific advances that emphasize simplicity in synthesis, new device designs, and recovery. Currently organic devices are not designed for materials recovery; any changes towards engineering products to recover valuable components must still remain economically attractive. This ideally needs to be achieved in the initial value chain flow, closing the loop from materials to end use. However, attention must continue to be paid to all sustainability approaches. We must minimise consumption, maximise circularity and simultaneously develop comprehensive recycling strategies for what is inevitably left behind.

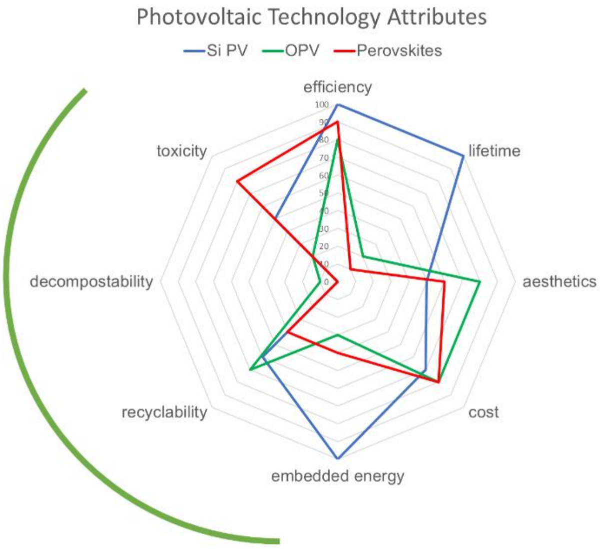

Figure 1: *A qualitative comparison of traditional and printed photovoltaics technologies. The four most common technology parameters are shown on the right while the non-correlated sustainability parameters are highlighted by the green arc.*

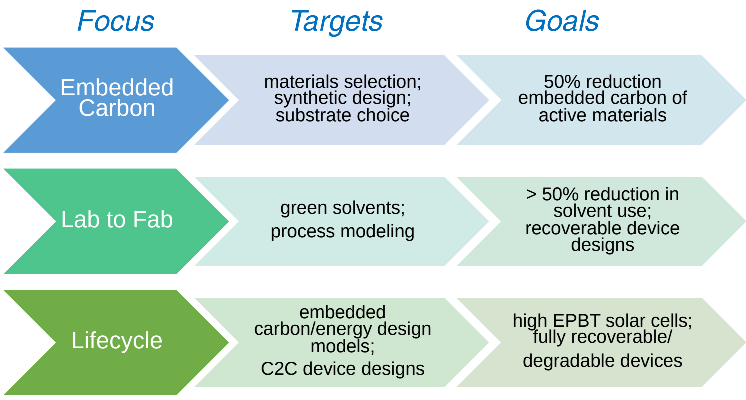

Figure 2 *Assessing the sustainability of emerging flexible electronics devices.*

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