

The case for organic photovoltaics

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Increasing demand for energy worldwide, driven largely by the developing world, coupled with the tremendous hidden costs associated with traditional energy sources necessitates an unprecedented fraction of the future global energy mix come from sustainable, renewable sources. The potential solar energy resource dwarfs that of all other renewable sources combined, yet only two photovoltaic technologies are known to have the potential to be scaled up to make dramatic impact on the overall energy mix: silicon and organic photovoltaics. In this paper, we present the long-term sustainability advantages of organics when compared to silicon and other photovoltaic technologies in terms of energy payback time and global warming potential while also discussing the outlook for transitional applications of organic solar cells.

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Introduction

The need for sustainable energy

Global demand for energy has been growing essentially unabated since the dawn of the Industrial Revolution, and nearly all projections provide a picture of continued expansion of energy use for the foreseeable future. Vast supplies of fuels have served as the engine for economic development and increased affluence for enormous numbers of people. While metrics for economic development can include per capita consumption of materials, waste product emissions, or expenditure on goods and services, energy use is an essential and easily quantified element of economic activity. Energy use reflects the intensity of industrial, agricultural, and transport activity, and is often a reliable indicator of GDP. Therefore, it is not surprising that the majority of the projected growth in energy demand over the coming decades will originate in the developing world, *e.g.* China, India, Brazil, and eventually African countries, which can be loosely collected under the heading of countries outside of the Organization for Economic Cooperation and Development (OECD). In other words, if these countries are to continue their development, growth in demand is inevitable. Energy efficiency and conservation can temper a portion of the global demand, and indeed represent the most cost-effective approaches available to address the energy challenge, but no matter how pervasive, efficiency and conservation alone far fall short of matching the anticipated need.

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In any discussion of energy, units play a central (and often confusing) role. Here we will adopt the convention of focusing on the average rate of energy use, measured in Watts, rather than energy itself, which is measured in any of a panoply of different units (*e.g.* Joules, Watt-hours, Btus, quads, tons of oil equivalent, therms, *etc.*). Fig. 1 depicts historical and projected global energy demand in terawatts (TW) from 1990–2035 as reported by the U.S. Energy Information Administration (EIA).¹ These data are broken down by OECD and non-OECD countries to highlight the relatively larger contribution to the future growth from the latter. From this chart, one can see that today we consume approximately 18 TW worldwide, a number that is projected to rise to over 25 TW by 2035 and widely



Fig. 1 Global energy demand based on data through 2010 and EIA projections from 2015–2035.¹



Fig. 2 Global energy consumption breakdown by energy source in 2013 derived from the EIA reference case.¹

believed to reach 30 TW by the year 2050. In other words, the projected demand in 2050 is about twice what we use today. This represents an enormous expansion of energy use, raising serious societal questions about (1) where we can obtain this amount of energy and (2) what are the consequences associated with the utilization of those energy sources at those scales. These questions are among the most important issues facing humanity, and how we answer them will have tremendous impact on the lives of future generations.

Before addressing our future energy mix, it is informative to survey the makeup of our current supply. Fossil fuels dominate today's energy mix, collectively representing over 80% of our total energy supply (Fig. 2). In contrast, renewable sources represent about 10%, the vast majority of which is contributed by hydropower. Despite their considerable presence in media and common conversation, sources such as wind, solar, and geothermal are currently tiny fractions of the overall blend (Fig. 2). The dominance of fossil fuels is a consequence of their abundance and a long history of government subsidies. U.S. land grants for coal in the 19th century and tax expenditures for oil and gas in the early 20th century, as well as various incentives continuing to the present day, have helped drive economic growth for more than 200 years. With the expense of many decades of infrastructure already invested, fossil fuel energy has a very low apparent cost, making it generally the most attractive in the energy marketplace.

The challenge going forward is not that fossil fuels are a limited resource, though this is indeed the case, but rather that their continued use on a massive scale—and a scale that continues to grow with time—is associated with tremendous hidden costs² that threaten to eventually overwhelm structures

central to society, taking an immense toll on human life and quality of life. Though global reserves of coal, gas, and especially oil will eventually be depleted, current reserves and resources are sufficient—particularly in light of developments in hydraulic fracturing technology to extract shale gas and oil—to provide the vast majority of our energy needs on one hand and to inflict unprecedented damage on the other. Emissions from fossil fuel power plants are associated with acid rain that deteriorates infrastructure; particulates and ozone that aggravate asthma, bronchitis, and other pulmonary conditions; heavy metals that lead to acute poisoning, cancer, and developmental disorders; air and water pollution that decrease crop yields and produce smog; and thermal pollution that kills aquatic ecosystems. Coal is the worst offender among the fossil sources, and though natural gas is the cleanest of the fossil fuels and is steadily displacing coal in the U.S. system, this means the emissions are less hazardous, not that they are innocuous. Moreover, coal use is expanding dramatically in the developing world. These impacts have a direct and substantial cost in our health insurance, food prices, tourism dollars, and taxes, among others yet do not show up on our electric bills. Dwarfing these hidden costs, though, are the ever increasing effects of another emission: greenhouse gases. Climate disruption caused by carbon dioxide, methane, nitrous oxide, and other greenhouse gases contributes to more frequent and more substantial droughts, floods, wildfires, and storms as well as biodiversity loss, sea level rise, and numerous other deleterious effects. When all of these hidden costs are folded into the overall economic decision making, fossil fuels no longer represent the most attractive option.

Nuclear energy is one of the major secondary sources in use today, and one whose use could in principle be expanded far beyond the current capacity. Though nuclear fission carries few of the same hidden costs associated with fossil fuels, it has several serious hidden costs of its own: (1) nuclear weapons proliferation, or so-called dual-use capabilities, and nuclear materials use for terrorism represent ongoing challenges that are difficult to connect to a specific economic cost. (2) There has been little progress on long-term management of high-level radioactive waste, though in principle deep underground repositories could eventually provide a solution. (3) Nuclear accidents such as those at Three Mile Island in 1979, Chernobyl in 1986, and most recently at Fukushima Daiichi in 2011 have both terrible short-term local effects on individuals and ecosystems and very long-lasting regional aftermaths. Estimates are that cleanup in Fukushima will end up costing over \$250 billion,³ with far larger impact on the overall Japanese economy. In all likelihood nuclear fission will continue to play a key role in our energy mix for decades to come, but the scale of that role must be tempered by these hidden costs.

Beyond fossil fuels and nuclear, the only other major energy sources are renewable energy sources. These sources are associated with vastly lower hidden costs (though still important to consider and minimize, such as with negative impacts on local wildlife); their relatively small current role in our energy mix is based primarily on their apparently higher cost. Here it is important to note that despite the common perspective that government subsidies for renewable energy

are unfairly propping up inferior technologies, subsidies have always played a critical role in shifting energy eras, and subsidies for renewables are actually substantially smaller than those provided for previous energy transitions. In inflation-adjusted dollars, U.S. federal spending on nuclear and oil/gas subsidies averaged \$3.3 billion and \$1.8 billion, respectively, over the first 15 years of subsidy life, while renewables averaged less than \$0.4 billion.⁴

A diverse mix of energy sources is both a practical necessity and a wise strategy for energy stability and security. Looking forward, the question is how large a role various energy sources could or should potentially play in such a mix. As discussed above, fossil fuels and nuclear could continue their dominance through 2050 from a resource quantity perspective, but in an effort to mitigate climate disruption and lessen other environmental, safety, health, and aesthetic costs connected with these sources, the feasible limits of renewable energy sources are of paramount interest. Additionally, because many renewable energy sources are distributed in nature, implementation in the developing world, where grid infrastructure is often of poor quality or even nonexistent, is more straightforward than would be implementation of traditional centralized power generation.

Hydropower already supplies on the order of 0.5 TW worldwide¹ and is unusual among the renewables in that it provides reliable, baseload electricity. However, the majority of technically and economically feasible locations for hydropower have already been exploited, leaving little room for expanded utilization of this energy source—perhaps ultimately reaching a doubling to ~ 1 TW.⁵ Wind energy has grown dramatically over the past few years, riding on technological advances in efficiency that have rapidly lowered costs as well as government subsidies. While the energy embedded within wind currents far exceed global energy demand, the technically feasible limit is on the order of 6 TW.⁶ Geothermal energy emerging from the Earth's core is substantial, but as with all sources, only a small fraction of this energy is technically feasible to use. Limitations imposed by deep drilling through the planet's crust restrict realistic geothermal generation to perhaps 1 TW.⁷ Biomass energy may play a significant role in the context of liquid fuels (particularly if a shift to cellulosic materials is successful), but makes little sense for electricity production because of global shortages of productive land, water, and fertilizer; moreover, energy farming competes with food production. Ocean energy (tidal, wave, and thermal or salinity gradients) is unlikely ever to lead to generation capacities beyond ~ 0.2 TW.⁸ Therefore, collectively, the renewable sources outlined above are limited in practice to ~ 8 TW, that is, well below the 30 TW global demand projected for 2050. Substantial additional sustainable energy is sorely needed.

A key realization in any conversation regarding energy is that many of the sources discussed above are actually solar energy in disguise. It is energy from the sun that produces air currents and waves, evaporates water to higher elevation, and grows plants through photosynthesis. Each of these processes results in a thermodynamic loss of useful, extractable energy, which brings one to the question of how much energy can be

used directly from sunlight—a topic explored in the next section.

Solar energy

Solar energy researchers are fond of the statement that “enough energy from the sun strikes the surface of the earth in one hour to power the planet for an entire year.” While this statement is factually correct, and is represented by the large blue circle on the left hand side of Fig. 3, it is also misleading in practice because of course it is impossible to capture the overwhelming majority of that 96 000 TW of energy. In order to establish a very rough approximation for how much of this vast source can be feasibly collected, one can step through a series of simple estimations and assumptions. First, only land area will be considered as deployment of solar panels on the oceans on a large scale seems unrealistic. Assuming that land and ocean receive the same level of insolation on average, this drops the solar energy source down to 28 000 TW (green circle in Fig. 3). Clearly, covering all of the Earth's land with solar collection systems is absurd. An aggressive, but not unreasonable assumption would be that it is feasible to cover 2% of land area with such systems. This would still represent a phenomenally large area, roughly equivalent to the percentage of land covered by roads in the U.S. While surely sunnier regions will always be preferred for solar installations, here we will make the simple assumption that these systems are deployed evenly, further decreasing the supply to 560 TW (yellow circle in Fig. 3). The final reduction is based on the fact that thermodynamics limit how efficiently sunlight can be converted into electricity. Without complex panel architectures, light concentration, or other technological feats, the thermodynamic limit for photovoltaic power conversion is $\sim 30\%$, known as the Shockley–Queisser limit.⁹ Here we will make a conservative estimate of 12% for an average power conversion efficiency. This assumption brings the final approximation for the feasible solar energy supply to 67 TW—a remarkably small fraction of the original number, but nonetheless more than twice the total projected global energy demand for the year 2050.

While solar energy does, in principle, have the capacity to power the planet alone, a blend of diverse energy sources is the proper approach. One of the central reasons underlying the need for an energy mix is the variability of sources such as solar and wind. As utilization of variable energy sources expands, wider and more sophisticated accommodations to variability will have to be implemented.¹⁰ Fortunately, wind and solar energy are complementary to one another in that wind generally peaks at night and sunlight, obviously, peaks during the day. Improved forecasting of cloud cover and wind speeds will enable utility providers to ramp up natural gas power plants on an as-needed basis. An electrical grid with smart interconnection between regions will allow for movement of power from geographic areas with sun or wind to those under clouds or calm. Shifting of flexible loads such as plug-in vehicles, clothes dryers, and dishwashers to times of excess supply and/or low demand will balance out the overall consumption curve. Probably the most important accommodation for energy variability, however, is integration of energy storage on a massive scale. In this way, power could be stored

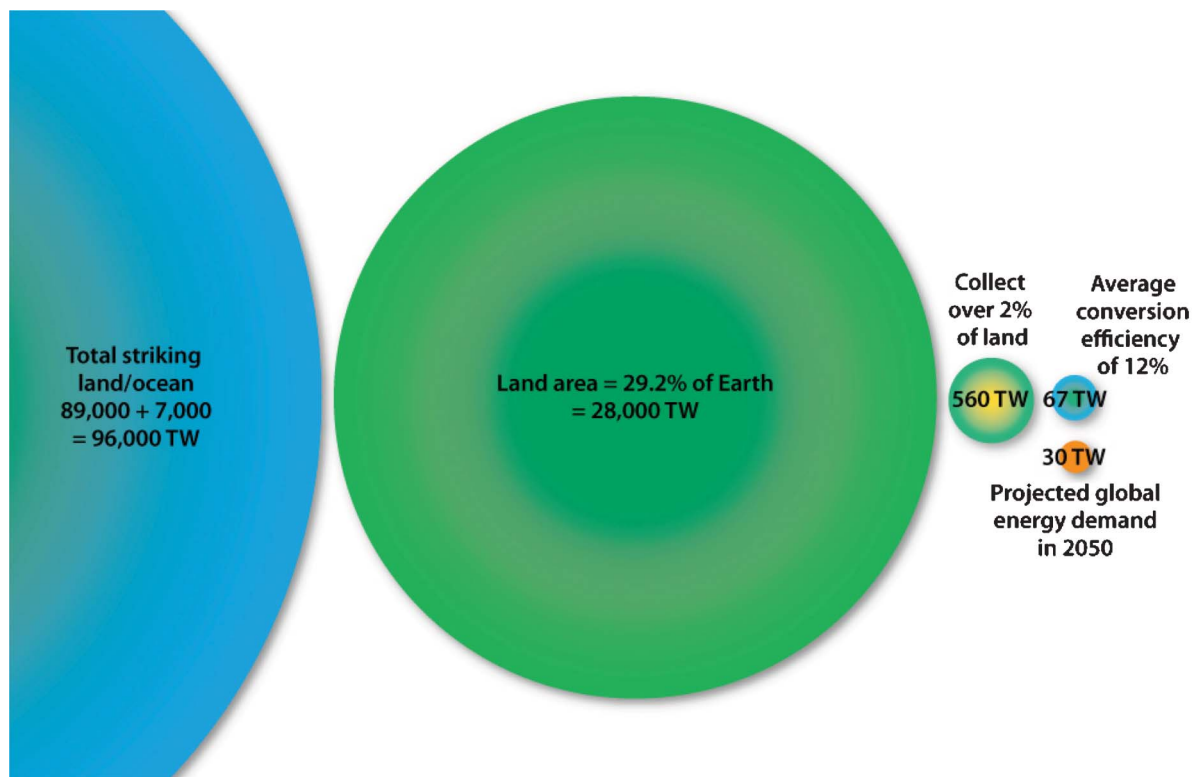


Fig. 3 Rough approximation of technically feasible photovoltaic solar energy worldwide supply based on usage of 2% of land area and a power conversion efficiency of 12%.

during periods of bright sunshine and strong winds and drawn down when needed. Interestingly, as plug-in vehicles become the norm, the fleet itself can serve as an electrical energy storage medium.

There are myriad ways in which energy from the sun can be utilized. The focus of this article is on photovoltaics, but other examples of effective approaches include concentrated solar power (CSP),¹¹ solar water and/or air heating,¹² natural lighting, solar water treatment, and solar fuels.¹³ Chemical fuels, in particular, are an exciting option because they offer the prospect of storage with high energy density—a critical property for many transportation applications. Given the dramatic climate impact of electricity production and the timescale imposed upon us by the pace of climate disruption coupled with the current immature status of solar fuels technology, however, photovoltaics will have to serve as the backbone of the solar energy contribution over the next few decades.

Photovoltaics have been fabricated from a wide variety of materials, with varying power conversion efficiencies (Fig. 4). Silicon solar panels dominate the market, and these come in three basic types: monocrystalline, polycrystalline, and amorphous. The first two are what most people think of when they picture solar modules, with rigid glass structures racked in metal frames, whereas amorphous silicon (a-Si) is a thin film technology and is often mechanically flexible. The next largest share of the PV market is taken by cadmium telluride (CdTe), commonly racked similarly to crystalline silicon panels,

though also a thin film technology. Copper indium gallium diselenide (CIGS) is the only other widely available commercial PV panel technology for the utility and residential/business markets at this time. CIGS panels are sold both in traditional racked form factors and as roof shingles for building integrated photovoltaics (BIPV). GaAs solar cells have burst onto the scene recently with efficiencies exceeding those of the best silicon cells, but at this time commercialization is still in progress, making an evaluation of scalability and cost difficult. Ultra-high-efficiency multijunction cells (*e.g.* GaInP/GaAs/GaInNAs) have applications in satellite power and concentrated photovoltaics, but are generally too expensive for routine solar installations. Technologies on the cusp of commercialization are dye-sensitized solar cells (DSSCs) and organic photovoltaics (OPVs), the latter being the subject of the next section.

Monocrystalline silicon is the leader in module efficiency, followed by polycrystalline silicon, CIGS, CdTe, and a-Si, but efficiency is not the only metric by which to evaluate the value of a given PV technology. Clearly, cost is a driving factor, and the most applicable metric for cost is the levelized cost of energy (LCOE),¹⁵ which is the lifetime cost of an energy system divided by its lifetime energy production. Calculating an accurate LCOE for a given installation is challenging since one must make a series of assumptions regarding the local weather looking perhaps 30 years into the future, panel degradation, *etc.*, but incorporating cost into the decision making enables one to evaluate the benefit of (sometimes expensive) efficiency

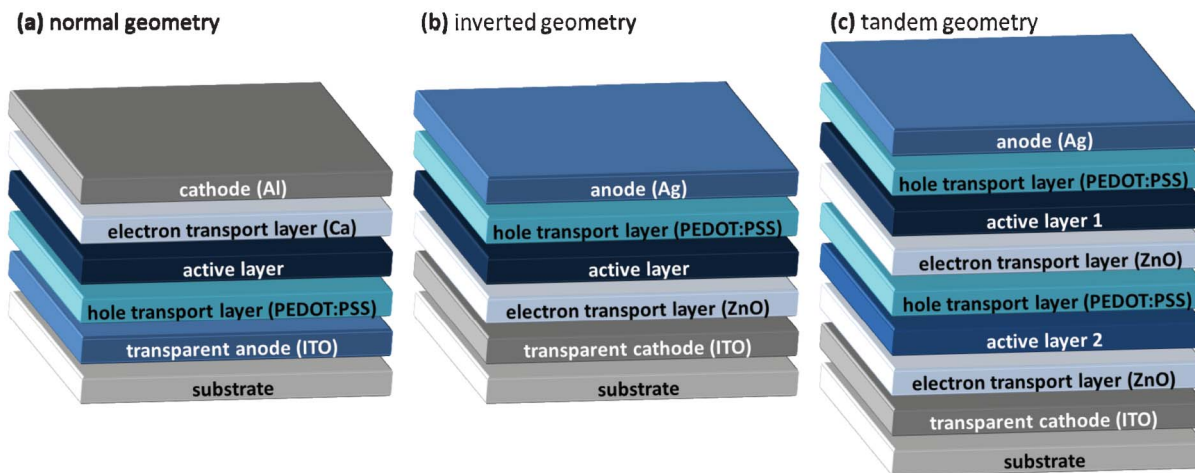


Fig. 6 Schematics of common layer structure of OPV devices in (a) normal, (b) inverted, and (c) tandem geometries with typical materials noted.

~0.6 eV less than the band gap of the absorber.^{17,18} A key parameter of the absorbing species, therefore, is the optical band gap, which is essentially the energy difference between its HOMO and LUMO. The nature of the charge separation process is still not fully understood and is the subject of many ongoing studies. In order for this charge transfer to occur, the exciton must survive long enough to reach the interface between a donor molecule and an acceptor molecule. Typical lifetimes for (singlet) excitons in organic semiconductors range from ~100 picoseconds to ~1 ns, which translates into a diffusion distance on the order of 10 nm; after this time elapses, recombination will occur if the exciton is not separated. This length scale imposes restrictions on the morphology of the active layer,¹⁹ since donor and acceptor species will have to be intimately mixed.²⁰ Once the carriers are free from each other, existing most often as polarons, they must be transported to their respective electrodes, which in organic materials involves a complex series of intermolecular and intramolecular movements. The driving force for transport is a combination of diffusion and drift, the relative roles of which are determined by the applied voltage, electrode materials, illumination intensity, and other parameters. Pathways for charge transport add further demands on the morphology of the active layer, a topic discussed extensively in the literature.^{21–24}

OPV devices are comprised of a number of layers (Fig. 6). In the standard configuration (Fig. 6a), a transparent substrate (glass or plastic) is coated with a transparent conductor that serves as the anode. In between the anode and the absorbing active layer is a hole-transport buffer layer that prevents electrons from reaching the anode. Likewise, on the other side of the active layer is an electron-transport buffer layer serving the complementary role, followed by the (optically reflective) cathode. Often, the low-work function metals used for the electron-transport layer in this configuration are highly reactive and contribute to device degradation, so inverted geometries (Fig. 6b) are sometimes employed where the electrodes are switched and different buffer layers are applied.

Inverted architectures are also generally more compatible with roll-to-roll processing.

Recent advances in OPVs

While there has been a steady stream of efficiency records reported for many second- and third-generation solar cell technologies over the past few years, no technology has matched the remarkable progress in OPVs. Power conversion efficiencies that seemed mired around 4–5% just a few years ago when poly(3-hexylthiophene) (P3HT)/[6,6]-phenyl-C₆₁-butyric acid methyl ester (PC₆₁BM) (Fig. 7) blends were the champion active layer material have skyrocketed recently riding on advances in synthesis of new low-band gap polymers such as poly[2,6'-4,8-di(5-ethylhexylthienyl)benzo[1,2-b;3,4-b]dithiophene-alt-5-dibutyl-3,6-bis(5-bromothiophen-2-yl)pyrrolo[3,4-c]pyrrole-1,4-dione] (PBDDT-DPP)²⁵ and poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-b]thiophenediyl]] (PTB7)²⁶ as well as alternative fullerene acceptor species such as PC₇₁BM and indene-C₆₀ bisadduct (ICBA)²⁷ (Fig. 7). Single-junction solar cells fabricated with materials such as PTB7/PC₇₁BM have been reported with efficiencies as high as 9.2%³²—approximately twice what can be achieved with P3HT-based systems.

Even higher OPV efficiencies can be achieved by fabricating tandem solar cells comprised of multiple active layers with different band gaps to capture a greater fraction of the solar spectrum (Fig. 6c). In these devices, high energy photons are absorbed by the first layer, which has the largest band gap, and lower energy photons pass through to the second absorbing layer for capture by a material with a lower band gap (architectures with additional absorbing layers are also possible). At the time of this writing, the current published and certified record for an OPV cell is held by Mitsubishi Chemical at 10.7% for a tandem device,³³ though even higher efficiencies have been reported.³⁴

Another notable recent development in OPVs is the introduction of high-performance small molecule absorbers/donors. Conjugated polymers have dominated the field for the

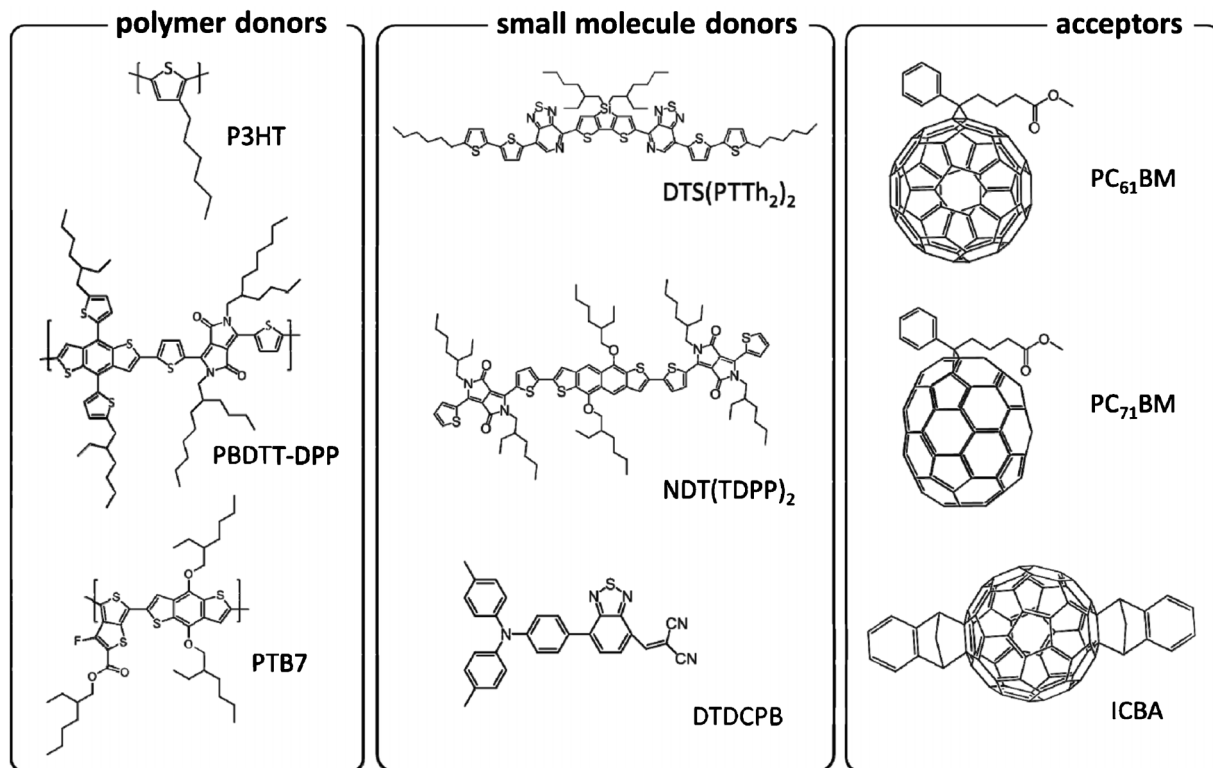


Fig. 7 Chemical structures of illustrative molecules used as electron-donors and -acceptors in organic solar cells. P3HT and PCBM represent archetypal materials, though many alternative high-performance materials have emerged in recent years, for example, PBDTT-DPP,²⁵ PTB7,²⁸ DTS(PTTh₂)₂,²⁹ NDT(TDPP)₂,³⁰ DTDCPB,³¹ and ICBA.²⁷

last decade, but challenges associated with polymer synthesis such as batch-to-batch variation in performance, have led to a search for small molecules that can rival polymers in devices.³⁵ In many cases, small molecules are not sufficiently soluble to be processed in solution, and vapor deposition processes are inherently more expensive and, therefore, less attractive. While vapor-deposited small molecule OPVs have made substantial progress recently,³¹ particular excitement has been generated by reports of solution-processible small molecule OPVs with efficiencies approaching 7% (Fig. 7).²⁹

Status of OPV industry

With performance of OPV devices entering a realm of potential commercial relevance, attention in the field is beginning to turn to processing methods that are scalable and efficient. Most laboratory-scale devices are fabricated using spin coating of solutions containing toxic solvents on small, rigid glass substrates. Ultimately, one needs a roll-to-roll compatible coating technique, environmentally friendly solution formulations, and mechanically flexible, large-area substrates. Krebs *et al.* have performed extensive studies evaluating a wide variety of coating and printing methods as well as suitable ink formulations for OPVs, and the reader is referred to a recent review for details.³⁶ Their work has led not only to demonstration of relatively large-scale OPV production, but also to impressive field studies demonstrating operational advantages of OPV arrays such as enhanced robustness to partial shadowing.³⁷

While some academic researchers have begun exploring processing of OPVs, several scientific leaders have also begun to explore the economic potential of OPV technology. The leading company in this space for years, and the first to develop a commercially available organic solar cell, was Konarka Technologies. In early 2012, Konarka filed for Chapter 7 bankruptcy protection and is in the process of liquidation, but prior to this culmination, Konarka performed a pivotal role in development of high-throughput roll-to-roll fabrication and marketing of OPVs as a commercial technology. A number of new players have entered the OPV market, including primarily polymer-based Plextronics, Solarmer Energy, and Polyera as well as primarily small molecule-based Mitsubishi Chemical, Heliatek GmbH, and Global Photonic Energy Corporation. In most cases, these companies utilize high-performance organic materials developed in academic laboratories or new materials derived from these, and they typically maintain close relationships with academia. Interestingly, it is often these companies that have set efficiency records with OPVs rather than academic researchers, demonstrating that a focus on optimization is probably most effective in a commercial setting. It remains to be seen if these specific companies will be the ones to bring OPV products to commercial success, but it is clear that the space is becoming increasingly populated and that investors and management in the industry have learned from the fate of Konarka and are adapting their approaches and business

Table 1 Efficiencies of record laboratory-scale devices and typical commercial PV modules of various technologies

PV technology	Lab cell record PCE ³³	Commercial module PCE	% Decrease
c-Si	25.0	20.1 ^a	19.6
p-Si	20.4	14.6 ^b	28.4
a-Si	10.1	5.1 ^c	49.5
CIGS	19.6	12.5 ^d	36.2
CdTe	18.3	12.5 ^e	31.7
OPV	10.7	1.65 ^f	84.6

^a SunPower. ^b Schott. ^c Uni-Solar. ^d Q-Cells. ^e First Solar. ^f Konarka.

models. Regardless, industry will continue to play an important synergistic role with academic research. Later in this article, we explore the short-term, mid-term, and long-term opportunities for OPVs in the energy marketplace.

Current challenges for OPVs

Three primary challenges remain for OPVs hindering their commercial application (1) power conversion efficiency of OPV modules remain lower than any of the commercially available competitors, (2) operational lifetime of OPVs lag far behind those of inorganic products, and (3) batch-to-batch variations in organic source materials make consistency of performance difficult.

Efficiency is not the absolute determinant of the value of a PV technology, but a certain minimum efficiency is required even if a panel costs virtually nothing to manufacture because of all the balance of systems and soft costs associated with installing PV power. (Note that balance of systems costs for OPVs are likely to be substantially lower than for traditional, raked PV systems because of their light weight and mechanical flexibility, considerably decreasing materials, labor, and overhead costs.) The consensus is that OPVs will continue to improve in performance, but the real challenge at this stage is translating the impressive gains in efficiency seen in laboratory-scale devices to the module scale. The difference between lab cell records and commercial module efficiency is far larger with OPVs than with any of the commercialized technologies (Table 1). This substantial performance gap must be narrowed if OPVs are to find a place in the energy market beyond a few niche applications. Indeed, a recent economic assessment of OPVs suggests that market competitiveness is achievable with this technology if large-area module efficiencies could reach ~7% with a 5-year device lifetime.³⁸ While that study may be overly optimistic, it highlights the critical importance of addressing the performance gap.

Though efficiency captures headlines, device lifetime is at least as important in ascertaining the usefulness of a PV technology. Understanding the degradation of OPV devices is critical for transferring this technology from research labs to the commercial market.^{39,40} Many organic materials currently used in organic solar cells are not air-stable because of photodegradation of semiconducting polymers induced by oxygen and water as well as degradation of electrodes and buffer layers.^{39–41} To increase lifetime, access of oxygen and (especially⁴²) water to the active regions of the device is

typically limited through encapsulation. Local meteorological conditions at the installation can have dramatic effects on the lifetime, but polymer-based OPVs have been reported with six-year lifetime,⁴³ and Heliatak projects a 21-year lifetime with their small-molecule process.⁴⁴ Improvements can be accomplished either through superior encapsulation with lower oxygen and water vapor transport rates, or through the use of inherently more stable materials.

In the case of polymer-based OPVs, which still represent the vast majority of systems studied, batch-to-batch variations in molecular weight/polydispersity, solubility, and purity⁴⁵ can result in different device performance and even in different processing properties.⁴⁶ Companies like Plextronics have developed large-batch syntheses of conjugated polymers to lessen the impact of batch variations of this nature, but if polymer-based solar cells are to achieve reliable fabrication consistency, rapid screening of polymer properties will have to be integrated into synthetic or manufacturing facilities to identify suitable materials rapidly and at low cost prior to their use in a production run. Small-molecule OPVs circumvent many of the problems with polymers because of the precise definition of the end products, though purity variations remain an issue for both classes of materials.⁴⁵

Short-term outlook (1–5 years)

As OPV performance and stability improve and production capacity increases, new markets having continually increasing size become relevant. It is apparent that, in the short term and probably also in the mid term, OPVs do not provide a viable alternative to silicon or other inorganic solar panels. During these early phases of OPV commercialization, niche markets are the most likely avenue. The most probable use for OPVs in the short term is as cheap, portable chargers for consumer electronics. OPVs' light weight, mechanical flexibility, strong low-light performance, and (potentially) low cost coupled with the relatively small power requirements of mobile phones, tablets, toys, and music players positions them well for this application. Limited lifetime of OPV devices is less important in this sector both because consumer electronics are not generally subjected to harsh conditions and because the practical lifetime of the electronics themselves is generally only a few years. An additional advantage of OPVs in this context is the ability to tune their color, bringing an aesthetic

function unavailable to competing flexible chargers such as those made using a-Si solar cells. Moreover, as consumer mindset evolves toward favoring green technologies and practices, energy consumption in consumer electronics attracts increasing scrutiny. Pairing external chargers with these devices, and ultimately integrating them into a single device, is anticipated as the pathway for commercial success.

The second short-term market for OPVs is in low-power applications in the developing world, most notably lighting in off-grid scenarios. The Lighting Africa program,⁴⁷ organized jointly by the International Finance Corporation (IFC) and the World Bank, works toward improving access to lighting in areas with no electrical grid service for low-income households and microenterprises. Currently, approximately 60% of the African population (~600 million people) has no access to electricity. This segment of the population increasingly relies on dangerous and polluting fuel-based energy sources. Lighting Africa primarily targets systems comprised of a low-power solar panel, a rechargeable battery, and a LED bulb. These systems must be affordable, and installed, assembled, and used without requiring assistance from a technician. Recent work has demonstrated that OPVs are well suited to meet these targets,⁴⁸ and as device performance continues to improve, this market opportunity is expected to expand for decades to come.

Mid-term outlook (5–10 years)

Mid-term applications

Building-integrated applications for OPVs are a daunting challenge. Lifetimes of standard inorganic BIPVs are at least 25 years; even if OPVs achieve 10% module efficiency and 10-year lifetime, costs would have to be tremendously low to compete because of the combination of lower energy production and the need to replace the modules several times during the guaranteed lifetime of a traditional system. However, there are potential BIPV applications for OPVs that are simply not possible using silicon or other traditional inorganic systems. OPV panels can be manufactured to be semi-transparent and laminated onto glass, enabling integration into the walls of buildings.⁴⁹ In many urban settings, building walls represent a larger amount of usable area than rooftops, and often much of that wall area is constructed of glass. The exceptional low-light performance of OPVs,⁵⁰ the fact that their efficiency increases with temperature (opposite from the effect with inorganic solar cells),⁵¹ their light weight, and their superior ability to capture incident light from many different angles⁵² render this technology well suited to such curtain wall applications. Once again, the ability to color OPVs through a wide range also provides flexibility in architectural design. These external applications will require far more robust devices than those for powering consumer electronics because of the exposure to temperature cycling, precipitation, and UV light. Therefore, improvements in encapsulation will be a prerequisite for BIPV end uses.

Military and emergency organizations have also expressed keen interest in the potential of OPV technology because of their prolific use of batteries and generators when deployed in theater. Primary batteries used by these groups are expensive because of their demanding performance requirements, and they are also cumbersome for transport. Integration of OPVs into uniforms, backpacks, tents, and sun screens/awnings are all under consideration, and indeed the U.S. military has provided financing to some OPV companies to explore these applications. The light weight and mechanical flexibility of OPVs are discriminating attributes in this context. Development along these lines will also have relevance for leisure and camping applications.

An intriguing potential use for OPVs was recently proposed by Beiley and McGehee in which OPVs would serve as the top cell in a tandem device with an inorganic bottom cell such as silicon or CIGS.⁵³ Unlike typical inorganic tandem cells, which generally incorporate very expensive III–V semiconductors, the top layer in these so-called hybrid tandem photovoltaics could be coated onto existing inorganic cells at modest temperatures with little marginal cost. Their modeling of 2-terminal (current-matched) and 4-terminal (independently-operated) tandem cells accounts for realistic challenges such as the additional parasitic loss of incident light in each transparent electrode and the possibility that the organic layer absorbs less than 100% of the light above its band gap. Results from their model are depicted in Fig. 8. These plots depict the power conversion efficiency of the tandem as a function of the organic layer band gap. The horizontal dashed lines represent the efficiency of the bottom, inorganic cell alone, so performance above this line indicates increased output power from the use of the tandem architecture. Clearly, even for non-ideal OPVs, there is an opportunity for increasing the efficiency with both silicon and CIGS modules, with projected overall values above 20% for both. Key to the success of this methodology will be development of OPV cells having lifetimes comparable to the bottom PV cells, so the likely timeframe for this technology to be fully realized is in the 5–10 year range. However, even using today's organic systems there may be opportunities for improvement of moderate-performance inorganic PVs.

Energy payback time and energy return on energy investment

OPVs are expected to have exceptional sustainability performance compared to other PV technologies in the mid-term. An important life cycle metric for evaluating the sustainability of an energy production technology is the time required to produce the energy invested during its life cycle. This is called the energy payback time (EPBT). Specifically for a PV module, the EPBT is the time required for the PV module to generate the equivalent amount of energy that originally was used to manufacture the PV module.⁵⁴ EPBT, which is usually measured in years, can be mathematically calculated as the ratio between the life cycle energy consumption of a PV module and the annual electricity generation of the PV module in terms of primary energy. The life cycle energy consumption includes the energy embedded in materials (*i.e.* primary energy demand to produce materials comprising the module); the direct process energy; and the energy for transportation,



Fig. 8 Power conversion efficiencies of hybrid tandem PVs as a function of the organic band gap and absorbance using silicon or CIGS bottom cells. Results for both 2-terminal, current-matched (a,c) and 4-terminal, independently operated (b,d) configurations are presented. Horizontal dashed lines depict the efficiency of the bottom cells by themselves. The colored dashed lines in panel (a) show the modeled efficiency of the organic cell by itself. Reprinted with permission from ref. 53, copyright 2012, Royal Society of Chemistry.

maintenance, and other activities involved in the system boundary defining the life cycle analysis of the PV module. Calculating the primary energy equivalent requires knowledge of the country-specific energy-conversion parameters for fuels and technologies used to generate energy and feedstock.⁵⁴ For PV modules, their annual electricity generation depends on the amount of sunlight available in the operating location, the module efficiency of electricity conversion at the demand side, and the performance ratio of the entire PV system (ratio of actual and theoretically possible energy output).

Energy return on energy invested (EROI) is another common metric used to evaluate sustainability of energy technologies. To translate between EPBT and EROI, one can use the following simple relationship:

$$\text{EROI} = T/\text{EPBT} \quad (1)$$

where T is the lifetime of the system. The EROI metric has been used to compare various commercial PV technologies with traditional electricity production technologies,⁵⁵ with the conclusion being that Si and CdTe PVs are comparable with oil-based electricity production and somewhat superior to coal-based electricity production. This result provides strong ammunition for renewable energy advocates, but the question

remains as to whether it is possible to do even better. In the following analysis, we focus exclusively on EPBT because of the tremendous uncertainty in the lifetime of OPV systems (T) given the rapid pace of development in this field and the lack of large-scale commercialization to date.

A number of life cycle analysis (LCA) studies revealed that PV technologies always generate more energy over their entire life cycle than the energy consumed during their manufacturing phase.^{56,59,65} EPBTs of major PV modules already on the market range from hundreds of days to less than 3 years, which are substantially shorter than the typical service lifetime of PV modules. A list of EPBTs of major PV technologies currently on the market is given in Table 2. Despite the current relatively low conversion efficiency of OPVs, they have relatively short EPBT compared to other PV technologies. A main reason, as pointed out in a number of LCA studies,^{61,64} is that OPV cells have significantly lower embedded energy of materials due to their material inventory and lower process energy associated with low-temperature roll-to-roll processing and flexible choice in plastic substrates. The most distinguishing feature of OPVs is the possibility to print or coat the device directly onto a thin flexible carrier substrate using roll-to-roll coating and printing methods, which enable simple handling and fast processing.⁶⁴ Thus, manufacturing speed of OPVs can

Table 2 EPBT of commercial PV modules. Note that efficiencies are representative from the sources cited and do not represent the full range commercially available

PV technology	EPBT (years)	Efficiency range	Sources
c-Si	4.12–2.38	11.5%–14%	54,56,57
p-Si	2–1.9	13%–13.2%	54,56,57
Ribbon-Si	1.4	11.5%	54
a-Si	1.13	7%	58
CIGS	2.26–2.2	8.9%–11%	59,60
CdTe	1.61–0.63	8%–13%	54,60
OPV	2.02–0.79	2%–4%	61–63

be very high and the thermal budget is very low. A comparison of process energy inputs of processing 1 m² of PV modules is displayed in Table 3, where one can see the low life cycle energy demand of OPV modules.

Although in the mid-term the power conversion efficiency of flexible roll-to-roll processed OPV modules is expected to increase to ~10% with an operational lifetime as long as 10 years,⁶⁶ both metrics will still be lower than commercial PV technologies, which can have module efficiency as high as 20% and an effective production life of 20–30 years (*e.g.* many silicon-based PV manufacturers now provide a 25-year warranty on their products). Despite the apparent weakness of these two important factors, OPVs are expected to have much shorter EPBTs than their silicon-based and thin film-based counterparts.

In this work, we conducted a LCA to estimate the EPBT of OPVs and major competitors in the mid-term. Our analysis focuses on a particular kind of OPV using a promising manufacturing technology reported at Risø DTU, which is denoted as “Process H” in the original paper.⁶⁴ Compared to other manufacturing routes, although the module efficiency may not be as high as for alternative technologies, this process leads to significant reductions in energy costs and avoids the use of rare elements having limited supply. These attributes would greatly facilitate up-scaling. Since the specific product produced by this process has not been commercialized yet, the data used for the analysis are obtained from pilot-scale experiments. Future processes could incorporate higher performance materials and more efficient processing technologies, which could increase device lifetime and/or power conversion efficiency. The detailed energy inputs of such OPV devices, in terms of embedded energy and direct process energy, are given in Tables 4 and 5, respectively.

Table 3 Energy input required to produce 1 m² of module for various PV technologies

PV technology	Electricity (kWh)	Oil (l)	Natural gas (MJ)	Sources
c-Si	282	0.05	361	54
p-Si	248	0.05	308	54
Ribbon-Si	182	0.05	166	54
CdTe	59	0.05	—	54
OPV	2.13	—	—	61,64

Table 4 Energy embedded in materials of 1 m² of OPV modules⁶⁴

Materials	Units (kg)	Embedded energy (MJ _{EPE})
PET substrate	0.0616500	4.98
Electrode ink (graphite)	0.0045902	0.80
Zn(OAc) ²	0.0002951	0.01
P3HT ^a	0.0000836	0.15
PCBM ^b	0.0000669	0.74
Chlorobenzene	0.0061869	0.38
Isopropanol	0.0388852	2.44
PEDOT:PSS ^c	0.0262295	4.18
Back electrode (silver)	0.0006330	0.20
Adhesive	0.0202400	4.05
PET encapsulation ^d	0.0616500	4.98
Subtotal	0.221	22.91

^a P3HT: poly(3-hexylthiophene). ^b PCBM: phenyl-C₆₁-butyric acid methylester. ^c PEDOT:PSS: poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate). ^d PET: polyethylene terephthalate.

We estimate the efficiency of OPV modules will achieve 10% in the mid-term—an efficiency already surpassed on the laboratory scale. The conversion efficiencies of c-Si, p-Si, ribbon-Si, and CdTe PVs will improve to 19%, 17%, 15%, and 12% in the mid-term future, as forecasted in a number of studies.^{54,67} (Note that c-Si modules are commercially available today with ~20% efficiency, but here we are exploring typical performance as opposed to champion models.) As the technologies are already rather mature, we assume PV modules based on silicon and CdTe will likely remain energy intensive in the mid-term future.^{65,71} The OPV module considered in this study has already been developed at the lab scale, and it is expected to be commercialized in the mid-term. Therefore, we assume the materials and energy inputs of the PV modules in the mid-term would be similar to the current case. The estimations are based on typical Southern European insolation, 1700 kWh m⁻² per year, a performance

Table 5 Direct process energy of 1 m² of OPV modules (Wh_{el})⁶⁴

S1 Front electrode processing	
Electrode coating	10.93
Drying	245.90
S2 ET layer deposition	
ZnO slot die coating	81.97
Drying	368.85
S3 Active layer deposition	
P3H6:PCBM ink preparation	5.57
P3H6:PCBM slot die coating	40.98
Drying	368.85
S4 PEDOT:PSS deposition	
PEDOT:PSS ink preparation	1.31
PEDOT:PSS slot die coating	74.52
Drying	670.64
S5 Back electrode deposition	
Slot die coating	10.93
Drying	245.90
S6 Lamination	
Encapsulation by R2R lamination ^a	4.10
Subtotal (Wh _{el})	2130.45
Subtotal (MJ_{EPE})	21.91

^a R2R: roll-to-roll.



Fig. 9 Energy payback time for silicon, CdTe, and OPV modules for current,^{56,60,61,64,67–70} mid-term, and long-term future scenarios. The estimations are based on rooftop-mount installation, Southern European insolation, 1700 kWh m⁻² per year, and a performance ratio of 0.75. Data on Si- and CdTe PVs are derived from reference 54. Estimations for the mid term only account for the increase of conversion efficiencies, while the analysis for the long term considers a number of changes of energy inputs and efficiencies.

ratio of 0.75, and having all modules produced in Western Europe.

With the estimates given above on the future energy requirements of modules and using the assumptions on module efficiency developments, we can determine the expected EPBT for the mid-term scenario of c-Si, p-Si, CdTe, and OPVs. In Fig. 9, these results are presented using the same assumptions on system performance ratio, insolation level, and electricity supply efficiency as mentioned above. The data for the present situation are also depicted.

We can see that, according to our energy input estimations and based on our efficiency assumptions, the EPBT values of future PV technology could improve significantly, resulting in values of less than two years for all the PV modules analyzed.

We also see that OPV modules are expected to gain a significant advantage over silicon PV and CdTe PV in terms of EPBT. Specifically, the EPBT of OPVs can be as short as 12 days in the mid-term scenario, leading to dramatically superior sustainability performance over all competing PV modules.

Long-term outlook (>10 years)

Large-scale PV energy production scenarios

As discussed in the introduction, photovoltaics represent perhaps the most powerful approach to harvest solar energy on a large scale in the long term. The production of future PV

Table 6 Comparison of investment costs of silicon PVs and OPVs for the current and long-term future scenarios (source data taken from reference⁶⁴)

Costs	Silicon PV, Current	OPV, Long-term (15%)	OPV, Current (1%)
Economic Investment			
Production capacity (GW _p)	1000	1000	1000
Cost per Watt of power produced (\$)	2.36	0.56	8.47
Cost of 1 terawatt (TW) plant (billion \$)	2354.07	564.23	8463.44
Energy Investment			
Equivalent primary energy (MJ W ⁻¹ _p)	37.43	0.30	4.51
Required Equivalent primary energy for 1 TW capacity (GJ)	3.74 E + 10	3.01 E + 08	4.51 E + 09

systems can be anticipated to achieve capacities measured in terawatts of electric power production. Based on the analysis presented herein, OPVs will play an important role in such a scenario due to a combination of material supply and economics.

There are currently only two classes of PV technologies that do not employ rare elements that technically prevent them from scaling up to terawatt capacity. Those are silicon-based PVs and OPVs. A number of efficient PV technologies, such as CdTe and CIGS, require substantial amounts of rare elements as raw materials (e.g. tellurium, indium, and gallium). Thus, these technologies are unlikely to be suitable for the long-term future market in the context of terawatt-scale PV production.^{72,73} Although many current OPV device architectures use rare materials, such as indium-tin oxide (ITO) for transparent electrodes, significant efforts have been directed recently toward ITO-free electrodes for OPVs (as well as for other PV technologies), and it is anticipated that OPVs will be fully rare-element-free in the long-term future. Although silicon-PVs do not face the problem of potential unavailability of critical elements or components, they do suffer from several drawbacks such as large thermal budget, relatively slow manufacturing speed, and energy-intensive production processing. Both laboratory and commercial efficiencies for all varieties of solar cells have risen steadily in recent years, indicating that research efforts could further enhance the performance of solar cells. Silicon-PV technologies will most likely maintain higher conversion efficiency than OPVs in the long term, but conversion efficiency should not be the sole metric as it does not consider the scale of the problem at the terawatt level, nor does it take into account potential economic, energy, and environmental issues. In contrast, OPVs have the lowest energy embedded in the modules (as well as the poorest optoelectronic performance). Yet, as the drop in efficiency when going from silicon to OPVs is a factor of 10–20 (on the module level) the drop in equivalent primary energy (EPE) drops by a factor of more than 150.^{56,64}

OPVs had approximately a \$2 million market share in 2011. In the coming decade, OPVs are projected to skyrocket to have a multi-billion-dollar market in revenue.⁷⁴ It is foreseeable that in the long term OPVs will be fully integrated with the power grid and will become a major producer of electric power with TW capacities. Silicon PV technologies also have the potential of being scaled up to the terawatt level in the long term, but this would require a vast investment both in terms of energy and capital. As shown in Table 6, the upscaling needed for silicon PV to produce 1 TW electric power production capacity would require an energy input of around 3.74×10^{10} GJ and an investment of \$2354 billion. In comparison, a similar OPV installation might need 100 times less energy and five times lower capital investment cost in the forecast long-term scenario with 15% electric power conversion efficiency.

Energy payback time in the long-term

We conducted an analogous LCA study to that for the mid-term scenario to estimate the EPBT of OPVs and other PV technologies in the long term. We estimate the efficiency of OPV will achieve 15% in the long term,⁷⁵ while the efficiency of silicon PV modules may optimistically reach 25%, close to

their thermodynamic limit, and that of CdTe modules may reach 20%, slightly outperforming the best lab-scale devices to date.

In addition to updating the efficiencies, the analysis also takes into account a number of possible improvements of the material and process energy inputs based on the outlook described in literature on silicon and CdTe PVs.^{54,67,76} Specifically, the analysis considers that silicon wafers will be thinned to 50 μm for p-Si and c-Si and 200 μm for ribbon-Si and that the energy demand during the casting of multi-crystalline ingots and the Czochralski growing of Si mono-crystals will fall as much as three-fold.⁶⁷ Moreover, the process energy input of poly-silicon might be reduced by a surprisingly large 90% due to the use of a fluidized bed reactor instead of the popular Siemens process.^{67,76} The CdTe process is projected to reduce its manufacturing electricity requirement by 25% through process optimization and ~20% of this manufacturing requirement will be met by on-site solar energy production. As silicon PV and CdTe PV are somewhat mature technologies, the remaining material and process inventory are assumed to have no major changes even in this longer time horizon.

Although the materials used in long-term future OPV modules will definitely differ from those used today, it is hard to predict at this stage what specific materials will emerge considering the rapid pace of change in the field (see recent advances in OPVs section). Thus, for an estimation, we use the same material inventory for OPVs as considered in the mid-term scenario. In this way, our analysis will provide an upper bound on the EPBTs for OPVs in the long run, assuming materials implemented in the future will have higher efficiency and equal or lower embedded energy. We also note that CdTe PVs are unlikely to have a large market share in the long term due to the expected scarcity of rare elements. Other assumptions of the analysis are the same as those in the mid-term scenario.

The EPBT analysis results are also shown in Fig. 9. One can see that the EPBT of all PV technologies continues to decrease due to technology evolution, increases of efficiency, and improvement of process energy efficiency. Similar to the mid-term scenario, OPVs have the shortest EPBT, around one week, while both c-Si and p-Si PV modules have more than 0.5-year EPBTs. It is clear the OPVs will remain the champion in terms of energy sustainability for the foreseeable future.

Environmental impact

LCA also provides a means to evaluate the environmental performance of PV technologies, by characterizing and quantifying the total environmental burdens of a product or system, from raw materials extraction to end-of-life management.

Greenhouse gas (GHG) emissions over a product's life cycle indicate its environmental impact on the global climate. This metric is especially important as climate disruption arouses increasing attention—particularly considering the long-standing link between energy production and GHGs. As a standard measurement, CO₂ equivalency is generally used. CO₂ equivalency is a quantity that describes, for a given mixture and amount of GHG, the amount of CO₂ that would have the same

global warming potential (GWP) when measured over a specified timescale (typically 100 years), where GWP is a relative measure of how much heat a GHG traps in the atmosphere. The major emissions included as GHG emissions are CO₂ (GWP = 1), CH₄ (GWP = 23), N₂O (GWP = 296), and chlorofluorocarbons (GWP = 4600–10 600).⁷⁷ The equivalent CO₂ emissions can be obtained by multiplying all energy and material inputs with their corresponding CO₂ emission factors. Electricity and fuel use during PV materials and module production are the main sources of GHG emissions for PV cycles. Since most of the energy inputs to the module are electricity inputs, for simplicity, we convert the equivalent primary energy into electricity and calculate the CO₂ emissions related to 1 m² of OPV modules by multiplying by the average electricity mix. Total GHG emissions are highly dependent on the fuel mix of the upstream electricity-generation methods. For instance, the GHG emission factor of the average U.S. electricity grid is 40% higher than that of the average Western European grid, resulting in higher GHG estimates for U.S.-produced PV modules.^{54,78}

The total life cycle GHG emissions associated with an OPV module come from raw materials extraction, the production phase, and the operation of PV modules. However, the CO₂ emission factor, which is calculated as the total embodied CO₂ emissions of the module divided by the total generated electricity over the module's lifetime, is more widely used for evaluating the sustainability of PV technologies. The total electric power generation of a PV module over its lifetime strongly depends on the duration of module lifetime and the system degradation rate, so the CO₂ emission factor also has strong correlation with these two factors. Detailed calculations of the CO₂ emission factor have been discussed in a number of existing publications.^{54,61}

We conducted a LCA to estimate the CO₂ emission factor of current and long-term future OPV modules. We consider the same OPV module analyzed in the EPBT study above. Although the materials of long-term future OPVs are likely to evolve, the results of this study provide a similar upper bound of the emission factor, based on the idea that long-term future materials in OPV modules would be more sustainable than the mid-term ones. In the current scenario, OPV modules have an efficiency of 1% and a lifetime of two years, while in the long-term scenario, the efficiency increases to 15% and the lifetime is as long as 20 years. The results are presented in Fig. 10. For comparison, we also take the current and future estimation of CO₂ emission factors of silicon-based and CdTe PVs from the literature based on material-inventory data from industry⁵⁴ and present them in Fig. 10.

One can see that, under the current scenario, the GHG emission factor of OPVs is higher than those of silicon and CdTe PVs, while CdTe has the lowest emission factor among all the PV technologies. However, it is worth mentioning that the emissions from CdTe PVs are mostly heavy metals, rather than GHGs, due to the treatment and use of cadmium and tellurium.⁷⁶ The CO₂ emission factors of all PV modules will decrease significantly in transitioning from the current scenario to the long-term future one. In particular, OPV emissions become the smallest in the long-term future scenario, representing only ~10% of the CO₂ emission factors

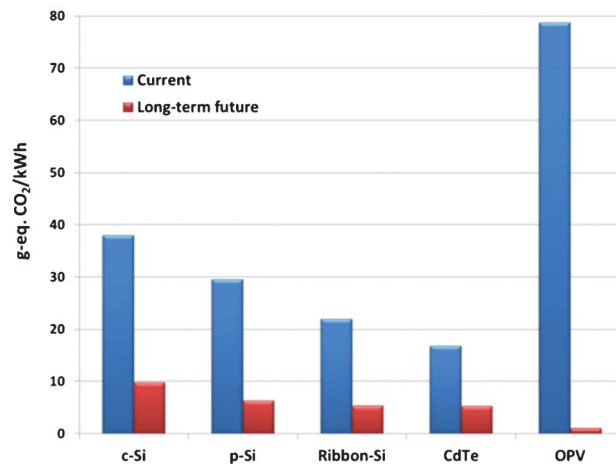


Fig. 10 Carbon emissions equivalence for silicon, CdTe, and OPV modules for current and long-term future scenarios. The estimations are based on rooftop-mount installation, Southern European insolation, 1700 kWh m⁻² per year, and a performance ratio of 0.75. Data on Si- and CdTe PVs are taken from reference 54. Estimations for the mid term only accounts for the increase of conversion efficiencies, while the analysis for the long term considers a number of changes of energy inputs and efficiencies.

of other PV modules. The significant decrease is mainly due to the increase of conversion efficiency and the extension of operating lifetime. We note that this picture is not a static one and expect that improvements in material and energy utilization and recycling will continue to improve the environmental profiles. Nonetheless, the study does reveal the significant environmental benefits of OPV technologies in the long-term future.

Conclusions

With current performance achievements, OPVs are positioned only for niche applications that take advantage of their light weight, mechanical flexibility, tunable color, and low-light performance, such as powering consumer electronics. As efficiencies and lifetimes continue to improve, however, new opportunities emerge. In the relatively near term, OPVs will find applications in third-world, off-grid uses as well as military/emergency and some BIPV functions. Another intriguing mid-term possibility is the implementation of tandem modules in which OPVs serve as the top layer with traditional inorganic cells underneath. In the long term, climate change and other factors demand TWs of energy be supplied by the sun, and—assuming anticipated technological advances are realized—OPVs of the future will have unique advantages for very large-scale power generation because of their scalability as well as their remarkably low energy payback time and carbon emissions, making them a major player in the energy marketplace.

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