Chapter

Sustainable Advanced Manufacturing of Printed Electronics: An Environmental Consideration

Bilge Nazli Altay, Martin Bolduc and Sylvain G. Cloutier

Abstract

Printing technologies have become a novel and disruptive innovation method of manufacturing electronic components to produce a diverse range of devices including photovoltaic cells, solar panels, energy harvesters, batteries, light sources, and sensors on really thin, lightweight, and flexible substrates. In traditional electronic manufacturing, a functional layer must be deposited, typically through a chemical vapor or physical vapor process for a copper layer for circuitry production. These subtractive techniques involve multiple production steps and use toxic etching chemicals to remove unwanted photoresist layers and metals. In printing, the same functional material can be selectively deposited only where it is needed on the substrate via plates or print heads. The process is additive and significantly reduces not only the number of manufacturing steps, but also the need for energy, time, consumables, as well as the waste. Thereby, printing has been in the focus for many applications as a green, efficient, energy-saving, environmentally friendly manufacturing method. This chapter presents a general vision on green energy resources and then details printed electronics that consolidates green energy and environment relative to traditional manufacturing system.

Keywords: additive manufacturing, printing, flexible electronics, functional inks, subtractive manufacturing

1. Green energy, environment, and electronics

Sustainable and renewable green energy and materials as an alternative to fossil fuels that take millions of years to be developed have been the most important challenge for all industries to secure the future energy demands, environment, and human health [1]. Burning fossil fuels for energy, production and transportation of fossil fuel-based materials, industrial/agricultural activities, as well as growing population yield greenhouse gasses (GHGs) that trap heat in the atmosphere [2]. The GHGs remain in the air for various amounts of time, from a few to thousands of years, causing global heating and drastic changes in climate [3, 4]. Therefore, innovations in all fields are critically important to reduce the GHGs, unsustainable energy and material usage, cost, toxic waste, and pollution which are the potential risks on human health and environment [5].

Worldwide energy consumption by source recorded to be an average of 18.4 trillion watts (TW) in 2018 [6]. **Figure 1** represents that the majority of the energy was based on fossil energy sources. For the future, the total consumption is projected to be 27.6 TW by 2050 and 43.0 TW by 2100 [7]. Researchers help formulating solutions to increase green energy production that comes from the natural sources such as solar, wind, ocean or tidal, hydropower, biomass, and geothermal energy. They are also called C-neutral sources [7]. Among these, solar energy is the largest source that enables more energy in an hour to the Earth than all of the energy consumed by humans in an entire year (if only this energy could be stored) [1]. Each energy sources have different potential to provide the projected power need. The theoretical delivery potentials of green sources in **Table 1** represents that using direct radiation from the sun is by far the only biggest source of energy [7].

The sun is a massive reactor where hydrogen atoms are fused into helium. The energy from this reaction is released into space in the form of radiation that creates electromagnetic energy—the entire range of light that exist (**Figure 2**). By using various technologies (solar panels and photovoltaics (PV)), the solar radiation can be turned into heat and electricity [8].

Part of the light radiated from the sun does not reach to the Earth due to various reasons [10]. Some portion for instance is reflected from the atmosphere back into the space, called *reflection of light*. Other portion is absorbed by the gasses and water

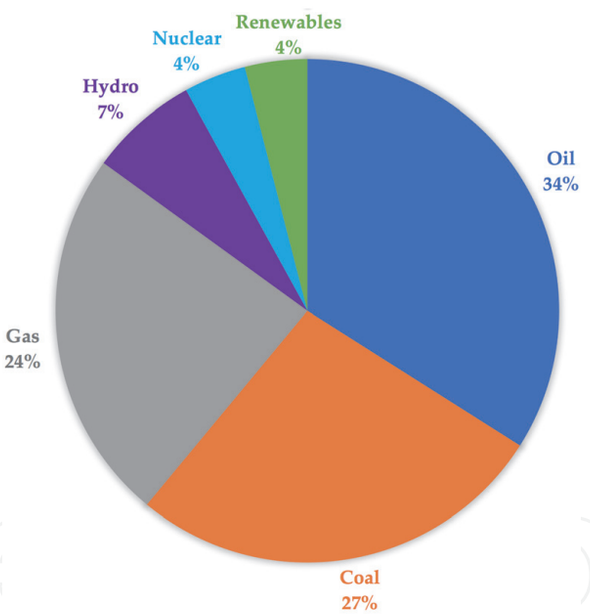

Figure 1.
Global energy consumption [6].

Green energy source	Theoretical potential (TW)
Solar energy	89,000 TW_p
Wind	1000 TW_m
Geothermal	44 TW_t
Hydropower	12 TW_m
Ocean tidal	2.4 TW_m

Subscripts denote mechanical, photonic, and thermal.

Table 1.
Energy delivery estimates of green energy sources.

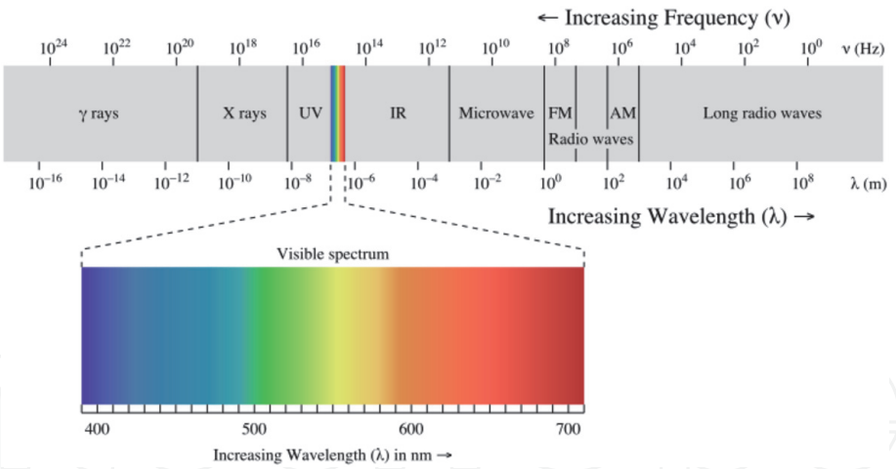

Figure 2.
Electromagnetic spectrum [9].

vapor molecules (O_2, O_3, H_2O, CO_2, etc.), called *absorption of light*. If the light comes on particles that are smaller than the wavelength of the radiation in the atmosphere, *Rayleigh scattering* occurs (mostly seen in gasses) and causes for instance the blue color of the sky. On the contrary, the particles larger than the wavelength of the radiation cause *Mie scattering* that happens due to aerosols and dust particles in the air. Therefore, the solar resource is broken down into three main components: (1) diffuse solar radiation (the light that are scattered), (2) direct beam solar radiation (the light that pass through the atmosphere), and (3) global solar radiation (the sum of (1) and (2)). The energy available from the sun that reaches the Earth, called *solar constant*, is considered to be 1367 W/m^2. However, due to the diffusion caused by the scatterings, usually 1000 W/m^2 (at 25°C, AM1.5G spectrum) is used to describe 1 day atmospheric condition for the standard test conditions of efficiency estimations of solar power [11]. The diffuse light is also known to limit the power generation efficiency of solar panels, alongside with the limited angle placement options for the rigid panel orientation (**Figure 3**), geographical location, time of the day, season, local landscape, and weather [12].

The basic working principle of solar panel is converting light energy directly into electricity through the photovoltaic effect. The panel is usually constructed by an n-type and p-type semiconductor material (silicon based in general) between the two metal conductor layers (**Figure 4**). The n-type semiconductor has extra electrons that carry negative charge, while the positive p-type semiconductor has

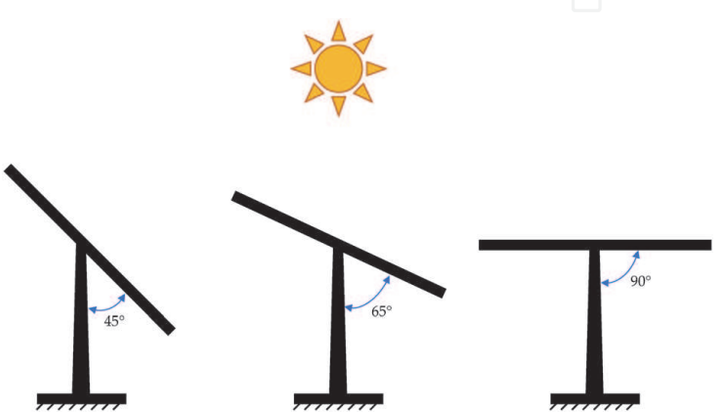

Figure 3.
Schematics of a conventional solar panel at different tilting angles.

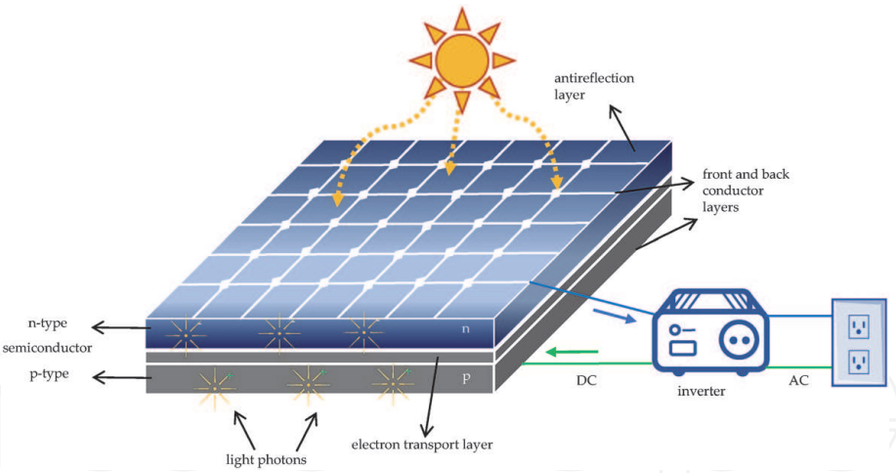

Figure 4.
Illustration of sunlight conversion to electricity.

missing electrons. When the light photons are absorbed, the extra electrons of the n-type get free (the so-called holes) and forced to travel in the electron transport layer by the top conductor. Meanwhile, the conductor on the bottom layer forces the missing positive electrons to travel in the transport layer. These moving electron–hole pairs induce the DC electric current formation that is converted into AC in the inverter unit of the solar system. In the case of solar heating (**Figure 5**), a panel of tubes heats up the water through the absorbed light energy and redistributes into the building for heating, air conditioning, and hot water usage.

Between the global energy need for electricity and heating, 10% is estimated to be for illumination purpose, while 90% is for the heat used to make products and to heat and cool buildings and homes and the energy used to drive motor vehicles [1]. One of the most critical factors is understanding not only how to produce the green energy, but also how to remanufacture, reduce, and reuse/recycle electronic products that use this energy. Thereby, as much as the effort goes into producing green energy from natural sources, the same effort is needed for electronic manufacturing since an electronic circuit is found in a surprising number of devices that we use in our daily life: from lighting to domestic/industrial appliances; from computers and its accessories to communication devices and cameras; from vehicle electronics to medical devices; or from the products that use displaying units, controlling apparatus, and switches to alarm systems and toys. The circuitry use is almost endless.

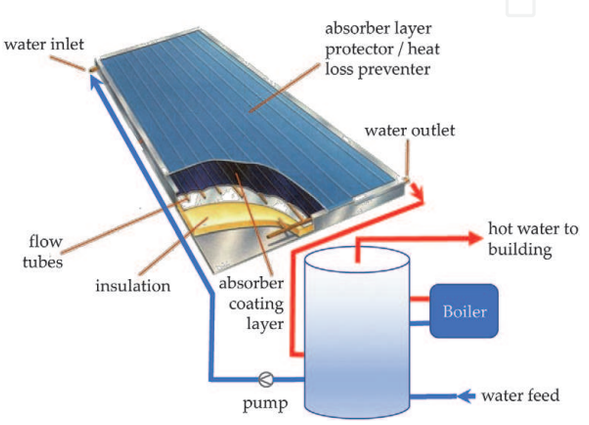

Figure 5.
Illustration of traditional solar water heating (edited) [13].

2. Traditional electronic manufacturing vs. printed electronics

2.1 Traditional electronic manufacturing

Traditional electronic manufacturing requires multiple production steps as illustrated in **Figure 6** [16]. First, a functional layer must be deposited on a substrate, typically through a chemical vapor or physical vapor process, for a copper layer production. The most common substrate used for the circuit board is a glass fiber-reinforced epoxy resin. Then, a photoresist layer is deposited on the substrate and experiences exposing, developing and curing processes. The next is the use of harsh etching chemicals to remove the photoresist layer and the unwanted metal that is not covered by the photoresist. The last step is striping the resist material and cleaning all the residues away. The entire manufacturing processes are highly time- and energy consuming, costly, and inherently wasteful. One main approach for green electronic manufacturing is called the three R's—"remanufacture, reduce, reuse/recycle"—focused on minimizing the use of energy, hazardous materials, toxic waste and pollution, and coolant consumption while machining, while promoting product take-back policies, the use of reusable/recyclable components, recycled feedstock in plastic parts, and lead-fee production [14].

2.2 Printed electronics manufacturing

Printing has received immense attention due to the additive nature of the manufacturing [15]. During printing, functional materials (or the so-called conductive/smart inks) can be patterned by selective deposition on where they are needed by the print heads in the case of digital printing, such as inkjet, 3D printing, and aerosol (**Figure 7**) or by the printing plates. Different functional materials are printed in a layer-on-layer manner, then followed by a curing process that forms necking between the pigment particles [16]. The additive approach and high production capability of the printing presses significantly reduce production cost, number of manufacturing steps, and the need for energy, time, and consumables, as well as offer great reduction in waste compared to traditional photolithography manufacturing. Printing allows sheet-to-sheet or roll-to-roll mass production; thereby electronics can be manufactured not only on rigid, but also on thin,

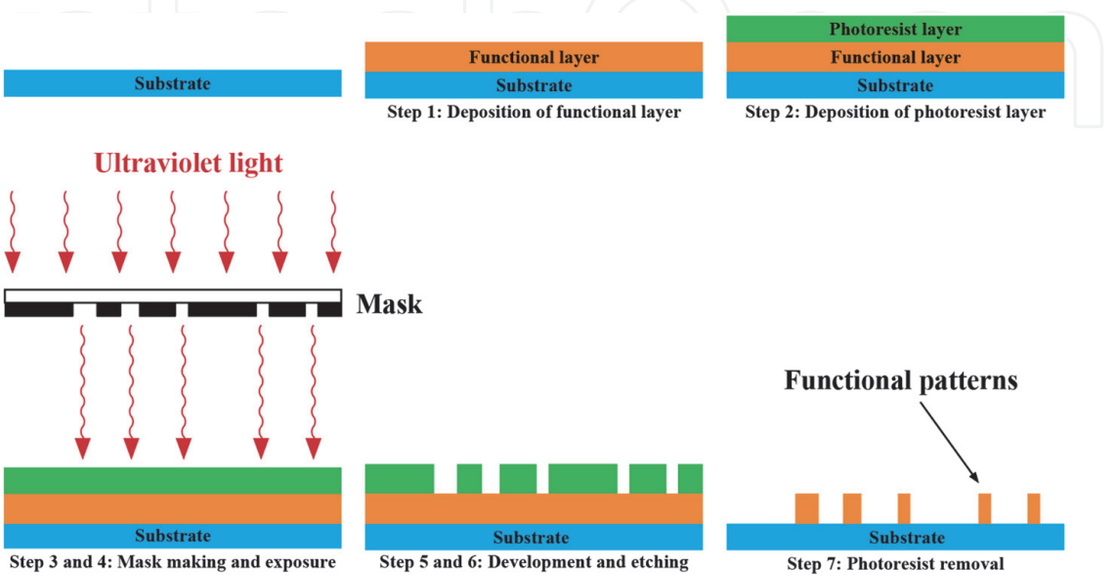

Figure 6.
Subtractive manufacturing steps [16].

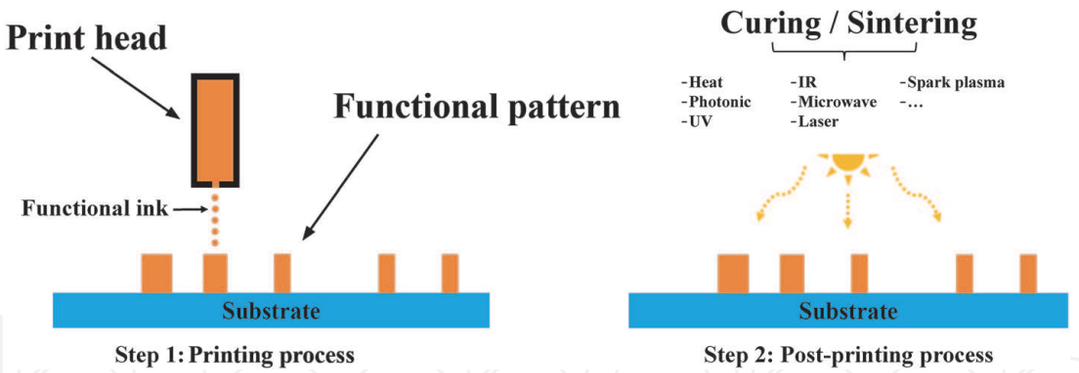

Figure 7.
Additive manufacturing steps [16].

lightweight, flexible, and large area substrates [17–22]. Printing technologies and the pluriformity of substrates open up launching brand new products that could have never existed before and realize bendable, rollable, wearable, or elastically stretchable devices. These printed electronics (PE) are environmentally friendly when compared to the traditional electronic methods. PEs are lightweight and not made with extremely harsh etching chemicals, and they do not occupy a massive amount of space in landfills. If the aim is to be green and sustainable, then printing technologies are certainly the future.

Printing techniques include conventional printing systems that require an intermediate printing plate to transfer a pattern (flexography, gravure, screen, and offset lithography) and nonimpact printing systems that print the pattern directly onto the substrates (digital and 3D) (**Figure 8**) [23]. However, nonprinting systems (liquid dispensing, aerosol) and coating systems (rod, blade, air knife metering) can also be used to dispense functional materials. The difference between the printing technologies originates from the ink characteristics (i.e., viscosity, rheology, surface tension), substrate types (i.e., papers, films, textiles), and printability properties (i.e., ink film thickness, resolution, speed, line quality) [24, 25]. **Table 2** shows some of the printed feature size capabilities of printing processes for PE applications.

In recent years, the advancements in digital inkjet printing technologies have shown great promises for printed electronics. Akin to more conventional additive manufacturing strategies such as using screen printing, digital inkjet printing has been rapidly and successfully applied for rapid prototyping, low-volume production, and hybrid integration of critical components for a wide range of optoelectronic applications including energy harvesting, wearables, and biomedical sensors [26, 27].

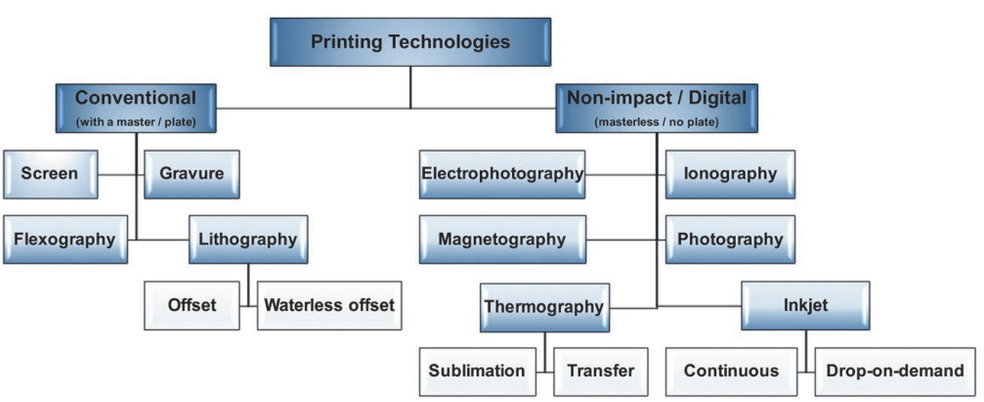

Figure 8.
Classification of printing technologies based on printing plate requirement [23].

Property	Screen	Flexo	Gravure	Inkjet
Viscosity (cP)	500–5000	50–500	100–1000	10–20
Minimum trace width (μ)	30–50	5–50	5–25	3–20
Minimum trace spacing (μ)	50–100	20–30	10–25	10–20
Ink film thickness (μ)	0.5–200	0.25–4	0.25–6	0.05–20

Table 2.
Common printed feature size of printing processes for PE applications.

Figure 9.
Printed electronics samples: circuit printed with nano-silver ink [35], printed sensor that shows food spoilage [36], smart box packaging that enables end-of-life display by color change [37], and various lighting applications [38].

2.2.1 Functional inks

There are PE components that have been researched and fabricated using these printing techniques such as solar cells, displays, and transistors [28–31]. Similar to subtractive electronic manufacturing, PE components (**Figure 9**) require specific inks to provide functionalities like conductivity, resistivity, semi-conductivity, or color change by heat, light, moisture, pressure, or spoilage.

The materials listed in **Table 3** present common functional pigments used in ink formulations. A typical ink formulation includes binders, vehicles, and additives besides the pigments [32]. Binders are the chemicals binding formulation

Functionality	Pigment type
Conductors	Copper, silver, gold, carbon, aluminum, nickel, indium tin oxide, tin, graphene, graphene oxide, PEDOT:PSS, polyaniline, iron, graphite [39–58]
Semiconductors	Zinc oxide, silicon, zinc selenide, indium-gallium-zinc oxide, cadmium selenide, gallium arsenide, MALH [59–64]
Resistors	Aluminum oxide, hafnium dioxide, poly(4-vinylphenol), spin-on glass, parylene, solid electrolytes [65–72]

Table 3.
Functional pigment examples for PE applications [16].

ingredients to each other and to the substrate. Vehicle is the liquid portion of the formulation that carries the ink onto the substrates. Generally, ink formulations are classified based on the vehicle type, such as water-based, solvent-based, ultraviolet light/electron beam (UV/EB) based, or soy-based. Additives are used for supplementary properties, such as promoting stability, or preventing oxidation, flocculation, etc. [33]. In PE applications, binders and some of the additives act as an insulator and reduce the conductivity. There are studies that suggest binder-free formulations that reverse this impact and enhance conductivity [34].

In terms of solar energy harvesting, lighting and displays, and sensing applications, the research has pioneered new and better low-cost and printable optoelectronic materials and devices. Methylammonium lead halide (MALH) perovskites for instance (e.g., $CH3NH3PbX_3$, X either I, Cl or Br) have shown great potential due to their unique optoelectronic properties and the ability to replace P-N junctions for various applications including light-emitting diodes, solar cells, and photodetectors [64]. The power-conversion efficiency of photovoltaic devices has been reported to increase from 3.8% in 2009 [73] to 22.1% in 2016 [74, 75]. Such progress is largely attributed to improved processing and longer charge-carrier lifetimes directly related to increased material quality. Yet, fundamental challenges including low carrier mobilities still prevent the fabrication of large-area devices with performances competing with state-of-the-art technologies [76].

2.2.2 Substrates

The thermal and mechanical stability of substrates are critically important for the precise registration of functional ink layers upon each other to create PE components (i.e., electroluminescence lamp, capacitors, organic light-emitting diodes). Polymer films [77], papers [19, 78], flexible glass [79], textiles [80], and metal [81] have been given significant consideration as a substrate material. In PE applications, substrates either act as a base material to mechanically support electrical components such as circuit board [82], or as a top material for touch panels and display and lighting applications [83], or as an interlayer in batteries as separator membranes [84].

The quality and type of the substrate affect electrical, optical, mechanical, and magnetic properties of the functional ink layer [85] as well as economics [48]; therefore, its properties need to be engineered depending on the application. For instance, defects on the surface of the substrates may lead to pinholes and block electron flow in circuitry [77]. General requirements of substrates for PE include flexibility, transparency, surface smoothness, low thermal expansion, stiffness, heat resistance, low cost, thinness, and lightweight [86]. **Table 4** presents different properties of substrates having the same 100 μm thickness for flexible backplane applications (glass, plastic films [PEN and PI], and stainless steel) [22].

2.2.3 Post-printing process

In printing industry, drying is performed with an oven or via UV lamps; however, the inks used for PE applications require higher temperatures for densification or crystallization to function properly. Once the functional ink layer is printed, the post-printing process is needed to enable connectivity in pigment particles, so the printed ink layer can conduct electricity (**Figure 7**). The connectivity is accomplished by means of one or multiple processes: drying, curing, sintering, reactive chemistry transformation, and annealing. These post processes change ink structure by volatilizing vehicle of the ink and form interparticle necking between the pigment particles that grow particle grain to form continuous functional layer, while

Property	Unit	Glass	Plastics	Stainless steel
Weight	g/m^2	250	120	800
Safe bending radius	cm	40	4	4
R2R processable	—	Unlikely	Yes	Yes
Transparency	—	Yes	Yes/some	No
Maximum process temperature	°C	600	180–300	1000
Coefficient thermal expansion	ppm/°C	4	16	10
Elastic modulus	GPa	70	5	200
Permeable to oxygen, water vapor	—	No	Yes	No
Coefficient of hydrolytic expansion	ppm/RH%	None	11	None
Electrical conductivity	—	None	None	High
Thermal conductivity	W/m°C	1	0.1–0.2	16

Table 4.
Comparison of substrate properties for flexible backplane application.

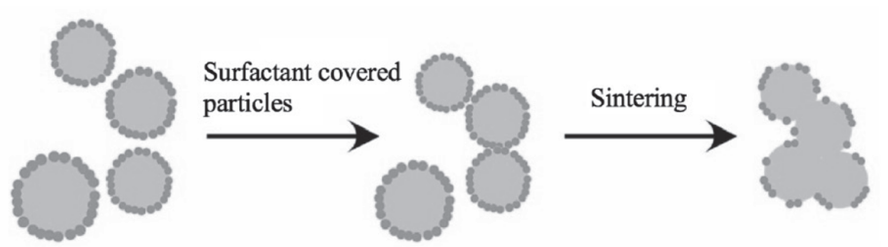

Figure 10.
Illustration of interparticle necking.

decomposing the binder (**Figure 10**) [87, 88]. The main types of post-printing methods are listed as microwave heating and electrical, spark plasma, laser, and photonic sintering [89].

The heat applied during curing volatilizes vehicle component of an ink formulation that allows functional pigments to contact each other. Sintering, on the other hand, is the process of pigment grain growth in the crystalline structure in the printed ink layer. However, the terms are used interchangeably. Sintering process requires optimization for each substrate as well as ink formulations since the chemical composition of the ink, particle size, shape and distribution, or degree of agglomeration varies. Different sintering parameters such as temperature, energy, time, or the atmosphere (ambient vs. inert) also cause variation in the performance of the same material. **Figure 11** shows an example of the effect of photonic energy variation on the sheet resistance of printed nickel ink [16]. As the energy applied increases, the sheet resistance decreases.

Photonic sintering has attracted great attention within the main types of sintering methods due to the instant heating applied during exposure, followed by an instant cooling, which is advantageous especially for the substrates with low glass transition temperatures. A pulse light from a xenon gas-filled flash lamp heats the functional ink layer in milliseconds beyond the maximum working temperature of the substrate. Then, the heat is removed rapidly in the interface of the substrate via conduction thanks to the thermal mass of the substrate and prevents structural degradation [90]. Three transient sintering conditions that are essential for an optimum photonic processing have been reported:

ink film thickness < substrate thickness
pulse of photonic light duration < thermal equilibration time of substrate
thermal equilibration time of ink film < pulse of photonic light duration

The thermal equilibration time of materials (τ_i) (s) is provided in Eq. (1), where K_i is the thermal conductivity (W/m K), ρ_i is the density (kg/m^3), c_{pi} is the specific heat (W s/kg K), and x_i is the thickness ink layer (m):

$$\tau_i = c_{pi}\rho_i x_i^2/4K_i \quad (1)$$

The thermal properties in **Table 5**, three transient conditions in **Table 6**, and the thermal profile presented in **Figure 12** exemplify photonic sintering of a 36-μm-thick nickel ink film printed on a 250-μm-thick solid bleached sulfate (SBS) paperboard that is processed at ~5 J/m^2 photonic energy that provides 12 Ω/□ of sheet resistance [16]. A millisecond of two overlapped light pulse heats the surface of printed nickel ink to a temperature between 350 and 500°C. Thanks to the rapid cooling, the temperature in the interface, 20 μm depth of the paperboard, reaches only 200–320°C. Although the ignition temperature of paper is 233°C, the heat

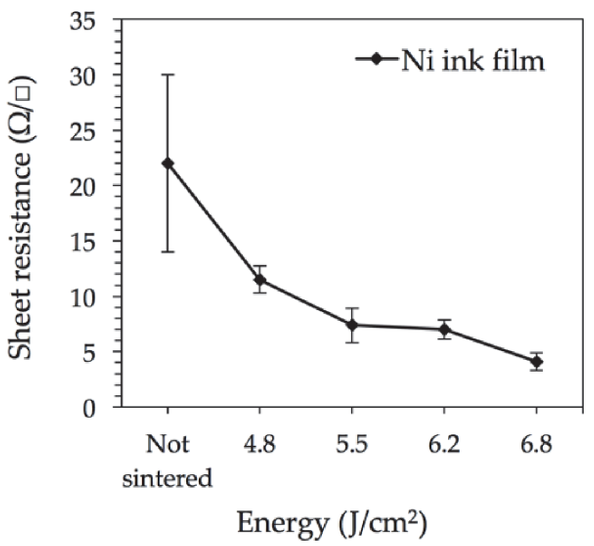

Figure 11.
Sheet resistance of printed Ni ink.

Factors	c_{pi}	ρ_i	x_i	K_is	τ_i
Nickel ink	440	8908	0.000036	90.9	1.4×10^{-5}
SBS	1400	900	0.000250	0.05	3.9×10^{-2}

Table 5.
Thermal properties of the ink and substrate.

Factors	
Ink film thickness < substrate thickness	36 μm < 250 μm
Pulse light time < substrate thermal equilibration time	0.001 s < 0.039 s
Ink thermal equilibration time < pulse light time	0.000014 s < 0.001 s

Table 6.
Three transient conditions.

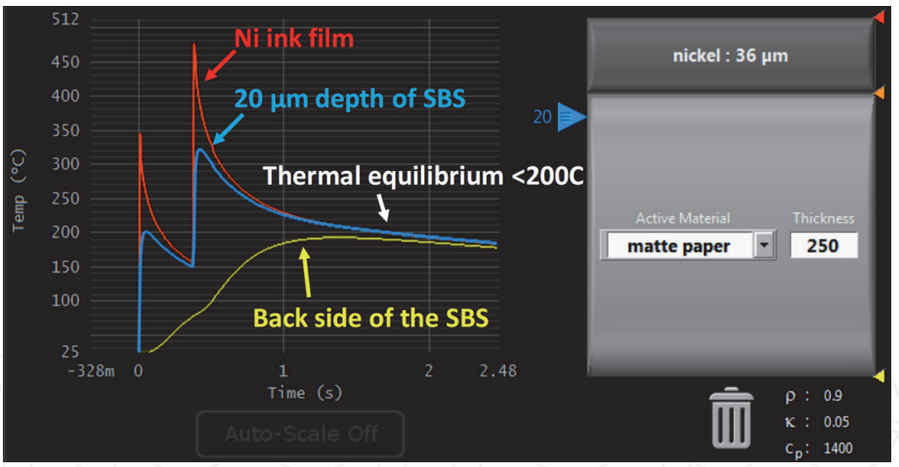

Figure 12.
Thermal profile simulation of nickel ink on a SBS paperboard.

equilibrates below 200°C in less than two milliseconds, which is too short for substrate to observe any deformation. Photonic sintering enables significant reduction both in processing time and energy in comparison to conventional oven that uses high temperature and processing time ranging from several minutes to hours.

3. Emerging advanced electronics manufacturing

In today's world, technological innovations accelerate at a much faster rate than before due to the more networked environment, advanced computers, data analytics, artificial intelligence (AI) tools, Internet of Things (IoT), and the speed of connectivity considering the ubiquitous information and communication technologies through Internet access, cloud computing, and smartphones [5, 91]. The innovations in the printed electronics area derive mostly from flexible and conformable disruptive device designs and structures (single or multilayer circuit constructions, sensors), formulation of materials (inks, substrates), and manufacturing process design (printing, post-printing, assembly). The performance of printed devices is mainly dependent on the complex ink formulation, adhesion, and the interactions between the inks and substrates to produce materials that can withstand post-printing, assembly, and environmental processes [48, 92, 93]. Therefore, most material providers follow closed innovation model and keep proprietary rights for their complex material formulation, processes, and methods to stabilize their position in the market [5].

The most common issues with the traditional screen-printed circuit manufacturing market are the limitation of printing finely spaced traces (**Figure 13 (a)**), the printing process that requires new platemaking phase at each design and client change (**Figure 13(b-c)**), and the usage of high ink amount during printing which generates large amount of waste materials that has fairly complex disposal handling process (**Figure 13(d)**). In contrast, digitally printed electronic circuit manufacturing (**Figure 13(e)**) allows instantaneous design modification by simply changing the Gerber design file as well as dramatically reduces the material consumption [94]. The digital inkjet system is a rapidly emerging technology that could be in-lined to a hybrid automated component assembly pick-and-place robot systems (**Figure 13(f)**) where large-scale advanced manufacturing strategies can be explored as a potential way to reach seamless manufacturing of high volumes and open entirely new markets. However, the inkjet printing of functional inks requires

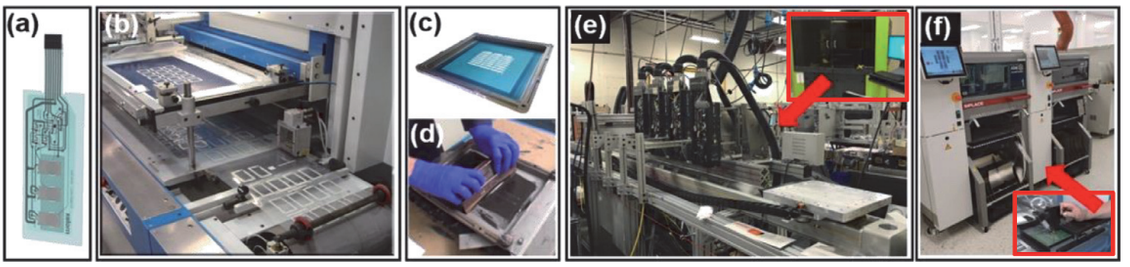

Figure 13.
(a) Commercial flexible hybrid electronic product that cannot be manufactured using screen printing (courtesies of Molex), (b) typical industrial grade screen-printing machine currently used for flexible circuit board manufacturing, (c) conventional screen stencil currently used for electronic board manufacturing, (d) typical screen printing application that uses tremendous amount of expensive functional inks, (e) industrial grade high-throughput digital inkjet printer vs. research grade in sectors like the graphic and consumer packaging industries (courtesy of Fujifilm), and (f) industrial grade fully automated pick-and-place robot for the assembly of electronic components of the circuit board (courtesies of C2MI and Varitron).

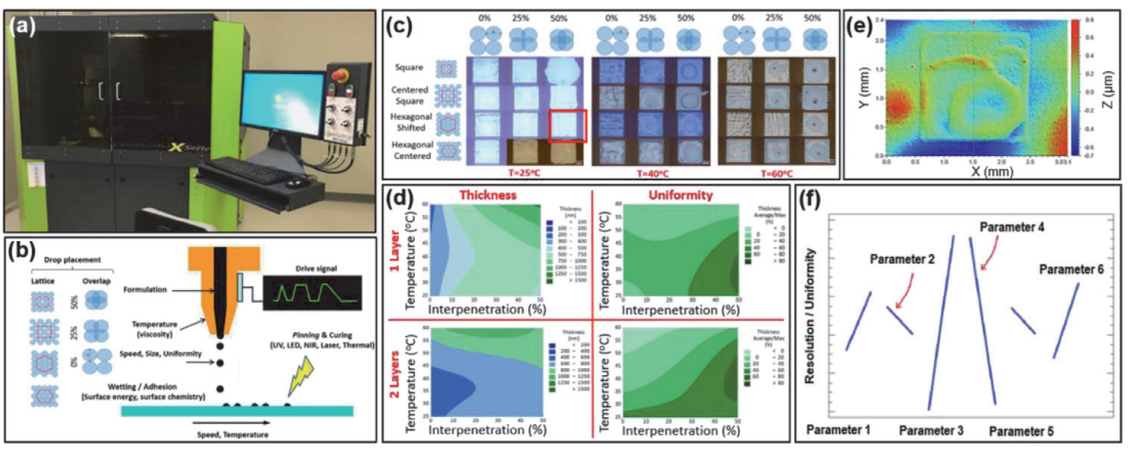

Figure 14.
Digital inkjet printing process mapping and optimization. (a) Research grade Ceradrop digital inkjet printing system at ÉTS; (b) precise control of a wide range of critical jetting parameters; (c) examples of inkjet-printed features using Ag ink on Kapton® for different printing lattices (drop placement configurations), drop interpenetration, and substrate temperatures; (d) example of one-layer and two-layer process mappings looking at the Ag features' thickness and uniformity for different substrate temperatures and drop interpenetrations in the hexagonal shifted lattice configuration; (e) typical high-resolution laser-scanning microscope image of the features obtained using a hexagonal shifted lattice with 50% interpenetration at 25°C substrate temperature; (f) example of a typical multivariate design-of-experiment analysis for process optimization (adapted from [94]).

a highly complex process optimization. **Figure 14** exemplifies a concrete process optimization done in ÉTS laboratory for only one silver ink formulation.

The massive push for intelligent cyber-physical systems associated with the Industry 4.0 and the IoT revolutions aims at taking better-informed decisions in real time, based on more complete and readily acquired sets of data. For the very reason, conformable printed sensors are deployed to collect data from places that are critical and difficult to access for energy, biomedical, transportations, manufacturing, smart building, or wearable electronics applications where better and cheaper flexible hybrid electronics circuits used as ubiquitous sensing elements would play a comprehensive role in ways that rigid devices cannot [95].

4. Conclusion

In this chapter, a general vision on energy sources and how an emerging field of printed electronics could consolidate green energy and environment is presented. An electronic circuit is found in a surprising number of devices that we use in our

daily life. Manufacturing digitally printed electronic circuits is a sustainable method that dramatically reduces high energy consumption and toxic etching chemical usage relative to traditional electronic manufacturing. Advanced printed electronics is truly a transdisciplinary research and production landscape that benefit greatly from strongly intertwined interrelationships between multiple diverse complementary fields, including material formulation engineering, printable electronic devices architecturing, computational robotics and process automation, and AI and process optimization. It is important to adopt an agile mindset for a complete ecosystem to conduct transformative R&D for disruptive and advanced printed electronics manufacturing solutions.

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Conflict of interest

There is no conflict of interest.

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