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Green Electronics and Sustainable Communication Technologies

¹Nandhana Pradeep, ²Anooja B

¹UG Scholar, Department of Electronics and Communication Engineering, Nehru College of Engineering and Research Centre, Thrissur, India

²Assistant Professor, Department of Electronics and Communication Engineering, Nehru College of Engineering and Research Centre, Thrissur, India

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ABSTRACT:

The electronic device and communication system usage is growing at an increasing rate and although these technologies have made life easier, they have significant energy costs and electronic waste. Green Electronics tackles this problem by designing and operating devices that require less energy, Sustainable Communication Technologies seek to provide communication services that use less energy and less environmental impact. This paper introduces the concept of green electronics and sustainable communication technologies, briefly summarizes the recent published literature in the area, and discusses the important components, working principle, and a representative example of green printed circuit board (PCB) fabrication by the electrohydrodynamic (EHD) printing technique. The use of these technologies, their potential benefits and drawbacks, as well as their future prospects, are also explored. The study concludes that green electronics and the use of sustainable communication technologies are crucial for a future characterised by reduced energy consumption, less e-waste and a cleaner, more efficient society.

Index Terms - Green Electronics, Sustainable Communication, Energy Efficiency, E-Waste Reduction, Green PCB, Renewable Energy, Internet of Things (IoT), 5G/6G Networks.

1. INTRODUCTION

Today electronic and communication systems are employed in various fields such as personal computers, mobile communications, industrial automation and smart infrastructure. The steady increase in these systems means that more energy is needed to manufacture and operate them. In parallel, many electronic products are being thrown out after a relatively brief period, which exacerbates the e-waste issue. Therefore, the performance is not the only factor that should be taken into account when designing a new electronic system. It is also important for it to have low energy consumption and environmental impact during its production, operation, and disposal. Green Electronics addresses these concerns primarily by designing electronics to be low power, efficient, and more readily produced and disposed of. Sustainable Communication Technologies takes this concept to communication networks and aims to minimise the energy demands and environmental footprint of the networks.

1.1 Need for the Technology

These technologies are in part called for because of the environmental issues that have arisen with the rapid global increase in electronics consumption. The number of electronic devices is growing, and of course, so is the energy consumption. Limited availability of recycling facilities and short product lifecycle can also contribute to e-waste. Both of these are environmental costs associated with electronic systems. For this reason, consideration of energy efficiency, responsible design, manufacture and management of e-waste have become significant components in the design of future electronic and communication systems.

1. The development of electronic devices is extremely fast.
2. High energy consumption
3. Increasing e-waste
4. Environmental impact
5. Need for a sustainable future

1.2 Objectives

This study aims to:

1. To learn the idea and the principle of Green Electronics.

2. To learn about sustainable communication technologies and their functioning.
3. To introduce students to energy efficient technologies in contemporary electronic/communication systems.
4. To explore how the e-waste and pollution from electronics can be reduced.
5. To support sustainable development by incorporating green design.

2. LITERATURE REVIEW

The survey of recent literature reveals an increasing number of research on energy harvesting, green communication, and sustainable design for IoT. Zeng et al. [1] conducted a survey of the green design approaches for energy harvesting backscatter communications, where they discussed its potential to power low power, battery-less, and sustainable IoT systems, but harvested energy and communication range is still limited. The 6G green wireless networks complementary research [2] investigated the use of federated learning, cloud computing, and artificial intelligence to achieve lower energy consumption and intelligent communication in the future wireless networks, but it incurred higher complexity and implementation costs. Naifar et al. [3] presented a survey of the various energy harvesting methods such as solar, thermal, vibration, and RF energy harvesting for IoT and wireless sensor networks that can increase the battery life of the devices and make the devices operate without human assistance, but energy availability depends on the environmental conditions. Alenezi et al. [4] analyzed green communication approaches for IoT in next generation wireless networks, showing a reduction of energy consumption and environmental impacts while at the same time energy management and scalability become issues in their large-scale deployments.

Table 1. Summary of Reviewed Literature

Sl. No.	Title	Year	Author(s)	Technology Used	Advantages	Disadvantages
1	A Survey on Green Designs for Energy Harvesting Backscatter Communications to Enable Sustainable IoT	2025	Deepak Mishra	Energy harvesting, backscatter communication, IoT	Low power, battery-free operation, sustainable IoT	Limited harvested energy and communication range
2	Research on Future 6G Green Wireless Networks	2025	Research team	Green 6G, AI, cloud, federated learning	Reduces network energy consumption, supports intelligent communication	High system complexity and implementation cost
3	Energy Harvesting Technologies and Applications for the Internet of Things and Wireless Sensor Networks	2024	Slim Naifar et al.	Solar, thermal, vibration and RF energy harvesting	Extends battery life, enables autonomous IoT devices	Energy availability depends on the environment
4	Green Communication in IoT for Enabling Next-Generation Wireless Systems	2024	Sami M. Alenezi et al.	Green IoT, energy-efficient communication, IoT	Reduces energy use and environmental impact	Energy management and scalability are challenging

3. TECHNOLOGY OVERVIEW

3.1 Definitions

Green Electronics is the design and application of electronic products with reduced energy use and reduced environmental impact in production, application and destruction. Sustainable Communication Technology is based on the same principle as communication systems. In this instance, the

goal is to deliver communications without consuming excessive energy, creating waste or pollution, or generating electronic waste. This enables communications networks to grow and takes into account their environmental footprint.

3.2 Key Components

Some of the essential elements that make green electronics and sustainable communication systems possible include:

- Renewable energy sources – clean energy, solar, wind.
- Energy harvesting – gathers usable energy in the environment.
- Low-power communication – decreases the energy consumed in the transmission.
- Energy management systems – control and store energy efficiently.
- Energy-efficient electronic devices – use less energy while operating.
- Environmental issues – minimizes the generation of e-waste.

4. Case Study: GREEN PCB Fabrication via EHD Printing

Printing of printed circuit boards (PCB) at the manufacturing stage is an example of the implementation of these ideas, in the form of green printed circuit board fabrication by electrohydrodynamic (EHD) printing. In conventional PCB manufacturing, unwanted material is removed and in chemical processing, waste is created. Unlike EHD printing, EHD inkjet printing involves depositing conductive material directly into the pattern. The method can also be used with flexible and biodegradable substrates. The following steps are the key steps in the fabrication process:

1. Eco-friendly ink – An eco-friendly special conductive ink is prepared as the printing medium.
2. Preparation of substrates – A flexible base material is used as the substrate, for example, a PVA film.
3. EHD printing – "high voltage" is applied to precisely print the conductive ink.
4. Substrate printing – The substrate is printed with the required pattern.
5. Curing – Low heat applied to make printed path conductive.
6. Green PCB – The process produces a light weight, flexible and eco-friendly printed circuit board.

The whole process, from the conductive ink to the actual PCB, illustrates the simplicity of the additive manufacturing concept: the material is added primarily where it is needed. This can help to minimize material waste and can be a good example to consider more sustainable PCB manufacturing by EHD printing.

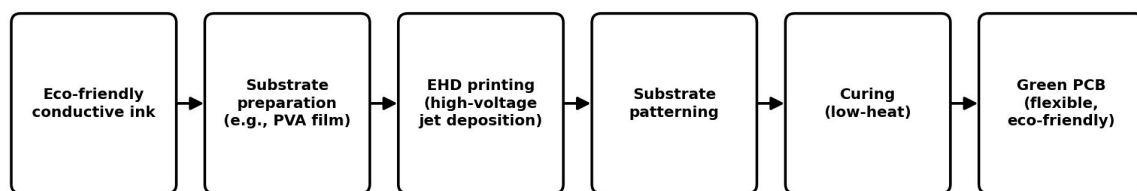


Fig. 1. Block diagram of the green PCB fabrication process via EHD printing.

4.1 Working Principle of EHD Printing

Electrohydrodynamic printing works on the principle of applying a strong electric field between a fine nozzle filled with conductive ink and a grounded collector plate holding the substrate. When the applied voltage exceeds a critical threshold, the electrostatic force overcomes the surface tension of the ink at the nozzle tip, drawing it into a fine, cone-shaped jet known as a Taylor cone. This jet breaks into extremely small, uniformly charged droplets that are pulled towards the substrate under the influence of the electric field. Because the droplet size and deposition path can be controlled electrically

rather than mechanically, EHD printing can achieve micro- and sub-micron scale resolution that is difficult to obtain using conventional inkjet or screen-printing methods, making it particularly suitable for fine-pitch, lightweight circuit patterns.

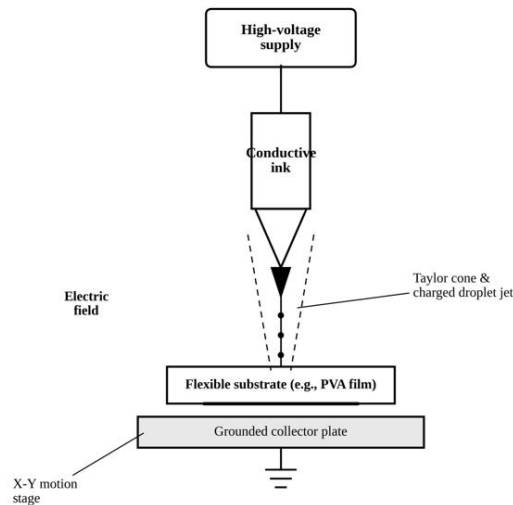


Fig. 2. Schematic of the electrohydrodynamic (EHD) printing setup.

4.2 Materials Used

The choice of materials plays a central role in making this fabrication process environmentally friendly. Conductive inks are typically formulated using silver nanoparticles, copper nanoparticles, or conducting polymers dispersed in low-toxicity solvents, replacing the harsh acids and heavy-metal etchants used in subtractive PCB manufacturing. Flexible and biodegradable substrates such as polyvinyl alcohol (PVA) film, cellulose-based paper, or other biopolymers are preferred over conventional fibreglass-reinforced epoxy laminates (FR-4) because they decompose more readily at the end of the product life cycle and reduce the long-term burden on landfills.

4.3 Comparison with Conventional PCB Manufacturing

Conventional PCB fabrication is largely subtractive: a full sheet of copper-clad laminate is coated, exposed, developed, and then etched using chemicals such as ferric chloride or ammonium persulfate to remove the unwanted copper, generating a significant volume of hazardous liquid waste and consuming copper that is simply discarded. EHD printing, by contrast, is an additive process in which conductive ink is deposited only where the circuit pattern requires it. This eliminates the etching step entirely, reduces water and chemical consumption, lowers material wastage, and shortens the overall fabrication time, since there is no need for masking, developing, or stripping stages. The trade-off is that EHD printing is currently better suited to low-to-medium volume, fine-featured, and flexible circuits rather than the large-scale rigid multilayer boards produced by conventional lamination and etching lines.

4.4 Observed Benefits of the Case Study

- No etching chemicals are required, which removes a major source of hazardous liquid effluent from the manufacturing line.
- Material usage is minimised since conductive ink is deposited only along the circuit pattern rather than removed from a full copper sheet.
- The use of flexible, biodegradable substrates such as PVA film makes the resulting boards lighter and easier to recycle or decompose at end of life compared with rigid FR-4 laminates.
- The low curing temperature used to make the printed traces conductive means less energy is consumed during fabrication compared with high-temperature soldering and lamination steps in conventional PCB production.

4.5 Challenges in EHD-Based Green PCB Fabrication

Despite its advantages, this fabrication route still faces certain practical challenges. Maintaining a stable Taylor cone and consistent droplet formation requires careful control of ink viscosity, surface tension, applied voltage, and nozzle-to-substrate distance, and small variations in any of these parameters can affect print resolution and repeatability. The conductivity of printed traces immediately after deposition is generally lower than that of solid copper, so an additional curing or sintering step is required, and this step must be carefully optimised so that it works with heat-sensitive biodegradable substrates. Throughput is also comparatively low relative to high-speed roll-to-roll copper etching lines, which currently limits EHD

printing to prototyping, flexible electronics, and other niche, low-to-medium volume applications rather than mass production of conventional rigid PCBs.

5. APPLICATIONS

A variety of electronic and communication systems can be used in the implementation of these ideas. These are some of the important areas:

- Green IoT and smart homes
- Electric vehicles
- Renewable energy systems
- Energy-efficient 5G/6G networks
- Smart grids

6. ADVANTAGES AND LIMITATIONS

6.1 Advantages

- Minimizes energy use
- Reduces electronic waste
- Reduces environmental pollution
- Saves operating cost
- Improves battery life
- Supports renewable energy integration

6.2 Limitations

- High initial implementation cost
- Limited energy availability from ambient sources
- Increased technological complexity
- Limited performance under certain operating conditions
- Ongoing maintenance requirements
- Challenges in recycling specialized materials

7. FUTURE SCOPE

These technologies are still under development and can be further improved. Future research can focus on enhancing the energy efficiency and sustainability of electronic devices and communication systems. Examples of possible areas are:

- Manufacture of electronic devices with low power consumption. Production of low-power electronic devices.
- Rising share of renewable energy supply Raising the proportion of renewable energy supply
- The rise in the development of Green IoT and smart gadgets. Expansion of Green IoT and smart devices.
- The development of energy efficient 6G networks. The development of 6G energy efficient networks.
- Improved e-waste recycling processes

8. CONCLUSION

The combination of green electronics and sustainable communication technologies is one of the greatest challenges of the digital age, where technology is going through rapid growth and environmental awareness is gaining importance. The strategies promote low power and low energy use and thus lower energy consumption, plus promoting recycling, reuse, and the use of more environmentally-friendly materials helps lower electronic waste. The

use of sustainable communication systems further optimises energy consumption by transmitting power in an energy-efficient manner, and the incorporation of renewable energy including solar and wind energy provides a viable solution to power electronic devices in an environmentally responsible way. These technologies have the potential of lowering pollution, saving natural resources, decreasing operating costs, and increasing the lifespan of devices when used together. In conclusion, green electronics and sustainable communication are crucial components in creating a sustainable and efficient technological future.

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