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Sustainable VLSI Design: Green Electronics for Energy Conscious Systems

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Abstract

Years have passed by and we have gone into an age of technology where electronic devices are being integrated in our daily lives. Smartphones to smart homes, these gadgets traverse the globe and have revolutionized the way we interact with each other as well as work and move in our lives. However, there comes a very large environmental cost to that boom. Because of the growing of electronic devices, energy consumption and electronic waste is a problem that we have no more to be without dealing with with something you cannot get rid of. In view of an atmosphere full of issues in a crowd, the very large scale integration (VLSI) design is moved towards green produce. This shift is not a by product of a trend but a necessity as electronics industry finally realises its environmental impact. The state of the art is research and development of the sustainable VLSI design — the energy efficient and environmental friendly electronic systems. Finally, in this article, the world of sustainable VLSI design is explored as it studies a specific aspect of green electronics and its role in shaping the path of energy conscious systems. We will take a look at the state of the art advancements and improvements, the challenges and possible solutions to the aforementioned dilemma of figuring out the correct balance of the advancement of this very fast moving industry and environmental stewardship.

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Environmental Impact of Electronics

The same holds true for the electronics industry, as are its considerable and diversified environmental footprint. These are such globally important carbon emissions and waste generation, including from application energy consumption on the one hand during use and, on the other hand, emissions and waste generation of these components from the manufacture and disposal processes.[1-2]

Electronic Manufacturing Carbon Footprint

Nowadays the manufacturing of electronic components especially integrated circuits and printed boards is an energy intensive process, the demand for chemicals in such industry contributed largely to the cost. These manufacturing steps are greenhouse gas emission and the source of resources depletion. To give you an example, around summer, a single smartphone actually contributes the same carbon dioxide as driving a car for the same number of miles from one to another. In the electronic device life cycle, after the device is transitioned into the hands of consumers, both demand for the movement to driving processes and subsequently reduction in negative environmental impacts through energy consumption persist. Data center is particularly energy hungry and form our digital backbone, so we really need to work on them. According to new studies, if things go on as they are now, information and communication technology (ICT) could be the cause for more than 20 percent of the electricity demand worldwide by 2030.[3]

Electronic Waste Crisis

Many electronic waste have been created by shorter product life cycles, as product lifetime has become shortened through rapid technological advancement. If taken carelessly, the hazardous substances in e waste can seep into soil and water systems jeopardising our health and the environment to a great risk. In addition, the recovered value of metals and rare earths in discarded electronics remains relatively inestimable and is wasted. Cumulatively, these factors play a great role in global climate change. As the demand for electronic devices has been on the rise alongside the emergence of internet of things (IoT), so has the need for viable solution to sustain its existence. A set of principles of sustainable design of VLSI based on tradeoffs between the environment impact and high performance and ef iency are proposed. This principles extend from material selection to power management strategies, as shown in the mentioned steps.[4]

Energy Efficiency at the Core

Sustainable VLSI design is based on energy efficiency. Circuits and systems to develop at much lower power, operating the way they're supposed to, are the thing. In energy saving, as long as the performance degradates, dynamic voltage and frequency scaling, clock and power gating are used to save energy. In sustainable VLSI design, environmentally friendly materials shall be chosen. The printed circuit boards (boards) also use substrates which are biodegradable or recyclable, lead free solder, and the use of rare earth elements. The are also looking at alternative materials that perform as, or even better, at a greatly reduced environmental toxicity. More concretely, Sustainable VLSI design is the sort of product creation that lasts longer. In short, the hardware is powerful, components are stronger, your hardware... is designed in modules, so you can upgrade it, easily repair your design, with software that works across a multitude of generations of hardware (Figure 1).[5]

Manufacturing Processes Optimization

A second crucial rule is to minimize manufacturing waste and energy usage. From the most fundamental literature unit, chip layout optimization to reduce waste on silicon wafers, to more advanced techniques such as more efficient use of fab equipment through layout optimization, to the use of renewable energy to power fab facilities. Ineffective thermal management impacts the energy efficiency as well as the product longevity. These sustainable VLSI designs incorporate advanced cooling solutions as well as thermal aware circuit layouts to lower heat generation and heat dissipation. The energy efficiency has become a sought after in VLSI design that prompted plenty of innovations leading to large reduction in power consumption without loss in performance. They are literally very important for the development of sustainable electronic systems. Power gating has not been solely on off switching only. Modern VLSI designs

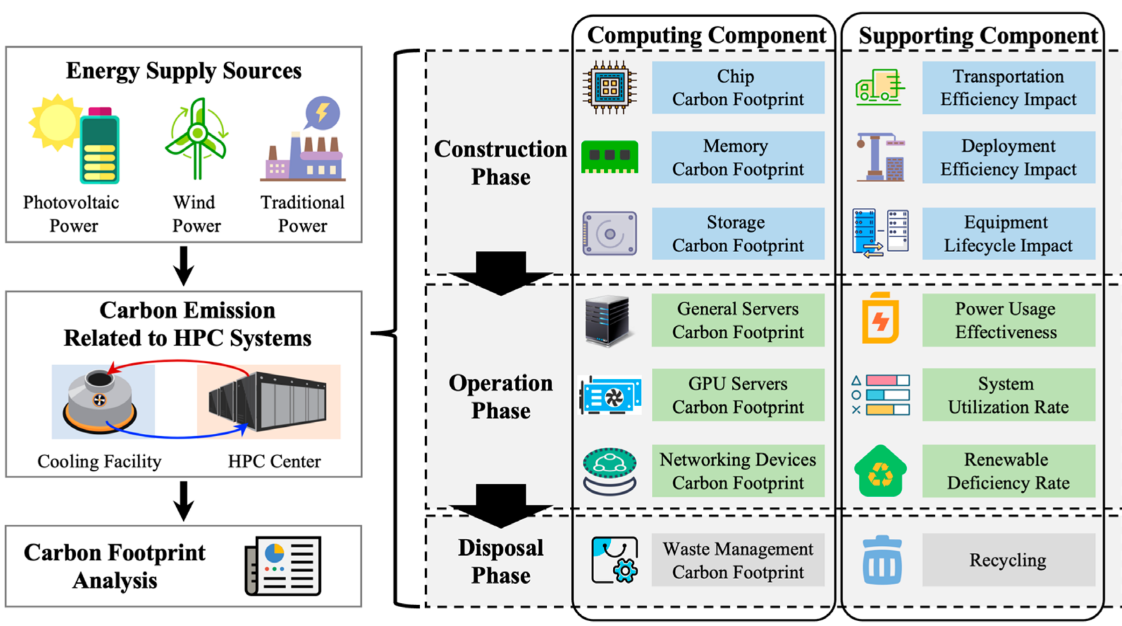


Fig. 1

are a gratified application of power gating where entire blocks of circuit are selectively turned off down to as small as a block of gates. For the rapidly wake up times for the critical components, the best power savings is offered by the fine controlled approach.[6-7]

Dynamic Voltage and Frequency Scaling (DVFS)

But over the past few years DVFS has become a sophisticated affair — either driven by AI and with pointers to algorithms for workload volume and adjust on the fly voltage and frequency. The system is always running at the most energy efficient point for the given task by using this predictive scaling (Table 1).

Near-Threshold Computing

One obvious way to reduce power consumption in an operating transistor is to operate it at or close to its threshold voltage. Nevertheless, while the work is done to solve the aforementioned performance and reliability issues, near threshold computing is considered for some low power applications. Notorious energy consumers are semiconductor fabrication cleanrooms. However, new technologies have come into play to reduce the footprint of these facilities as well, such as energy efficient air handling systems, advanced filtration methods and smart lighting. What causes foot to chip is water usage. New systems are designed and developed at the miniaturized level that recycle water and dry etch for the reduction of the water consumption and generated water waste.[8-9]

VLSI manufacturing Renewable Energy

In fact, the semiconductor companies are starting to phase out the regimen of using traditional energy source for power of their manufacturing facilities and are starting to make use of renewable energy source as their sources of power. Factory designs that decrease depending on fossil fuels, including solar panels, wind turbines, and geothermal systems, are being developed, all of which are in experiments. Advanced process control systems are used for the VLSI manufacturing to achieve the reduction of waste and increase the material usage. Additionally, new recycling technologies are being developed to recover materials of value from manufacturing byproducts and their end of life electronic components.[10]

Semiconductor Processing Green Chemistry

Attempts are being made to find alternatives which would minimize the damage that chemical processes used in semiconductor industry have caused to the environment. Included 0are chemical recycling systems and supercritical CO_2 cleaning as well as bio based photoresists (Figure 3).

Energy Efficient Circuit Design Techniques

The other pillar of sustainable VLSI design is energy efficient circuits, and the latter is really at the core of sustainable VSLI design. These techniques focus on minimizing power consumption at all levels of the design hierarchy including single transistors, and complex system on chip architectures. Extreme low power consumption is obtained by operating transistors in subthreshold regions with the drawback of reduced speed. This is especially useful for these IoT devices and sensors where battery life is a precious king beyond performance.

Table 1: Challenges in Sustainable VLSI Design

Sustainability Challenge	Environmental Concern	Mitigation Priority
High Power Consumption	Increased carbon footprint and energy usage in electronics.	Develop low-power design strategies.
E-Waste Generation	Rapid accumulation of obsolete semiconductor devices.	Design for recyclability and reuse.
Toxic Material Usage	Use of hazardous substances harmful to the environment and health.	Adopt environmentally friendly materials.
Short Product Lifecycles	Frequent hardware upgrades leading to resource depletion.	Implement modular and upgradable architectures.
Thermal Management Issues	Excess heat reduces energy efficiency and device reliability.	Enhance cooling mechanisms and thermal-aware designs.

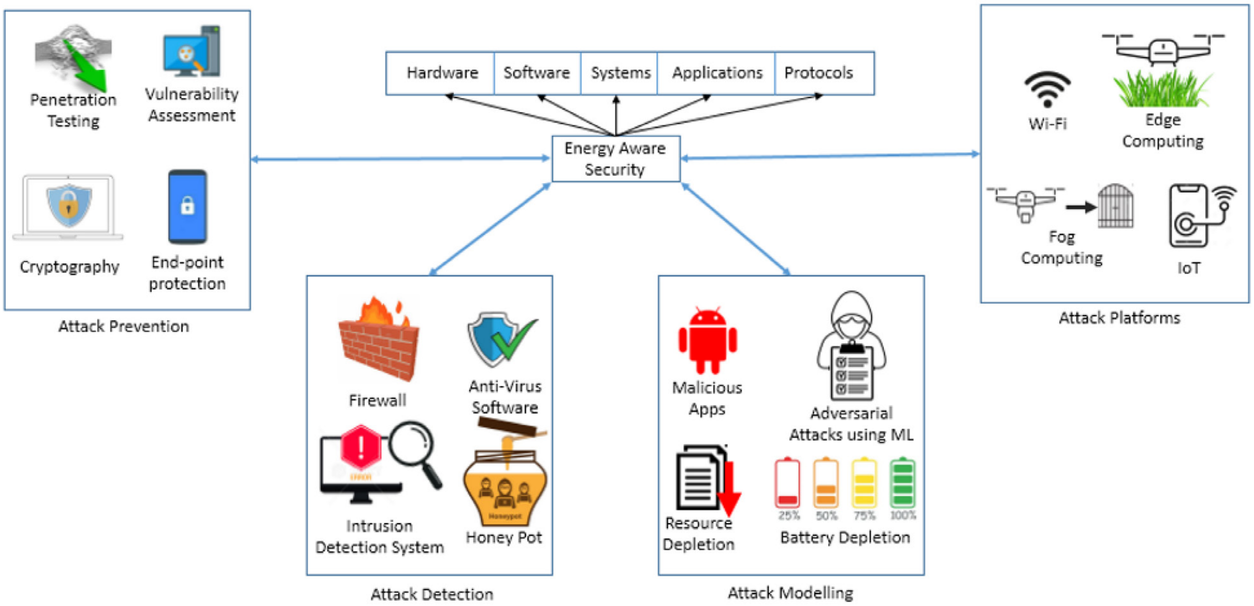


Fig. 3.

Clock and Power Domain Partitioning

Clock and power domains can be divided into several fine grained power domains to allow implement fine grained power management. This performs much better, in overall terms, by selecting the items to enable to be activated on, only when they are needed. Power consumption is dominated by leakage current because the transistor size shrinks. In order to deal with the problem above, advanced techniques, like body biasing, high k dielectrics and multi-threshold CMOS (MTCMOS) are used. This can free up power for realizing substantial power savings in the physical layout of circuits. With respect to energy, placement and routing algorithms have been energy aware, i.e., the wire length and switching activity are considered, and power dissipation in interconnects are reduced .[11]

Savings in power are possible through such asynchronous or clockless circuits, which avoid a global clock signal. All of these designs are inherently event driven and would consume power only when the data are actively processing. In general, VLSI chips succeed by the packaging of the chips. Newer packaging solutions such as thermal management to feed in better material waste and house electronic package components with a better recycle, can be provided. New thermal interface materials, graphene based compounds and phase change materials are being developed to enhance the heat dissipation of the chips. Improving the energy efficiency and reliability of electronic devices, the materials are also very useful.

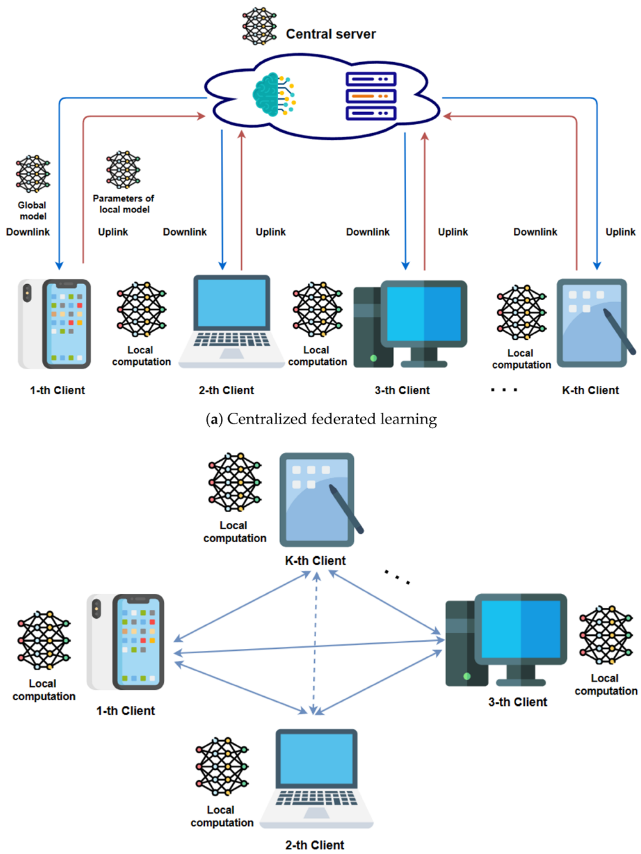
Recyclable and biodegradable Packaging

Biodegradable polymers and recyclable metals for chip packaging are being worked on. These materials are used toward reduction of the environmental impact of electronic waste while keeping semiconductive components protected. More compact, economical chip designs are possible using current technologies (e.g., via silicons and interposer via integrated technologies). Performs and consumes power in such a manner in a smaller form factor is a requirement.

It offers more efficient packaging and reduced cost comparison to fanout wafer level packaging (FOWLP). By using this technique, the amount of material used is considerably reduced, which offers better passive component integration and a better overall system efficiency. By combining sensors directly in the packaging of the chip, real time temperature, humidity etc. sensing becomes possible. Additionally, it can be of use for finer power management and electronic device lifespan (Figure 4).[12]

Energy Harvesting and Self Powered Systems

The field of sustainable VLSI design that includes energy harvesting has been experiencing incredible growth as a potential selfpowered, nonpowered electronic systems that are capable of working untethered for an indefinite time with no power. The technology of thin film solar cell is mature enough to provide photovoltaic components that can be integrated directly onto VLSI chips. This can be used to power devices with ambient



(a) Centralized federated learning

(b) Decentralized federated learning

Fig. 4.

light, either adding to or replacing always on battery power in some cases.[13]

Thermoelectric energy harvesting

They (thermoelectric generators) can convert temperature differential into electricity. Owing to their application to recovering waste heat from chips, these devices can be used to drive other auxiliary circuits or sensors in VLSI design.

Piezoelectric Energy Scavenging for Vibration Communication

The piezoelectric property is a property of a material that produces electricity when it is mechanically forced. These materials would be much to the interest of the VLSI designer as they are also been studied for use on chip packages to harvest energy from vibrations or motion in the environment. Radio frequency (RF) energy harvesting techniques are being developed for powering low energy IoT devices. These systems are capable of capturing ambient RF signals and providing power to small electronic devices from wireless networks, cell networks, or dedicated transmitters, in a continuous power mode.

Hybrid Energy Harvesting Systems

This energy harvesting convergence, however, combines multiple energy harvesting technologies in a way that can offer a more reliable and efficient power source for VLSI systems. Continuous operation in varying environments is needed by some future applications and these are being developed as hybrid systems of solar, thermal and vibrational energy harvesting. In addressing the challenges and opportunities for sustainable VLSI design coming from the proliferation of Internet of Things (IoT) devices and the rise of edge computing, temporal properties become central. Ultra low power consumption and reliable long term operation in harsh environmental conditions are typical for these systems.

Sensors and Actuators of Ultra-Low Power

We need sensors and actuators that can work on minimal power for sustainable IoT deployment. MEMS technology and low power CMOS design are now enabling the construction of sensors that can run for years on a battery, or even extract energy from their environment. A significant percentage of the energy burden on an IoT device is spent in communicating. The focus of sustainable VLSI design for IoT is on the integration of communication protocols that are energy efficient and the optimization of radio frequency (RF) circuits to mitigate the power consumption in transmitting information (Table 2).[14-15]

Table 2: Green Techniques in VLSI Design

Green Technique	Implementation Focus
Dynamic Voltage and Frequency Scaling (DVFS)	Adjust voltage and frequency based on workload to reduce power usage.
Use of Biodegradable Substrates	Replace traditional substrates with biodegradable alternatives.
Clock Gating and Power Gating	Switch off idle circuits to conserve power.
Energy-Efficient Logic Design	Design logic gates and circuits with minimal energy loss.
Reconfigurable Architecture Integration	Incorporate flexible architecture to reduce waste and prolong life.

Edge Intelligent Power Management

Sophisticated power management is necessary for edge computing devices that need to perform balanced power and energy efficiency. AI driven power management systems that are a part of edge computing platform are already integrated to adjust to changing workloads and environmental conditions. With such scale of IoT deployments, supplies must remain sustainable. In the world of impacting the environment with billions of connected devices, biodegradable sensors, recyclable packaging and eco friendly printed circuit boards are new frontiers. How to extend the life of an IoT device? It features use of robust components, over the air updates and modular systems that will make easy repair and upgrade possible.[16-25]

Sustainable VLSI Design Challenges and Future Directions

Despite a large amount of progress, there are many unsolved problems in sustainable VLSI design. Such issues play an important role in green electronics and in energy conscious systems.

The Performance and Sustainability Balance.

One of the major challenges in sustainable VLSI design is to satisfy or at least maintain and bring, in case of deterioration, the performances demanded by the consumers at the same time. That is because as applications become more demanding, the methods of power efficiency optimization will become ever more important, but will need to survive without sacrificing functionality. A lot of work still remains to be done, but sustainable practices being implemented at scale. For this reason, the industry needs to develop standardized methodologies and tools that are easily plug into existing design workflows to achieve sustainable VLSI design as the norm rather than the exception.[26-28]

The environmental footprint of the electronic device is contributed greatly by the embodied energy (before expended) of the energy used to manufacture the electronic device. Embodied energy could be heavily reduced in future research in more efficient manufacturing processes and in the material choices.[29-33]

Recyclability and Circular Design Enhancement

In order to reduce the e waste, electronic components should be made more recylable ad adopt circular design principles. They include new materials and new design methodologies that foster facile disassembly and return of resources. In order for designers to be able to make decisions when considering the environmental impact of the design, EDA tools will have to incorporate sustainability metrics. It further seems to require development of some standardized way for assessing and quantifying the sustainability of VLSI systems.

Conclusion

Green electronics and energy conscious systems, in general, is a critical frontier in sustainable VLSI design. These are tremendous challenges, but the opportunity to do great things by improving the environment are huge as we've discussed throughout this article. This field comprises of evolving advanced low power circuit techniques to green manufacturing process and energy harvester solutions for the benefit of the future more sustainable world. For the journey we take in getting to truly sustainable electronics making sure that everything that has to do with the lifecycle of the product is taken into consideration from the very design, production, use and finally recycling. Pulled together by an eclectic collection of electrical engineering, materials science, environmental studies, and policy making, a solution involves putting together a gears of many different types. There is an increasing need for principles of sustainable VLSI design in a technology landscape looking into the future. By continuing to expand the boundries of our energy efficiency while closing the gap of materials and manufacturing, combining Sustainability into every step of the electronic design process we can create a world where Technological growth and environmental protection become one in the same. So the path forward is clear; for the Electronics industry, the seemingly simple change of sustainable VLSI design, is not an option, it is a necessity. If these principles were to be adopted and further innovated for, this is the future to build the digital revolution on green principles for the generations to come.

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