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Cradle-to-gate life cycle assessment of nano-enabled all-carbon recyclable electronic (ACRE) materials

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The fabrication of semiconductor devices, particularly those used in flat-panel displays, is one of the significant climate-change challenges identified by the US Environmental Protection Agency (EPA) due to the associated greenhouse gas emissions. This study investigates the potential of all-carbon recyclable electronic (ACRE) materials as an innovative, eco-friendly alternative to conventional semiconductor materials in thin-film transistor (TFT) production. Using ink-processable materials such as crystalline nanocellulose (CNC), carbon nanotubes (CNT), and graphene, reduced greenhouse gas (GHG) emissions and enhanced material recyclability, can be realized. A cradle-to-gate Life Cycle Assessment (LCA) was conducted to evaluate the environmental performance of ACRE-based TFTs compared to conventional transistors across six scenarios that include different CNT production methods. The results demonstrate the baseline ACRE scenario consistently achieves the lowest environmental impact, with the High-Pressure Carbon Monoxide (HiPco) method emerging as the most sustainable production approach. Although the Ink contributes only minimally to the final product—given its very small mass relative to the total glass weight—HiPco still performs better than the Arc and CVD methods by approximately 0.1% and 0.2%, respectively. However, key challenges remain, including the energy-intensive nature of material synthesis and the environmental impacts associated with the glass substrate and ink preparation processes. The findings underscore the importance of targeted material processing and substrate production improvements to reduce environmental burdens further. Indeed, CNTs, CNC, and graphene, which are the base materials for printing the transistor on glass, contribute more than 40% to the total impact in multiple environmental categories. Moreover, the study highlights the need for a holistic approach to TFT design and manufacturing, integrating energy efficiency and sustainable material selection. The sensitivity analysis shows how a ±50% change in energy consumption can influence the environmental impact, particularly for the ionizing radiation and land use categories, which exhibit sensitivities of approximately 30% and 25%, respectively. Future work could expand this analysis by conducting a cradle-to-grave LCA to assess the impacts of the entire life cycle, as use and end-of-life stages. This research establishes a foundation for advancing ACRE technologies and underscores their potential to mitigate the challenges posed by e-waste, paving the way for more sustainable practices in the electronics sector.

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Sustainability spotlight

This innovative study explores all-carbon recyclable electronic (ACRE) materials—CNC, CNT, and graphene—as sustainable alternatives to conventional semiconductors in thin-film transistor (TFT) production. It contributes to SDG 9 by promoting sustainable industrialization through low-impact, ink-processable electronics. Since TFTs are essential to devices like phones, TVs, and displays, the work supports SDG 11 by enabling cleaner technologies in urban infrastructure. The full recyclability of ACRE materials aligns with SDG 12, fostering responsible production and reducing electronic waste. Finally, the potential to lower greenhouse gas emissions directly supports SDG 13, advancing climate action through eco-friendly material innovation.

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1. Introduction

The urgent need to significantly reduce greenhouse gas (GHG) emissions by 2030 to limit global temperature rise to below 1.5 °C this century was emphasized in the United Nations Environment Programme (UNEP) Emissions Gap Report published in

October 2021.[1] The report underscored the critical importance of addressing various sources of GHG emissions to mitigate the impacts of climate change. One of the significant challenges to climate change identified by the US Environmental Protection Agency (EPA) is the emission of greenhouse gases during the fabrication of semiconductor devices, particularly flat-panel displays. In modern displays, the control circuitry—collectively referred to as the display backplane—is typically formed by TFTs that employ low-temperature polycrystalline silicon (LTPS) or metal oxides such as indium gallium zinc oxide (IGZO) as the semiconductor channel.[2] However, these materials present several drawbacks, including a substantial environmental burden associated with their fabrication.[3–5] The fabrication of these components involves using various acidic and basic solutions, organic solvents, and toxic gases, releasing significant pollutants, wastewater, and waste gases.[6] Additionally, the manufacturing processes of silicon- or metal oxide-based semiconductor materials for devices like flat-panel displays release high levels of greenhouse gases (GHGs) into the atmosphere.[7] In particular, semiconductor fabrication relies on a wide range of fluorinated gases with extremely high global warming potential (GWP). These gases are used to etch intricate circuitry patterns on silicon wafers and to clean chemical vapor deposition (CVD) chambers. Common examples include perfluorocarbons (*e.g.*, CF_4, C_2F_6, C_3F_8, c-C_4F_8), hydrofluorocarbons (CHF_3, CH_3F, CH_2F_2), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6). The industry also employs fluorinated heat-transfer fluids and nitrous oxide (N_2O), all of which significantly contribute to the sector's GHG emissions.[7] Further, the semiconductor industry makes up 1.3–2.0% of the overall electricity usage in the manufacturing sector in the US.[8] The energy-intensive manufacturing processes for electronic components contribute to greenhouse gas emissions.[9] This results in direct carbon dioxide emissions and other greenhouse gases and indirectly contributes to climate change by increasing the demand for energy resources. Besides GHGs, these displays produce electronic waste (e-waste) as well.

E-waste is a rapidly growing global issue, significantly contributing to environmental pollution. It is also among the fastest-expanding categories of waste worldwide.[4,10] In 2019, global e-waste production reached 53.6 million metric tonnes (Mt), representing an increase of 9.2 Mt since 2014.[11] Among the regions, Asia was the largest contributor, generating 24.9 Mt, while the Americas accounted for 13.1 Mt of the total e-waste.[12] Projections suggest that, by 2030, this figure will surpass 74.7 Mt.[13] This poses severe environmental and health risks, as hazardous substances from e-waste can leach into soil and water,[14] contaminating ecosystems and endangering human health.[15] Recycling, recovery, and disposal are key challenges in e-waste management. Globally, only a minute fraction (approximately 20–30%) of e-waste is recycled.[13]

Hazardous substances usage in the electronics industry, such as lead, bromine-based fire retardants, and volatile organic compounds, pose significant risks during production, use, and disposal.[16] The extraction of rare earth minerals, essential for many electronic devices, often involves environmentally destructive methods.[17] Rare earth minerals, such as neodymium, dysprosium, and terbium, are critical components in the manufacture of electronic devices, including smartphones, laptops, and flat-panel displays.[18] The extraction process for these minerals typically involves open-pit mining, which can lead to habitat destruction, soil erosion, and water pollution.[19] Moreover, refining rare earth minerals generates substantial amounts of toxic waste, posing additional workers' safety issues.[20]

Addressing these challenges requires improved collection systems, consumer awareness, and sustainable practices throughout the electronics industry. One promising solution is the development of innovative materials for electronics that can reduce the ecological and health impacts of e-waste. One such innovation is the development of all-carbon recyclable electronic (ACRE) materials,[21] which have the potential to revolutionize the manufacturing of semiconductor components and reduce associated emissions. ACRE materials, such as crystalline nanocellulose (CNC), carbon nanotubes (CNTs), and graphene, can be used to replace traditional silicon- or metal-oxide-based materials for thin-film electronics. Semiconducting carbon nanotubes (CNTs) and conductive graphene have been extensively investigated as key materials for printed electronics,[21,22] while the work of Williams *et al.* showcase the development of ACRE created using a crystalline nanocellulose (CNC) dielectric ink, that is printable at room temperature and with compatible CNT and graphene inks.

Franklin *et al.*, Doherty *et al.*, Cao *et al.*, and Williams *et al.* have showcased the creation of carbon-based thin-film transistors (TFTs) as a viable substitute for traditional thin-film electronics reliant on rare-earth elements and silicon.[3,21,23,24] Their research highlights sustainable fabrication techniques and performance enhancement, demonstrating that fully printed, flexible CNT-TFTs exhibit low threshold voltage, minimal hysteresis, and durability through over 1000 bending cycles,[25] making them promising for wearable electronic applications.

Given the recent emergence of ACRE TFTs, the availability of life cycle assessment (LCA) data for this transistor type is still limited. This study aims to compare cradle-to-gate life cycle assessment (LCA) of ACRE thin-film transistors (TFTs) compared to classic TFTs used in liquid crystal displays (LCDs). A classic transistor is considered a transistor already available on the market. The most common type of TFT is the amorphous silicon TFT, which is used in applications such as LCDs. By comparing the environmental impacts of these products, this research seeks to understand the potential benefits of switching to ACRE materials, particularly in reducing GHG emissions and mitigating climate change.

2. Materials and methods

2.1. Life cycle assessment (LCA) methodology (ISO 14040, 2021)

LCA is a standardized scientific method for systematically analyzing flows (*e.g.*, mass and energy) associated with the life cycle of a specified product, technology, service or manufacturing process.[26] This method is employed across diverse industrial and research sectors to evaluate environmental impacts throughout a product's entire life cycle. LCA enables the assessment of impacts from raw material extraction, production, use, and end-of-life disposal, introducing the concept of cradle-to-grave assessment.[27] LCA provides a Framework to evaluate the interactions between a product's environmental impact and its effects on Human Health, Resource Depletion, and Ecosystem Quality, referred to as Endpoint categories. The methodological foundations for conducting these assessments were established in the 1990s and standardized according to ISO 14040–14044 norms.[28] ISO 14040 and 14044 define four phases of an LCA, Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation of Results. Goal and Scope Definition phase involves describing the problem, defining objectives, and outlining the scope of the investigation. It includes defining the functional unit, system boundaries, data availability, assumptions, and methodology limitations. The Functional Unit is a standardized measure that aligns with the study's goals and scope, facilitating the organization and presentation of LCA data. It is a reference point for connecting energy and material flows and enables comparisons between LCA studies. System boundaries define the scope by specifying which processes and stages of the product's life cycle are included and excluded. There are several system boundaries used in LCA, and each one offers a unique perspective on environmental impact and can be chosen based on the specific goals of the analysis or the information available at the time of the study. Every system boundary allows for exact analysis of different stages in a product's life cycle. Cradle-to-grave approach covers the entire life cycle from resource extraction to end-of-life, offering a complete view of overall impacts. Cradle-to-gate limits the analysis to processes up to the factory gate, excluding use and disposal, and is often applied when downstream data are unavailable. Cradle-to-cradle follows the same logic as cradle-to-grave but replaces disposal with recycling, aiming to close material loops. Finally, a gate-to-gate boundary focuses on a single production stage, with results that can be combined to build a broader assessment.

Representativeness of data refers to the ability of inventory data to accurately describe the emissions and environmental impacts of the system being modeled. Achieving good representativeness is especially crucial for significant processes. Assumptions and limitations are necessary when there is missing information. Documenting the reasoning behind these decisions helps the audience understand the results more comprehensively. Clearly defining the objectives and scope is crucial to prevent misinterpretation of results. Life Cycle Inventory (LCI) involves measuring the inputs and outputs of mass and energy flows per functional unit along the product value chain. Data collection and system modeling must align with defined objectives. LCI results are crucial input for the Life Cycle Impact Assessment (LCIA) phase. Life Cycle Impact Assessment (LCIA) phase Identifies and quantifies potential impacts of a product or process. Various impact assessment methods have implications on human health, ecosystem quality, climate change, and resource depletion. LCIA translates LCI results into potential environmental impacts using characterization factors. Methods may focus on midpoint categories (*e.g.*, IPCC, EDIP 2003) or both midpoint and endpoint categories (*e.g.*, IMPACT 2002+ and ReCipe).

Finally, interpretation of results phase involves evaluating Life Cycle Impact Assessment (LCIA) results, identifying relevant issues, drawing conclusions, and formulating recommendations.

2.2. LCA software, database and method

The LCA was conducted using the software SimaPro, developed by PRé Consultants (Product Ecology Consultants) in the Netherlands. SimaPro was chosen due to its status as one of the most widely utilized LCA software, offering significant flexibility and a wide array of features. This professional tool collects, analyzes, and monitors sustainability performance data for a company's products and services. Additionally, it incorporates the most recent version of the leading life cycle inventory data source, Ecoinvent Version 3.12. The Ecoinvent database contains comprehensive international industrial life cycle inventory data covering energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management, and transport services. It adheres to ISO 14040 and 14044 standards for LCA studies and assessments, ensuring transparency and consistency. To evaluate the environmental impacts, the ReCiPe method was applied using the hierarchist perspective, which represents a balanced view based on widely accepted scientific assumptions. This method facilitates the interpretation of emissions, resource consumption, and other outputs generated from the Life Cycle Inventory (LCI).[29]

3. Results

3.1. Goal and scope

3.1.1 Case study. The material under assessment is an all-carbon recyclable electronic (ACRE) thin-film transistor (TFT). A transistor is a semiconductor device that manages the flow of current or voltage while also amplifying and producing electrical signals. Additionally, it functions as a switch or gate to control these signals.[30] Classic and state-of-the-art TFTs are composed of components made from silicon- or metal-oxide-based semiconductor materials, such as amorphous silicon (a-Si), low-temperature polysilicon (LTPS), and indium gallium zinc oxide (IGZO). However, as highlighted in the introduction, the manufacturing processes for these materials are associated with significant greenhouse gas (GHG) emissions, among other environmental impacts. ACRE transistor components are suspensions (or inks) of electronic nanomaterials such as CNTs, crystalline nanocellulose (CNC) and graphene. Carbon nanotubes are carbon-based, tube-shaped materials with diameters measured on a nanometer scale.[31] They can be conceptualized as rolled-up graphene sheets, resembling a continuously rolled hexagonal mesh structure with carbon atoms positioned at the vertices of these hexagons. Crystalline nanocellulose (CNCs), on the other hand, are needle-like nanometric particles derived from cellulose. They exhibit a highly crystalline structure, with

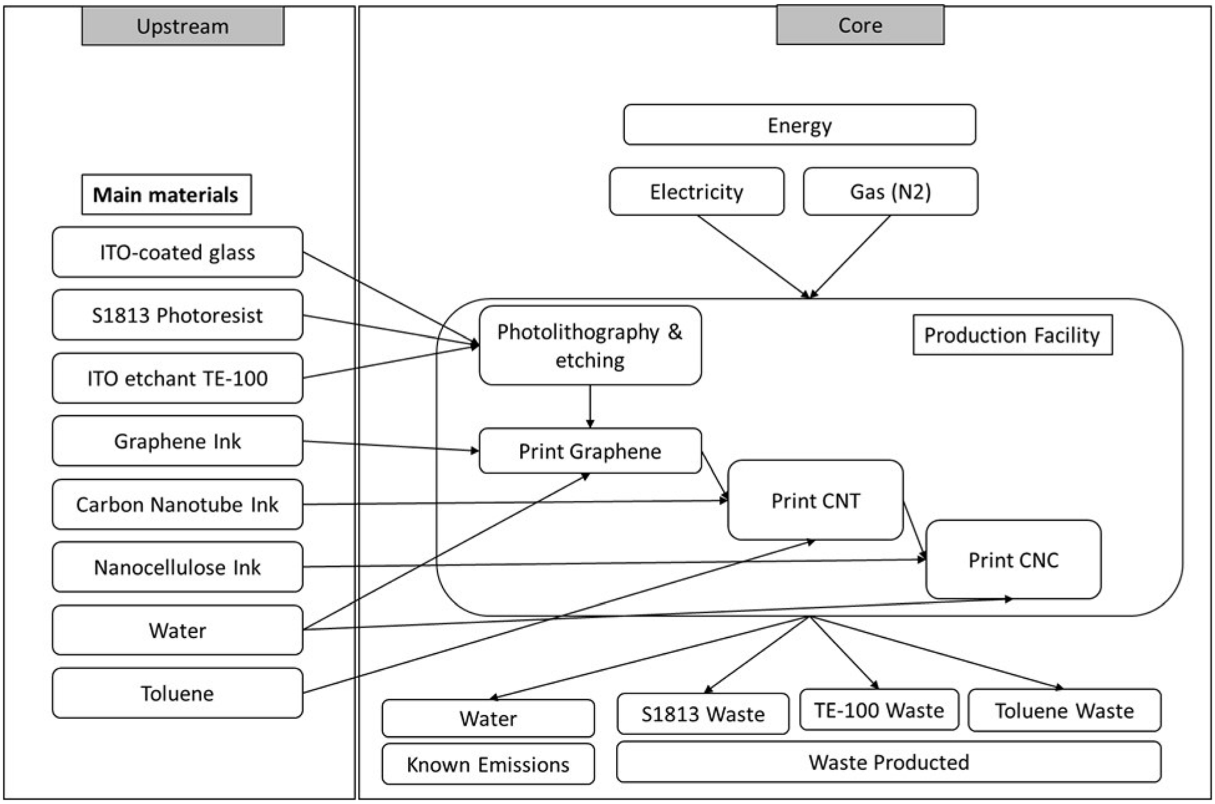


Fig. 1 Upstream and core of the ACRE TFT.

at least one dimension less than 100 nanometers.[32] Graphene consists of a single layer of carbon atoms arranged in a hexagonal lattice.[33] This remarkable material is distinguished by its exceptional mechanical strength, as well as its outstanding thermal and electrical properties.[34] These carbon-based materials—CNTs, CNC, and graphene—offer unique properties that make them suitable for advanced applications in electronics. The benchmark considered in this study is a standard transistor. Further details about the benchmark are provided in Section 3.2: Life cycle inventory.

3.1.2 Goal and scope definition. The goal of the cradle-to-gate LCA was to minimize the environmental impacts of an ACRE thin-film transistor (TFT). The functional unit (FU) selected was the production of 1 transistor, used as a simple and easily interpretable reference unit. In this study, the FU does not imply any specific performance requirement: it represents one manufactured transistor regardless of its electrical characteristics. This choice was made to facilitate a clear comparison between the ACRE TFT and the benchmark, focusing solely on the environmental burdens associated with production. In the study, the impacts of the use and the end of life are not considered since a cradle-to-gate assessment is carried out. Data for the benchmark comes from LCA database processes and literature review. In the following paragraphs, we describe the system boundaries of the ACRE TFT and the benchmark.

3.1.3 ACRE TFT. Based on information obtained from professionals developing the innovative transistor, the product system for the ACRE TFT was modelled using the SimaPro software. The diagram of the system under assessment is illustrated in Fig. 1.

The LCA study considers the environmental impacts related to the Upstream and Core of 1 ACRE TFT. As shown in Fig. 1, the primary materials are purchased and transported to the University developing the ACRE TFTs, where the manufacturing core process of the ACRE TFT takes place.

3.1.4 Benchmark. For the LCA of the benchmark, the production of a classic transistor is considered. Data from the Ecoinvent database served as the primary reference for developing the benchmark. Since a cradle-to-gate LCA is carried out, only the process of producing a classic transistor is considered.

3.2. Life cycle inventory

3.2.1 ACRE TFT. For the LCA of the ACRE TFT, primary data was collected in 2023 through questionnaires filled in by university researchers developing the ACRE TFTs. However, some assumptions have been made since the final product is still in the design phase and currently lies between TRL 3 and TRL 4. Indeed, complete data will be available when the product is at a higher Technology Readiness Level (TRL). In producing ACRE TFTs, three distinct types of inks are utilized: one based on carbon nanotubes (CNT), one incorporating graphene, and one using crystalline nanocellulose (CNC). The production of CNTs can be achieved through three methods: Arc discharge, Chemical Vapor Deposition (CVD), and High-Pressure Carbon

Table 1 Overview of the six LCA scenarios for ACRE TFT production, combining two material- and energy-allocation approaches (divided-by-four *vs.* full energy for one device) with three CNT production routes (Arc discharge, CVD, and HiPco)

1 ACRE TFT					
1	2	3	4	5	6
Graphene	Graphene	Graphene	Graphene	Graphene	Graphene
CNT (Arc)	CNT (HiPco)	CNT (CVD)	CNT (Arc)	CNT (HiPco)	CNT (CVD)
CNC	CNC	CNC	CNC	CNC	CNC
Energy to print 1	Energy to print 1	Energy to print 1	Energy to print 4	Energy to print 4	Energy to print 4

Monoxide (HiPco). The Simapro software modeled CNTs using all three methods to create various scenarios.

For the other resources used to produce ACRE TFTs, data was collected in 2023 through questionnaires. However, data from the questionnaire pertained to the production of four ACRE TFTs. The production of ACRE TFTs was analyzed using different scenarios to ensure clarity. In one scenario, the input materials, including energy and other resources, were divided by four to assess the impact on a single ACRE TFT. The quantities of graphene, CNT, and CNC inks used per device are identical across all transistors, as each ACRE TFT is fabricated following the same design and printing parameters. For this reason, the total material consumption was divided by four to estimate the contribution per individual transistor. In contrast, the energy consumption associated with printer start-up and operation is not explicitly known. Consequently, in the first scenario, the total energy demand was also divided by four to approximate the energy burden attributable to a single ACRE TFT, while a second scenario consider the production of one ACRE TFT with material input as one but using the same amount of energy as required for producing four ACRE TFTs. This approach accounts for the potentially high energy consumption associated with the printer's startup. The exact energy consumption of the machinery between startup and printing operations is unknown, which prompted the creation of various scenarios. These scenarios help to better understand and estimate the potential energy usage across different operation phases, ensuring a more comprehensive assessment of the printer's overall impact. Both material- and energy-related scenarios were evaluated for ACRE TFTs produced using CNTs from the Arc, CVD, and HiPco methods, resulting in six distinct scenarios (Table 1).

In the next paragraphs, LCA-related assumptions and the processes selected from the databases for the ACRE TFT and benchmark are reported.

3.2.2 **LCA inventory.** For the LCA study, the assumptions made are the following:

• Because only the country of origin of the raw materials was known and no detailed supply-chain data were available, the study used the appropriate ecoinvent market processes. These processes already incorporate average production shares and transport distances from different supplying regions, making them suitable for representing generic supply conditions. The carbon nanotubes (CNT) produced by Arc discharge, CVD, and HiPco are modelled based on the Environmental Assessment of Single-Walled Carbon Nanotube Processes reported by Healy *et al.* (2008).[35]

• The graphene is modelled following the prospective LCA of Graphene Production by Ultrasonication and Chemical Reduction presented by Arvidsson *et al.* (2014).[36]

• The crystalline nanocellulose (CNC) is modelled following the life cycle assessment methodology described by Li *et al.* (2013).[37]

• The substrate glass used for printing the inks was prepared using ITO-coated glass, a photoresist, and an etchant. However, as the specific processes for these materials were not available in the ecoinvent database, an alternative approach was required. To ensure a reasonable approximation of the environmental impact, the process related to glass for liquid crystal displays was selected as the closest available option.

Table 2 reports all the LCA processes selected from the EcoInvent database v3.9.1 to model an ACRE TFT. The quantities of raw materials are reported according to the first scenario, where the input materials, including energy and other resources, are divided by four to assess the impact on a single ACRE TFT. The quantities inputs were obtained directly from the experimental team developing the ACRE transistors. The glass substrate is the physical support used for printing. Water, nitrogen, and toluene were originally reported for each individual printing step associated with CNC, CNT, and graphene inks, while Table 2 presents the aggregated values normalized to the functional unit of 1 transistor.

3.2.3 **Benchmark.** For the LCA study, the Ecoinvent database was used as the source of data related to the transistor. The data represent a typical wired, small-size transistor used in information and communication technology, specifically reflecting the global production process for transistors with through-hole mounting. The dataset includes information on material composition, manufacturing steps such as silicon die bonding, wire bonding, encapsulation, plating, and trimming, as well as infrastructure considerations. However, it does not specify whether the transistor is a MOSFET, Bipolar Junction Transistor (BJT), or another type. Within the Table 3 reports the LCA process selected from the EcoInvent database v3.9.1 to model the benchmark.

3.3. Life cycle impact assessment

LCA was carried out with the use of the SimaPro LCA software developed by PRé Sustainability. The database EcoInvent Version 3.9.1 was used for the LCA. ReCiPe 2016 Endpoint and Midpoint methods were used to calculate environmental impacts. ReCiPe 2016 was selected as the characterization method because it provides a scientifically consistent

Table 2 LCA processes from EcoInvent 3.9.1 database to model 1 ACRE TFT of the final weight of 1793×10^{-3} kg. Arc, CVD and HiPco denote the carbon nanotube production routes considered. GLO, RoW and US specify the corresponding geographical system models (Global, Rest of World and United States)

Type	Raw materials	Process name in EcoInvent 3.9.1 (cut-off) database	Amount per transistor
Material	Carbon nanotubes (Arc/CVD/HiPco)	Modelization following ref. 35	$2,5 \times 10^{-9}$ kg
Material	Graphene	Modelization following ref. 36	5.75×10^{-6} kg
Material	Nanocellulose ink	Modelization following ref. 37	1.50×10^{-5} kg
Material	Glass	Glass, for liquid crystal display {GLO}| market for glass, for liquid crystal display|cut-off, S	1.094×10^{-3} kg
Material	Nitrogen	Nitrogen, *via* cryogenic air separation, production mix, at plant, gaseous EU-27 S	2.13×10^{-4} kg
Material	Toluene	Toluene, liquid {RoW}| market for toluene, liquid|cut-off, S	1.1011×10^{-2} kg
Material	Water to dilute graphene and CNC ink	Water, decarbonised {US}| water production, decarbonised|cut-off, S	2.93×10^{-4} kg
Waste	Toluene waste	Spent solvent mixture {RoW}| market for spent solvent mixture|cut-off, S	1.0838×10^{-2} kg
Energy	Electricity to print ink	Electricity, medium voltage {US}| market group for electricity, medium voltage|cut-off, S	3.5485×10^{-2} kW h

framework with a comprehensive set of midpoint indicators and a coherent link to endpoint damage categories. This structure supports both detailed analysis and clear interpretation. Moreover, ReCiPe has a broad impact coverage, global applicability, and regular scientific updates, which together ensure completeness and transparency in the assessment. The LCA results for the ACRE TFT compared to the benchmark, a classic transistor. The ACRE TFT has been modelled using six scenarios that consider different production techniques and energy inputs to fabricate transistors with CNTs *via* Arc, CVD, and HiPco methods. Next to each scenario is the acronym used in both the LCA results shown in Table 4 and Fig. 2. The scenarios are as follows:

(1) 1 ACRE TFT with CNT ink produced *via* Arc method (1 TFT ACRE Arc);

(2) 1 ACRE TFT with CNT ink produced *via* CVD method (1 ACRE TFT CVD);

(3) 1 ACRE TFT with CNT ink produced *via* HiPco method (1 ACRE TFT HiPco);

(4) 1 ACRE TFT with CNT ink produced *via* Arc method, using the higher energy consumption required to produce 4 TFTs (1 ACRE TFT Arc en4);

(5) 1 ACRE TFT with CNT ink produced *via* CVD method, using the higher energy consumption required to produce 4 TFTs (1 ACRE TFT CVD en4);

(6) 1 ACRE TFT with CNT ink produced *via* HiPco method, using the higher energy consumption required to produce 4 TFTs (1 ACRE TFT HiPco en4).

The results are presented at both the Midpoint and Endpoint levels. Midpoint results are shown in Table 4 as characterized results while Fig. 2 illustrates the same results as percentages, with each impact category set to 100%. Due to the density of the data, the results have been split into two images: Fig. 2a presents the midpoint characterization for half of the impact categories, while Fig. 2b displays the remaining categories. For each impact category, the most relevant contribution is provided by the benchmark, except for ionizing radiation and fossil resource scarcity. From Fig. 2 it is possible to see that for the category of ionizing radiation, the greatest impact is generated by ACRE TFTs ("en4"), followed by the benchmark. Similarly, when considering the category of resource scarcity, ACRE TFTs ("en4") again account for a substantial portion of the impact due to their energy consumption, followed by the benchmark. A clear stepwise increase can be observed when comparing a single ACRE TFT, the benchmark device, and the ACRE TFT

Table 3 LCA processes from EcoInvent 3.9.1 database to model the classic transistor. GLO specify the corresponding geographical system models (global)

Type	Raw materials	Process name in EcoInvent 3.9.1 (cut-off) database	Amount per transistor
Material	Transistor	Transistor, wired, small size, through-hole mounting {GLO}| market for transistor, wired, small size, through-hole mounting|cut-off, S	$8,18 \times 10^{-4}$ kg

Table 4 Midpoint characterization results of 1 ACRE TFT according to six scenarios and a classic transistor

Impact category	1 ACRE TFT Arc	1 ACRE TFT Arc en4	1 ACRE TFT CVD	1 ACRE TFT CVD en4	1 ACRE TFT HiPco	1 ACRE TFT HiPco en4	Benchmark	Unit
Global warming	5.69×10^{-2}	9.51×10^{-2}	5.71×10^{-2}	9.52×10^{-2}	5.68×10^{-2}	9.50×10^{-2}	1.47×10^{-1}	kg CO_2 eq.
Stratospheric ozone depletion	1.22×10^{-3}	2.97×10^{-3}	1.20×10^{-4}	2.95×10^{-3}	1.20×10^{-3}	2.94×10^{-3}	6.23×10^{-3}	kg CFC11 eq.
Ionizing radiation	7.23×10^{-3}	2.64×10^{-2}	7.29×10^{-3}	2.65×10^{-2}	7.21×10^{-3}	2.64×10^{-2}	1.65×10^{-2}	kBq Co-60 eq.
Ozone formation, human health	8.49	1.42×10^{-4}	8.51	1.42×10^{-4}	8.47×10^{-1}	1.42×10^{-4}	4.97×10^{-4}	kg NO_x eq.
Fine particulate matter formation	4.99	9.49	5.03×10^{-1}	9.53	4.97×10^{-1}	9.47	5.64×10^{-4}	kg PM2.5 eq.
Ozone formation, terrestrial ecosystems	9.10	1.51×10^{-4}	9.12	1.51×10^{-4}	9.08	1.51×10^{-4}	5.40×10^{-4}	kg NO_x eq.
Terrestrial acidification	1.15×10^{-4}	1.80×10^{-4}	1.15×10^{-4}	1.80×10^{-4}	1.15×10^{-4}	1.80×10^{-4}	1.27×10^{-3}	kg SO_2 eq.
Freshwater eutrophication	1.36	2.61	1.37	2.62	1.35	2.61	1.55×10^{-4}	kg P eq.
Marine eutrophication	9.68×10^{-2}	2.11×10^{-1}	9.75×10^{-2}	2.12×10^{-1}	9.60×10^{-2}	2.10×10^{-1}	8.04×10^{-1}	kg N eq.
Terrestrial ecotoxicity	1.86×10^{-1}	2.38×10^{-1}	1.86×10^{-1}	2.38×10^{-1}	1.86×10^{-1}	2.38×10^{-1}	6.26×10^{9}	kg 1,4-DCB
Freshwater ecotoxicity	2.17×10^{-3}	3.17×10^{-3}	2.17×10^{-3}	3.18×10^{-3}	2.16×10^{-3}	3.17×10^{-3}	7.25×10^{-2}	kg 1,4-DCB
Marine ecotoxicity	2.80×10^{-3}	4.10×10^{-3}	2.80×10^{-3}	4.11×10^{-3}	2.80×10^{-3}	4.10×10^{-3}	9.29×10^{-2}	kg 1,4-DCB
Human carcinogenic toxicity	1.41×10^{-3}	2.81×10^{-3}	1.42×10^{-3}	2.82×10^{-3}	1.41×10^{-3}	2.81×10^{-3}	1.35×10^{-2}	kg 1,4-DCB
Human non-carcinogenic toxicity	3.81×10^{-2}	6.17×10^{-2}	3.82×10^{-2}	6.19×10^{-2}	3.80×10^{-2}	6.17×10^{-2}	1.25×10^{9}	kg 1,4-DCB
Land use	1.28×10^{-3}	3.83×10^{-3}	1.29×10^{-3}	3.83×10^{-3}	1.28×10^{-3}	3.83×10^{-3}	4.28×10^{-3}	m^2a crop eq.
Mineral resource scarcity	1.42×10^{-4}	2.01×10^{-4}	1.42×10^{-4}	2.01×10^{-4}	1.41×10^{-4}	2.01×10^{-4}	6.40×10^{-3}	kg Cu eq.
Fossil resource scarcity	2.57×10^{-2}	3.77×10^{-2}	2.58×10^{-2}	3.77×10^{-2}	2.57×10^{-2}	3.77×10^{-2}	3.68×10^{-2}	kg oil eq.
Water consumption	5.94×10^{-4}	8.02×10^{-4}	5.95×10^{-4}	8.03×10^{-4}	5.95×10^{-4}	8.03×10^{-4}	1.71×10^{-3}	m^3

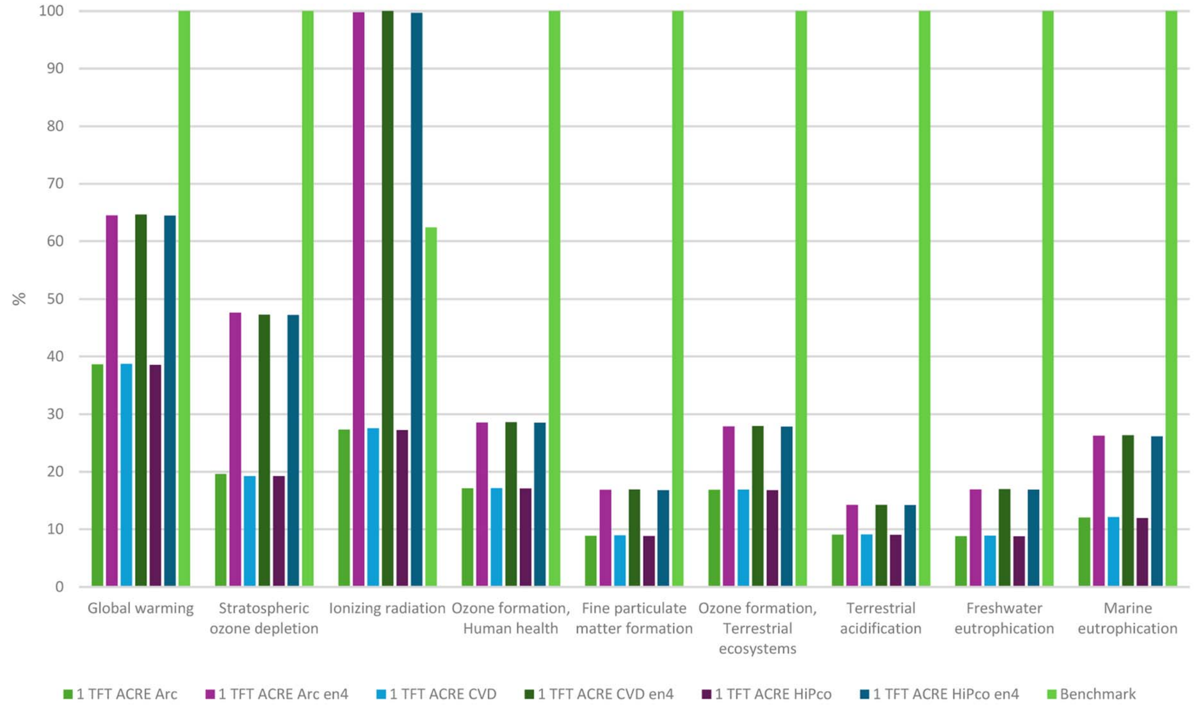
under the "en4" scenario. This progression highlights how strongly electricity consumption influences these impact categories. The higher impacts of the "en4" scenarios relative to the benchmark are therefore primarily driven by the elevated energy demand assumed for this case, which amplifies contributions to ionizing radiation and fossil resource scarcity.

Although the benchmark device is based on silicon- or metal-oxide semiconductor technologies—whose manufacturing processes are known to release significant greenhouse gases and require substantial electricity inputs—the "en4" scenario surpasses it because the assumed energy consumption for producing a single ACRE TFT is disproportionately high. The semiconductor industry itself accounts for 1.3–2.0% of total electricity use in the U.S. manufacturing sector, reflecting the energy-intensive nature of conventional electronic component fabrication. However, when the ACRE TFT is modeled with the full energy load of producing four devices (as in "en4"), the electricity-related impacts become dominant, exceeding even those of the benchmark. In the category of ionizing radiation, the impact percentages are as follows: ACRE en4 stands at 100%, the benchmark at 60%, and ACRE at 25%, while in the category of fossil resource scarcity, the impact percentages are: ACRE en4 at 100%, the benchmark at 95%, and ACRE at 65%.

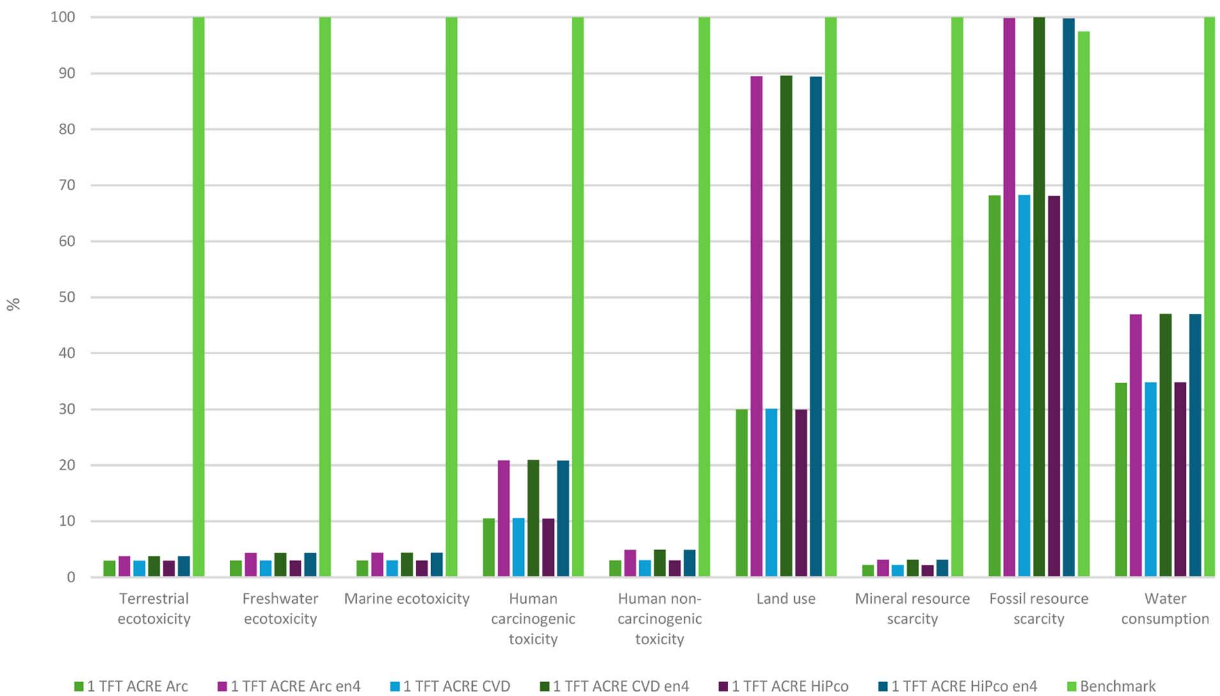
In general, the data shows that the benchmark or ACRE "en4" consistently account for the highest impacts, whereas the baseline ACRE contributes the least. In addition, among the six scenarios, the one with the least impact is the ACRE TFT produced using CNTs made with the HiPco method (Table 4). This finding suggests that the HiPco method offers a more sustainable approach, reducing the overall environmental impact compared to other production methods. This underscores how energy consumption significantly affects the total impact generated by the production of an ACRE TFT. Endpoint results provide an overview of damages to human health, ecosystems and resources caused by the life cycle of both the six scenarios of the ACRE TFT transistors and the benchmark. The normalized results of the three endpoint indicators are reported in Fig. 3. Similar to the midpoint results, the largest contributions to the calculated damages for human health and ecosystem categories are related to the benchmark, except for the resource category, where the highest contribution is given by the ACRE TFT'en4'. Furthermore, the most significant endpoint is the damage to resources for both the six scenarios of ACREs TFT and the benchmark.

The impacts of producing a single thin-film transistor (TFT) with carbon nanotubes (CNTs) produced using the HiPco method are reported in Table 5 as characterized results and Fig. 4 as a percentage. The results reveal significant insights into the environmental impacts associated with the use of different materials and processes in the production of TFTs.

Firstly, it is evident that CNTs, CNC, and graphene, which are the base materials for printing the transistor on glass, contribute more than 40% to the total impact in multiple environmental categories. These categories include global warming potential, ozone formation (both human health and terrestrial), terrestrial acidification, fossil resource scarcity, and water consumption. This substantial impact can be attributed



a



b

Fig. 2 Midpoint characterization results of 1 ACRE TFT according to six scenarios and a classic transistor. (a) presents the midpoint characterization for half of the impact categories, while (b) displays the remaining categories.

to the energy-intensive processes required for the synthesis and preparation of these materials. For instance, the production of CNTs *via* the HiPco method involves high temperatures and pressures, leading to significant energy consumption and associated emissions. Similarly, the production of CNC and graphene also entails various chemical and mechanical processes that contribute to their environmental footprint. Conversely, the glass substrate on which these materials are printed demonstrates a different environmental impact profile. The glass has an impact of over 40% in the categories of terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, and mineral resource scarcity. These impacts are largely due to the extraction and processing of raw materials required to produce the glass, as well as the associated waste and emissions. For example, the mining of silica, which is a primary component of glass, can lead to habitat destruction, soil erosion, and water pollution. Additionally, the processing of silica into glass involves the use of high temperatures and various chemicals, contributing to its overall environmental impact.

The energy required for the printing process itself, on the other hand, never exceeds 40% in any of the assessed environmental categories. This finding suggests that while the printing process is energy-intensive, it does not dominate the environmental impact compared to the production of the materials and the glass substrate. However, it is important to note that the energy required for the production of the inks used in the printing process does surpass 40% in the categories of ionizing radiation and land use. This is primarily due to the energy mix used during graphene ink production, which includes a substantial share of nuclear power—driving up ionizing radiation—and biomass sources such as wood chips, whose cultivation contributes significantly to land occupation. In addition to these contributions, the disposal of the solvent used during CNT printing—specifically toluene—represents a further relevant hotspot. Solvent waste management accounts for 20% or more of the impacts in four categories: global warming (24%), stratospheric ozone depletion (28.3%), freshwater eutrophication (20%), and marine eutrophication (28.3%).

3.3.1 Sensitivity analysis. A sensitivity analysis was carried out on the most influential parameters of the ACRE TFT system: printing energy consumption, CNTs, CNC, and graphene material inputs, as well as the choice of CNT production route. The first part of the analysis examines the production of 1 ACRE TFT using three CNT synthesis methods (Arc, CVD, and HiPco) under three scenarios: baseline, low, and high consumption of both energy and materials. The low and high scenarios correspond to a 50% decrease and increase, respectively, relative to the baseline values. A variation of ±50% was selected to reflect the high uncertainty associated with laboratory-scale processes, where energy and material consumption can deviate substantially from those expected at industrial scale.

Fig. 5 presents the midpoint characterization results for 1 ACRE TFT across the three CNT synthesis methods under the baseline, low, and high scenarios. Overall, the sensitivity analysis indicates that changes in energy and material use—rather than the choice of CNT production method—are the primary drivers influencing the environmental profile of 1 ACRE TFTs. Since the results obtained for the three CNT production methods were extremely similar across all scenarios (baseline-low-high), typically differing by only about 1%, the values were averaged for each scenario to provide a representative comparison. Once the average value for each impact category and each scenario was obtained, a comparison between the baseline, low, and high results was carried out to quantify the variation. Fig. 6 provides a graphical representation the sensitivity analysis workflow just explained.

Since the analysis applied a ±50% change to both energy and material inputs, the percentage variation between baseline and

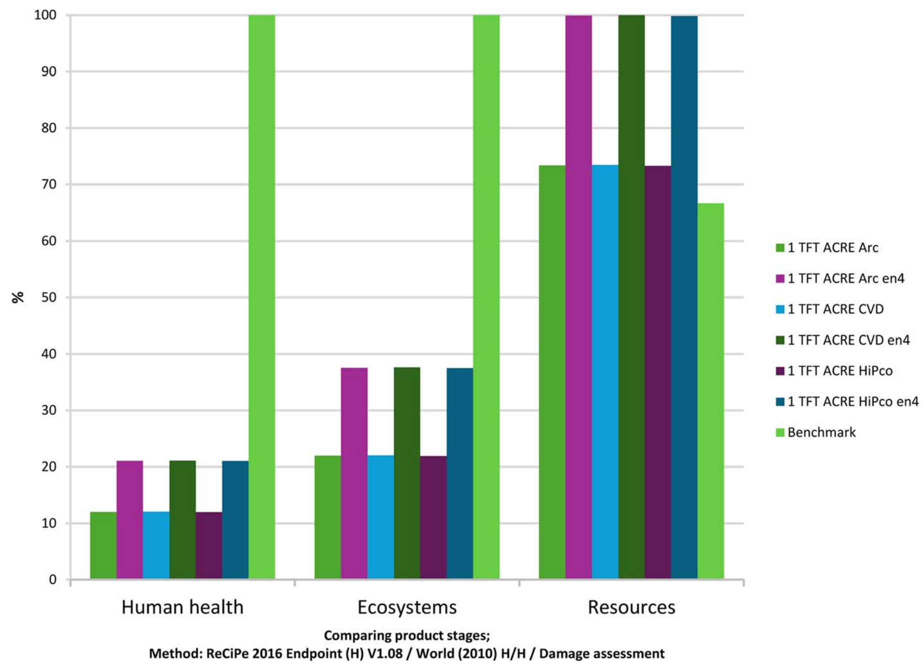


Fig. 3 Endpoint results of 1 ACRE TFT according to six scenarios and a classic transistor.

Table 5 Midpoint results of 1 ACRE TFT with percentage of environmental impact according to the materials and energy used and waste produced

Impact category	Materials (CNT, CNC, graphene)	Glass	Energy to produce inks	Energy to print	Waste	Unit
Global warming	1.00×10^{-1}	1.94×10^{-2}	2.96×10^{-2}	2.34×10^{-2}	5.45×10^{-2}	kg CO_2 eq.
Stratospheric ozone depletion	3.61×10^{-4}	6.48×10^{-4}	1.63×10^{-3}	7.96×10^{-4}	1.36×10^{-3}	kg CFC11 eq.
Ionizing radiation	4.82×10^{-4}	1.31×10^{-3}	1.94×10^{-2}	7.44×10^{-3}	2.14×10^{-4}	kBq Co-60 eq.
Ozone formation, human health	1.83×10^{-4}	5.32	5.05	2.83	2.43	kg NO_x eq.
Fine particulate matter formation	7.17	5.49	1.68	4.60×10^{-1}	9.25×10^{-1}	kg PM2.5 eq.
Ozone formation, terrestrial ecosystems	2.01×10^{-4}	5.45	5.24	3.01	2.51	kg NO_x eq.
Terrestrial acidification	2.13×10^{-4}	1.34×10^{-4}	4.74	4.40	2.03	kg SO_2 eq.
Freshwater eutrophication	1.18	1.32	4.10×10^{-1}	1.43×10^{-1}	1.08	kg P eq.
Marine eutrophication	3.89×10^{-2}	7.16×10^{-2}	6.26×10^{-2}	1.02×10^{-1}	1.09×10^{-1}	kg N eq.
Terrestrial ecotoxicity	1.14×10^{-1}	5.44×10^{-1}	5.07×10^{-2}	2.08×10^{-2}	1.56×10^{-2}	kg 1,4-DCB
Freshwater ecotoxicity	9.45×10^{-4}	6.12×10^{-3}	7.88×10^{-4}	6.45×10^{-4}	1.59×10^{-4}	kg 1,4-DCB
Marine ecotoxicity	1.27×10^{-3}	7.84×10^{-3}	1.00×10^{-3}	8.52×10^{-4}	2.16×10^{-4}	kg 1,4-DCB
Human carcinogenic toxicity	1.89×10^{-3}	1.36×10^{-3}	9.27×10^{-4}	1.07×10^{-3}	3.84×10^{-4}	kg 1,4-DCB
Human non-carcinogenic toxicity	1.84×10^{-2}	9.59×10^{-2}	1.48×10^{-2}	1.89×10^{-2}	3.99×10^{-3}	kg 1,4-DCB
Land use	8.32×10^{-4}	7.42×10^{-4}	2.95×10^{-3}	4.99×10^{-4}	9.90	m^2a crop eq.
Mineral resource scarcity	7.88	3.84×10^{-4}	5.82	2.54	1.82	kg Cu eq.
Fossil resource scarcity	7.97×10^{-2}	4.69×10^{-3}	9.84×10^{-3}	6.69×10^{-3}	1.82×10^{-3}	kg oil eq.
Water consumption	1.74×10^{-3}	1.45×10^{-4}	2.75×10^{-4}	1.49×10^{-4}	6.91	m^3

low is identical to that between baseline and high. For this reason, the variation is reported only once, as shown in Table 6.

The outcomes, show that the most sensitive impact category is ionizing radiation, with a 32% variation, suggesting a strong dependence on nuclear energy. In contrast, terrestrial ecotoxicity exhibits the lowest variation, at just 8%, indicating relative stability under consumption changes. Most other categories fall within a moderate range of 11% to 22%, with lower sensitivity observed for marine and freshwater ecotoxicity, and higher sensitivity for stratospheric ozone depletion and land use.

In addition to the ±50% variation applied simultaneously to energy and material consumption, a second, more detailed sensitivity analysis was performed to disentangle the individual contribution of these two parameters. For each CNT production method (Arc, CVD, and HiPco), the environmental impacts associated with the fabrication of one ACRE TFT were recalculated by varying either energy use or material inputs while keeping the other parameter fixed at its baseline value. Specifically, for each CNT synthesis route, three scenarios were modelled by fixing material consumption at the baseline and

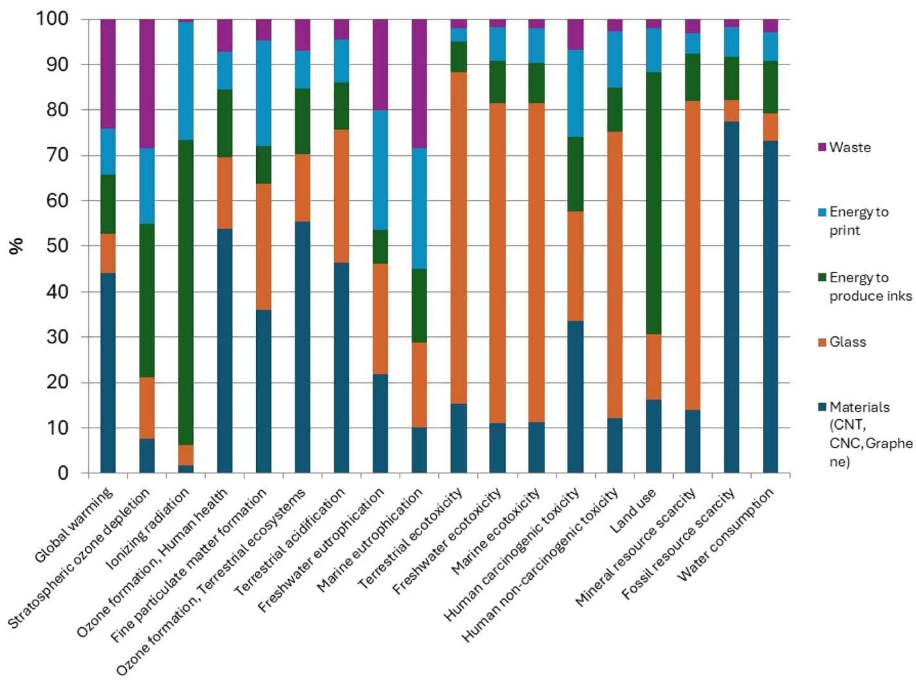


Fig. 4 Midpoint results of 1 ACRE TFT with the percentage of environmental impact according to the materials and energy used and waste produced.

varying energy demand (Fig. A in SI), and three scenarios by fixing energy consumption at the baseline level and varying material use (Fig. B in SI). This approach allows isolating the relative influence of energy-intensive *versus* material-intensive stages within the system and provides a clearer understanding of which parameter drives the variability observed in the overall environmental profile.

Since the results obtained for the three CNT production methods were extremely similar across all scenarios (baseline-low-high), typically differing by only about 1%, the values were averaged for each scenario to provide a representative comparison. Once the average value for each impact category and each scenario was obtained, a comparison between the baseline, low, and high results was carried out to quantify the variation. Since the analysis applied a ±50% change, the percentage difference between baseline and low is identical to that between baseline and high. For this reason, the variation is reported only once. Table 7 reports the percentage difference in sensitivity for both cases: when material consumption is fixed at the baseline and energy demand varies (percentage variation (En)), and the reverse (percentage variation (Mat)).

Table 7 shows how each impact category responds when either energy demand varies while material consumption is fixed at the baseline, or *vice versa*. When energy consumption is varied, the most affected categories are ionizing radiation (+30%) and land use (+25%), indicating a strong dependence on energy-intensive processes. In contrast, terrestrial ecotoxicity (+4%) and water consumption (+5%) show the lowest sensitivity, suggesting that these impacts are only marginally influenced by changes in energy use.

When material inputs are varied, the overall sensitivity is lower, with the highest variation observed for freshwater eutrophication (+11%). Several categories show minimal response, including ionizing radiation (+3%), terrestrial ecotoxicity (+4%), and stratospheric ozone depletion (+4%). This pattern indicates that, for most categories, material consumption plays a smaller role than energy use in driving environmental variability. Overall, the comparison highlights that energy-related changes tend to produce larger variations across impact categories than material-related changes, reinforcing the dominant influence of energy consumption on the environmental profile of the system.

Building on this evidence, it becomes essential not only to quantify how much energy is used, but also to examine how the choice of electricity source influences the overall environmental profile. Fig. 7 illustrates the results of this comparison across the three energy scenarios considered.

The baseline configuration, represented by 1 TFT ACRE HiPco, reflects the U.S. energy mix used in the previous assessment. The second scenario, 1 TFT ACRE HiPco 1/2 R, corresponds to a hybrid supply in which 50% of the electricity is provided by photovoltaic generation and 50% by the same U.S. energy mix. The third scenario, 1 TFT ACRE HiPco R, represents a fully renewable configuration relying exclusively on photovoltaic electricity. This scenario is further justified by the growing adoption of on-site solar installations among energy-intensive U.S. companies such as Meta, Amazon, Google, and Apple, which have deployed large-scale photovoltaic systems to reduce operational emissions, enhance energy security, and mitigate long-term electricity costs.[38]

As shown in Fig. 7, shifting to 100% renewable electricity leads to a substantial reduction in impacts for 14 out of the 18 categories assessed. Five categories—Stratospheric ozone depletion, fine particulate matter formation, freshwater eutrophication, marine eutrophication, and land use—show reductions of approximately 40%.

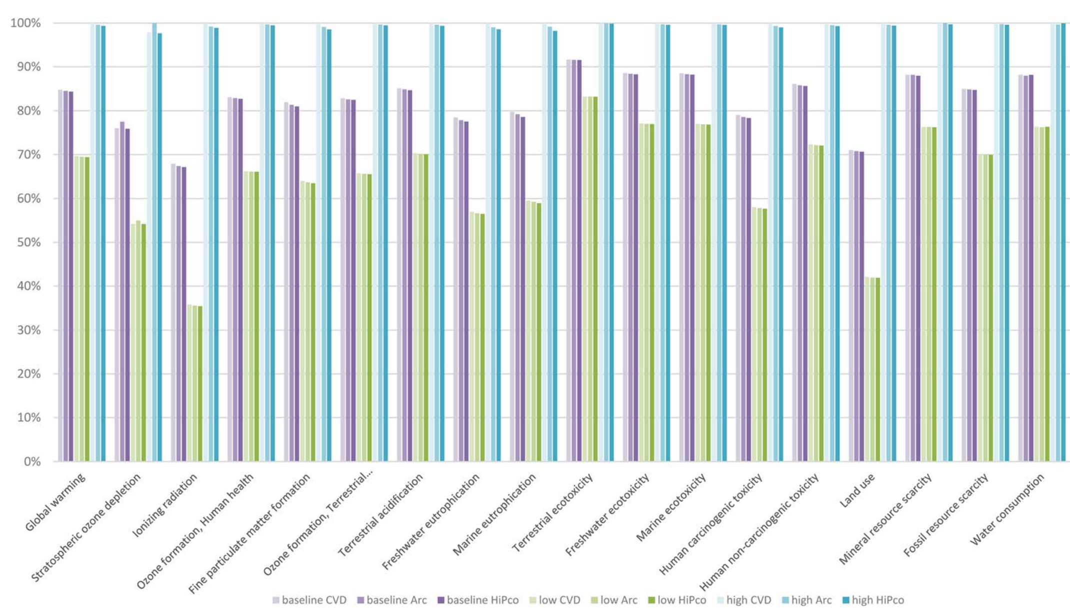


Fig. 5 Midpoint characterization results of 1 ACRE TFT according to three CNT synthesis methods (Arc, CVD, and HiPco) under three scenarios: baseline, low, and high consumption of both energy and materials.

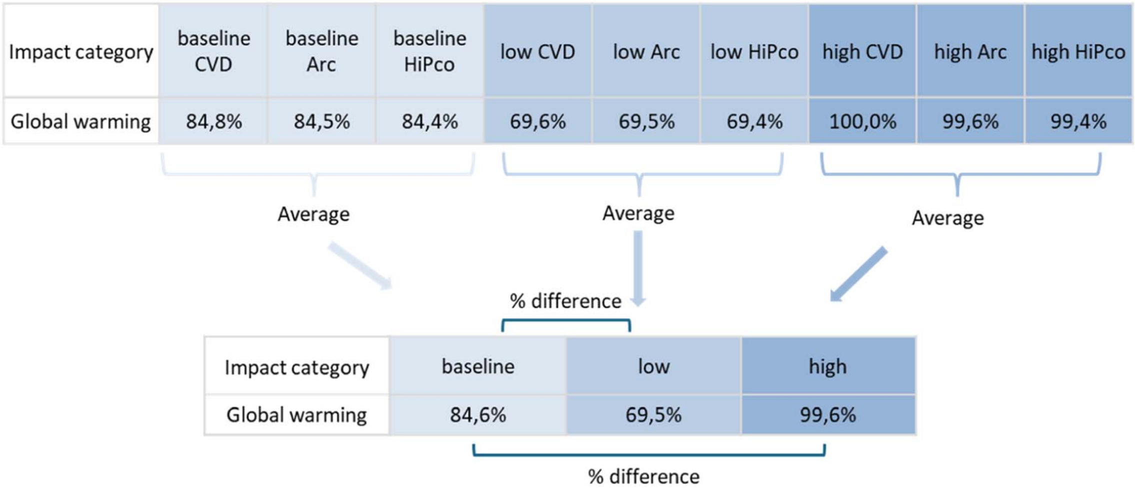


Fig. 6 Graphical representation of the sensitivity analysis workflow. The figure illustrates how the midpoint results obtained for the three CNT synthesis methods (Arc, CVD, and HiPco) were averaged for each scenario (baseline, low, high), followed by the comparison of these averaged values to calculate the percentage variation for each impact category.

The decrease in stratospheric ozone depletion (−42%) is primarily associated with the elimination of emissions linked to hard coal and natural gas in the baseline U.S. energy mix, where these two sources together account for roughly 50% of electricity generation. The reduction in fine particulate matter formation (−42%) is driven by the avoidance of sulfur oxide emissions typically retained during flue gas desulfurisation in lignite power plants; approximately 7% of the electricity in the baseline mix originates from lignite.

The reductions observed for freshwater eutrophication (−46%) and marine eutrophication (−48%) are linked to the avoided waste treatment of spoil generated from lignite and hard coal mining. The decrease in land use (−38%) is related to the avoided production and harvesting of wood chips required in the baseline energy system.

One category, ionizing radiation, shows an even more pronounced reduction (−84%). This outcome is consistent with the composition of the baseline U.S. energy mix, in which more than 20% of electricity is generated from nuclear power, a major contributor to this indicator.

Conversely, four categories—mineral resource scarcity and terrestrial, freshwater, and marine ecotoxicity—exhibit higher impacts under the 100% photovoltaic scenario. Mineral resource scarcity increases by 10%, while terrestrial, freshwater, and marine ecotoxicity rise by 24%, 18%, and 17%, respectively. For the three ecotoxicity indicators, this increase is primarily associated with the materials required for photovoltaic panel manufacturing, including the photovoltaic cell and the copper-based components of the cathode, as well as the end-of-life treatment of electronic components. The elevated impact in mineral resource scarcity is similarly driven by the copper demand for the cathode and other components of multi-Si photovoltaic panels and the inverter. This interpretation is consistent with the well-documented uncertainty associated with toxicity-related characterization factors. Several studies report that model and parameter uncertainty can span one to three orders of magnitude, particularly for human toxicity and ecotoxicity.[39] Within this context, the percent variations observed in our sensitivity analysis should therefore be interpreted as indicative trends rather than statistically significant differences.

4. Discussion

In response to the impact on climate change due to greenhouse gas emissions generated during the fabrication of

Table 6 Percentage variation of sensitivity for midpoint impact categories

Impact category	Percentage variation	Impact category	Percentage variation
Terrestrial ecotoxicity	8%	Ozone formation, human health	17%
Freshwater ecotoxicity	11%	Ozone formation, terrestrial ecosystems	17%
Marine ecotoxicity	11%	Fine particulate matter formation	18%
Water consumption	12%	Marine eutrophication	20%
Mineral resource scarcity	12%	Human carcinogenic toxicity	21%
Human non-carcinogenic toxicity	14%	Freshwater eutrophication	21%
Terrestrial acidification	15%	Stratospheric ozone depletion	22%
Fossil resource scarcity	15%	Land use	29%
Global warming	15%	Ionizing radiation	32%

Table 7 Percentage variation of sensitivity for midpoint impact categories under two sensitivity scenarios: energy demand varied while material consumption is fixed at the baseline (percentage variation (En)), and material consumption varied while energy demand is fixed at the baseline (percentage variation (Mat))

Impact categories	Percentage variation (En)	Impact category	Percentage variation (Mat)
Terrestrial ecotoxicity	4%	Ionizing radiation	3%
Water consumption	5%	Terrestrial ecotoxicity	4%
Mineral resource use	7%	Stratospheric ozone depletion	4%
Fossil resource use	7%	Freshwater ecotoxicity	5%
Freshwater ecotoxicity	7%	Marine ecotoxicity	5%
Marine ecotoxicity	7%	Marine eutrophication	5%
Terrestrial acidification	9%	Human toxicity non cancer	5%
Human toxicity non-cancer	9%	Mineral resource use	6%
Ozone formation (2)	10%	Global warming	6%
Global warming	10%	Fine particulate matter formation	6%
Ozone formation	10%	Water consumption	7%
Fine particulate matter formation	13%	Land use	7%
Freshwater eutrophication	13%	Terrestrial acidification	7%
Human toxicity cancer	14%	Ozone formation	8%
Marine eutrophication	16%	Ozone formation (2)	9%
Stratospheric ozone depletion	19%	Fossil resource use	9%
Land use	25%	Human toxicity cancer	9%
Ionizing radiation	30%	Freshwater eutrophication	11%

semiconductor devices—particularly flat-panel displays, ACRE materials offer an innovative and promising solution. By substituting traditional semiconductor materials, such as silicon or metal oxides, with ink-processable options like crystalline nanocellulose (CNC), carbon nanotubes (CNT), and graphene, significant benefits can be achieved, including reduced energy consumption and a corresponding decrease in greenhouse gas (GHG) emissions. This study conducted a comparative LCA to evaluate the environmental performance of thin-film transistors (TFTs) made with ACRE materials against conventional TFTs. The results highlight the environmental benefits of adopting ACRE materials, particularly in reducing GHG emissions and enhancing sustainability through recycling and material reuse. The analysis underscores the technological and environmental advantages of ACRE materials and explores their potential implications for the electronics industry, emphasizing the importance of sustainable manufacturing practices to mitigate the environmental and health risks posed by electronic waste.

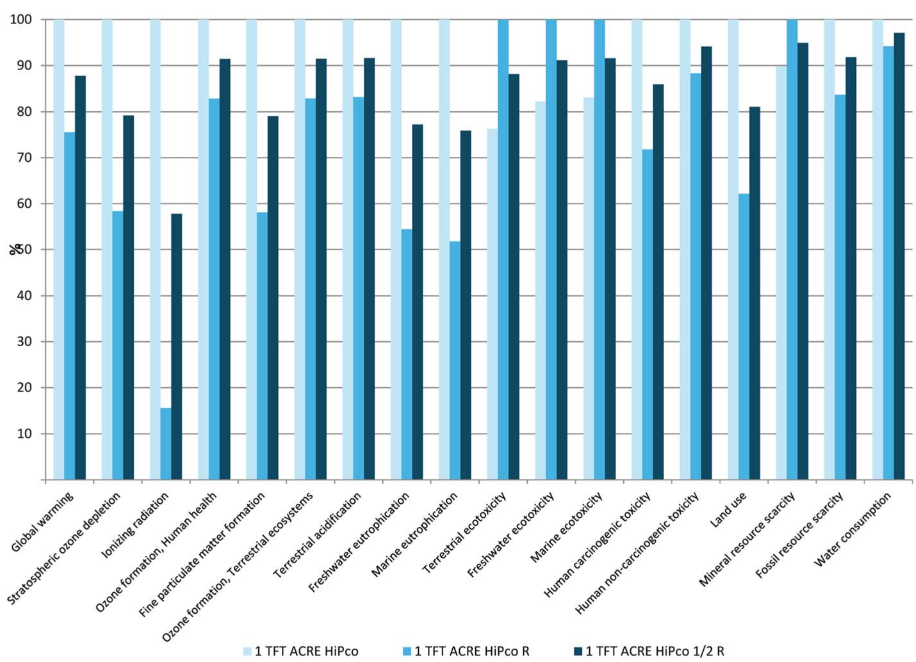


Fig. 7 Midpoint characterization of 1 ACRE TFT using CNTs (HiPco method) under three electricity supply scenarios: baseline U.S. energy mix (1 TFT ACRE HiPco), hybrid 50% photovoltaic (1 TFT ACRE HiPco 1/2 R), and 100% photovoltaic (1 TFT ACRE HiPco R).

The study employed a cradle-to-gate LCA, comparing ACRE TFTs with a benchmark classic transistor across six scenarios. These scenarios involved various production techniques and energy inputs for manufacturing the CNTs present within ACRE TFTs using Arc, Chemical Vapor Deposition (CVD), and HiPco methods. Each scenario was assessed for its environmental impact, as outlined in Table 4, Fig. 2, and 3. The midpoint results revealed that, for most impact categories, the benchmark had the highest environmental impact, except for ionizing radiation and fossil resource scarcity. The three TFTs made with the ACRE "en4" scenario in these two categories showed the most significant impact, primarily due to higher energy consumption.

The data indicates that scenarios with elevated energy requirements tend to exacerbate environmental impacts in these categories. The baseline ACRE scenario consistently displayed the least environmental impact, while the benchmark or ACRE "en4" scenarios exhibited the highest. These findings underscore the critical role of energy consumption in shaping the total environmental footprint of ACRE TFT production. Among the six scenarios, TFTs manufactured using CNTs *via* the HiPco method demonstrated the lowest environmental impact, suggesting this method is the most sustainable for ACRE material production.

Finally, the endpoint results provided insights into the broader impacts on human health, ecosystems, and resource depletion across the six ACRE scenarios and the benchmark. The normalized data showed that the benchmark contributed the most to human health and ecosystem damages. However, in the resource depletion category, the greatest impact was associated with the three ACRE TFT "en4" scenario, highlighting resource scarcity as a key concern in producing ACRE TFTs, regardless of the manufacturing method. These findings offer valuable guidance for improving the sustainability of ACRE production and integrating environmentally conscious practices into the electronics industry. The results in Fig. 4 provide critical insights into the environmental impacts of thin-film transistors (TFTs) using carbon nanotubes (CNTs) produced through the HiPco method. Base materials such as CNT, crystalline nanocellulose (CNC), and graphene contribute over 40% of the environmental impact in categories like global warming potential and fossil resource scarcity. This reflects the energy-intensive processes involved in their production.

Due to silica extraction and processing, the glass substrate significantly affects categories like terrestrial and marine ecotoxicity, emphasizing the need for alternative or more sustainable substrates. While the printing process does not dominate environmental impacts, ink production notably contributes to ionizing radiation and land use, underscoring the importance of improving ink preparation processes. Moreover, the treatment of toluene used during CNT printing, substantially increases the environmental burden. In fact, solvent waste management accounts for 20% or more of the impacts in four categories as global warming, stratospheric ozone depletion, freshwater eutrophication and marine eutrophication. When extrapolated to industrial production volumes and to the millions of tons of e-waste generated annually worldwide, the environmental burden associated with hazardous solvent use becomes substantially more critical. Efforts should focus on energy-efficient material synthesis, sustainable substrate production, and reduced resource depletion. A holistic approach to design and production can minimize environmental burdens and enhance the sustainability of TFT manufacturing.

The sensitivity analysis shows that, when varying the percentage of material and energy consumption, the impact categories most responsive to these changes are ionizing radiation and land use. In the more detailed assessment—where either the material inputs are fixed at baseline while energy consumption is varied, or *vice versa*—it becomes evident that energy use is the dominant driver of variability. Both the ionizing radiation and land use categories exhibit pronounced sensitivity to changes in electricity consumption because these impact pathways are strongly influenced by the energy mix and the upstream processes associated with electricity generation. As a result, even moderate adjustments in energy demand lead to substantial shifts in these categories, highlighting the critical role of energy efficiency in shaping the overall environmental profile of ACRE TFT production. The additional sensitivity analysis on electricity supply further confirms the dominant role of energy use in shaping the environmental profile of ACRE TFTs. When replacing the baseline U.S. energy mix with photovoltaic electricity, most impact categories decrease substantially, demonstrating the strong dependence of the system on upstream electricity generation. At the same time, the increases observed in resource-related categories highlight the presence of trade-offs associated with the material intensity of photovoltaic technologies. These results align with broader evidence from industrial decarbonization studies, indicating that renewable electricity procurement effectively reduces emission-related impacts but may shift burdens toward mineral resource use.

Looking ahead, it will also be essential to assess the end-of-life impacts of ACRE TFTs, given that recyclability is a central objective of their design. Future analyses should therefore evaluate the environmental performance of a complete ACRE TFT system by varying the recycling rates of its individual components and by considering alternative disposal routes, including incineration.

Moreover, the present study evaluates ACRE TFT production at laboratory scale, and the resulting environmental impacts should therefore be interpreted within this context. Industrial-scale manufacturing may lead to substantially different outcomes due to process optimization, improved material efficiency, and more stable energy demands. This expectation is already reflected in the sensitivity analysis, which shows that reductions in material inputs—and especially in electricity consumption—produce significant variations in the overall impact. To support experimental researchers working with ACRE materials, our results highlight several actionable directions. Reducing the energy intensity of material synthesis is essential, as adopting lower-energy CNT production routes such as HiPco can decrease environmental burdens. The ink preparation processes could be improved by replacing high-impact solvents with bio-based or aqueous alternatives and implementing solvent-recovery strategies. Moreover, given the dominant role of electricity consumption identified in both the main results and the sensitivity analysis, researchers can significantly reduce impacts by powering energy-intensive steps with renewable electricity. Finally, as ACRE TFTs transition from laboratory to industrial scale, process optimization and continuous monitoring of energy use will be crucial to achieving the sustainability potential identified in this study.

5. Conclusions

This study highlights the potential of ACRE materials as an innovative and sustainable alternative to conventional semiconductor materials in producing thin-film transistors (TFTs). By replacing silicon or metal oxides with ink-processable materials such as crystalline nanocellulose (CNC), carbon nanotubes (CNT), and graphene, significant environmental benefits can be achieved, including reduced greenhouse gas (GHG) emissions and enhanced material recyclability. The results from the cradle-to-gate LCA underscore the importance of addressing energy consumption and resource depletion as critical factors influencing the overall environmental performance of ACRE TFTs.

The findings demonstrate that the baseline ACRE scenario consistently results in the lowest environmental impact, while the HiPco production method for CNTs emerges as the most sustainable option. However, the study also reveals areas of concern, particularly the energy-intensive nature of material synthesis and the environmental impacts associated with the glass substrate and ink preparation. These insights emphasize the need for targeted improvements in material processing, substrate production, and ink formulation to enhance sustainability further.

This research provides valuable guidance for integrating environmentally conscious practices into the electronics industry by identifying key environmental hotspots. A holistic approach to design and manufacturing that prioritizes energy efficiency, sustainable material choices, and reduced resource depletion is essential for minimizing environmental burdens.

Ultimately, this study lays the foundation for advancing ACRE technologies and underscores their potential to address the growing challenges of e-waste, offering a path toward a more sustainable future for the electronics sector.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data used in the study, along with the software-generated results derived from it, are reported within the manuscript.

Supplementary information (SI) is available. See DOI: https://doi.org/10.1039/d5su00815h.

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