Cradle-to-Gate Life Cycle Assessment of Nano-enabled All-Carbon Recyclable Electronic (ACRE) Materials for Flat-panel Displays

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1. Introduction

The production of semiconductor components causes the usage of various acid/base solutions, organic solvents, and toxic gases releasing highly polluting toxins, wastewater, and waste gas (Lin, Lin, e Lu 2019). Additionally, the manufacturing processes of silicon- or metal oxide-based semiconductor materials for devices like flat-panel displays are known to release high levels of greenhouse gases (GHGs) into the atmosphere. Indeed, the semiconductor industry makes up 1.3–2.0% of the overall electricity usage in the manufacturing sector in the US. (Kuo, Kuo, e Chen 2022). In response to this problem, the *LEAP-HI: All-Carbon Recyclable Electronics (ACRE) Realizing a Sustainable Electronics Lifecycle* project, awarded by the National Science Foundation, aims to develop all-carbon recyclable electronic (ACRE) materials as a more environmentally friendly alternative to traditional semiconductor materials. A transistor typically consists of various components constructed using silicon- or metal oxide-based semiconductor materials. In the case of an ACRE transistor, these components are replaced with materials in the form of ink such as crystalline nano-cellulose (CNC), carbon nanotubes (CNT), and graphene. By using carbon-based materials, the expectation is to significantly reduce the emissions associated with electronic manufacturing processes. This study aims to conduct a comparative cradle-to-gate life cycle assessment (LCA) between ACRE thin-film transistors (TFTs) and classic TFTs. A classic transistor is considered as a transistor already available on the market, modelled thanks to ecoinvent database. By comparing the environmental impacts of these products, it is possible to better understand the potential benefits of switching to ACRE materials in terms of such factors as reducing GHG emissions to mitigate climate change.

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2. Materials and methods

LCA is a methodology used to assess the environmental impacts associated with a product, process, or activity throughout its entire life cycle, from raw material extraction to end-of-life disposal. The LCA results provide valuable insights into the environmental performance of different products and can help identify areas for improvement. In this study ACRE TFTs are compared with two classic TFTs. The functional unit of the assessment, which is a quantified performance measure used to define the function of a product or system, was defined as “the production of 4 transistors”. The production of 4 transistors, rather than just 1 transistor, has been chosen with the aim of encompassing all relevant data collected for the ACRE TFTs within the LEAP-HI project. Any alteration to this unit would necessitate making assumptions that would bring additional uncertainty to the assessment. The two selected benchmarks are represented by “the production of 4 classic transistors”, and “the production of 4 classic transistors with the same weight of the 4 ACRE TFTs”. The latter was chosen to balance the weight of the ink used to print the 4 ACRE TFTs, which, due to technical issues encountered in the initial development phases, leads to an overestimation of the overall weight of the 4 TFTs. Therefore, four classic transistors, each weighing the same as four ACRE TFTs, were selected as a secondary benchmark to a more appropriate comparison scenario than the significantly lighter primary benchmark. In the next paragraph, the results of the comparative cradle-to-gate LCA are reported.

3. Results

In this section, the comparative LCA between the production of 4 ACRE TFTs, the production of 4 classic transistors and the production of 4 classic transistors with the same weight of the 4 ACRE TFTs is presented. Figure 1 displays the characterized endpoints across the various examined categories. The characterized endpoints included human health impacts such as respiratory diseases, cancer, and neurological disorders. Environmental impacts were also assessed, including climate change, acidification, eutrophication, and ozone depletion. Additionally, resource depletion and ecosystem quality were considered in the LCA analysis. Overall, the characterized endpoints highlighted the potential negative impacts of the product throughout its life cycle. For each impact category, the higher impacts are related to the production of 4 classic transistors with the same weight of the 4 ACRE TFTs. Additionally, the lower impacts are related to the production of 4 ACRE TFT for all the impact categories except for one. Indeed, the least relevant contribution to the “fossil resource scarcity” impact category is provided by the production of 4 classic transistors.

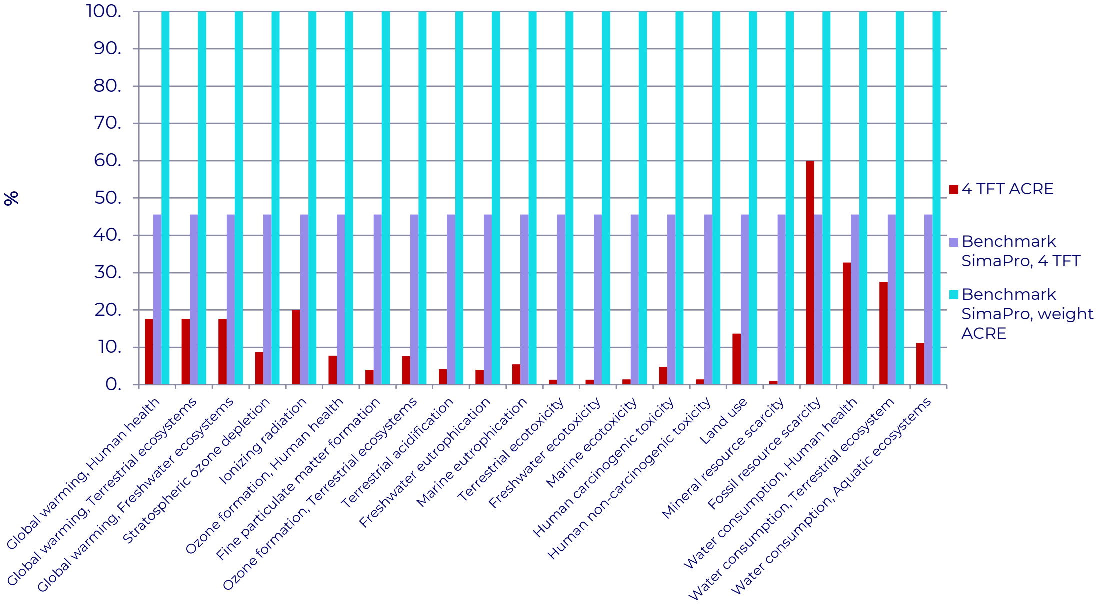

Figure 1: characterized endpoints for "4 ACRE TFT" compared to "4 classic transistors" and "4 classic transistors with the same weight of the 4 ACRE TFTs"

4. Conclusions

This study showed a comparative cradle-to-gate life cycle assessment (LCA) between the production of 4 ACRE TFTs, the production of 4 classic transistors and the production of 4 classic transistors with the same weight of the 4 ACRE TFTs. By comparing the environmental impacts of these materials, it was possible to understand the potential benefits of switching to ACRE materials in terms of reducing the environmental impacts, specifically reducing GHG emissions thus to mitigate the climate change. Indeed, it is important to consider these endpoints when making decisions about the product's design, production to minimize its environmental and human health impacts. Further research is needed to explore potential improvements and alternatives that could reduce these negative endpoints and promote sustainability in product life cycles.

5. References

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