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Life cycle assessment of the Spark Assisted Chemical Engraving (SACE) micro-machining method

Louis Liogier[1*], Andrew D. Henderson[2], Lucas A. Hof[1]

[1]Mechanical Engineering, École de technologie supérieure, Montreal, Canada
[2]Construction Engineering, École de technologie supérieure, Montreal, Canada
[*]louis.liogier@hotmail.fr

***Abstract*—This study presents a life cycle assessment (LCA) of the SACE (Spark Assisted Chemical Engraving) micro-machining process for brittle materials, identifying opportunities to improve its environmental profile, focusing on greenhouse gas emissions. Key contributors to the environmental footprint, such as electricity consumption, system production, and chemical usage in the electrolyte solution, were evaluated. Electricity consumption during use has relatively low impact. A sensitivity analysis showed that variations in electricity consumption and location-based energy mixes have limited influence on the overall environmental profile. Production of the SACE system itself is a relatively important source of impacts. Production of electrolyte solution is also a potential source of impact. The study highlights that improving system design, material choices, and extending the system's lifespan are critical to reducing the environmental impact. These findings provide direction for improving the environmental profile of the SACE machining system–and similar systems–with emphasis on reducing upstream production impacts, optimizing electrolyte choices, and enhancing system longevity.

***Keywords-Spark assisted chemical engraving*—Life cycle assessment; Micro-machining; Sustainable manufacturing; Electrolyte; System production**

I. INTRODUCTION

The growing demand for precision machining in micro-manufacturing has driven the development of specialized processes such as Spark Assisted Chemical Engraving (SACE). SACE is particularly useful for machining hard, brittle materials like glass, offering a non-contact method to create intricate features without the mechanical stresses of traditional methods. The SACE process applies a voltage between a machining tool and a workpiece, which is submerged in an electrolyte flow, to create an electrical discharge to heat and machine the workpiece locally, due to reaction with the electrolyte [1], [2], [3].

However, as with any process, there are environmental impacts associated with SACE; analyzing these impacts and understanding their drivers can support sustainable development goals in the manufacturing sector, as it is already happening with emerging circular economy based glass waste revalorization approaches [4]. Towards this goal, it is necessary for researchers and designers to understand the different elements in their systems that contribute to environmental impacts. Life Cycle Assessment (LCA) is a tool for understanding and minimizing the environmental impacts of processes [5]. By assessing the entire life cycle of a system—from raw material extraction to disposal—LCA enables informed decisions about where improvements can be made, and helps to avoid burden-shifting.

While there are LCA studies of machining (e.g., reviewed by [6]), there are no studies applying LCA to the novel SACE system or to micro-machining of glass. In this study, we apply LCA, based on the guidelines of ISO 14040 [7] and ISO 14044 [8] to the SACE system to evaluate its environmental impacts and to provide insight into how system design, material choices, and the lifetime of the equipment can influence the overall sustainability of SACE micro-machining.

II. METHODS

A. SACE system description and data collection

The SACE system under study, illustrated in Figure 1, is made up of a main machine, in Figure 2 and auxiliary systems. The main machine is composed of linear tables (moving the tool), a spindle, the tool machining and materials (metals and polymers). The auxiliary systems include a computer, a screen, an axis controller, a power supply, an oscilloscope, a function generator, and a steel table. The majority of the auxiliary systems are used for precise control of the tool which machines the glass. During the machining, there is a continuous flow (0.25 L / hour) of an electrolyte solution, as well as energy consumption by the machine and auxiliary systems.

The SACE system is a prototype; the components of the SACE and auxiliary systems and their masses were taken from design documents for the prototype. The electricity

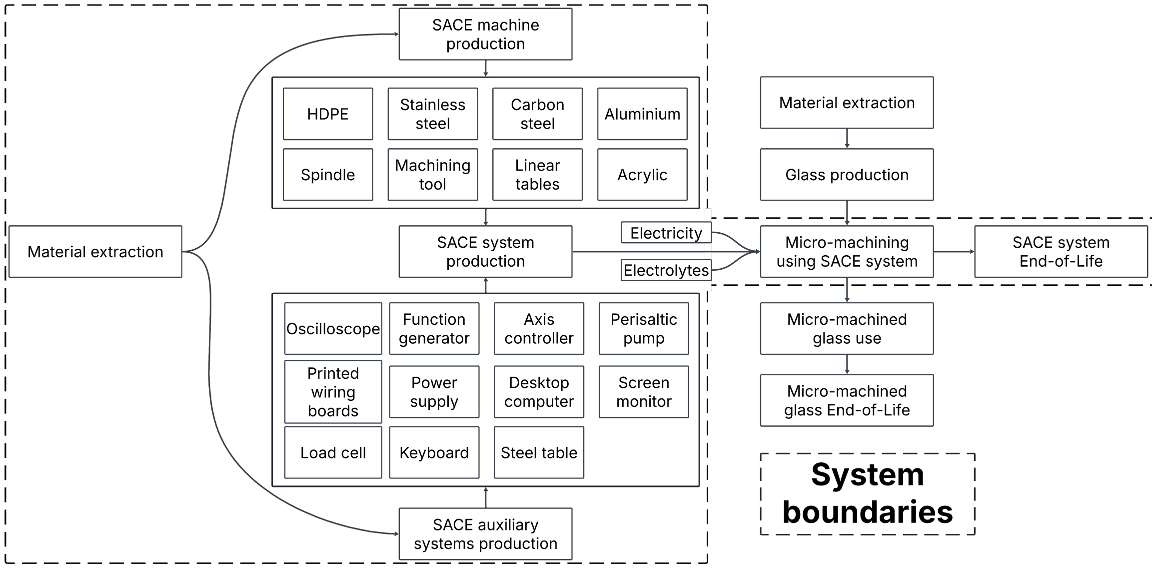

Figure. 1. System model and boundaries

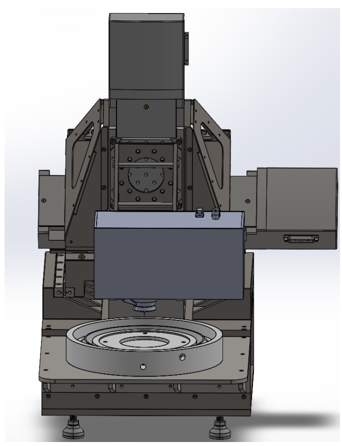

Figure. 2. SACE machine 3D representation

consumption of the system has been measured during two machining runs, each for three hours. Power required by the system was relatively constant during sampling, regardless of cutting speed or applied voltage; therefore, constant power was assumed. The electrolyte consumption was provided by the laboratory staff.

B. Life cycle model description and data collection

The goal of the LCA model is to identify potential environmental issues and solutions associated with the SACE system. We evaluate a functional unit of one hour of SACE machining. In the system, as shown in Figure 1, the production of the SACE machine and components, the auxiliary systems, and electrolytes were included in the system boundaries. Consumption of electricity and electrolyte solution are also included. The production and the EoL (End-of-life) of the workpiece are only considered in one part of the system that will be explicit, in the others, they are not taken into account.

The model has been created using the *openLCA v2.4* [9], the database *ecoinvent v3.7* [10] and the method for calculation of impacts is *Impact World+ v2.1* [11]. LCA results in this method are available for individual impacts (e.g., short-term climate change category, which is commonly referred to as the carbon footprint), and aggregated to overall ecosystem quality impacts or human health impacts.

C. Modeling assumptions

As is consistent with other LCAs of machining, we found proxies for the components of the system without direct matches in the life cycle inventory. Many of the auxiliary systems are electronics without matches; therefore, they were modelled as computers with a few differences: the axis controller was modelled as a desktop computer (i.e., without screen) without a hard disk, a CD/DVD player, or a lithium battery ; the oscilloscope and function generator were modelled the same way, with one difference: the network cables and outlets were not considered. The weights of SACE auxiliary systems were scaled relative to the weight of the model used in the ecoinvent process, following (1).

$$impact_{element} = impact_{model} * \frac{weight_{element}}{weight_{model}}. \quad (1)$$

One exception to the above is the computer screen, for which the scaling has been done using screen size (discussed in Section III.C).

We were unable to find adequate proxies for the load cell, the spindle or the machining tool (which are all low mass and likely made of typical machining materials), so they were not considered. The production and the use of ventilation were not considered, nor were the emissions of particles, to water and air, produced during the SACE process, based on the professional judgment of the laboratory staff.

Given the novelty of the system, assumptions are necessary regarding end-of-life (EoL). The EoL of the SACE machine itself was approximated using the EoL of its constituent materials, specifically polymers and metals. Data from Montreal's residual waste streams [12] were used to estimate recycling rates: approximately 45% of metals and 18% of plastics are recycled, while the remaining 55% of metals and 82% of plastics are sent to landfills. We have made the assumption, consistent with some LCA approaches, that recycled materials are assigned no impact nor 'credit'. The rest of the materials were assigned specific processes representing disposal in sanitary landfills (also known as engineered landfills), the predominant landfill type in Quebec, as close to 90% of wastes are disposed of in sanitary landfills [13].

For auxiliary components modelled as a modified version of a computer (excluding certain elements), the EoL of a standard computer from the ecoinvent database was selected. The same approach was applied to the keyboard, monitor, and printed wiring boards. However, certain components, such as the peristaltic pump and power supply, lacked detailed EoL data, and insufficient information was available to model them accurately, so no EoL has been considered. However, the EoL of these components is unlikely to affect the overall model.

A sensitivity analysis (not shown) was conducted on the impact of wastewater treatment, which was ultimately excluded due to its negligible contribution to various impact categories.

III. RESULTS

This section presents selected results from the LCA model. We include both single impacts, in order to highlight individual concerns (e.g., climate change or land use), as well as overall ecosystem quality and human health. We do not present the contributions of individual impacts to overall impacts; however, we note that climate change (both short and long term) is typically one of the largest contributors to ecosystem and human health impacts.

A. Impact of an hour of SACE use

Each hour of SACE operation emits approximately 0.4 kgCO_2eq. The largest contributions to environmental impacts, as it is shown in Figure 3, stem from, in order of significance, the production (and EoL) of the SACE system, followed by the production of potassium hydroxide, sodium hydroxide, and, lastly, electricity consumption. There are exceptions, e.g., for land use impacts, where electricity use is important; or for ozone layer depletion (data not shown), where sodium hydroxide production is a key contributor due to emissions of carbon tetrachloride.

Quebec's electricity mix relies predominantly on hydropower [14]. While this type of energy generation has notable impacts on land use due to the areas required for dams, it remains a relatively minor contributor (5-15%) to the overall environmental impacts in this study. We nonetheless show land use because it shows different trends from other categories (water scarcity impacts have a similar profile as land use ones). For context, the electricity mix of the United States (US) has a broader mix of sources and much less hydropower; per kWh, it is 20 times more impactful for climate change and human health, 35 times for particulate matter formation and 8 times for ecosystem quality but 5 times less impactful for land use.

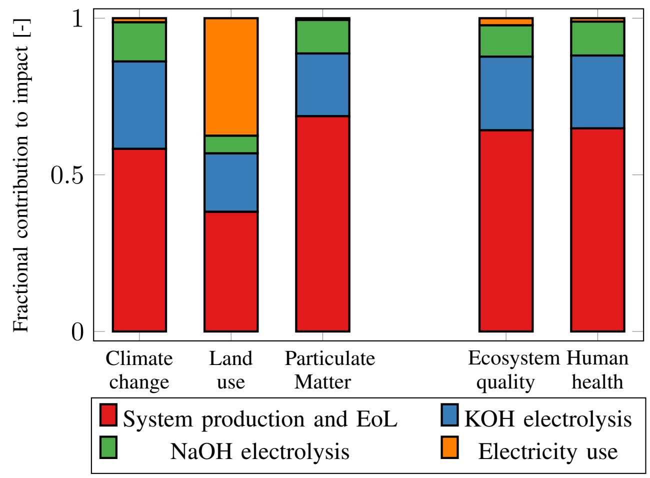

Figure. 3. Contribution to environmental impacts from different processes, for 1 hour of SACE use.

B. Comparison with glass

Although we focus on the environmental impact of one hour of SACE operation, it is important to contextualize this impact within its actual or potential applications. We thus compare the impact of SACE machining with the production and disposal of a workpiece–glass to be machined. This glass workpiece, made of borosilicate glass, was machined in the laboratory for an application to separate microplastics in a solution. The piece has dimensions of approximately $5\text{ cm}\times 7\text{ cm}\times 0.3\text{ cm}$, and a weight of 27.4 g. It was machined on the SACE system for 18 hours. For this specific workpiece, the contribution of the glass production itself is negligible: SACE machining contributes from 97.7% to 99.8% of impacts across all impact categories (data not shown).

To further evaluate the relative importance of glass production, a hypothetical scenario involving a workpiece with a mass of 1 kg, machined for 1 hour was considered. In this case, the contribution of SACE machining ranges from 6% to 41% of the impact, depending on the impact category. For categories such as climate change, human health, and ecosystem quality, the machining contributes between 16% and 19%. Therefore, even in the extreme case of a high-mass workpiece and minimal SACE use, the machining process remains a significant contributor to overall impacts.

C. SACE production

The SACE system includes both the SACE machine and its auxiliary systems; the production of the components with high mass and/or involving electronics is a major contributor to overall environmental impacts. Figure 4 shows the relative contribution of the production of the screen, aluminium,

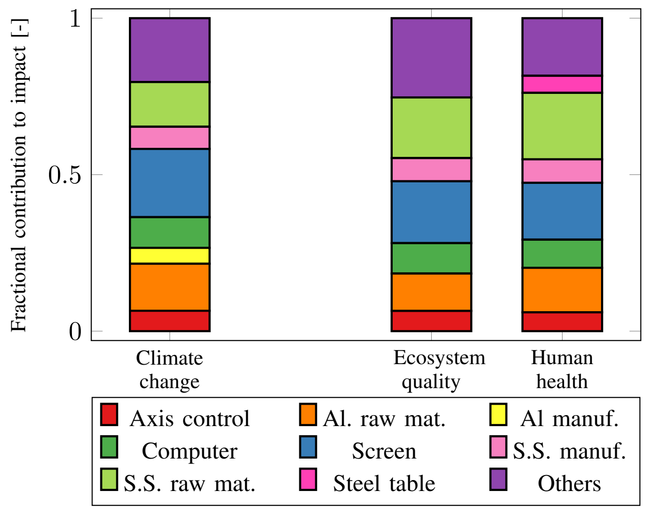

Figure. 4. Contribution processes to SACE system production and EoL, (Al=Aluminium, S.S.=Stainless Steel)

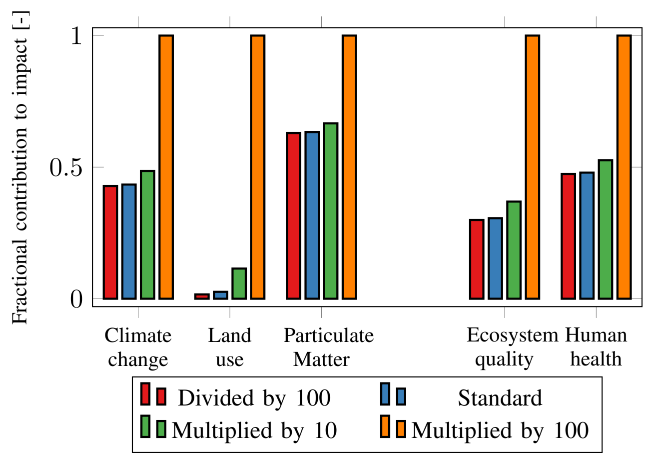

Figure. 5. Sensitivity analysis on electricity

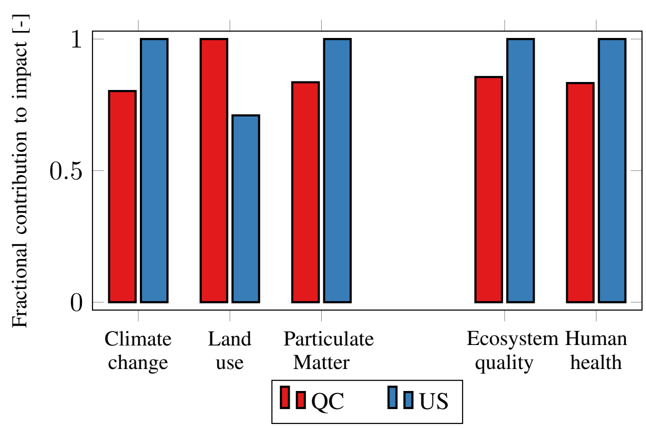

Figure. 6. Sensitivity analysis on SACE use location

stainless steel, computer, and axis controller, as well as the processing of aluminium and stainless steel to the production (and EoL) of the SACE system. Any process contributing less than 5% has been grouped under the "Others" category.

The importance of aluminium and stainless steel production is expected, given the resource- and energy-intensive nature of metal manufacturing. However, one potentially surprising contributor among the top impacts is the production of the computer screen. This has been observed in other LCAs of computer equipment, and the carbon footprint calculated in the model aligns with public data provided by Dell [15].

D. Sensitivity analysis

1) Electricity: Although electricity consumption was measured directly, we consider the degree to which electricity could matter under different scenarios, as it is shown in Figure 5. This figure indicates that if the system used 100 times less electricity, the overall environmental impacts would remain almost unchanged. Similarly, if the system consumed 10 times more electricity, the final result would remain largely unaffected.

Even in the extreme case where electricity consumption was 100 times higher, the environmental impact would increase by a factor of between 1.5 to 3.5, depending on the category, except for land use, for which the factor would be 38 – as a result of assuming Quebec electricity.

We also consider the impact of the electricity grid for use of the SACE system. The system is used in Montreal, Quebec, Canada, which has a low-carbon grid due to hydropower. If the location of use is considered in a more carbon-intensive electricity grid, such as the US mix, for example, then figure 6 shows that the total impact of an hour of SACE use has restricted sensitivity to the electricity mix: using SACE in Quebec is 20% less impactful, except for land use, than using it in the US. The contribution of electricity production to the final result, in the case of the US being the location of use, varies between 10% and 20%.

2) SACE Lifetime: The baseline lifetime of the SACE machine is 10000 hours. Figure 7 demonstrates that as the lifetime of the SACE machine increases, its environmental impact decreases (the climate change category is represented, but each category follows the same trend), following an asymptotic trend. This behavior is typical in LCAs, where the longer a machine is used, the more its initial production impact is spread over time [16]. As the machine's lifetime extends, its impact per hour of operation becomes progressively smaller, with the use phase coming to dominate the overall impact. The impact diminishes toward a fixed value, comprised of the auxiliary systems production (whose lifetimes have been assumed constant), electrolyte consumption, and electricity use.

3) Electrolyte composition: During the preparation of the electrolyte solution, either potassium hydroxide or sodium hydroxide can be mixed with distilled water [17]. The choice of chemical affects the environmental impact. Sodium hydroxide is less impactful than potassium hydroxide, with

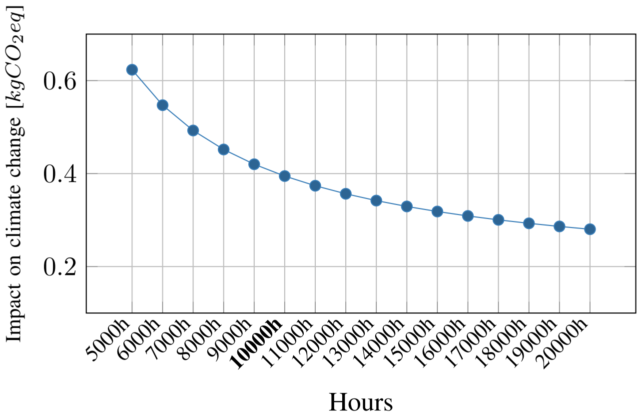

Figure. 7. Impact of changes in SACE lifetime on the impact of an hour of SACE work on climate change

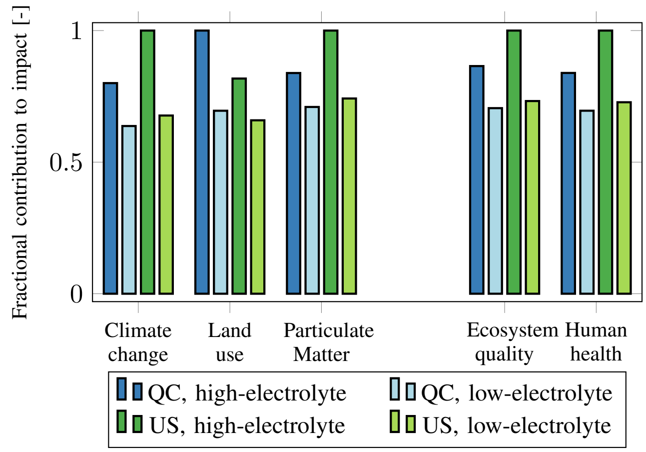

Figure. 8. Impact of different electrolyte scenarios

a difference of about 15% to 25% per kg. This difference arises from the production processes: potassium hydroxide production is more energy-intensive than sodium hydroxide's and requires more potassium chloride than sodium hydroxide requires sodium chloride. Additionally, the production of potassium chloride has a greater environmental burden, in every category, from 1.5 to 3 times more than sodium chloride (data not shown), further contributing to the higher impact of potassium hydroxide.

4) Electrolyte use: Apart from the composition of the electrolyte, other parameters influence the environmental impact of the consumed electrolyte. Two consumption scenarios were considered: in the first, named "high-electrolyte", 2 liters of electrolytes are used every 8 hours; in the second, named "low-electrolyte", only 1 liter of distilled water is consumed every 8 hours, with the chemical quantities (KOH or NaOH) reduced to one fifth of the first scenario. Another important parameter is the origin of the electrolyte production. If produced in Quebec, we again see the impact of hydropower relative to the US mix.

In Figure 8, the blue colors represent a scenario in which the production of electrolytes took place in Quebec, green colors for the US, the dark colors represent the high-electrolyte scenario, the light colors represent the low one. The figure shows that for a given scenario regarding chemical quantities, the location of production results in approximately a 20% difference in impact, with the US having higher impacts in every category except land use. When comparing the two scenarios within the same location (either Quebec or the US), the second scenario consistently shows lower impacts across all categories. This is expected, as the second scenario involves using fewer chemicals and water without substituting with other inputs. The reduction in impacts from the second scenario compared to the first ranges between 15% and 30%.

IV. DISCUSSION

One of the key findings from the analysis is that the production of the machine plays a critical role in its overall environmental profile. While designers may have limited influence over material sourcing, extending the machine's lifespan could have a more substantial effect on reducing environmental impacts than further energy efficiency improvements.

Relative to the production of the system, the impact of electricity use is relatively low – below 1% of the contribution, except for a few impact categories, suggesting that efficiency improvements would have a limited effect on overall system performance. Even in carbon-intensive electricity mixes, the contribution of electricity use to total environmental impacts remains modest, averaging between 10% and 20%. The electricity rarely surpasses the third-largest contributor to overall impacts. This suggests that further improvements to the energy efficiency of the SACE system would yield only limited environmental benefits. Instead, focusing on other aspects—such as extending the machine's lifespan, improving system production efficiency, and minimizing electrolyte consumption—offers more potential for reducing the overall impact.

If the analysis were instead focused on the machined products, we see that machining has a significantly larger footprint than production of the workpiece in real-world applications. Even in a hypothetical scenario involving a heavier workpiece and minimal machining time, the environmental impact of the machining process remains non-negligible.

This analysis underscores the importance of adopting a life cycle perspective. While designers typically focus on improving the system they control, this study highlights that the consumption and the choice of electrolytes play a crucial role in environmental impacts due to upstream production processes. Sodium hydroxide consistently has a lower environmental burden than potassium hydroxide, with a 15% to 25% reduction in impacts across categories.

Designers should also not overlook the environmental impacts of auxiliary systems. In the case of climate change, the impacts of SACE machine production and auxiliary system production are nearly equal. For instance, the 24-inch screen used in the SACE system contributes significantly to the overall footprint. Opting for a smaller screen may seem trivial, but given the screen's significant contribution to the environmental impact, even small reductions in screen size could lead to improvements.

Finally, we note that end-of-life (EoL) of materials contributed very little to overall environmental impacts(accounting for between 0.0001% and 0.01% in most categories). However, if a system uses hazardous materials, EoL can become important. Also, we have assigned no credit for recycling. From a broader perspective, though, an LCA that includes downstream product, made of recycled materials, would show the importance of recycling. Indeed, designing for reuse or repurposing could improve the circularity of the system. This could reduce the system's overall environmental impact by contributing to downstream environmental benefits.

It is important to note that this paper has focused on relative impacts, investigating which systems contribute to impacts, towards the goal of prioritizing efforts to reduce absolute impacts. It would also be instructive to consider absolute impacts in future studies. As the SACE machine is novel, we have not attempted to perform a comparison of this system to other micromachining approaches, nor to other processes, e.g., for producing and distributing microfluidic products at scale.

V. CONCLUSION

The analysis of the SACE micro-machining process reveals key insights for reducing its environmental footprint. While electricity consumption is low, particularly in regions like Quebec with low-carbon grids, the production of the SACE system itself remains the biggest contributor to environmental impacts. The choice of chemicals in the electrolyte, particularly between sodium hydroxide and potassium hydroxide, also plays a significant role, with sodium hydroxide offering lower impacts.

Sensitivity analysis showed that electricity use has a limited effect on the overall results, highlighting the greater importance of optimizing system design, material sourcing, and extending the machine's lifespan. Additionally, auxiliary components like computer screens can have a disproportionate environmental impact.

This study also emphasizes the importance of considering the full life cycle of the system and its materials. The SACE process can account for a significant part of the environmental burden in real-world applications.

In conclusion, improving the environmental performance of SACE machining requires a focus beyond energy efficiency. Efforts should target system production, chemical choices, longevity, and auxiliary components to significantly reduce impacts and contribute to sustainable manufacturing practices.

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