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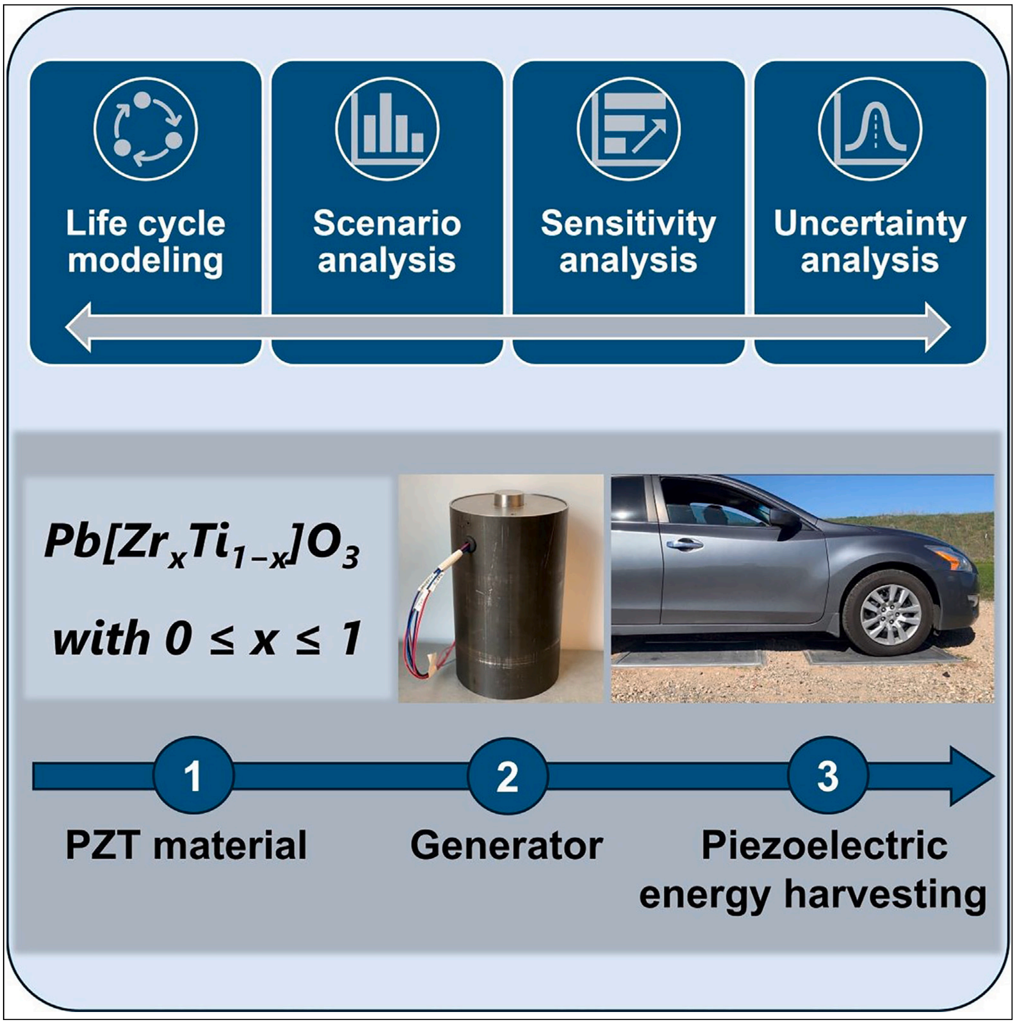

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Highlights

Pilot data were used for the first LCA of piezoelectric energy harvesting in roads

Environmental impacts of PZT piezoelectric in bulk and stack layers were determined

Sensitivity and uncertainty analyses identified conditions leading to lower impacts

Monte Carlo analysis showed impacts ranging from low-GHG to higher than natural gas

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Carbon footprint of piezoelectrics from multi-layer PZT stacks to piezoelectric energy harvesting systems in roads

Amir Sharafi,[1] Cheng Chen,[2] Jian-Qiao Sun,[2] and Marie-Odile Fortier[3,4,*]

SUMMARY

Piezoelectric energy harvesting devices (PEHDs) for road installation are being researched as potentially low-emission electrical generators, but their life cycle greenhouse gas (GHG) emissions must be assessed to guide their design and implementation toward minimizing their carbon footprint. Parametric life cycle assessments (LCAs) of a PEHD, its generator, and the piezoelectric material were performed using data from a pilot-scale PEHD installation. The GHG emissions of the lead zirconate titanate (PZT) piezoelectric stack were determined to be lower than previously reported in the literature at 10.81–15.90 kg CO_{2eq}/kg piezoelectric. The GHG emissions of electricity generated by a PEHD range from 48.65–588.63 g CO_{2eq}/kWh, spanning from similar to renewables to slightly higher than electricity from natural gas. Sensitivity analysis indicated that spatial parameters and the device lifetime had the largest influence on the LCA results. PEHDs installed on roads show potential to be low-GHG emission energy systems.

INTRODUCTION

Electricity generation in conventional power plants is one of the primary sources of greenhouse gas (GHG) emissions driven by human activities.[1] In order to reduce GHG emissions and improve energy security, a diversity of lower emission electricity sources must be developed and adapted to meet the needs of different communities.[2,3] In addition to renewable energy systems that use natural resources such as solar or wind energy, energy harvesting devices, which harness energy from unconventional sources in the environment like waste mechanical energy from human activities, should be considered in the energy transition. One such technology involves piezoelectric materials, which can generate electricity upon bending, twisting, stretching, or compressing when placed under mechanical stress, an ability called the piezoelectric effect.[4,5] Piezoelectric energy harvesting devices (PEHDs) contain multilayer piezoelectric stacks that generate electricity when deformed under a load from a temporary force, both when the stack is squeezed and when released after compression.[6]

PEHDs for road installations are currently being developed at the pilot-scale level as potentially low-emission electrical generators.[7] As vehicles pass over the device installed in a road, they would provide a high-density vertical load that would be converted and magnified as a horizontal pressure on the piezoelectric material, deforming it and consequently generating electricity (Figure 1). There is substantial mechanical energy in the heavy traffic of ground vehicles on highways, roads, and streets, which can be a vast potential source of electricity on the scale of wind farms or solar farms through the use of PEHDs.[8,9]

Although a PEHD would not directly emit GHGs during electricity generation, there are GHGs emitted from the raw material extraction, manufacturing, transportation, installation, maintenance, and end-of-life management steps along its life cycle. A comprehensive tool to determine the environmental impacts of a system from cradle to grave is life cycle assessment (LCA). LCA of emerging technology can also guide design toward minimizing environmental impacts, assist investors in choosing effective projects to fund, and guide authorities in policymaking.[10,11] Emerging technologies in early phases of development frequently lack sufficient analysis to identify their potential environmental impacts, which tend to be determined after installing a system at commercial scale. This can lead to high costs for modification, whereas improving a device during the research and development stage is generally more feasible and less expensive, and faces fewer constraints.[12] Performing an LCA prior to the implementation of a project facilitates adaptable and iterative design of a future commercial scale system toward lower life cycle environmental impacts.

To the authors' knowledge, no LCA has yet been published on piezoelectric energy harvesting systems to evaluate their life cycle GHG emissions and compare them against the impacts of other electricity sources. An LCA can determine whether PEHDs can be categorized as a low carbon footprint energy system, and under what design and implementation conditions. Furthermore, additional data can be

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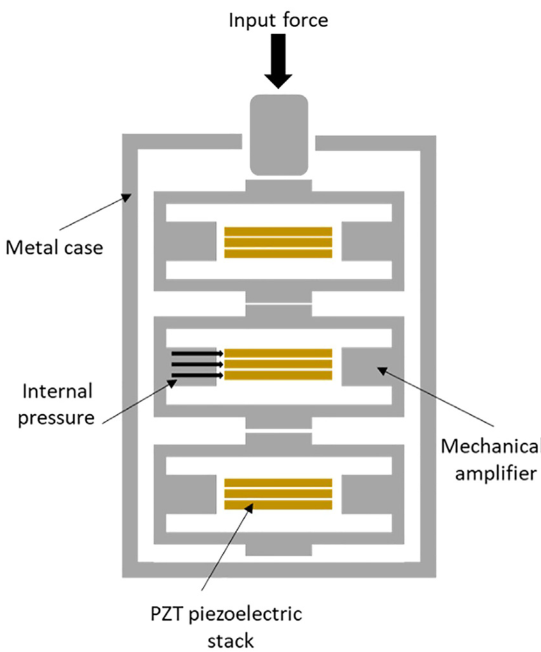


Figure 1. Schematic of the main components of piezoelectric energy harvesting device

obtained on the environmental impacts of the less common material components of the PEHD through LCA, like its lead zirconate titanate (PZT) material.

The PZT material in the generator is a relatively large component of the device, but there exists only one peer-reviewed LCA that has measured the environmental impacts of PZT,[13] and there is no life cycle inventory in known databases for this component. Most uses of PZT are in small quantities in low-power applications such as in medical test devices and monitoring systems as sensors, or in advanced active control systems as actuators, for which LCAs that include detailed information on the piezoelectric element have not previously been published. Unlike in these prior uses, a PEHD relies upon thousands of piezoelectric stacks across the energy harvesting system's length, which could be between 8 and 32 km at commercial scale, thus making it necessary to have highly accurate PZT production impacts to conduct a reliable LCA. The single existing LCA of PZT determined a climate change impact of the bulk piezoelectric material of 55.74 kg CO_{2eq}/kg[13]; however, this value is 10–70 times the impact of manufacturing most ceramics with available inventories in the Ecoinvent 3 database, which undergo similar manufacturing processes as PZT. Consequently, to perform a reliable LCA of a PEHD, both recalculation of the impacts of

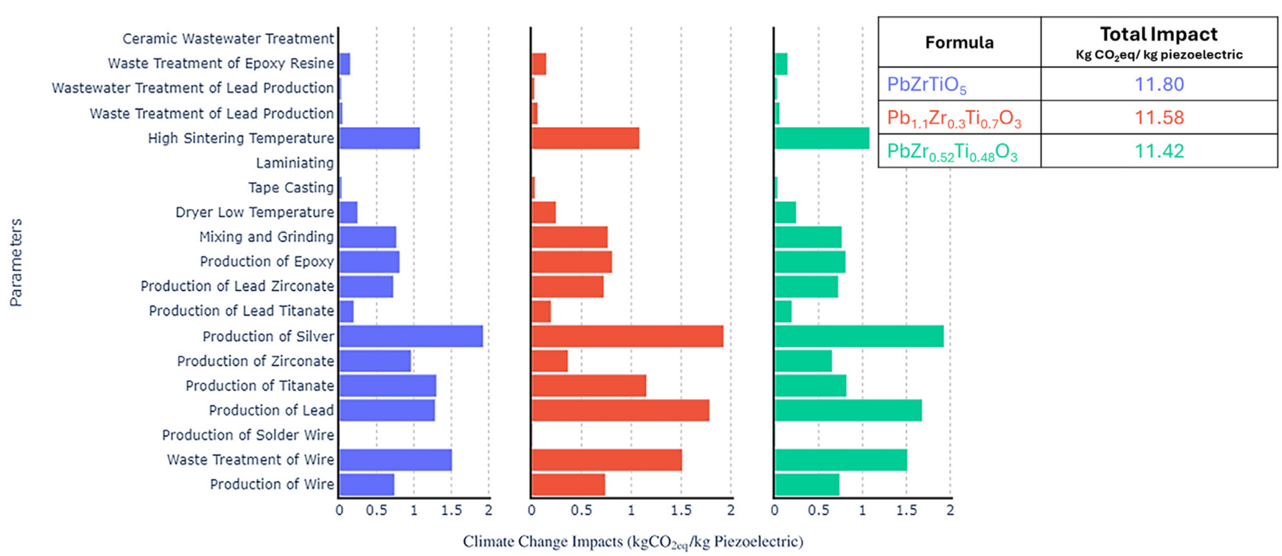


Figure 2. Baseline LCA results of global warming potential for three possible structural formulas of PZT piezoelectric with dimensions of 7 × 7 × 32.5 mm produced by CeramTec (Plochingen, Germany)

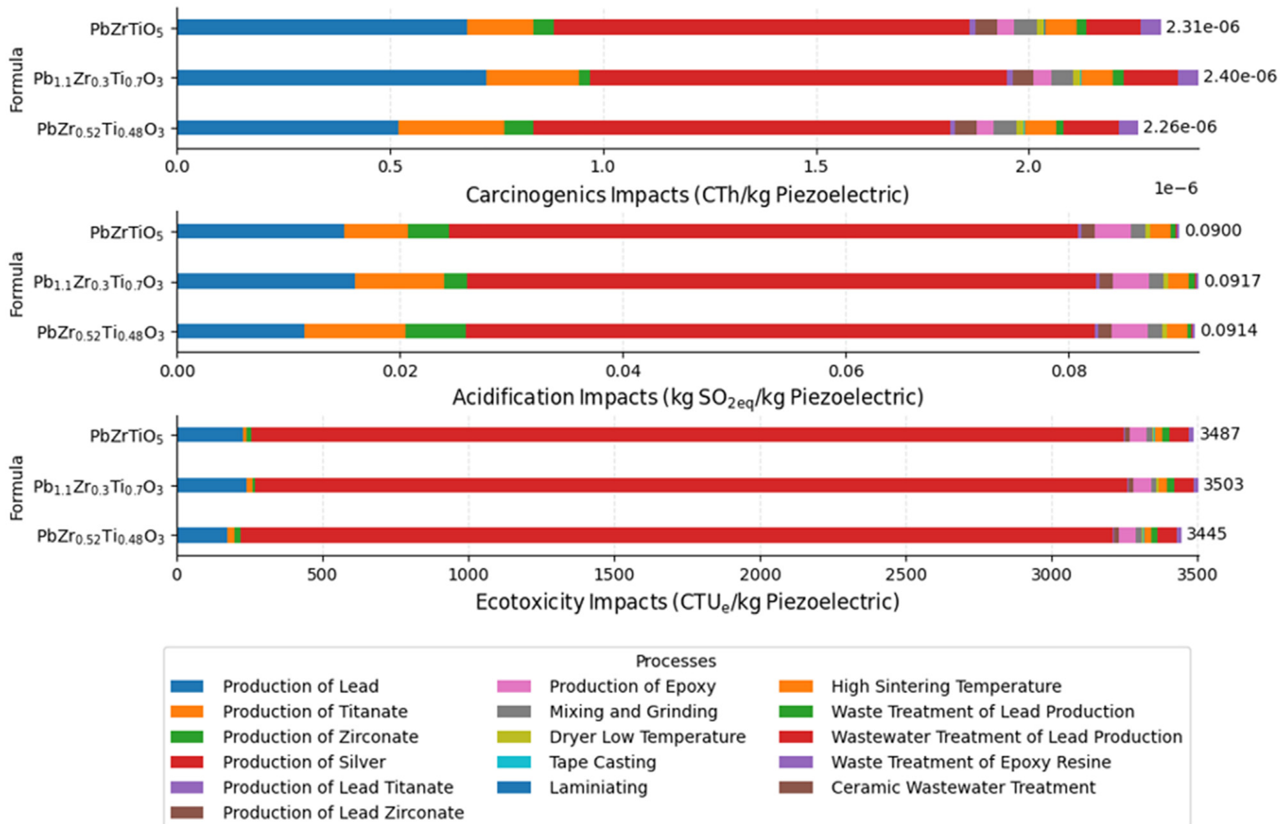


Figure 3. LCA results for acidification, carcinogenics, and ecotoxicity potential for three chemical formulas of the PZT piezoelectric stack with dimensions of 7 × 7 × 32.5 mm produced by CeramTec

producing the PZT for a multilayer stack application and experimental determination of its electricity generation potential under different deformation conditions are needed.

Data quality and availability are a major challenge for LCA of emerging technologies like PEHDs. Because of a high level of data uncertainty in emerging technologies, particularly in the early stages, anticipatory LCA should be conducted to study environmental impacts in possible future scenarios.[11] Research stages can be categorized into technology readiness levels (TRLs). The lowest TRL that can lead to anticipatory LCAs that yield trustworthy results may be TRL 4, which involves the device being validated in the laboratory.[10] Obviously, with the progress of the project to that stage, many decisions have been made that reduce uncertainties, and more accurate data from a pilot-scale prototype or commercial-scale system would be available. Thus, LCA results will be more precise at those levels. Still, applying LCA during the laboratory stage can clarify an estimate of the potential environmental burden in order to decide on the continuation of the project and the next design and scale-up steps.

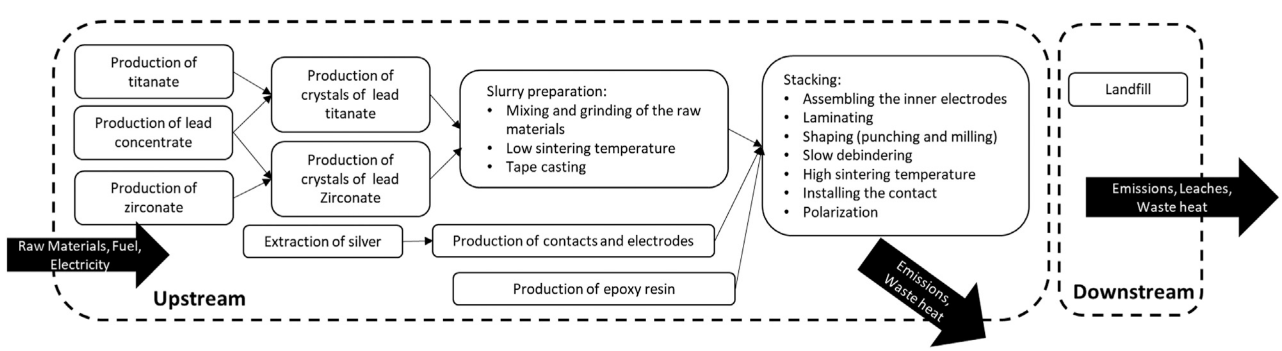


Figure 4. System diagram of the processes included in the LCA model for the multilayer PZT piezoelectric stack

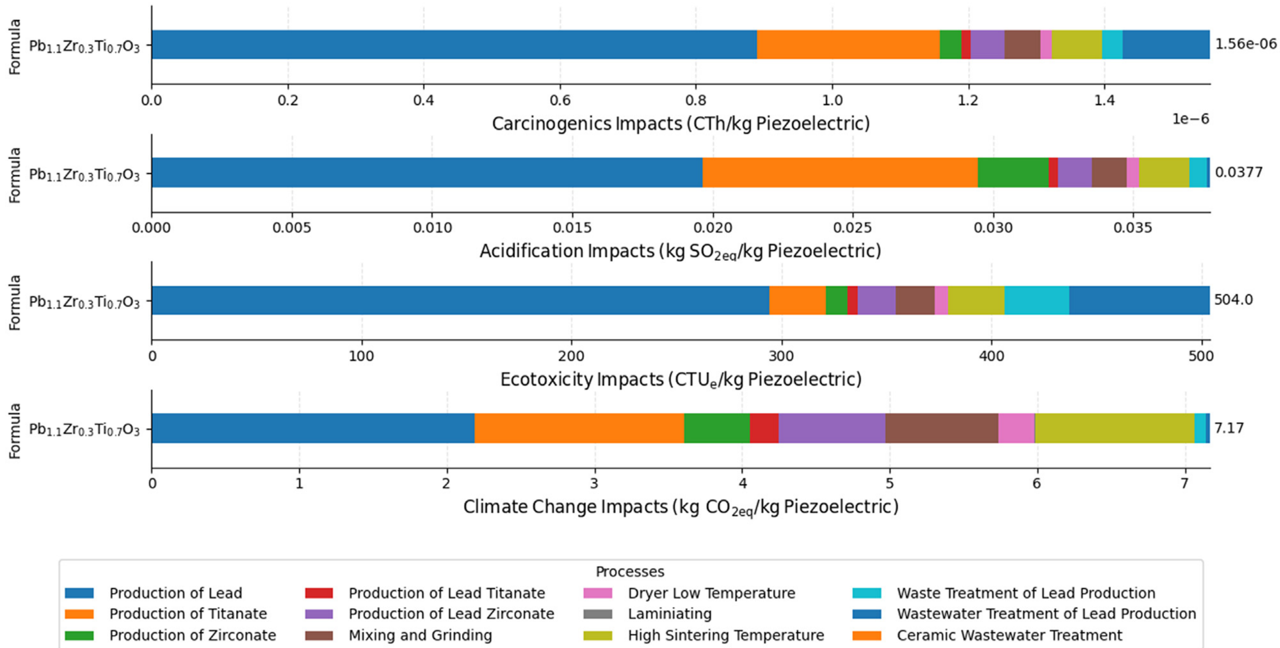


Figure 5. LCA results for acidification, carcinogenics, ecotoxicity, and climate change potential for a single crystal of one chemical formula of the PZT piezoelectric material

We present the first PEHD LCA with data informed by a TRL 4 prototype and a TRL 6 pilot-scale system, both developed and tested at the University of California, Merced.[7,14] In order to provide greater opportunity to use these LCA results to design future PEHDs with lower carbon footprints, the analysis separately reports the environmental impacts of (1) three different chemical compositions for the PZT material that is embedded in the generator, (2) the piezoelectric generator, and (3) electricity generated by the complete PEHD simulated under various operational conditions. The PEHD operational conditions were studied by applying force using an INSTRON machine to simulate street conditions, providing crucial data on the operational steps, which were used along with manufacturing data for the prototype to perform the anticipatory LCA.[7] Ultimately, the results of this study can be used to improve the device to reduce life cycle GHG emissions in the future, through changes in design or implementation decisions.

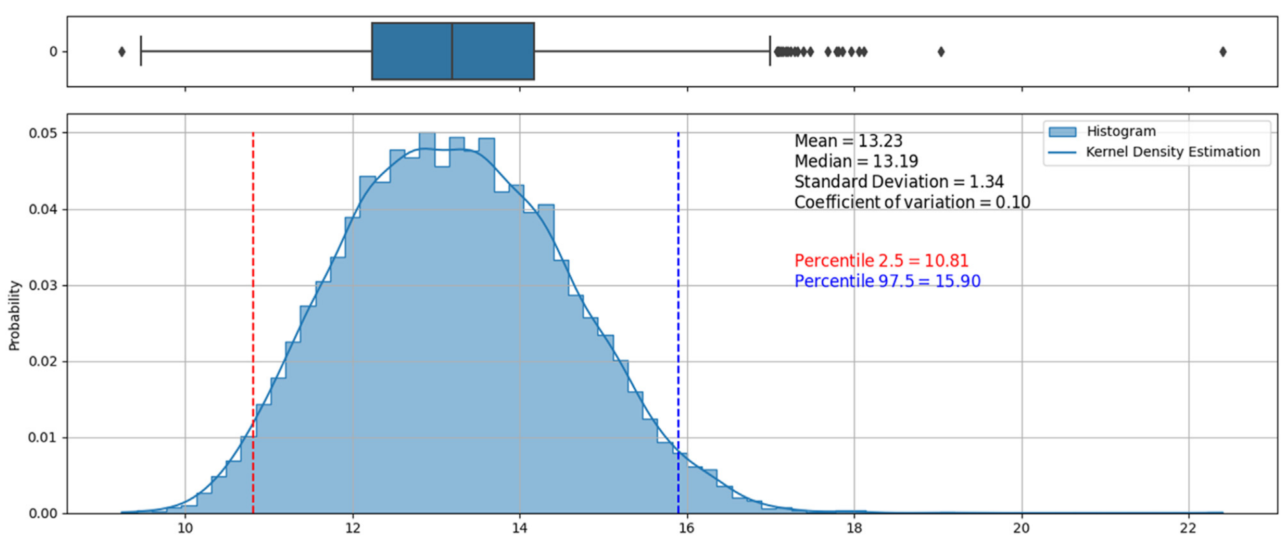


Figure 6. Monte Carlo analysis results for life cycle climate change impacts of PZT piezoelectric stacks with a chemical structure of $Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$

The span of the bar graph above indicates the 95th percentile range and the points indicate outliers.

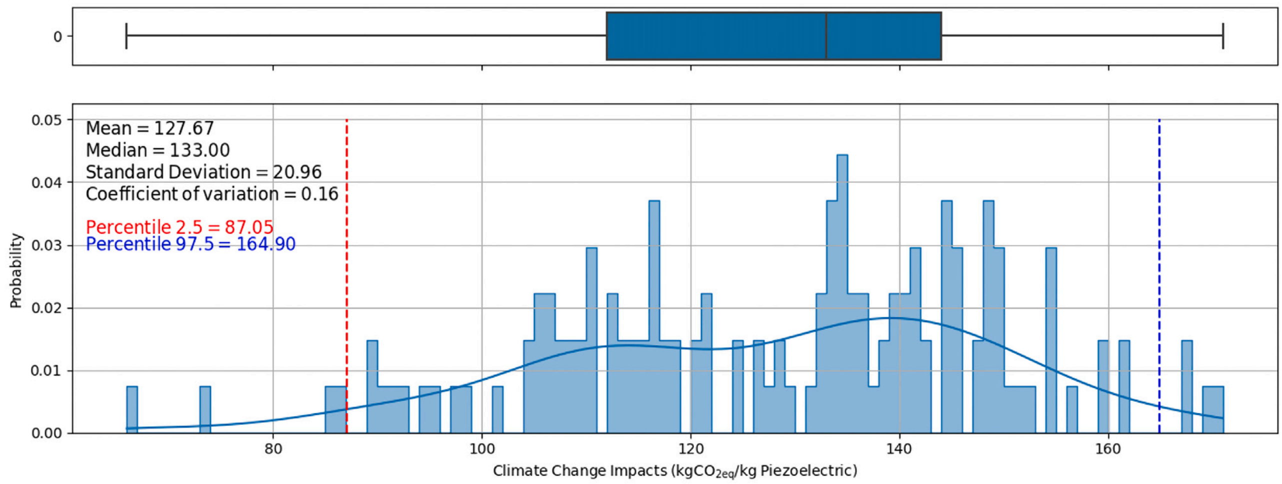


Figure 7. Distribution of generated voltage by the generator under a load of 1350 N
The full range is depicted by the bar graph above.

RESULTS AND DISCUSSION

Piezoelectric LCA results

The LCA scenario results show the differences between the three chemical formulas for the PZT piezoelectric material of $PbZrTiO_5$, $Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$, and $PbZr_{0.52}Ti_{0.48}O_3$ in the four life cycle impact categories assessed: global warming potential, acidification potential, carcinogenics, and ecotoxicity (Figures 2 and 3). The composition that yielded the highest impacts overall, $PbZrTiO_5$, showed a global warming potential of 11.8 kg CO_{2eq}/kg of PZT material. Because piezoelectric materials are capable of operating for billions of cycles during their lifetime,[15] this evaluation only focused on the upstream and downstream impacts associated with its materials, excluding its operational stage (Figure 4).

It was expected that most of the variations in results would appear in the preparation of the material, because the production processes are nearly identical to those of other ceramics. However, the impacts emerging from the manufacturing of PZT components are higher than those of ceramics. The environmental impacts of the production of PZT piezoelectric material at lab-scale were evaluated in this study, while industrial-scale production would most likely be more efficient in its energy consumption, especially for high-temperature sintering, mixing, and grinding. Beyond these differences arising from economies of scale, PZT piezoelectric requires silver electrodes and wires that have relatively high environmental impacts and that are not within the scope of ceramics production. There is a substantial difference between the results of this study and the impacts of the Ibn-Mohammad et al. (2016) study,[13] which reported 55.74 kg CO_{2eq}/kg for the climate change impact and 0.23 kg SO_{2eq}/kg for acidification potential for piezoelectric material, nearly 5 and 2.5 times as high, respectively, as these LCA results. In their study, the highest impacts across multiple impact categories originate from electricity use at about 90%,[13] which is inconsistent with producing a substance from the ceramic family.

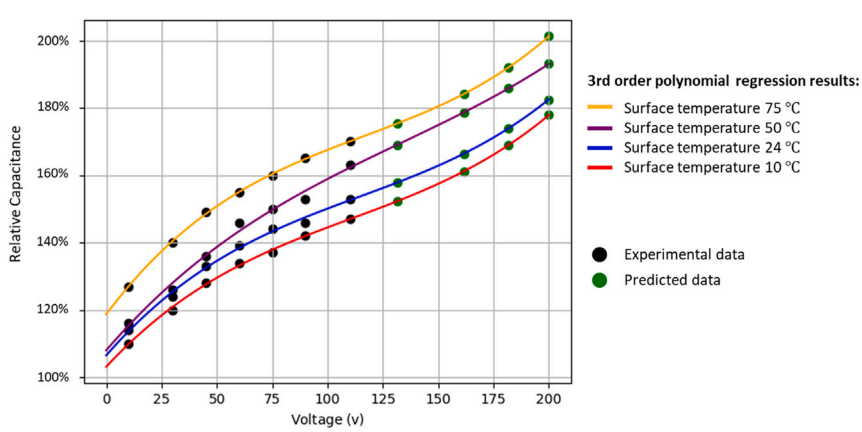


Figure 8. Relationships between the applied voltage and capacitance of the PZT piezoelectric at four surface temperatures

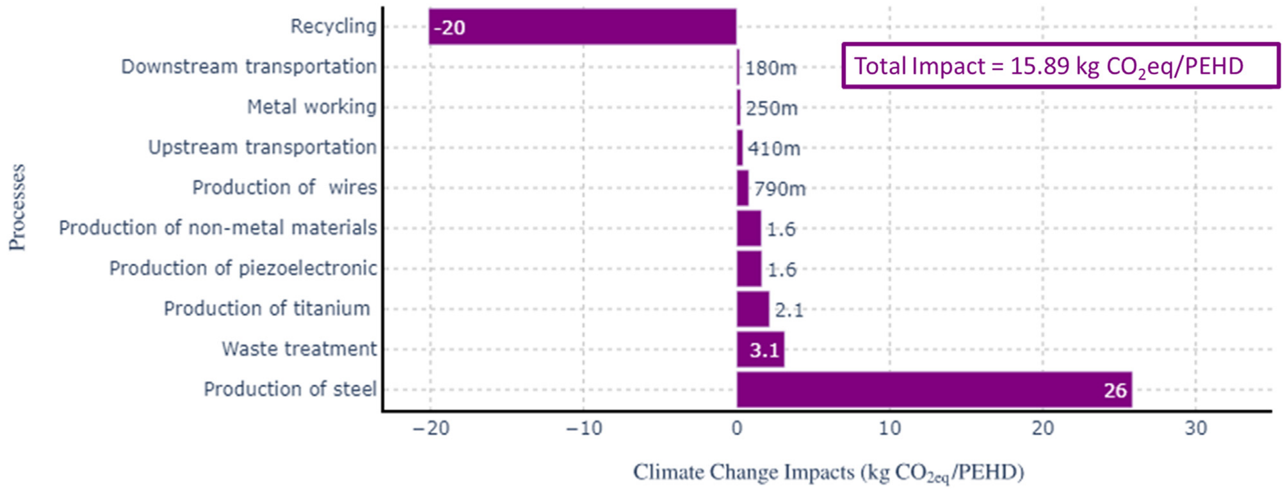


Figure 9. Baseline life cycle GHG emissions of the generator, by life cycle stage excluding operation and maintenance

The highest impacts calculated among the three chemical compositions of the PZT material were 0.0917 kg SO_{2eq}/kg for acidification potential, 2.40 × 10^{-6} CTUh/kg for carcinogenic potential, and 3,503 CTUe/kg for the ecotoxicity potential (Figure 3). The highest contributing process for the acidification, carcinogenics, and ecotoxicity potential of PZT is the production of silver. Silver is an auxiliary component used in the electrodes, which could potentially be replaced by copper or other conductors in future designs. Still, the life cycle GHG emissions of silver production may be even higher than the 196 kg CO_{2eq}/kg[16] reported by Nuss and Eckelman (2014) and modeled in this study; for example, using the life cycle inventory for silver production from Ecoinvent 3 instead would add 3.4 kg CO_{2eq}/kg PZT material to the total impact. In addition, the effects of landfilling and leachate leakage may also vary from the results of this model due to limited data availability on actual leakage.[17]

As a result of the high contribution to the impacts from auxiliary components like wire or silver that are needed to conduct the generated electricity, the environmental impacts on a kg basis of the same PZT piezoelectric products would differ for various shapes. Therefore, LCA results for a single crystal of PZT piezoelectric of $Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$ are also reported in Figure 5 for all four categories to facilitate use in future studies of PZT in energy harvesting systems or other sectors that may use various shapes and auxiliary components. The single crystal LCA excludes silver, wires, and other components beyond a PZT layer, as well as the manufacturing processes involved in producing a stack from the PZT layers. The highest baseline LCA results of this single crystal are 0.0377 kg SO_{2eq}/kg for acidification potential, 1.56 × 10^{-6} CTUh/kg for carcinogenic potential, 504 CTUe/kg for the ecotoxicity potential, and 7.17 kg CO_{2eq}/kg for the climate change potential, which is closer to the potential impacts of ceramics determined from the Ecoinvent 3 database, but still higher. This result is expected due to the use of materials like lead, titanium, and zirconate, which are not included in the traditional ceramics and which tend to have high environmental impacts of production. Among these processes, lead production followed by titanate production contribute the most to the life cycle environmental impacts of the crystal (Figure 5).

The influence of uncertainties in background data and variable parameters was examined by applying 10,000 Monte Carlo iterations for the $Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$-based piezoelectric stack to check the reliability of the scenario analysis results and the level of uncertainty in the system. The outcomes of this Monte Carlo analysis (Figure 6) illustrate that the possible range of impacts between the 2.5th percentile and the 97.5th

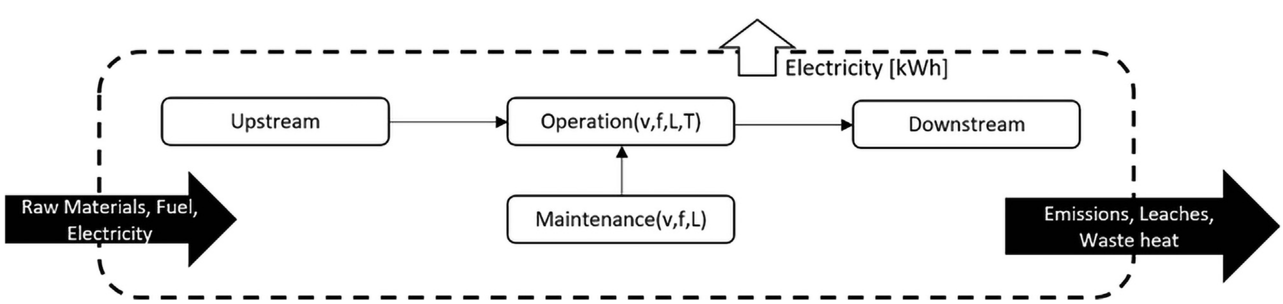


Figure 10. System diagram for the LCA of PEHD model with electricity generation and maintenance steps, in which v is measured voltage which represents the weight of passing vehicles; f is frequency of dynamic load which represents traffic flows; L represents lifetime; and T is the temperature of the road surface

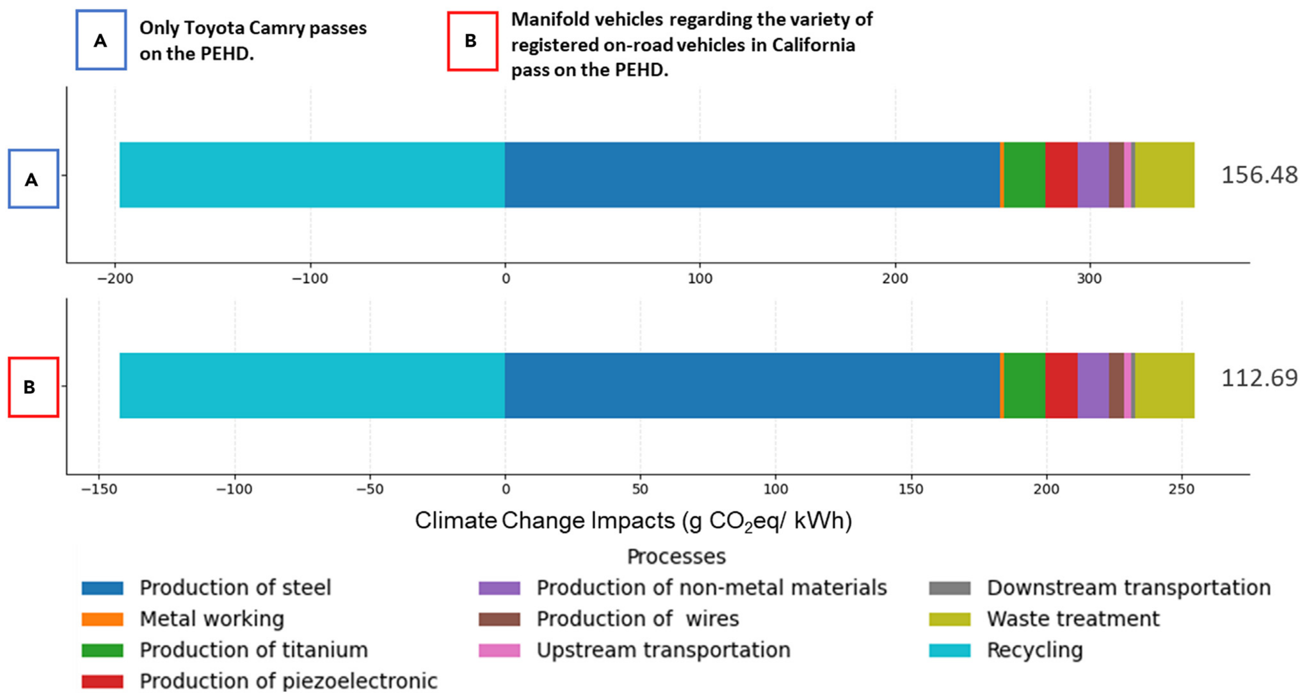


Figure 11. Life cycle GHG emissions of the PEHD generator with a lifetime of 45 years under busy street conditions

(A) With recorded data of generated electricity in the laboratory.

(B) With a simulated load of manifold vehicles registered on-road vehicles in California.

percentile is 10.8–15.9 kg CO_{2eq}/kg. Also, the median and mean of the Monte Carlo results are similar at approximately 13.2 kg CO_{2eq}/kg, while the baseline LCA result is slightly lower at 11.6 kg CO_{2eq}/kg piezoelectric.

Generator LCA results

To subsequently add the operation of the generator (electricity generation) in the LCA model, the relative capacitance of the piezoelectric was estimated in the range of 100–200 V by applying a third order polynomial regression method in Python to experimental data collected on the PZT piezoelectric in the range of ~10–200 V (Figures 7 and 8).[18] The maximum electrical power structurally secure for a PEHD to generate electricity is around 200 V. The surface temperature of a road during the day is higher than the air temperature of the surrounding environment; therefore, temperatures of 10°C, 24°C, 50°C, and 75°C were tested. Because the road temperature affects PZT piezoelectric capacitance and thus the electricity that would be generated (Figure 8), a more precise representation of a PEHD in practice would be possible from measuring the temperature over time at a prospective installation location.[19]

The life cycle climate change impact for the generator was first obtained by performing an LCA scenario analysis including only the upstream and downstream stages (without operation and maintenance) scaled to a functional unit of one PEHD generator. The cumulative GHG emission for these two life cycle stages of the generator for a PEHD was calculated to be 15.89 kg CO_{2eq}/PEHD (Figure 9). The highest contributing process to these GHG emissions is the production and manufacturing of steel at 26 kg CO_2eq/PEHD, followed by waste treatment of the system's parts throughout its lifetime at 3.1 kg CO_2eq/PEHD. This result was due to steel comprising 95% of the mass of the device. Furthermore, an additional 10% production of parts made from steel and 20% higher production of titanium parts were included in the baseline analysis to account for the possible need for such components in future maintenance activities.

Because the used steel parts in the PEHD would have been covered with waterproof materials and experience only a minimal probability of abrasion and erosion during operation, they would remain in good condition at the end of the generator's lifespan. Thus, the steel could be recovered and recycled without a notable decrease in quality. As the recycling of steel parts is possible and beneficial both environmentally and economically in this product, a reduction in the total impact by −20 g CO_2eq/PEHD from steel recycling is included in the analysis.

Although only steel recycling was modeled, it would be possible to recycle silver and titanium as well in practice. As the production and waste treatment of these two materials contributed far less to the total climate change impact than the same processes for steel, the recycling of silver and titanium is less likely to lead to substantial reductions in the GHG emissions of a PEHD. Similarly, the transportation steps accrue to only 3% of the total GHG emissions. The result indicates that transportation contributes minimally to the total climate change impact, thus designers have broader options to optimize the PEHD in other aspects beyond minimizing transportation distances.

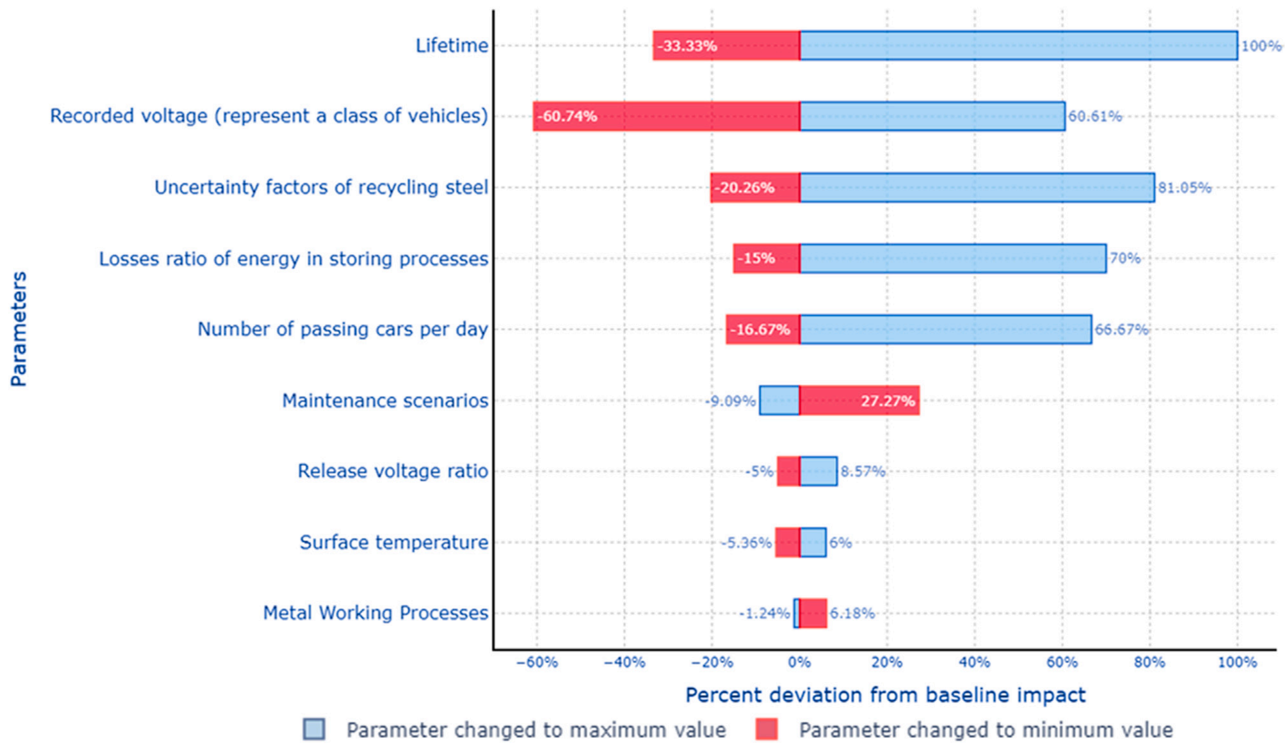


Figure 12. Sensitivity analysis results depicting the percent deviation from the baseline life cycle GHG emissions for a PEHD, showing only the nine most influential input parameters that were varied

LCA results for electricity generation by PEHD

To develop the parametric LCA model for the electricity generated by a PEHD, the electricity generation and maintenance processes were incorporated into the PEHD LCA model (Figure 10), and the cradle-to-grave impacts were rescaled to a functional unit of 1 kWh of electricity generated by a PEHD. The total electricity generated by a PEHD during its lifetime depends on the weights of vehicles, the number of cars passing over the device, the temperature of the device, and the generator's lifetime. For the baseline scenario analyses, the PEHD was assumed to have a 45-year lifetime and a temperature close to 25°C. Busy traffic flow conditions were assumed to represent the dynamic load experienced by the PEHD, and the average voltage of generated electricity was informed by lab experiments applying a load approximately the weight of a Toyota Camry to a PEHD in an INSTRON machine. Under these conditions, the calculated carbon footprint was 156.5 g CO_2eq/kWh (Figure 11A). In actuality, a combination of many types of road vehicles will pass over the device during its lifetime. A second LCA scenario was developed representing this possible combination of passing vehicles as informed by the variety of registered on-road vehicles and their relative numbers in California. This scenario used a simulated mechanical load to estimate the voltage of generated electricity under these conditions, while otherwise maintaining the same assumptions as in the first LCA scenario. With this varied load including heavier vehicles than the Toyota Camry passing over the generator, the amount of electricity generated increased, and the carbon footprint was thus reduced to 112.7 g CO_2eq/kWh (Figure 11B).

Sensitivity analysis results

A one-at-a-time sensitivity analysis was conducted to determine the influence of individual input parameter values on the life cycle GHG emissions of the PEHD. At this analysis level, the impact of both variability and uncertainty parameters were studied to aid in making future decisions and characterizing the performance of the PEHD. The baseline value for the one-at-the-time sensitivity analysis is 145.3 g CO_2eq/kWh, representing the carbon footprint of electricity generated during seasonal conditions (spring) from a PEHD embedded in a busy street with only Toyota Camrys passing over it. The deviations from this baseline carbon footprint caused by individually varying the most influential parameters to their minimum and maximum values are depicted in Figure 12.

Many of the parameters that most affect the carbon footprint in this model were related to the total electricity generation of the PEHD during its lifetime. This is due to scaling GHG emissions to the functional unit of 1 kWh by dividing the cradle-to-grave impacts of a PEHD by its lifetime electricity generation. The amount of generated electricity depends on several variables, including the roundtrip energy storage efficiency, device lifetime, the voltage resulting from a given load, the temperature of the PZT piezoelectric, the number of cars passing over the system, and the class combination of vehicles, which all were among the parameters to which the LCA model was most sensitive. The

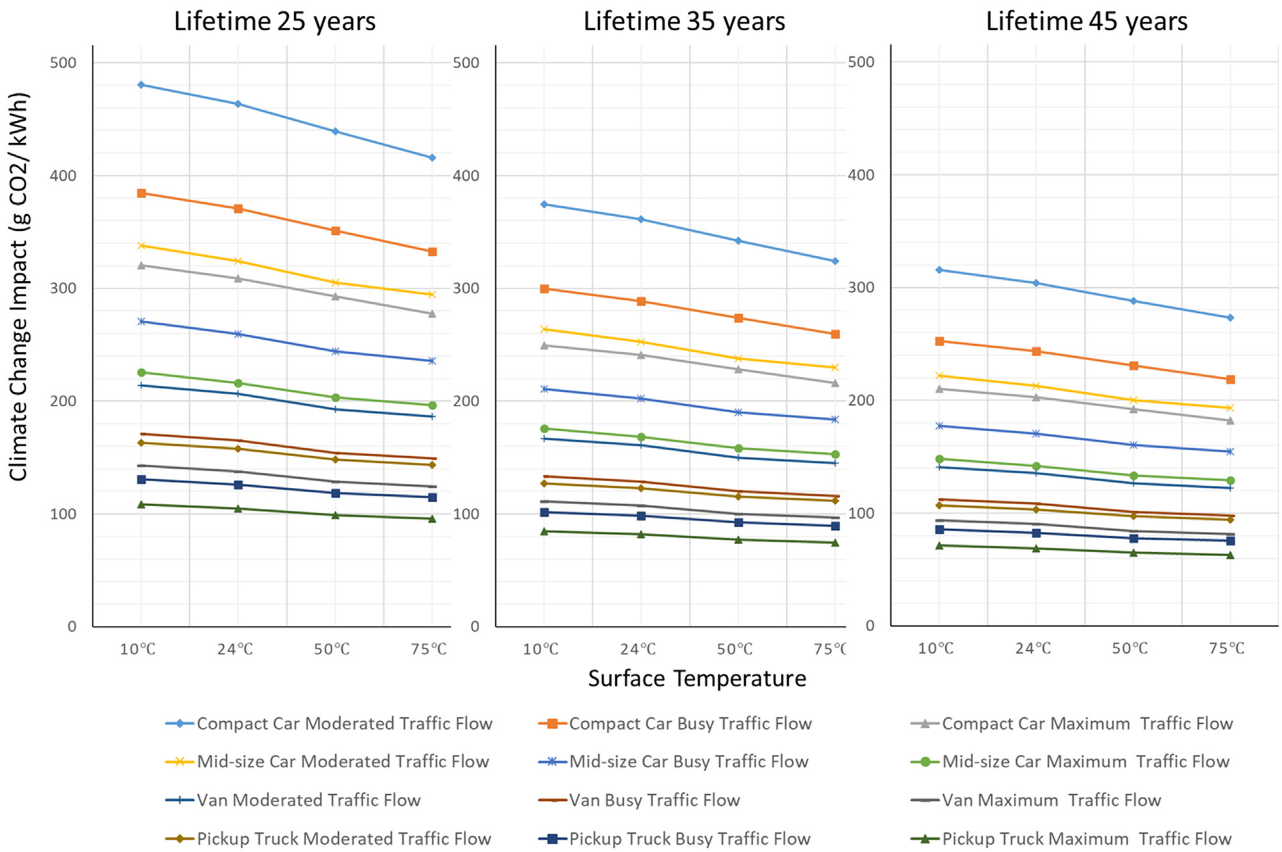


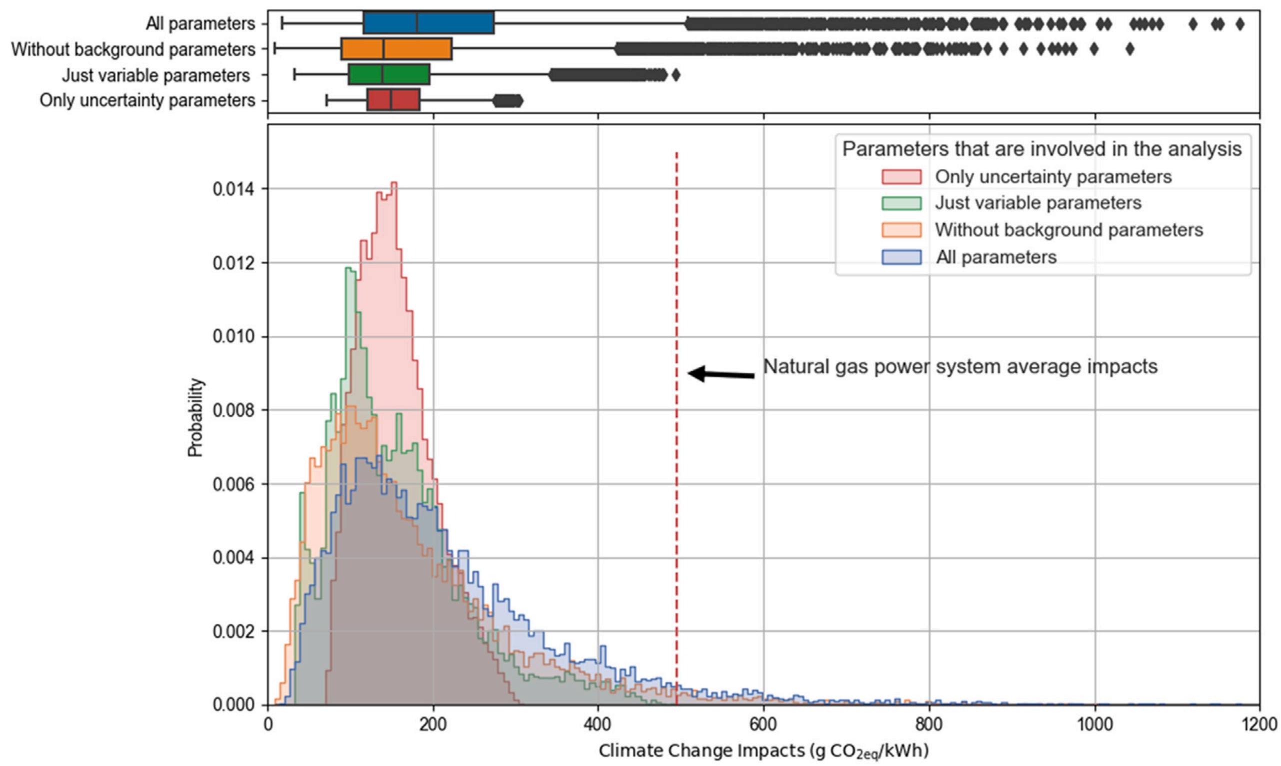
Figure 13. Life cycle greenhouse gas emissions of a PEHD under various combinations of class of cars, surface temperatures, number of passing cars, and system lifetimes

variability in some of these factors causes electricity production to differ seasonally over the course of a year and at different hours of the day. The temperatures and the types and rates of passing vehicles will also differ site to site. Therefore, selecting an appropriate location for the installation of the system is critical to ensuring that life cycle GHG emissions are minimized.

The carbon footprint of electricity generated was noticeably influenced by the values of the PEHD lifetime and the recorded voltage. There is a substantial difference between the minimum and maximum values modeled for the PEHD lifetime (20–60 years) and for the voltage resulting from passing vehicles (110–190 V), for which, as a novel technology, more precise values with smaller ranges would be predicted prior to implementation that would then be further refined after installation and operation at a commercial scale. The design of the circuitry and battery in the system could also optimize the roundtrip efficiency of energy storage in order to decrease life cycle GHG emissions per kWh of electricity provided. This may affect performance in additional ways beyond the relationships modeled, due to the unique way piezoelectric stacks generate electricity in a quick pulse.

Several LCA scenarios were created based on the outcomes of the one-at-a-time sensitivity analysis to produce comprehensive graphs by this scenario sensitivity analysis to depict the performance of the PEHD in various situations. In each scenario, only one class of cars was modeled at a time, including compact cars, mid-size cars, pickup trucks, and vans, but excluding vehicles with more than two axles. The effects of setting the PEHD lifetime to 25, 35, and 45 years; the surface temperature to 10°C, 24°C, 50°C, and 75°C; and the traffic flow to 800, 1,000, and 1,200 vehicles/hour, representing moderate, busy, and maximum flow conditions, respectively, were investigated. In this analysis, the system's maintenance needs increase as the system's lifetime expands or when heavier vehicles pass over the PEHD. The scenario sensitivity analysis results are shown in Figure 13.

The highest carbon footprint resulting from the scenario sensitivity analysis, 470 g CO_2eq/kWh, occurs under a combination of the lowest modeled: lifetime (25 years), weight of vehicle class (compact), traffic flow (moderate), and surface temperature (10°C). This carbon footprint is nearly equal to the reported impact of electricity generated from natural gas.[20] The best performance was observed for a lifetime of 45 years, for which the carbon footprint spans from 60 g CO_2eq/kWh to 107 g CO_2eq/kWh, depending on the combination of passing vehicles. The analysis showed that, under a constant traffic flow and vehicle class, the productivity of a PEHD at a given site could vary from 12% to 15% as temperatures change between daytime and night or from hot to freezing days over the course of a year.



Parameters that are involved in the analysis	Mean	Median	Standard Deviation	Coefficient of variation	Percentile 2.5th	Percentile 97.5th
All parameters	214.23	180.91	141.63	0.66	48.75	588.63
Without background parameters	173.55	140.65	123.05	0.71	34.83	501.13
Just variable parameters	156.14	139.50	81.71	0.52	42.88	377.48
Only uncertainty parameters	155.68	149.75	45.81	0.29	85.31	261.02

* Units of all values in the table are g CO2eq/ kWh.

Figure 14. Monte Carlo analysis results for the PEHD LCA for varying all parameters, only design parameters, only uncertainty parameters, and only variability parameters

The spans of the bar graphs above indicate the 95th percentile ranges and the points indicate outliers.

Monte Carlo analysis results

Monte Carlo analyses of 10,000 simulations each were performed for four facets of uncertainty in the LCA model to investigate the relative influence of different classifications of parameters and characteristics of the system: (1) variation in all input parameters, (2) variation in design and implementation parameters only (without background variability and uncertainty from inventory data), (3) variation in parameters representing uncertainties in the system only (e.g., lifetime), and (4) variation in parameters representing variabilities in the system only (e.g., temperature) (Figure 14).

When all parameters are varied in the Monte Carlo analysis, the potential range of the carbon footprint of electricity from a PEHD can be between 49 and 589 g CO_2eq/kWh (blue bar in Figure 14). The upper band of the range may be reduced by applying proper adjustments on the PEHD design before building the commercial scale system. In the second Monte Carlo analysis, in which the uncertainties of background parameters were excluded to isolate variations in design and implementation parameters, the carbon footprint is between 35 and 501 g CO_2eq/kWh. However, because approaches for handling uncertainty and variability parameters are different, they were next analyzed separately. By comparing uncertainty and variability parameters' Monte Carlo analysis results, it is revealed that the variability parameters modeled dominates the probability distribution of the carbon footprint over the uncertainty parameters. The interval between the 2.5^{th} and the 97.5^{th} percentiles is smaller in the Monte Carlo analysis results for the uncertainty parameters (175) than in the results for variability parameters (334). Further research and development into the design and function of PEHDs to clarify more ambiguities is expected to reduce uncertainty, while the availability of more experimental data will facilitate improved characterization of inherent variability. As many variability-related parameters encompass geographic differences, careful selection of the installation location of a PEHD may play an essential role in decreasing the climate change impact of the system.

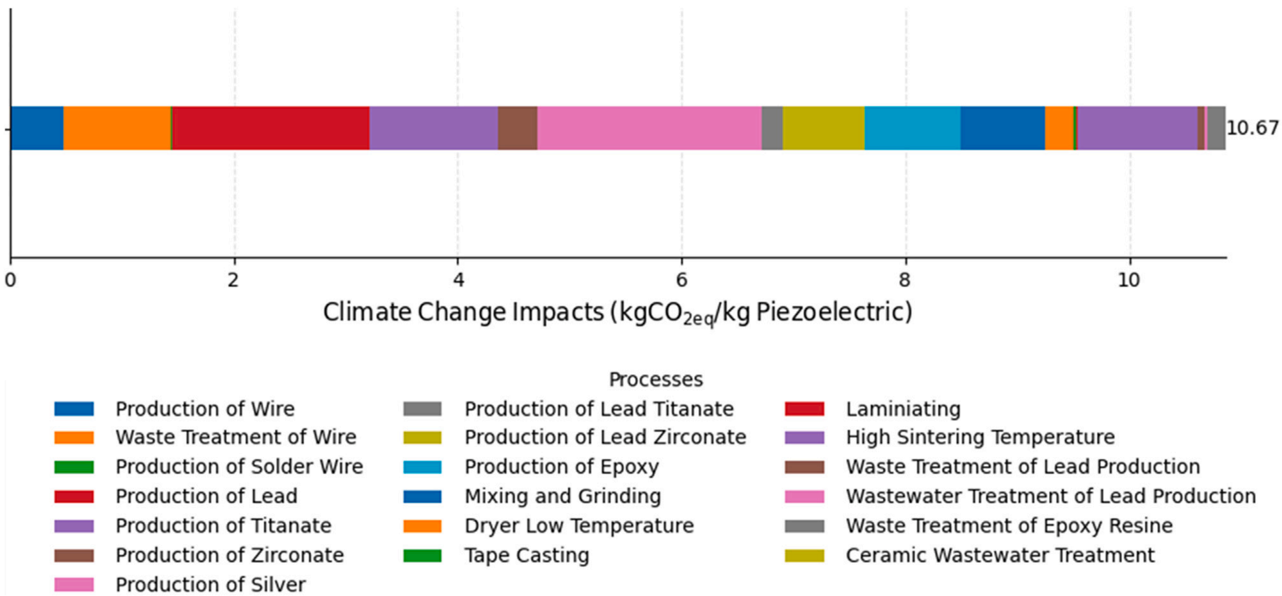


Figure 15. LCA results for the climate change impact of the PZT piezoelectric stack ($Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$) with dimensions of 7 × 7 × 50 mm

Recommended design improvements

As the sensitivity analysis confirmed that the quantity of generated electricity has a substantial influence on the climate change impact of the PEHD, opportunities to optimize electricity generation were investigated. One possible improvement to increase the electricity generated is through using the longest possible PZT piezoelectric stacks in the generator so that the mechanical amplifier of the PEHD does not need a considerable change in shape. A 50-mm, instead of 32.5-mm, length for the PZT piezoelectric ($Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$) with the same cross-sectional area was assessed using the LCA model. The carbon footprint of the PZT piezoelectric was reduced to 10.67 kg CO_{2eq}/kg (from 11.58 kg CO_{2eq}/kg) due to the changes in the weight ratio of components like silver or wires when longer stacks are used (Figure 15).

Upon updating the generator LCA model to reflect this change in PZT piezoelectric stack length, the climate change impact of the modified device showed a higher carbon footprint, increasing from 15.89 kg CO_2eq/PEHD to 16.81 kg CO_2eq/PEHD, as a result of using more PZT piezoelectric stack in each device (Figure 16).

With a PZT piezoelectric that is almost 60% longer with the same size cross-section, the electricity generation characteristics would also change. As determined using Equation 1, the primary capacitance of the selected PZT piezoelectric would be 4.08 mF, which is 70% higher than the original device. By employing methods in Cheng et al. (2020),[7] the measured open voltage of the modified generator for the same amount of vertical load is estimated to be 10% lower than the original design because the internal pressure would be reduced by changing the

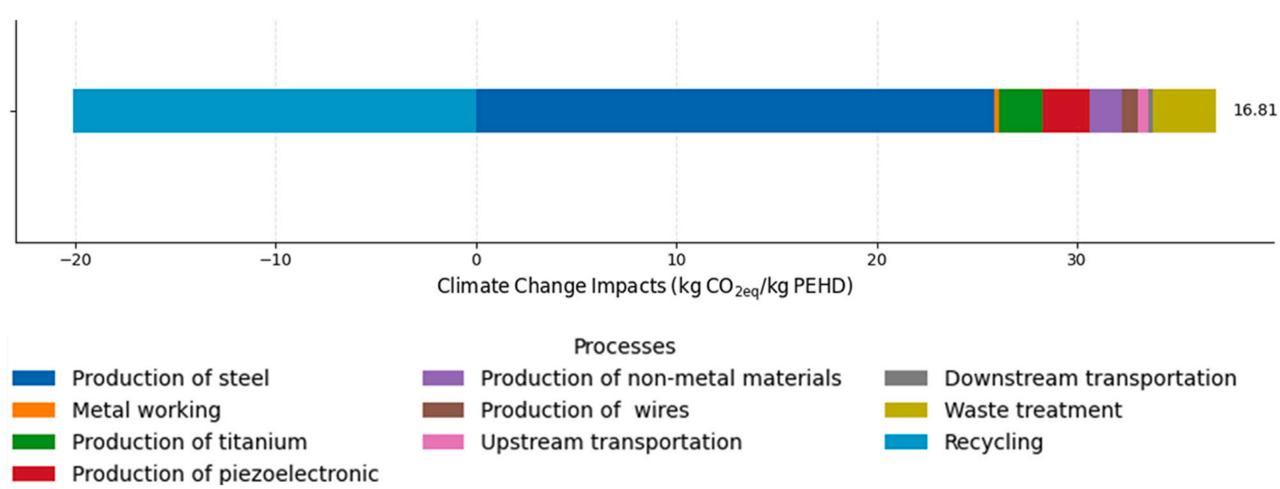


Figure 16. Baseline life cycle GHG emissions of optimized PEHD, sorted by process stage

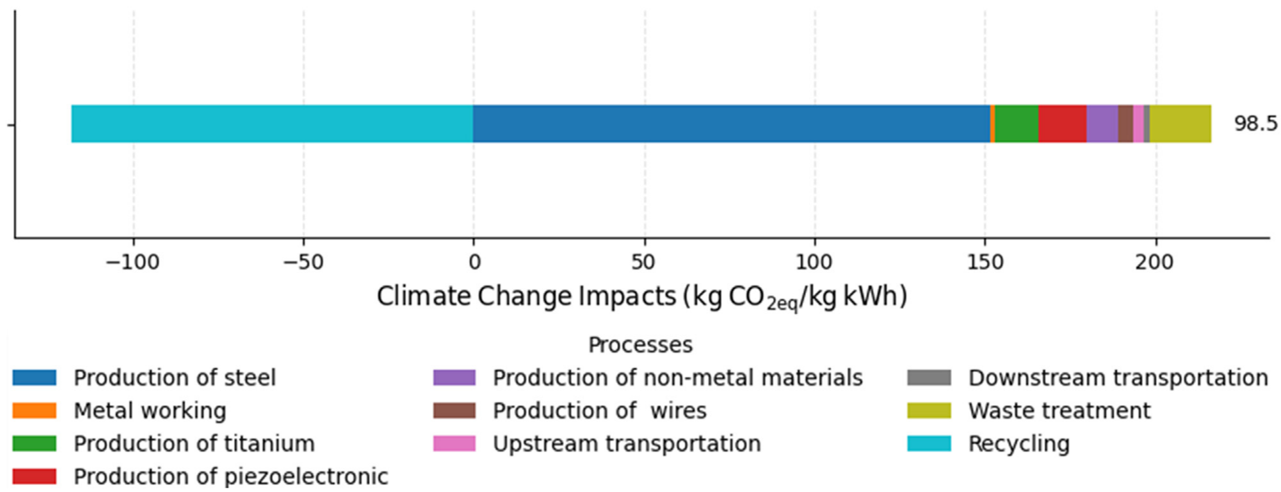


Figure 17. Life cycle GHG emissions of the modified PEHD generator with a lifetime of 45 years and a surface temperature of 24°C, installed in a busy street upon which only Toyota Camrys drive

elasticity of the structure [5]. Despite the decrease in internal pressure on the stack, the amount of generated electricity for the exact same conditions as in the original device would be 70% higher with the modified device with a longer stack. Overall, these changes would affect the climate change impacts of electricity generated by a PEHD. Using the scenario of only Toyota Camrys passing over a PEHD on a busy street at 24°C with a lifetime of 45 years, the carbon footprint would be 98.5 g CO_2eq/kWh (Figure 17), which is lower than the climate change impact of the original LCA baseline outcome (156.8 g CO_2eq/kWh). Therefore, the modeled increase in PZT stack length is recommended to decrease the carbon footprint of electricity generation by a PEHD, especially if location-specific parameters cannot be optimized.

Under specific conditions related to the location installed and specific design parameters, especially those affecting lifetime electricity generation and the steel from production to end-of-life management, a PEHD can be a low-GHG emission energy system. However, it may match the climate change impact of electricity from natural gas under suboptimal conditions; this anticipatory LCA highlights the opportunities for optimization of a novel energy technology toward a carbon footprint within the range of renewable energy sources. The LCA on PZT piezoelectric demonstrated that its impacts are not as high as previously reported; this is important mainly due to its heavy use in a wide range of applications. The PZT results can be applied as life cycle inventory data in other LCAs. Additional methodology details to facilitate use of this model are provided in the STAR Methods, Supplementary Information, Tables 1–3, and Figures 4, 7, 10, 18, 19, and 20.

Limitations of the study

Although multiple scenarios were assessed in this work, as PEHDs are a novel technology, it is possible that changes in design and manufacturing lead to different life cycle GHG emissions for an implemented system. The maintenance frequency was assumed based on the component design standards, and its intensity, frequency, duration, and effect on the system lifetime may differ in practice, thus affecting the life cycle GHG emissions. Several surface temperatures, traffic conditions, and types of vehicles were modeled in this study, but additional combinations of these factors may exist. The climate change impacts calculated in this work may be decreased through installation during road resurfacing or the construction of new roads, which would be accounted for using system expansion methods in LCA.

Table 1. Modeled input parameters and their values for the PZT piezoelectric LCA

Variable parameter	Baseline value modeled for $PbZrTiO_5$	Baseline value modeled for $Pb_{1.1}Zr_{0.3}Ti_{0.7}O_3$	Baseline value modeled for $PbZr_{0.52}Ti_{0.48}O_3$	Units
Percentage of lead in leachate	15	15	15	%
Mass of electrodes and connectors	10	10	10	g/kg piezoelectric
Mass of epoxy resins	168.5	168.5	168.5	g/kg piezoelectric
Mass of lead	426.7	594	558.6	g/kg piezoelectric
Mass of zirconate	235.5	89.5	160.3	g/kg piezoelectric
Mass of titanate	152.7	135.3	96	g/kg piezoelectric

Table 2. Generator LCA model input parameter values

Variable parameter	Units	Minimum value	Baseline value	Maximum value
Mass of the steel tower	kg/tower	10.0	10.4	10.7
Mass of scrap steel	kg/tower	0.95	1	1.05
Mass of tube	kg/tower	1.0	1.2	1.3
Distance from steel mill to the vendor (Los Angeles, CA)	km	100	2800	3271
Distance from steel mill to tube company (Modesto, CA)	km	400	3027	3624
Mass of titanium	kg/tower	0.035	0.045	0.055
Mass of scrap titanium	kg/tower	0.013	0.013	0.017
Distance from titanium company to the machine shop	km	100	2000	4036
Welding line length	m/tower	0.01	0.015	0.02
Mass of piezoelectric	kg/tower	0.1	0.110	0.12
Distance from piezoelectric manufacturer to San Francisco airport (SFO)	km	9000	9288	9500
Distance from SFO to the installation site (Merced, CA)	km	230	240	250
Mass of silicon	kg/tower	0.055	0.06	0.065
Distance from GE Silicones vendor to vender (LA)	km	3700	4146	4500
Mass of rubber seal	kg/tower	0.07	0.075	0.08
Distance of rubber company to vendor (Los Angeles, CA)	km	4000	4330	4500
Mass of rubber cover	kg/tower	0.24	0.25	0.27
Distance rubber town to site (Merced, CA)	km	2000	3000	3650
Mass of heat shrink tube	kg/tower	0.24	0.025	0.26
Length of wire	m/tower	0.8	1	1.2
Distance manufacturing co to port China	km	95	100	105
Distance China to LA	km	9000	10,567	11,500
Distance from vendor (Los Angeles) to site (Merced)	km	400	439	490
Distance from vendor (Los Angeles) to machine shop	km	430	479	530
Distance from site (Merced) to machine shop	km	39	42	45
Distance from tube company to machine shop	km	14	15	16
Distance from system to landfill and recycling	km	20	25	30
Cutting time	s/TI plate	3.25	3.3	3.35

RESOURCE AVAILABILITY

Lead contact

Please contact the corresponding author Dr. Marie-Odile Fortier (marie-odile.fortier@unlv.edu) for further information on the data and methods that are detailed in the Experimental Procedures section.

Table 3. PEHD LCA modeled input parameter values

Variable parameter	Units	Minimum value	Baseline value	Maximum value
Surface temperature	°C	24	50	75
Impact of PZT piezoelectric production	kg CO_{2eq}/kg	8	9.58	16
Release voltage ratio	N/A	0.7	0.85	1.0
Maintenance events during PEHD lifetime	N/A	1	1.1	1.4
Recorded voltage (representing vehicle class)	V	110	160	190
Number of passing cars per day	N/A	14,400	24,000	28,800
Energy storage roundtrip efficiency	N/A	50%	85%	95%
Percent of steel recycled	N/A	0	70%	100%
Lifetime	years	20	40	60

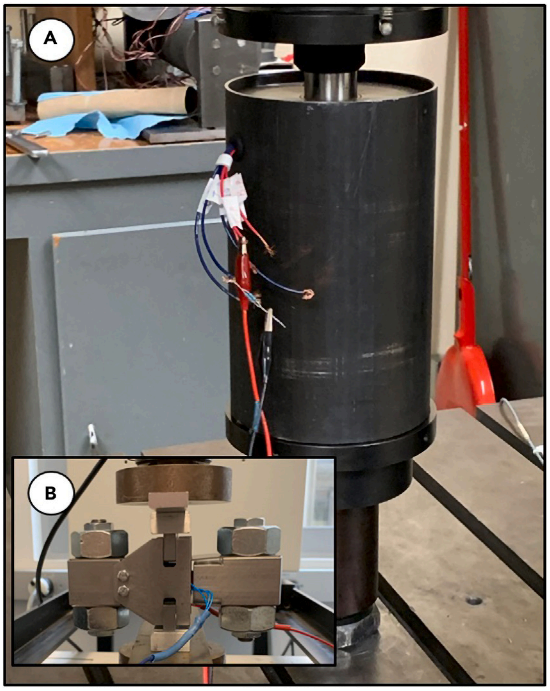


Figure 18. Experimental setup
(A) The piezoelectric generator tested.
(B) The mechanical force amplifier used.

Materials availability

Not applicable in this study.

Data and code availability

- All data reported in this paper will be shared by the lead contact upon request.
- All original code is available in this paper's supplemental information.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

ACKNOWLEDGMENTS

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Figure 19. A waterproofed piezoelectric generator

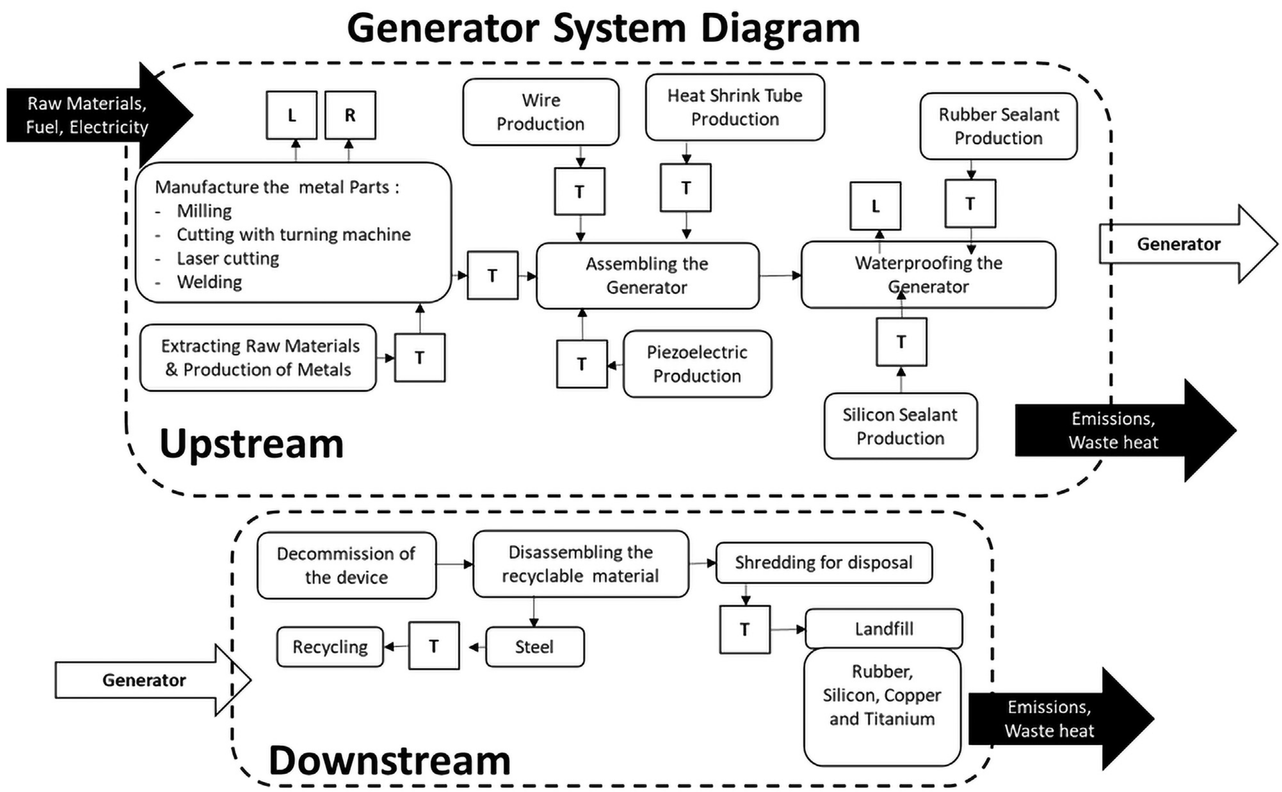

Figure 20. A general overview of the system diagram of the PEHD generator during its production (upstream stages) and its decommissioning (downstream phases), in which T = transportation, R = recycling, and L = landfilling

AUTHOR CONTRIBUTIONS

A.S., J.-Q.S., and M.-O.F. conceptualized the study; A.S. led the formal analysis, investigation, methodology, and visualization with M.-O.F. supporting in these roles; A.S. and C.C. conducted the laboratory experiments component; J.-Q.S. secured funding and resources for the study, while M.-O.F. provided software and supervised the life cycle assessment components of the study; A.S. wrote the original draft of the paper, and J.-Q.S., C.C., and M.-O.F. reviewed and edited the paper.

DECLARATION OF INTERESTS

Three of the authors (A.S., C.C., and J.-Q.S.) have a patent on a high-power-density piezoelectric energy harvesting system (US Patent 11,800,807).

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- METHOD DETAILS
  - Electricity generation experiments with the test subject
  - LCA goal and scope
  - LCA of the multilayer PZT piezoelectric stack
  - LCA of the generator
  - LCA of electricity generated by PEHD
  - Accounting for the possibility of higher vehicle fuel consumption

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110786.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
https://doi.org/10.1016/j.apenergy.2020.115073	Chen et al.[7]	N/A
Software and algorithms		
Scenario analysis, sensitivity analysis, and Monte Carlo analysis codes for parametric life cycle assessment, 2021 first release version.	Fortier, M-O. GERLCA parametric LCA code (2021) https://github.com/GERLCA/GERLCA_parametric_LCA	N/A

METHOD DETAILS

Electricity generation experiments with the test subject

The piezoelectric electricity generator has the capability to absorb a high-density load and transform it into electrical energy. Because the production of electricity by the piezoelectric is dependent on the range of deformation, applying a large force is necessary to generate a significant amount of electricity. Therefore, this generator should ideally be installed where there is a high amount of waste load or pressure available, like under roads or railways, warehouses, or in construction vehicles. This LCA focuses on the generator component of a PEHD that was designed to be placed under a road, as shown in Figure 18A. Even though the system's input will be a high-density load through the weight of cars or trucks, it still is not enough to sufficiently deform the piezoelectric stack. Hence, the generator was designed as a mechanical amplifier structure that converts the sheer load from vehicles' weights to a horizontal force that is almost 11 times larger, shown in Figure 18B, that can compress the piezoelectric adequately. Chen et al. (2020) explained the mechanism of the mechanical amplifier that was used in this generator.[7] In order to determine the relationship between the force applied and electricity generated for the LCA model, the generator was triggered in an INSTRON machine to simulate the conditions of a vehicle passing over it.

The electricity stored in a battery in the circuit depends on the dynamic load features and the electrical circuit prototype used to convert the high voltage pulse to direct current. Because development of the energy storage circuit of the piezoelectric energy system had not been completed at lab-stage, direct measurement of the electricity generated was not possible and was instead obtained from measuring open-circuit voltage only. The electrical energy generated in the PHED was obtained by measuring the open-circuit voltage and determining the capacitance C_v of the PHED using Equation 1 [21]:

$$C_v = n_p C_p = n_p R_c (n - 1) \frac{e^T A_p}{l_p} \quad \text{(Equation 1)}$$

in which C_v is the capacitance of PZT (F), n_p is the number of PZT layers, n is the number of PZT in the generator, e^T is the coefficient of PZT ($\frac{F}{m}$), A_p is the area of PZT (m^2), l_p is the thickness of one PZT layer (m), and R_c is the relative capacitance. The capacitance of the piezoelectric is increased by raising the environmental temperature and energy in a PZT piezoelectric stack, a phenomenon represented by the relative capacitance (R_c) in Equation 1. The relative capacitance relationship from low voltage to 120 V is available from industry.[18] In addition, the reported capacitance at low voltages and 200 V is 2.44 and 4.8 μF (at room temperature), respectively, by employing nonlinear regression to the upper range of voltage. The average voltage output from 100 to 200 V was selected as appropriate for the load applied by the weights of cars and trucks to the PEHD, and because the nine piezoelectric stacks in the PEHD were connected in parallel, their voltage also will range from 100 to 200 V.

Equation 2, which determines the generated electricity of a single compression or release of the system based on the measured open-circuit voltage,[21] was then adapted in order to determine the energy harvested by a tower (E_T).

$$E_T = \frac{1}{2} C_v V_T \quad \text{(Equation 2)}$$

The voltage value V_T (V) depends on the amount of force; in the energy harvesting system for a road, a heavier vehicle has a higher output voltage and will generate more electricity. Thus, the electricity generated by the Piezoelectric SONOX P505[22,23] (designed and manufactured by CeramTec, Plochingen, Germany) was obtained by applying the recorded voltage and calculated capacitance in Equation 2. The open-circuit voltage had to be measured by applying a simulated force similar to the actual situation in a commercial-scale application on a road. However, because of typical manufacturing defects in the production of PZT and the generator and the fact that deformation of the PZT is only about 0.02 mm, the value of the open-circuit voltage differs greatly between devices. Thus, 60 PEHD prototypes were tested in the INSTRON machine, with each being recorded twice to obtain the average generated voltage measured in open-circuit mode. The resulting distribution of electricity generated by the PEHD when the applied load is 1350 N is shown in Figure 7. This load was selected to represent the conditions when the system is installed under a road, and it is equivalent to one-third of the weight from a wheel in a Toyota Camry that would be applied to the generator. To define the dynamic load behavior for a piezoelectric generator installed in a road energy harvesting system, it was assumed that only two-axle vehicles would be passing.

Subsequently, by using Equation 2 and the relevant capacitance and voltage values, the electricity generated by the device was calculated. Energy is also harnessed when the force is removed, as the piezoelectric stacks extend back to their initial length. Still, the generated electricity is highly variable and the amount harnessed upon decompression is lower than through compression. The "release voltage ratio" determined from the experimental data is incorporated into the LCA models to cover this variability. To represent commercial-scale installations, an average roundtrip energy loss from charging and discharging a battery reported in the scientific literature was incorporated into the PEHD prototype LCA model.[24]

LCA goal and scope

Three parametric LCA models were developed in Python 3.9 code for PZT, the piezoelectric generator, and electricity generated by a PHED to determine (1) their total climate change impact, including the carbon footprint of manufacturing, the energy storage system, and end-of-life management; (2) which processes contribute the highest amounts of GHG emissions along the life cycle; and (3) the factors to which the climate change impacts are most sensitive.[25] Because the PHED is a novel technology, the effects of the uncertainty and variability associated with some of its characteristics were assessed through Monte Carlo analysis in addition to sensitivity analysis to improve interpretation. The intended application of the results of these LCA scenarios, sensitivity analyses, and Monte Carlo analyses is to guide device optimization towards a lower carbon footprint.

Because of the lack of reliable life cycle inventory data on the piezoelectric material, an LCA of the PZT piezoelectric stack was first performed. This LCA model fed into the LCA model for the generator, representing a PEHD excluding its electricity generation and maintenance impacts. The LCA model of the generator was subsequently integrated into a full cradle-to-grave LCA model for electricity from the PEHD. For additional clarity on the impacts of these first two components (the piezoelectric stack and the generator), their results are reported separately in addition to the cradle-to-grave PEHD LCA results in this study.

LCA of the multilayer PZT piezoelectric stack

This first analysis was conducted for piezoelectric material with a chemical formula of $PbZr_xTi_{1-x}O_3$ to determine the impacts of production and disposal of 1 kg of piezoelectric. Four impact categories were assessed using the life cycle impact assessment method EPA TRACI 2.1[26]: global warming potential, acidification potential, carcinogenic potential, and ecotoxicity. The results of this LCA can also serve as a life cycle inventory for uses of PZT in other applications like actuators, ultrasound power transducers, and ultrasonic sensors. Although a multi-layer PZT piezoelectric was selected for this study, its production processes are not much different from bulk PZT. The system boundary of the PZT was cradle to grave with one modification: the operational impacts are excluded to facilitate integration into other LCAs involving PZT material. The upstream (materials extraction, refining, manufacturing) impacts and downstream (landfilling) impacts are included in this LCA model (Figure 4). The functional unit was chosen to be 1 kg multilayer piezoelectric PZT stack for this first analysis. The lifetime of a piezoelectric is not bounded, and such a functional unit allows for flexibility in applications and operational lifetime for use in other LCAs. Tests have shown that PZT multilayer piezoelectric stacks may work 5 billion to 100 billion cycles without losing performance; however, they may break under high pressure.[15,27]

Recycling piezoelectric material is possible, but it has yet to be widely applied. Nevertheless, recycling may release more GHG emissions than disposal; however, accounting for the carbon credits from the material obtained via recycling, applying expansion methods, and assuming them as coproducts would change the results. Additionally, the performance of the materials could be affected by recovery and reuse. Recycling piezoelectric stacks from energy harvesting systems was tested by Zhu et al. (2023),[28] reporting that the charge constant (d33) of the piezoelectric would drop by 25%. The performance in generating electricity decreased by ~10%, and the stacks could only tolerate 200 MPa pressure. Because recycling is not practiced currently, disposal is considered for end-of-life management in this analysis.[28]

PZT piezoelectric material contains a substantial amount of lead that is a toxic metal dangerous for human health. However, in most applications, the PZT piezoelectric is well covered to prevent leaching of lead, as demonstrated in Figure 19. Still, there is the possibility of lead exposure to the environment in the upstream and downstream stages of the PZT piezoelectric lifetime. Therefore, carcinogenic potential and ecotoxicity potential were included as impact categories in this analysis, and because there are multiple metals and thus mining processes involved, the acidification potential was calculated as well. However, the potential impact of leaching of lead during the operational stage was not included as it is dependent on the PZT application; it is recommended that this impact be added in LCAs for specific PZT applications that use these results. In this study, in addition to the main crystal's chemical formula of $PbZrTiO_5$, the two most common chemical structures of $PbZr_xTi_{1-x}O_3$ (PZT piezoelectric) were assessed: the most studied composition $PbZr_{0.52}Ti_{0.48}O_3$ and lead zirconate titanate 30/70 with the chemical formula of $Pb_{1.1}(Zr_{0.3}Ti_{0.7})O_3$ which is the most stable combination with a high probability of formation in regular manufacturing processes.[29] The actual SONOX P505 chemical formula is not publicly reported.

Uncertainty analysis was conducted in this segment to understand the probability of a range of impacts under possible combinations of input parameter values. Because there was no exact information for the impact of disposing of the PZT piezoelectric, this impact was determined by adding the impacts of manufacturing residuals and landfilling the ceramic and lead materials, as PZT piezoelectric is a lead-containing ceramic. For LCA scenario analysis, a worst-case scenario for landfilling was considered, assuming that 15% of the lead in the piezoelectric would leach. The net weight of the PZT piezoelectric material in a 1 kg piezoelectric stack is almost 815 g. The amount of lead oxide, zirconate, and titanate for preparing the ceramic slurry was calculated based on the fractions of Pb, Zr, and Ti that exist in 815 g of each type of piezoelectric ceramic material. The variable input parameters for the parametric LCA model of PZT piezoelectric are shown in Table 1.

This study aimed to determine globally applicable results for PZT piezoelectric impacts through choosing the market types of Ecoinvent life cycle inventories. For climate change and the baseline result, Monte Carlo analysis was performed to identify the uncertainties of the system and the range of possible climate change impacts because there are some differences in production methods by suppliers and also background data uncertainties.

LCA of the generator

The second LCA model developed and assessed was for the production of the generator, with a system boundary of cradle-to-grave excluding operations, and a functional unit of 1 generator ready to install and use in the piezoelectric harvesting system. Both the upstream impacts of manufacturing and assembly and the downstream impacts of decommissioning and end-of-life materials management were included in this analysis (Figure 20). However, the impacts of plastic bags, pallets, and cardboard used in the packaging of goods and parts were excluded from the calculations assuming that the impact of packaging is negligible in this system. The PHED, like other renewable energy systems, is intended to mitigate GHGs, and so the most relevant impact category of climate change impact was evaluated for the LCA of its generator.[26] A midpoint life cycle impact assessment method, the EPA TRACI 2.1 method was employed due to the locations of activities along the life cycle, with almost 90% of manufacturing parts and materials originating in North America, excluding the PZT manufactured in Germany and some components, such as wires, cables, electronics parts, and battery, imported from China. Though EPA TRACI was created for North American conditions, it still has location-agnostic accounting for the rest of the world in the climate change impact category as GHG emissions have global consequences that are unaffected by their site of emission. The locations for disposing or recycling the system's elements after their useful lifetime were assumed to be in the United States.

Table 2 illustrates the variable input parameters of the generator LCA with the minimum, baseline, and maximum values modeled. The baseline and maximum distances modeled represent those of the least expensive products in the United States, and the minimum distances are for Californian manufacturers or companies near California and thus close to the prototype production site. The minimum and maximum values of the masses for parts like wires or cables were measured during the first series of production of the 120 PEHD prototypes, and the baseline values represent the average value among the 120 products. By enhancing manufacturing efficiency at commercial scale, these component masses can be decreased in the future.

LCA of electricity generated by PEHD

The preceding LCA model of the upstream and downstream processes of the generator was aggregated with an operational life cycle stage to create the LCA model for electricity generated by a PEHD (Figure 10). Thus, the system boundary for this PEHD LCA model was cradle-to-grave, including all raw materials extraction and production, manufacturing of the generator, additional processes and assembly, transportation, electricity generation, maintenance (involving the production of replacement parts), and disposal that should be provided or performed for this system throughout its lifetime. The operational process of electricity generation directly depends on the generated voltage, frequency of loads, location, temperature, and system lifetime. Equations were developed for this LCA model to maintain these relationships as input parameters were varied for sensitivity and Monte Carlo analyses. These equations included the relationship between electricity generation and loads applied, which was previously determined by experiments with high-density dynamic loads applied by an INSTRON machine on the lab-scale system. Maintenance needs and impacts were also dependent on other parameters in the model, as greater voltages (through a more powerful load), higher frequencies, and longer lifetimes increase maintenance needs logarithmically in the LCA model. The calculated impacts were scaled to a functional unit of 1 kWh of electricity generated for this PEHD LCA. The use of 1 kWh of electricity generated as a functional unit is a standard selection for electric power systems, which facilitates comparison of LCA results to those of other electricity generating devices.

The goal of this component of the study was to determine the conditions under which a PEHD can have a low carbon footprint, so that this information can be used to select appropriate locations to install a commercial-scale PEHD. Therefore, several values for four variables of operational processes and maintenance were examined by conducting scenario sensitivity analysis to cover the majority conditions of the possible sites. For this analysis, the impacts of the upstream and downstream stages (Figure 20) were assumed constant in accordance with the production of current prototypes, represented by the baseline input parameter values in Table 2. Then, as illustrated in Figure 10, all the impacts were integrated to evaluate the environmental performance of the system in various situations. Scenario analyses, sensitivity analyses, and Monte Carlo analyses were performed for the carbon footprint of electricity generated by the PEHD. Two LCA scenarios for the PEHD with a functional unit of 1 kWh were developed, both with an assumed lifetime of 45 years under busy street conditions of 1000 vehicles/hour, with the device maintaining room temperature. The first LCA scenario used recorded data in the lab to simulate the load of a Toyota Camry passing over the system. The second LCA scenario used a simulated load of manifold registered on-road vehicles in California. The car classes modeled included compact, mid-size, pickup, and van, but excluded vehicles with more than two axles such as trucks and buses.

This study employed two types of sensitivity analyses in order to identify the influence of uncertainties and location-specific variables on the life cycle GHG emissions of the electricity generated by a PEHD. First, an approach similar to a local sensitivity analysis with a one-at-a-time system[30] was performed. In this method, the climate change impact was recalculated upon changing the value of each parameter to its minimum and maximum values one at a time. In contrast, the other parameters remain set at their baseline values to isolate the individual influence of each parameter on the total impact. This analysis was coded in Python. Table 3 shows the modeled values of the variability and uncertainty parameters in the system, which were used for sensitivity and Monte Carlo analysis.

Next, scenario sensitivity analysis[30] was conducted based on the variabilities and uncertainties in the operation and maintenance processes of PEHD, with a focus on four variables while keeping the impacts of the upstream and downstream stages constant. These four variables were the amount of generated electricity, ambient temperature, frequency of applying load, and the system's lifetime. The maintenance frequency is subsequently dependent on these four variables. Instead of using the mechanical load to estimate the amount of generated electricity, the name of a class of vehicles that can produce nearly the same loads when passing over the PEHD was used to communicate the results of these scenarios better. Lifetimes of 25, 35, and 45 years were assigned for analysis. The possibility of replacing up to 60% of parts during the lifetime of each PEHD was assumed for a portion of maintenance, considering that the contacts of components in the structure are so few, and there is a low probability of failure. Caltrans reports were used to select streets in California with 800, 1000, and 1200 passing vehicles per hour, which were identified as moderate, busy, and maximum traffic flows, respectively, although some streets in California experience higher traffic flows than this chosen maximum.[31] Temperatures of 10, 24, 50, and 75°C were selected to cover likely temperatures at the modeled locations.

As an emerging technology, many uncertainties exist in the PEHD system that make the interpretation of baseline LCA results less reliable than LCA results that incorporate uncertainty and variability in modeled parameter values. There were uncertain parameters as a result of a lack of experimental data or variables that are typically unknown for new devices, like the actual lifetime of components or energy loss during energy storage. There was also natural variability in parameter values, such as those obtained by measuring the electricity generated by each generator and the actual "release voltage ratio," which is an estimated ratio that estimates the generated electricity when the force is gone, and the system is relaxed. Consequently, four separate Monte Carlo analyses were performed with different approaches for different purposes. First, a Monte Carlo analysis was conducted that varied the values of all parameters to understand the possible range of life cycle GHG emissions of electricity from the PEHD. Then, a Monte Carlo analysis was performed without changing the values of background data in order to study the level of uncertainty in the system due to the novelty of the research. Then, two other Monte Carlo analyses were performed: one that only varied the parameters related to uncertainty, and the other altering parameter values related to variability, in order to determine the dominant parameters for future action in reducing uncertainty parameters and characterizing variability.[30] These Monte Carlo analyses were each performed using 10,000 iterations because of the degree of uncertainties in the study parameters. Input parameters were constrained to vary between their minimum and maximum values, with a uniform probability distribution except in cases for which the raw data was available to define the probability distribution. The percentage of steel that will be recycled is unknown at this stage; the ratio was set constant in Monte Carlo analysis to handle this pure decision-making uncertainty (i.e., it was not included in sensitivity analysis).

The piezoelectric generator is a novel technology for which even the core material, the PZT piezoelectric stacks, did not previously have a known life cycle inventory. Therefore, interpretation of the LCA results focused on identifying the effects of uncertain and variable parameters to make recommendations on the design and implementation decisions that could lead to minimal life cycle GHG emissions.

Accounting for the possibility of higher vehicle fuel consumption

It is believed that vehicles consume more fuel on a softer road.[32] Some papers and articles have discussed this possibility, but no mathematical relationships have been determined to calculate additional fuel consumption as the result of increased road flexibility when a PEHD is embedded under its surface. The maximum permissible amount of additional fuel consumption in gallons per vehicle passing due to the softer road could be defined as the amount that equates the life cycle GHG emissions of PEHD-generated electricity to those of electricity from a natural gas-fired power plant, when the fuel life cycle emissions are included in the PEHD LCA. This maximum permissible increase in fuel consumption was calculated in this study as 0.076 gallons/vehicle or 0.29 L/vehicle. The calculation is based on a carbon footprint of 0.057 kg CO_{2eq}/kWh for piezoelectricity, 0.500 kg CO_{2eq}/kWh for natural gas, and 0.0913 kg CO_{2eq}/MJ for production through combustion of gasoline. For a vehicle that has a 25 miles/gallon or 10.6 km/L consumption of fuel, this is equivalent to driving 1.97 miles or 3.17 km more on the same stretch of road. This is unlikely to be the case for future installations of PEHDs, as this would represent severe impacts on vehicular performance that would preclude PEHDs from being implemented. Furthermore, replacing conventional vehicles with electrical types in the near future would reduce the possible increase in GHG emissions from the effects of driving on softer roads.