# Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerator

Abdelsalam Ahmed[1,2], Islam Hassan[2,3], Taofeeq Ibn-Mohammed[4,5], Hassan Mostafa[7,8], Ian M. Reaney[6], Lenny S.C. Koh[4,5], Jean Zu[2], Zhong Lin Wang[1,9*]

[1]School of Materials Science & Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0245, USA
[2]NanoGenerators & NanoEngineering Laboratory, School of Mechanical & Industrial Engineering, University of Toronto, Toronto, M5S 3G8, Canada
[3]Design & Production Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, 11535, Egypt
[4]Centre for Energy, Environment & Sustainability, The University of Sheffield, Sheffield, S10 1FL, UK
[5]Advanced Resource Efficiency Centre, The University of Sheffield, Sheffield, S10 1FL, UK
[6]Departments of Materials Science & Engineering, University of Sheffield, Sheffield, S1 3JD, UK
[7]Department of Electronics and Communications, Faculty of Engineering, Cairo University, Giza, Egypt
[8]Center of Nanoelectronics and Devices (CND) at Zewail City and AUC
[9]Beijing Institute of Nanoenergy & Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China

Corresponding Authors

*E-mail: zlwang@gatech.edu

*E-mail: i.m.reaney@sheffield.ac.uk

Author Contributions

#A. Ahmed, I. Hassan, and T. Ibn-Mohammed contributed equally to this work.

Notes

The authors declare no competing financial interest.

## Supporting information

## This document contains:

1. Supplementary information on performance specification and designed parameters for TENG modules A and B
2. Supplementary cost data for techno economic analysis detailed in tables S2 to S10
3. Supplementary comparison between TENG modules A and B

1. **Supplementary information on performance specification and designed parameters for TENG modules A and B**

**Table S1. Designed parameters of Module A and Module B**

| Module parameters | Module A | Module B |
|---|---|---|
| "TENG" Module size | 60 $cm^2$ | 78.95 $cm^2$ |
| Distance between TENG unit | 1 cm | 1 cm |
| Margin areas at left and right sides of module | 1 cm | 1 cm |
| Expected water area covered | 2 $km^2$ | |
| Number of units | 33333300 | 66664210 |
| Unit efficiency | 50 % | 24 % |
| Power output of one piece of module W | 3 | 1.5 |
| Power output of one piece of TENG W/$m^2$ | 500 | 190 |
| Power output of TENGs covered 1 $km^2$ | 100 MW | 100 MW |

We assume that device efficiency of module A and module B are 50 % and 24 % respectively according to previous research.

2. **Supplementary cost data for techno economic analysis detailed in tables S2 to S10**

**Table S2 Estimation of capital cost for Module A**

| | **Processes** |
|---|---|
| Deposition, Microstructure Patterning | Roll –to –roll fabrication Machine with estimation cost from direct quotation from manufacturer $10,000 |
| Cutting Operation | Using Laser cutting Machine with cost around $1,000. |
| Adhesion Process Electrode wires Welding, Device Assembly Device. | Sandwiching operation, pressing and welding operations with equipments around $10,000 |
| Estimated capital investment of 100 MW TENGs production line | 7 million US$ |

**Table S3 Estimation of capital cost for Module B**

| | **Processes** |
|---|---|
| Deposition, Microstructure Patterning | Roll –to –roll fabrication Machine with estimation cost from direct quotation from manufacturer $10,000. |
| Cutting Operation | Using Laser cutting Machine with cost around $1,000. |
| Adhesion Process Electrode Wires Welding Machining / Forming Device Assembly Device Sealing | Sandwiching operation, pressing and welding operations with equipments around $10,000 |
| Estimated capital investment of 100 MW TENGs production line | 14 million US$ |

**Table S4. Capital cost of Module A along with facility depreciation**

| Year | Investment million US$ | Rate of depreciation | Depreciation percentage | Capacity MW | Capital cost US$/W |
|---|---|---|---|---|---|
| 1st | 7 | 50% | 100% | 100 | 0.07 |
| 2nd | 3.5 | 50% | 50.0% | 100 | 0.035 |
| 3rd | 1.75 | 50% | 25.0% | 100 | 0.0175 |
| 4th | 0.875 | 50% | 12.5% | 100 | 0.00875 |
| 5th | 0.4375 | 50% | 6.3% | 100 | 0.004375 |
| After 5th | 0.4375 | - | - | 100 | 0.004375 |

**Table S5. Capital cost of Module B along with facility depreciation**

| Year | Investment million US$ | Rate of depreciation | Depreciation percentage | Capacity MW | Capital cost US$/W |
|---|---|---|---|---|---|
| 1st | 14 | 50% | 100% | 100 | 0.14 |
| 2nd | 7 | 50% | 50.0% | 100 | 0.07 |
| 3rd | 3.5 | 50% | 25.0% | 100 | 0.035 |
| 4th | 1.75 | 50% | 12.5% | 100 | 0.0175 |
| 5th | 0.875 | 50% | 6.3% | 100 | 0.00875 |
| After 5th | 0.875 | - | - | 100 | 0.00875 |

**Table S6 Estimation of materials cost for Module A and Module B**

| | **Module A** | **Module B** |
|---|---|---|
| Device Structure Material US$/TENG (DSM) | 0.6398 | 1.125 |
| Electrode /Dielectric Material US$/TENG (D/EM) | 0.558335 | 1.667 |
| Lead wire US$/TENG (LW) | 0.2835 | 0.2835 |
| TI/CU deposition US$/TENG (Other) | 0.0009 | 0.0009 |
| Materials use ratio | 80 % | 80 % |
| Expected materials cost US$/TENG | 1.4825 | 3.0764 |
| Expected materials cost US$/ $m^2$ | 247.089 | 642.74 |
| Module output W/$m^2$ | 500 | 190 |
| Material US$/W | 0.617 | 2.56 |

**Table S7. (a) Labor cost of manufacturing line for Module A**

| | **number** | **Average wage US$/year** | **Cost US$/year** |
|---|---|---|---|
| employee | 76 | 40000 | 3040000 |
| | Labor cost US$/W | | 0.0304 |

**Table S7. (b) Labor cost of manufacturing line for Module B**

| | **number** | **Average wage US$/year** | **Cost US$/year** |
|---|---|---|---|
| employee | 76 | 40000 | 3040000 |

| | |
|---|---|
| Labor cost US$/W | 0.0304 |

**Table S8. Estimated overhead cost for Module A and Module B**

| Cost component | Module A cost (US$/W) | Module B cost (US$/W) |
|---|---|---|
| Facilities (e.g. rent) | 0.00792 | 0.021 |
| Utilities (electricity, water) | 0.00792 | 0.022 |
| Labor | 0.0304 | 0.0304 |
| Maintenance | 0.0016 | 0.0016 |
| Sum | 0.04784 | 0.075 |

**Table S9. Estimation of module cost for TENGs**

| Year | Capital cost US$/W | Cost of materials US$/W | Overhead cost US$/W | Module cost US$/W |
|---|---|---|---|---|
| Module A | 0.016 | 0.617 | 0.04784 | 0.68084 |
| Module B | 0.032 | 2.56 | 0.075 | 2.667 |

**Table S10. Calculation of levelized cost of TENGs based on different module efficiency**

| | Module A | | Module B | |
|---|---|---|---|---|
| Module efficacy | 50 % | 40 % | 24 % | 20 % |
| Module cost US$/W | 0.68084 | 0.68084 | 2.667 | 2.667 |
| BOS | 0.15 | 0.1875 | 0.394 | 0.474 |
| ICC | 0.83084 | 0.86834 | 4.731 | 4.811 |
| CRF | 0.1 | 0.1 | 0.1 | 0.1 |
| CF | 0.37 | 0.37 | 0.37 | 0.37 |
| O M | 0.001 | 0.001 | 0.001 | 0.001 |
| LCOE US cents/KWh | 2.569 | 2.681077 | 9.198 | 9.43 |

To assess the manufacturing line, assuming that the production capacity ($C$) of Module A is 100 MW. Eq. 3 presents the parameters of the production capacity:

$$C = P * V * T \qquad \text{(Eq. S1)}$$

where $P$ is the output power of one piece of TENGs module, based on an output power per square meter of 1000 W, $P$ is defined as $P$ = 1000* $m_{\text{odule}}$ (Eq. 4), the calculated value of $P$ (Module A) is 500W/m$^2$; $T$ is the producing time by 350 days/year (504000 min/year), $V$ is the producing rate calculated as 100MW/(504000min*120W/m2) =1.654 m2/min. As an important factor of capacity, producing rate depends largely on the technologies used for the manufacturing line.

The capacity of Module A is compared with that of DSCs manufacturing line to assume capital investment of Module A. Table S2 shows that the technologies and facilities of TENGs and Module A manufacturing line are very similar. Thus, estimated capital investment of 100MW Module A is 7 million US$ and 14 million for module B.

Capital depreciation is an important tool for businesses to recover certain capital costs over the property's lifetime. Allowing businesses to deduct the depreciable basis over five years reduces tax liability and accelerates the rate of return on a solar investment. This has been a significant driver for the TENG industry and other energy industries.

A simple, but important arithmetic relationship underlies the analysis. Most TENG costs are given in dollars per watt peak (US$/W). This is fine for the end user (especially if it is a system price), but it hides the nature of the technical challenges, especially in thin films. Two components go into a cost in US$/W: the output or efficiency of the device; and its manufacturing cost per unit area. By combining them you get a cost in US$/W. The actual relationship is very simple: the dollars per watt cost can be found simply by dividing the manufacturing costs per unit area (say US$/m2) by the output of the same area (which for a m2 is 1000 W/m2 times the efficiency). The same relationship works at the module level: the module cost (in US$/module) divided by its output (W/module) is its US$/W cost. Obviously, the same relationships show how to go the other way: if one knows the US$/W cost and either the efficiency (or unit output) or the area cost, one can calculate the missing parameter. The simple relationship is as follows Eq S2:

$$\text{US\$/W} = (\text{Cost/unit area}) / (\text{output/unit area}). \qquad \text{Eq. S2}$$

Unit area can be the module area; or the cost per square meter. Output per square meter is 1000 W/m$^2$ times the efficiency. The materials cost is calculated as follows: expected materials cost divided by module output and materials use ratio. One manufacturing line requires three groups switch every 8h for one day, and one group is ready for switch on holidays. There are 15 operators in one group; 12 technicians and 4 managers to direct the operators, the number of employees is 76 in total. The labor cost is 0.0304 USD/W for year estimated in table S5. The average wage is assumed by considering the balance between developing country such as China and developed country such as USA.

All cost data were obtained from the powder manufacturer's[1] and from direct quotation from manufacturers.

## 3. Supplementary comparison between TENG modules A and B

The results of the comparison are presented in Figures S1 through S3. Figure S1 displays proportions between impacts of the two types of commercial TENG products with respect to various damage categories, the bigger value taken as 100%. The Module B has greater environmental impact in some cases, though the scores are large for Ecotoxicity and fuel fossils. Normalization applied in Figure S2 means that these impacts are measured as a fraction of average impact of the kind, experienced (and caused) by a West European per year. The high scores for fossil fuels extraction and respiratory organics emissions reflect the large transportation needs.

Weighing the normalized impacts according to the Eco indicator 99 Europe E/E methodology in Figure 10 (main article) has flattened the relative importance of different impacts and levelled up the scores for the two analyzed subjects when compared to Figure 11 (main article). Ecosystem quality clearly has the highest relative aggregated impact of the three when it is judged after normalization. The difference between the two types of boxes is also most conspicuous in this case. Weighing the impacts, as before, has had an effect of flattening the scores and diminishing the differences between the two subjects. The hierarchy among the three aggregate impact categories has remained untouched. Single scores (Figures 11, main article) confirm that a bigger overall environmental impact comes from the Module B, mainly from a much greater longevity of a Module A.

**Table S11** Abbreviations list

| Abbreviation | Definition |
|---|---|
| TENG | Triboelectric nanogenerator |
| EPBP | Energy payback period |
| IoT | Internet of Things |
| LED | light-emitting diodes |
| MG-TENG | Micro-grating triboelectric nanogenerator |
| $V_{OC}$ | Open-circuit voltage |
| $I_{sc}$ | Short-circuit current |
| LCA | Lifecycle assessment |
| PZT | lead zirconate titanate |
| KNN | Sodium niobate |
| R2R | Roll-to-roll |
| BoS | Balance of system |
| LCI | life cycle inventory |
| ISO | International Organization for Standardization |
| GWP | Global warming potential |
| GHG | Greenhouse gas |
| CI | Capital investment |
| ICC | Installed Capacity Cost |
| CRF | Capital Recovery Factor |
| CF | Alternating current Capacity Factor |
| O&M | Operation and maintenance cost |
| FEP | Fluorinated ethylene propylene |
| $CO_2$-eq | carbon dioxide equivalent |
| PTFE | polytetrafluoroethylene |
| CEF | $CO_2$ emissions factor |
| DSM | Device structural materials |
| D/EM | Electrode dielectric materials |
| LW | Electrode wire |
| LCOE | Levelized Cost of Electricity Produced |

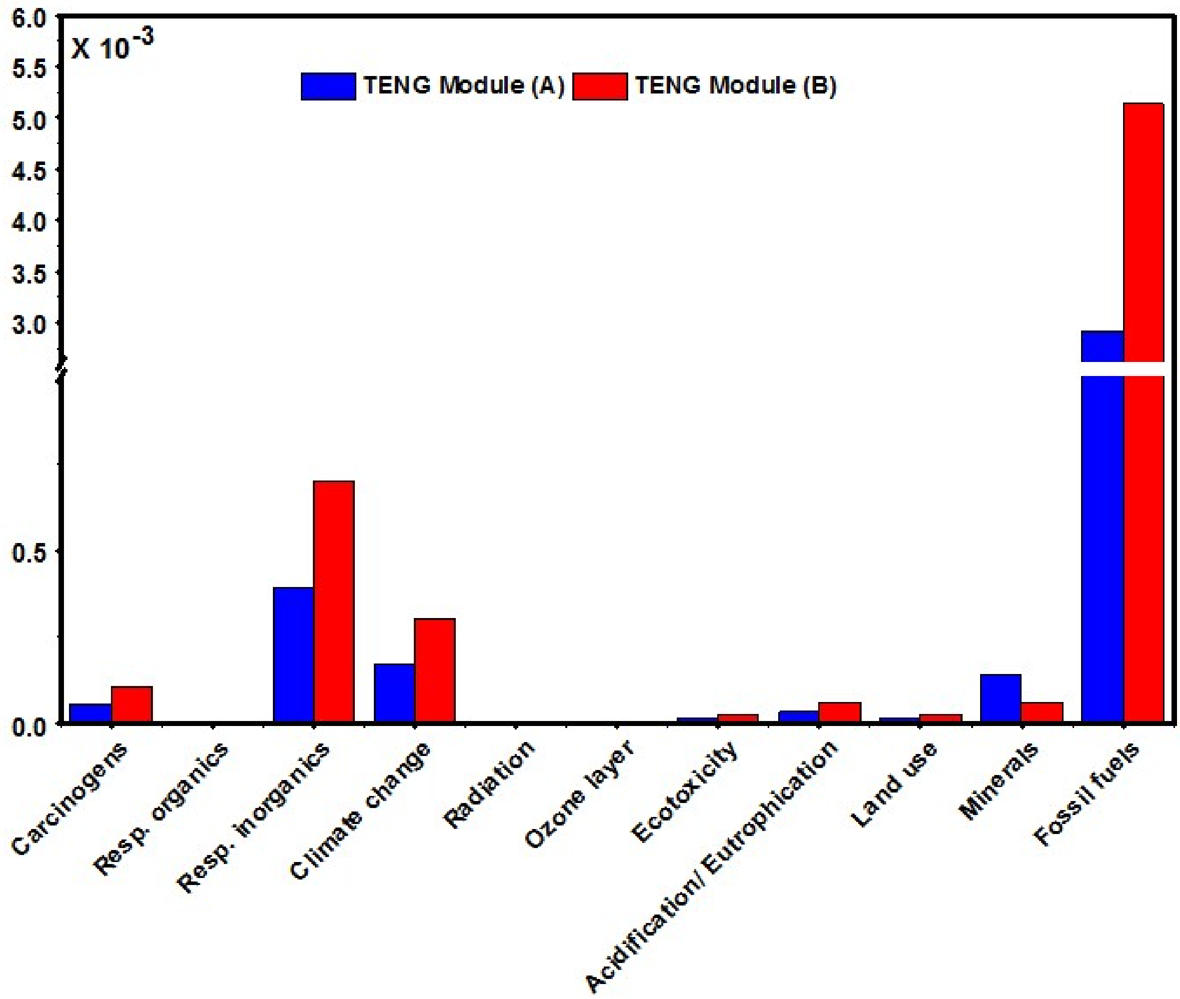


**Figure S1** Comparison per impact category, normalization of individual impacts, Ecoindicator 99 Europe E/E methodology

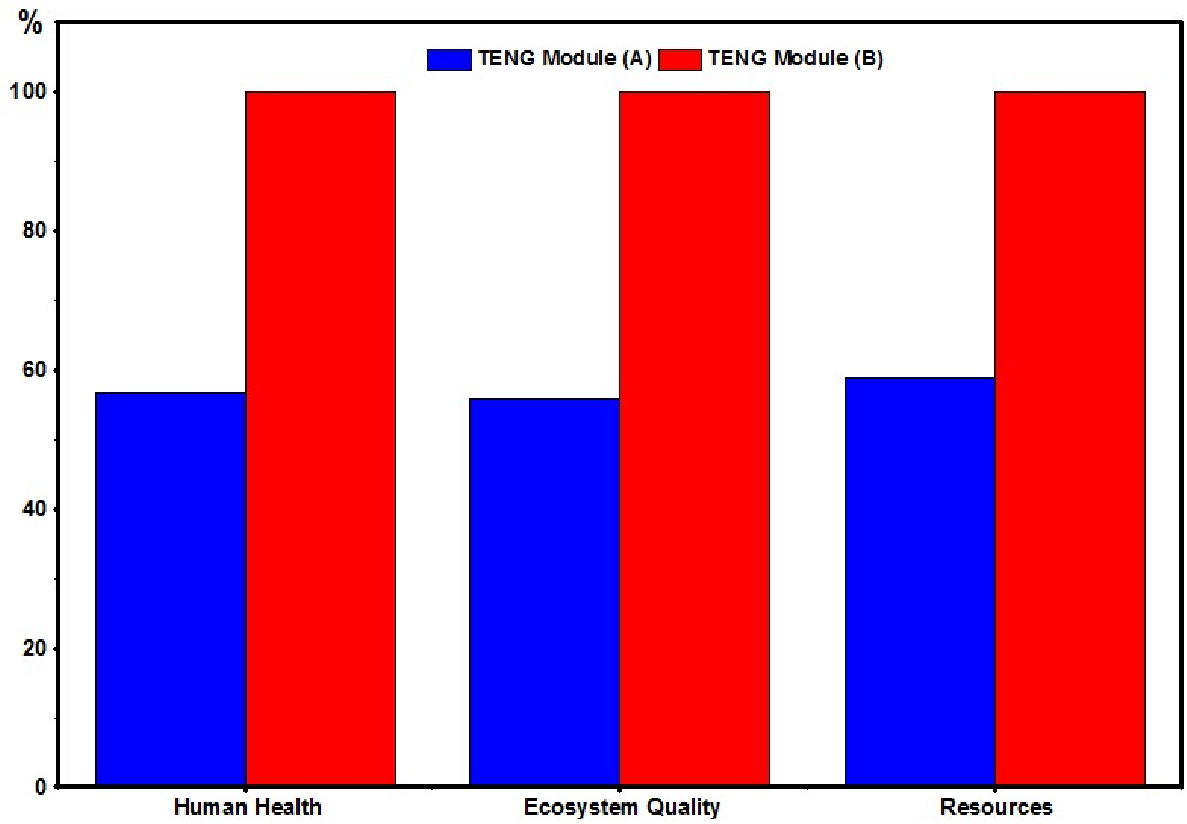


**Figure S2:** Comparison per endpoint impact category, by summation of individual impacts, the higher endpoint impact set equal to 100, Ecoindicator 99 Europe E/E methodology

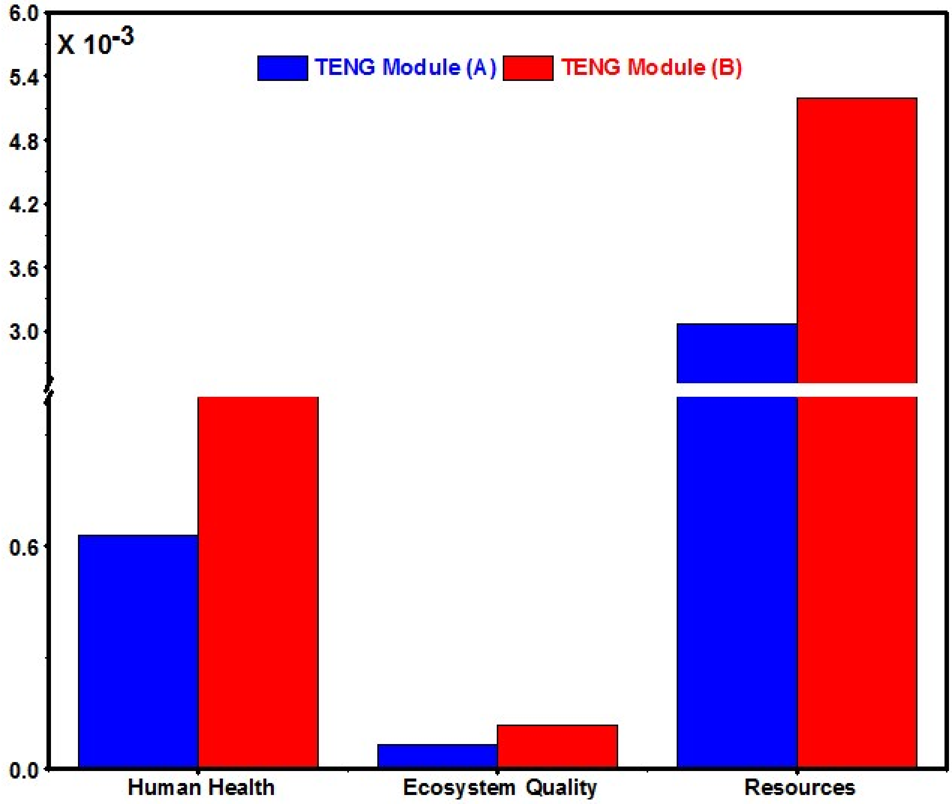


**Figure S3** Endpoint comparison after normalisation, Ecoindicator 99 Europe E/E methodology

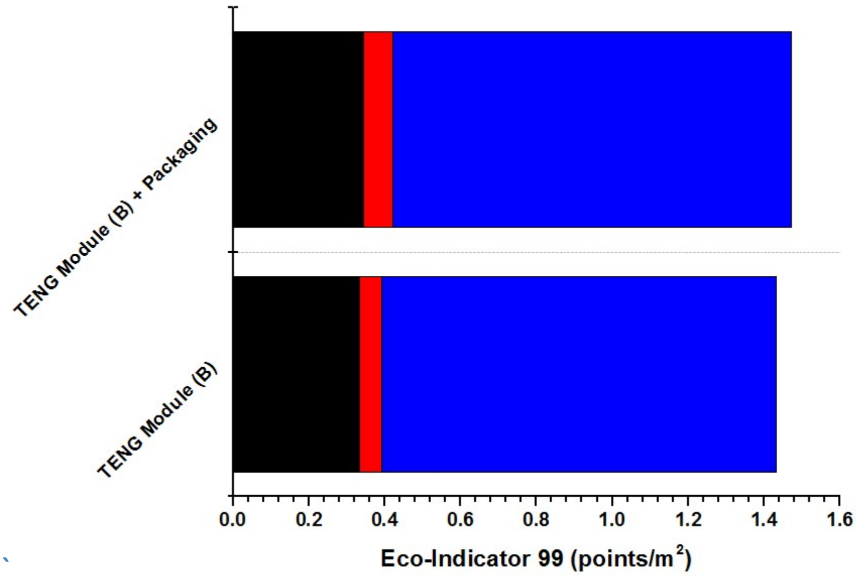


**Figure S4** Single score comparison by impact category, Eco indicator 99 Europe E/E methodology for Module B before and after adding the packaging.

# References


1. https://www.mcmaster.com/, Accessed January, 2017.