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Piezoelectric energy harvesters: A critical assessment and a standardized reporting of power-producing vibrational harvesters

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ABSTRACT

Energy harvesting devices have emerged as an auspicious sustainable energy source for low-power electronics, where delivering electricity using conventional means is not feasible nor desirable. This clear technological impact has drawn huge attention and driven research into energy harvesting materials and devices. Reports are often published, even in high-caliber journals claiming high-efficiency devices. However, these are typically based on poorly defined or even undefined metrics and lack the details needed for re-evaluation and comparing different devices for peer assessment. The enthusiasm to publish is pushing the field towards qualitative rather than quantitative research. Here, after introducing the basic concepts of energy harvesting, randomly selected research papers on piezoelectric energy harvesting devices published over the last two decades, have been assessed. It is shown that essential parameters which are needed for a quantitative evaluation of materials and devices are missing from nearly 90% of the reviewed papers, thus rendering them less reproducible (or even irreproducible) for peer assessment. Such a frequent occurrence of improper data reporting damages the credibility and reliability of the energy harvesting field. To enhance reproducibility and facilitate progress, we herein suggest a measurement and data reporting protocol that should be followed when reporting energy harvesting devices and concomitant performances. The standardized protocol can be further adapted for other vibrational harvesters based on other mechanisms such as triboelectricity.

1. Introduction

The emerging Internet of Things (IoT), defined essentially by a network of many thousands of embedded sensors, connected to autonomously decode and produce human-relevant data, is strongly dependent on local and sustainable energy supply. The energy harvesting field has been identified as a sustainable alternative to supply the IoT, specifically for low-power electronic devices and sensors, wearable technologies and even for self-powered medical implants, such as the heart pacemakers. [1–7] For many of the envisioned applications, energy harvesting devices based on piezoelectric or triboelectric materials have emerged as promising candidates to produce a small amount of electrical power using micro- or nano-structuring, hence the term *nanogenerators*. In this paper, we focus on piezoelectric nanogenerators (PNGs). Nevertheless, the discussions and guidelines presented are equally relevant for researchers working with triboelectric nanogenerators.

The fabrication of PNGs is relatively simple. Typically, a layer of a poled piezoelectric medium, being a ceramic, polymer or composite with other piezoelectric (nano)particles, is sandwiched between two electrodes, typically made of electrically conductive metals. [8] As the PNG undergoes mechanical stress, the polarisation of the piezoelectric layer changes, and therefore there will be a current flow in the circuit, under short circuit conditions. The electrical output is relatively small, and various material combinations and concepts are being developed to increase the power output of PNGs. Due to its simplicity, PNGs are perfect demonstrators for outreach activities because upon simply

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pressing a finger against it, the device generates a voltage pulse, which can be captured using an oscilloscope or generate a spark, a spectacle that is attractive to primary or high school students.

As a result of the simplicity of energy harvesting-related experiments, poor research practices have developed over the years that are sadly becoming a routine. For example, claims of high efficiency are usually not substantiated, or the parameters needed to examine the reported efficiencies independently, are either missing from the reports or not measured at all. Frequently, details of experimental conditions are lacking, which makes reproducing the claimed efficiencies an impossible task. Qualitative approaches such as finger tapping, although very close to the actual modes of excitation in applications, are unreliable because force and frequency are uncontrolled and unquantified, thereby not adding to our understanding of the materials and devices. Even the choice of the measurement instruments is, in most cases, questionable or their impedance characteristics are not reported. Consequently, it is hard, if not impossible, to evaluate many of the newly reported composites in the literature and identify the promising materials, which inevitably delays the mainstreaming of PNGs.

Qualitative research practices have two major negative side effects; (i) they do not contribute to our understanding and advancement of the materials and their comprising energy devices, and consequentially, (ii) they damage the credibility of the field and thereby the confidence of funding agencies and policy makers in the potential impact of vibration energy harvesting technologies. The provision of good scientific and technical practices is therefore crucial.

There are already some papers that have examined the existing literature in this regard. In a detailed paper, Uchino has targeted common misconceptions regarding the energy flow from the initial mechanical input to the electrical output and has explored a range of options to increase the efficiency of PNGs. [9] Briscoe et al. have highlighted the misconceptions surrounding power calculations and the significance of impedance matching. [10] Su et al. discussed the effect of measurement instruments on the reported output of the PNGs. [11] In a more recent paper, Šutka et al. discussed issues regarding contact electrification and initiated a discussion about the standardisation of measurements. [12] Despite these valuable attempts, a critical literature assessment and a standardised measurement protocol are still lacking.

This paper aims to overcome this issue and is organised as follows. We initially provide an explanation of our literature assessment methodology that enables a critical assessment of randomly selected papers published over the last decade. We introduce the underlying concepts related to a piezoelectric energy harvester, which are most prone to misconception and malpractices. We then demonstrate the consequence of improper experimental methods by measuring two PNGs and highlight the shortcomings in the literature. Finally, a measurement protocol is proposed that lists the experimental *dos* and *don'ts* as well as the material and device parameters that should be reported in future reports dealing with PNGs.

2. Experimental Section

Two piezoelectric materials were commercially obtained; a Macro-Fiber Composite™ (MFC), from Smart Material (type P2), which has upper and lower electrodes and is optimised for its 31-mode piezoelectric response. [18] The second material tested was PVDF sandwiched between two laminated sheets of Mylar.

The P2-MFC device had an area of 2.8 × 1.4 cm with an active layer thickness of 300 μm. The PVDF device had an area of 3.0 × 1.2 cm with an active layer thickness of 180 μm. The Young's moduli of P2-MFC and PVDF were 15.9 GPa [19] and 2 GPa [20], respectively.

The vibration harvesting experiments were conducted in 31-mode, with the piezoelectric strips fixated on to a cantilever, that was attached to a magnetic shaker. Vibration was produced via a sinusoidal wave form produced by a function generator that was fed into an amplifier to drive the shaker to create oscillations of the same frequency. The amount of force delivered to the cantilever were monitored using the accelerometer, and the force exerted on the piezoelectric strip was measured using a strain gauge sensor. Both sensors were controlled by different software, but were synchronised. The signals generator by the piezoelectric harvester was recorded using various methods, with and without variable load using either an oscilloscope (Keysight InfiniiVision DSOX2024A) which has an input impedance of 1 M Ω or an electrometer (Keysight B2980A) with an input impedance of > 200 T Ω. The variable load was systematically changed between 1 kΩ to 900 MΩ. The rectifying circuits were assembled using silicon pn-junction diodes, Schottky diodes, or junction field-effect transistors (LT4320).

3. Literature review method

The literature review is conducted to assess the ongoing research practices in the field of energy harvesting devices. Hence the target of the review is entirely different from what is traditionally undertaken. [13] In this review process, less attention is paid to the claims made regarding the magnitude of voltages, powers and efficiencies and attention is paid to how the parameters are measured or calculated from the measurement results. Therefore, the papers are scrutinised purely based on the experimental procedures. In total, 80 papers have been reviewed that cover various materials systems, which have been classified into three major categories, i.e. i) purely polymer-based systems, including polymer blends, ii) purely inorganic-based systems, which include ceramics and ceramic-ceramic composites and finally, iii) polymer-inorganic composite systems, which are called hereafter as polymers, inorganics and composites, respectively.

Four sets of parameters are extracted from every paper. The first set relates to fundamental material properties, namely the type of the piezoelectric material, its piezoelectric constant, relative permittivity, Young's Modulus, and elastic constants. The second set of parameters collects the reported PNG device parameters, namely, the active area, the thickness of the piezoelectric layer, the internal resistance and the capacitance of the comprising PNG capacitor. Note that we have left out considerations with regard to the metal electrodes as the issues with the electrodes have already been critically discussed. [12] The third set summarises the method through which the mechanical excitations have been applied, namely the force, strain or stress, and their frequency. The final set of parameters shows how the electrical outputs of the nanogenerators, namely their open circuit voltage, short circuit current or power under mechanical excitation, have been measured. It also summarises the methods via which absolute power, areal power, volumetric power and the efficiencies have been calculated.

4. Literature assessment of PNGs

4.1. Materials properties

Research of PNGs starts with the piezoelectric material. As shown in Figs. 1a, 46.3% of the papers employ inorganic material systems, whereas 22.5% employ purely polymeric materials and 27.5% use composites of a polymer with inorganic particles. It is surprising that three papers (3.7%) have not mentioned the materials used in their report. There are at least three sets of highly relevant material parameters related to the mechanical, electromechanical and dielectric properties. The important mechanical properties of piezoelectric materials for energy harvesting applications include Young's modulus and elastic constants, which characterise the deformation of the material under mechanical excitations. The electromechanical properties, namely the piezoelectric constants, including charge (d_{ij}) and voltage (g_{ij}) constants, characterise how well the material responds to an external mechanical stimulus by generating charges or voltage. Finally, the relative permittivity of the piezoelectric indicates the ability of the material to store electric energy in the presence of an electric field; for a poled piezoelectric material the permittivity is ideally reported under conditions of

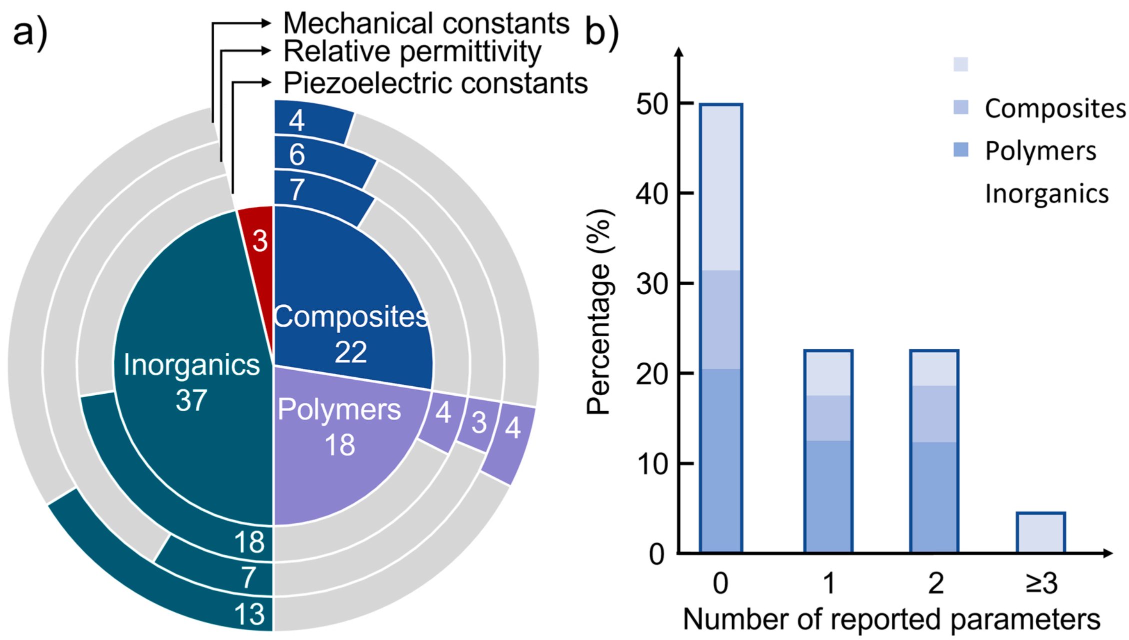

Fig. 1. a) The pie chart showing the distribution of the assessed papers and the reported parameters for every category. b) Distribution of the number of reported parameters per category for the assessed papers.

constant stress (ε_{ij}^T), or strain (ε_{ij}^s). Dielectric loss (ε''), the imaginary part of the relative permittivity, is a crucial factor that indicates how well a dielectric in a capacitor withstands self-discharge due to leakage; this is also reported in the form of $\tan\delta = \varepsilon''/\varepsilon'$. A low-loss (ideally loss-free) piezoelectric is a suitable material candidate for energy harvesting applications. Therefore, it is expected that a paper discussing piezoelectric energy harvesters reports these parameters, as they are directly linked with the performance of the nanogenerator.

In our literature assessment, these parameters have been examined. We note that no other source, such as materials datasheet or handbooks have been consulted if the parameters are not reported in the paper under review. It is found that papers discussing inorganic materials generally provide more information regarding the material parameters than papers dealing with composites and polymers. For example, the piezoelectric constant for the material is reported in nearly 50% of the papers dealing with inorganic materials. In contrast, this less of reporting falls to 32% and 22% for composites and polymers, respectively. The relative permittivity of the materials is the least reported parameter which has been reported only in 20% of all the reports.

As shown in Fig. 1b, nearly 50% of all the papers do not report any of the relevant material parameters, even in cases where well-studied materials such as barium titanate ($BaTiO_3$) or poly(vinylidene fluoride) (PVDF) with tabulated parameters are used. In 22.5% of the papers, only one parameter is reported, of which 12.5% report one of the piezoelectric constants (any parameter including d_{ij} and g_{ij}), 5% report relative permittivity and another 5% report one of the mechanical parameters. Of the papers that report two parameters, 12.5% report one of the piezoelectric and one of the mechanical constants, 6.25% report one of the piezoelectric constant and relative permittivity, and the remaining 3.75% report a mechanical constant and relative permittivity. For a minimal evaluation of the material, at least three of the material parameters are required, depending on the excitation mode. However, the number of papers that report at least three material parameters is low at only 5%. It is advised that authors of future publications pay closer attention to reporting sufficient material parameters. It should be noted that both modulus and relative permittivity are frequency dependent. Consequently, the piezoelectric constants of the materials also depend on the frequency. It is, therefore, necessary to report the frequency of the mechanical excitation used in testing the proposed PNGs.

For most single-phase piezoelectrics, such as $BaTiO_3$ and PVDF, the mechanical, piezoelectric and relative permittivity as a function of frequency have been well studied and documented. However, limited data for composites, particularly polymer-particulate composites, is available because the dielectric spectra of the composites strongly depend on the preparation conditions and the final microstructure of the film. For example, it has been shown that nanoparticle agglomeration plays a vital role in the reliable measurement of the relative permittivity and dielectric loss. Therefore, it is encouraged that the researchers report the frequency dependence of at least one of the parameters. For that matter, dielectric spectra of the material (both real and imaginary parts) should be provided; for example the real part of permittivity and conductivity. In the cases where measuring such parameters is impossible, future papers are encouraged to include the tabulated or previously reported values from the literature, which are used as the basis for their investigation.

4.2. Device fabrication and geometry

It is difficult to report on a PNG without fabricating an actual device. Details of device fabrication are the only ingredients for the reproduction of experiments and re-evaluation of the reported results. In addition to device preparation details, it is also crucial to report the thickness of the active piezoelectric layer and the active device area. Determining the device impedance is also crucial because it enables the efficient design of the harvesting circuit to extract the maximum power from the generator as a result of impedance matching. As shown in Fig. 2a, the device area is the most frequent reported parameter, amounting to 70%, followed by thickness, which amounts to only 37.5% of all analysed cases. Interestingly, the determination of the PNG's internal impedance has received less attention and represents only 2.5% of the whole analysed papers. Strikingly, Fig. 2b reveals that 15% of the reports have not reported any information on the device parameters. In contrast, a large number of publications, 42.5%, have reported only a single parameter. The fraction of papers that reported at least two parameters is 40%,

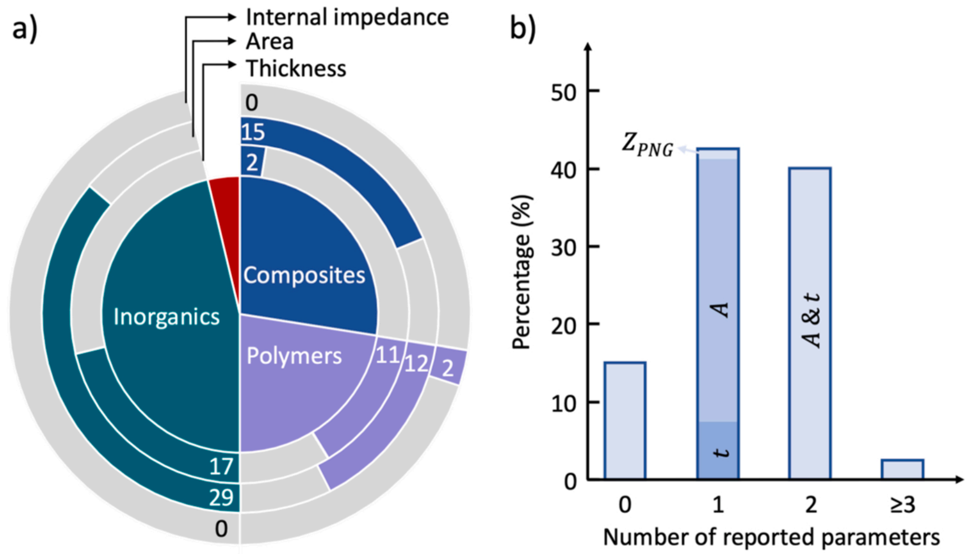

Fig. 2. a) Statistics of reported device-relevant parameters. b) Distribution of the number of reported device-related parameters.

where the thickness of the piezoelectric layer and the device area are reported in all cases. Again, only 2.5% of the reports (2 out of 80) reported three device parameters. Observation of such a low number indicates that nearly 97.5% of the reports in the literature face reproducibility issues due to a lack of knowledge of device geometry or impedance. Therefore, future papers on PNGs should contain information about the thickness of the piezoelectric film, device area, and the impedance of the device.

4.3. Mechanical excitation method

Following the fabrication of a device comes the measurement. Assume a piezoelectric material with a piezoelectric charge coefficient of d_{33} (or piezoelectric voltage coefficient of g_{33}) and relative permittivity at constant stress of ε_{33}^{T} sandwiched between two metal electrodes, thus forming a capacitor and a simple PNG. Under mechanical stress, as shown in Fig. 3a, a voltage develops across the capacitor plates. The off-resonance developed voltage under open-circuit conditions, V_{oc}, is written as follows:

$$V_{oc} = \frac{d_{33}}{\varepsilon_0 \varepsilon_{33}^{T}} \frac{F}{A} t = g_{33} \frac{F}{A} t \quad (1)$$

where F is the applied force in Newton, ε_0 is vacuum permittivity, t is the thickness of the piezoelectric layer, and A is the area of the PNG electrodes. Note that A is the total metallised electrode area forming a capacitor – hence A does not represent the region which is under stress such as impact. The mode of excitation is defined based on the direction of stress with respect to the polar axis of the piezoelectric layer. The most common approach is '*33-mode*', where the mechanical excitation is applied in parallel with the poling direction along the '3′ axis, as indicated in Fig. 3**a**. The next common approach is '*31-mode*', where the polar axis is along the '3′ direction and at a right angle with the applied force, typically along the '1′ direction, as indicated in Fig. 3**a**. [11].

Eq. 1 shows that the V_{oc} in any PNG is linked with five different parameters, two consist of the material property (d_{33} or g_{33} and ε_{33}^{T}), two being device area and piezoelectric film thickness (A, t) and one being the external excitation, F. Moreover, as the name suggests, V_{oc} should be measured across an open circuit or across an infinite load. Alternatively,

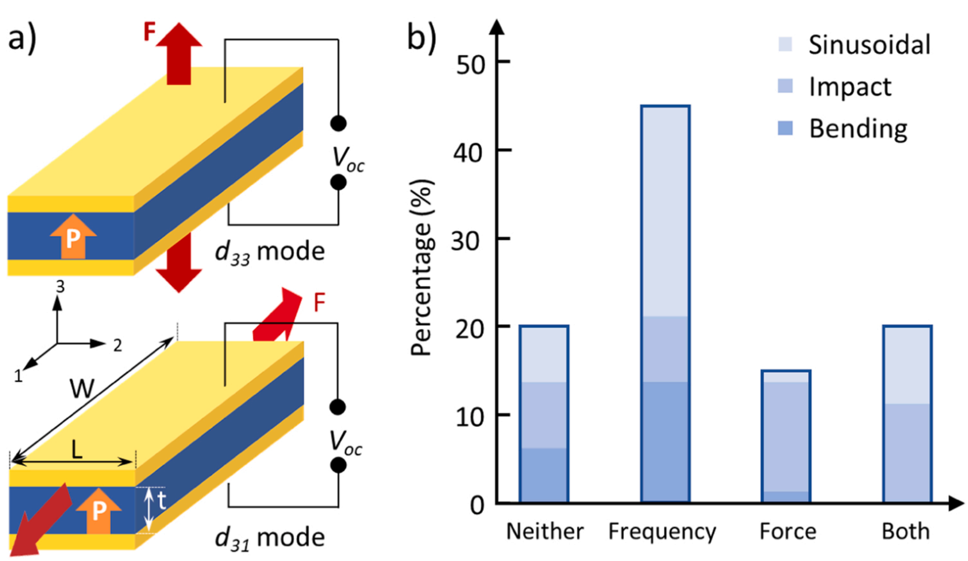

Fig. 3. a) Typical configuration of the PNG devices with (top) parallel and (bottom) perpendicular applied force and polarisation directions. b) Distribution of the reported parameters for various modes of excitations reported in the literature.

the short circuit current, I_{sc}, can be measured over zero external load; where $I_{sc} = dQ/dt = d_{33} \cdot \frac{dF}{dt}$. There is another hidden dependency of V_{oc} which is not highlighted by Eq. 1. As discussed earlier, the material parameters, d_{33} (or g_{33}) and ε_{33}^{T} are frequency dependent, thus highlighting the importance of reporting the frequency of the mechanical excitations. Moreover, every piezoelectric has its own natural frequencies and resonance, which can depend on the size and geometry of the material. Therefore, when the mechanical excitation frequency matches one of the natural frequencies, a higher V_{oc} is reached. Hence, it is crucial that besides A, t, d_{33} (or g_{33}), and ε_{33}^{T} PNG papers present the magnitude of force, F, and the frequency at which the force is applied.

Both force and frequency of the mechanical input should be reported when performing energy harvesting experiments. The result of the literature survey is given in Fig. 3**b**. Three major methods have been employed to excite the PNGs, which include i) bending of a stand-alone PNG or a PNG mounted on a beam, ii) application of a sinusoidal force and iii) using the force of a (usually controlled) impact. The impact and bending forces typically excite the piezoelectrics in 33- or 31-modes, whereas for the case of a sinusoidal force, it should be made clear which mode is being excited. It is found that 20% of the reports contain no information about the mechanical excitation, whereas 45% of the reports have only provided the frequency of excitation with no mention of the applied force, and 15% have mentioned the applied force without mentioning the frequency. Hence a total of 80% of the reports contain insufficient information regarding the two essential parameters. Only 20% of the reports (16 out of the 80 papers) reported both force and frequency, which are required for reproducing the experiments by others. Another pattern that has emerged from the survey is that not a single paper that has used cyclic bending has reported both force and frequency.

It is expected that PNGs will be subjected to millions of stress cycles. It is therefore highly relevant to run fatigue tests which subjects the PNGs to repeated mechanical excitations. Unfortunately, the fatigue test is treated rather loosely in the literature. Yet, given its importance, we have also analysed the reported fatigue tests. We have considered a "fatigue test" measurement when the number of excitations exceeded ten, which is admittedly a low number. Even with this loose criterion, the number of papers that reported fatigue tests has not exceeded 27.5%.

A striking finding is that 30% of the reports (24 out of the 80) have used some form of human involvement (usually finger tapping or walking) to excite the piezoelectric materials. Even more interesting is that six of these papers (7.5% of the total) have conducted fatigue test with finger tapping. Although these are realistic methods of excitation when PNGs are employed in applications, they are unreliable because humans are not made to apply force and frequency in a quantitative manner that is required to guarantee the reproducibility of the experimental results. In addition, contact electrification resulting from friction or static discharge from a human finger or rubber glove during tapping can lead to false piezoelectric measurements. [12] It should also be noted that some applications require encapsulation or packaging of the piezoelectric layers. In such cases, extra care should also be taken to prevent contact electrification, whose presence would hinder the correct evaluation of the piezoelectric energy harvester.

4.4. Measurement of V_{oc} or I_{sc}

After a mechanical excitation, a PNG device produces a voltage, which should be measured to evaluate performance parameters such as power and efficiencies. Note that V_{oc} and I_{sc} cannot be simultaneously measured as this represent the extremes of electrical boundary condition (at open circuit the electrical load can be considered as infinite, while at closed circuit the electrical load is zero). As the first step in PNG device evaluation, we have determined the instruments employed to measure V_{oc} (or voltage in general). Fig. 4**a** shows a summary of the literature review.

It is striking again to find out that above 40% of the published reports do not mention how the V_{oc} or I_{sc} have been measured. A significant number of the analysed research papers, nearly 40%, use an oscilloscope. In contrast, nearly 12% of the reports have used a multi-meter or source-measure units. A 6.3% fraction have used computer-controlled data acquisition systems, details of which are not fully explained in those papers; such as the input impedance. A small fraction, 5%, of the reports used a high impedance electrometer to measure the voltage.

Measuring voltage or current is the prerequisite for estimating the power that a PNG can generate, which is needed to estimate the efficiency. However, as seen from Fig. 4b, a significant portion of the papers, to be exact 41.25%, fail to report any values for either of the parameters, whereas 27.5% of the papers reported only one. As shall be discussed in the next section, the measuring instrument plays a critical role in the correct evaluation of voltage and current parameters, and the number of trustworthy reports will fall significantly.

4.5. Input impedance of measurement instrument

Measuring voltage or current seems to be trivial. However, there is more to this seemingly simple measurement. Until now, we have frequently discussed the input impedance of the measurement instrument. [14] Therefore, it is appropriate to now devote a discussion to this critical issue, particularly in relation to the measurement of V_{oc} and I_{sc} of the PNGs, which serves as the primary experimental parameters from which the performance of the PNG is evaluated. Measurement of V_{oc}, as

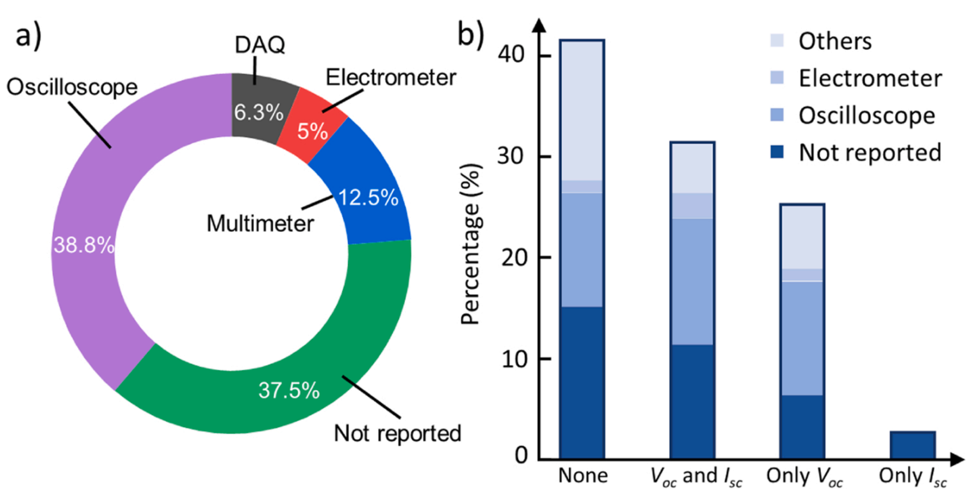

Fig. 4. a) Distribution of measuring instruments used to evaluate PNGs. b) Distribution of reported parameters for the most and least frequently used instruments.

the name suggests, requires a voltage measurement under open-circuit conditions. Various instruments have variable input impedances. For example, the input impedance for an oscilloscope is typically 1 – 10 MΩ, while the input impedance of an electrometer is in excess TΩ.

According to the definition, for the V_{oc}, no current should pass through the circuit, implying that the input impedance of the measuring instrument should be ideally infinite to block current flow. Otherwise, there is a voltage drop across the measuring instrument. Fig. 5a shows a simplified equivalent circuit for a PNG on the left, which consists of an ideal voltage source, V_{oc}, in series with an equivalent internal impedance Z_{PNG}, and on the right, a typical input stage of a measuring instrument with an input impedance of Z_{in}. The measurement instrument measures:

$$V = V_{oc} \times \frac{Z_{in}}{Z_{PNG} + Z_{in}} \quad (2)$$

Therefore, it is only under the condition $Z_{in} \gg Z_{PNG}$ that the measurement instrument accurately measures a voltage that is $V \approx V_{oc}$.

The above condition is almost always fulfilled during the voltage measurement of typical voltage sources since the internal impedance of the voltage sources is usually very small and negligible. Consequently, multi-meters, typical voltmeters and oscilloscopes can be reliably used. However, in the case of a PNG, there is a need to pay extra attention to ensure that the condition, $Z_{in} \gg Z_{PNG}$, is fulfilled because piezoelectric voltage sources are ideally low-loss capacitors that can have considerably high impedances comparable with or exceeding the input impedance of the many measuring instruments.

Let us now clarify the input impedance further by setting up a PNG experiment using two commercially available samples based on an inorganic lead zirconate titanate (PZT) and a polymer PVDF. All details regarding material and device parameters are given in the experimental section. The generated voltage for both PNGs are recorded using two different instruments, namely an oscilloscope and an electrometer, which are, respectively, the most-used and least-used instruments by the community with low and high input resistances. For the PZT device, nearly the same V values of 3.0 ± 0.2 V are obtained using both instruments. However, for the PVDF device, V values of 0.4 V and 1.6 V are obtained using the oscilloscope and electrometer, respectively. Clearly, the factor of four difference in the measured voltages for PVDF indicated there is an measurement error and this is purely a result of the relatively low input impedance of the oscilloscope, which is 1 MΩ in this case. Note that the input impedance of the oscilloscope is usually imprinted next to their input terminal and datasheet. For the PVDF device, the impedance of the PNG at the excitation frequency is nearly 3.5 GΩ, much larger than the input impedance of the oscilloscope. Therefore, when using an oscilloscope to record voltages, the input impedance is limiting and does not meet the open circuit conditions measuring a voltage much less than the actual V_{oc}. On the other hand, the input impedance of an electrometer is very large (TΩ), much larger than that of the PVDF PNG. Hence when using the electrometer, the measurement conditions are nearly close to the open circuit condition, and the measured voltage is $\approx V_{oc}$.

A critical reader may now question why for the PZT device, similar voltages are obtained using both instruments. The answer is related to the internal impedance of the PZT device (in combination with the input resistance of the measurement instrument). The impedance of the PZT device at the measurement frequency is 180 kΩ, which is about six times smaller than the input resistance of the oscilloscope and several orders of magnitude smaller than that of an electrometer. Hence both instruments can be used to reliably measure the V_{oc} of the PZT device. It is now evident why the internal impedance of a PNG device should be known and how that relates to the measured voltages.

The simple explanation given above already indicates that values for V_{oc} and I_{sc} alone are not good performance indicators, and we should avoid drawing conclusions about the usefulness of a material simply based on enhancement or reduction in the magnitude of these two parameters.

4.6. Measuring and calculating power

Following the determination of V_{oc} (and / or I_{sc}) power should be calculated. Power is the precursor for comparison between various materials systems but is not yet a comparison metric. The correct comparison metrics are the areal power density (power per PNG area in μW cm^{-2} and volumetric power (power per PNG volume in mW cm^{-3}) at the optimum external load. Power can be measured when the PNG source is connected to an energy consumer, typically an external load, as shown in Fig. 5b. The power that the PNG delivers to the external load is instantaneous power, P_i:

$$P_i = I_L \times V_{out} = \frac{Z_L V^2}{(Z_{PNG} + Z_L)^2} \quad (3)$$

where I_L is the current passing through the external load, Z_L, and V_{out} is the voltage. One can easily show that the maximum power is delivered to the external load when $Z_L = Z_{PNG}$. Since the PNG has a capacitive behaviour, its impedance varies inversely with frequency. Hence it is

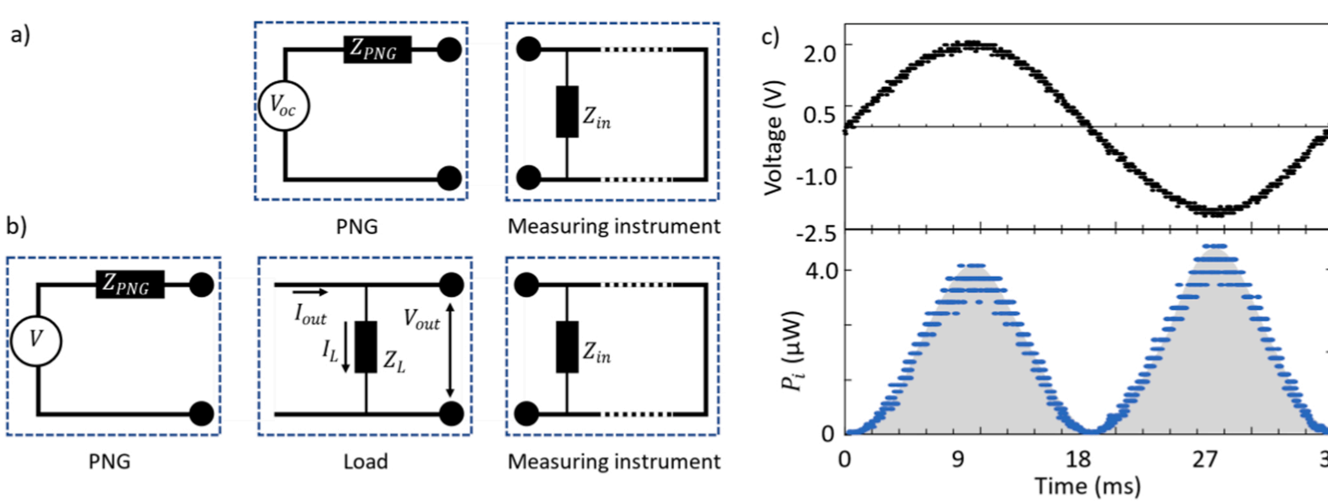

Fig. 5. Critical aspects in measuring the Voltage and Power of a PNG. (a) Simplified equivalent circuit of an ideal Voltage Source in series with the PNG's internal impedance, Z_{PNG}. On the right dashed square, the instrument's input impedance Z_i. (b) Simplified equivalent circuit of the PNG coupled to an external load for power extraction (c) A generated voltage signal and its corresponding instantaneous power trace.

important to match the impedance at the excitation frequency. When the internal impedance of the PNG is known, selecting the optimum external load is simple and this indicates why the frequency of the mechanical excitations and the impedance for the PNG element should be reported. When the internal impedance of the PNG is unknown, it is required to change Z_L systematically, and to experimentally determine the maximum power point.

In the derivation of Eq. (3), IT is assumed that the input impedance of the measurement instrument, $Z_{in} \gg Z_{PNG}$. The situation changes when $Z_{in} \leq Z_{PNG}$. In this case, the external load is not Z_L, but is, in fact $Z_L || Z_{in} = \frac{Z_L \times Z_{in}}{Z_L + Z_{in}}$. Consequently, the instantaneous power should be written as:

$$P_i = I_L \times V_{out} = V_{out}^2 \times \frac{Z_L || Z_{in}}{(Z_{PNG} + Z_L || Z_{in})^2} \tag{4}$$

In this case, when $Z_{PNG} \geq Z_{in}$, the maximum external load will always be limited by the input impedance of the measuring instrument because of the parallel configuration of Z_L and Z_{in}. Consequently, all measurements for $Z_L \gg Z_{in}$ becomes irrelevant.

Eqs. (3 and 4) retrieve the instantaneous power. However, in an actual experiment, the voltage is constantly changing with time which implies that the average power per force cycle, P_{av}, should be calculated:

$$P_{av} = \frac{1}{\tau} \int_0^{\tau} P_i dt \tag{5}$$

where P_i is calculated using Eqs. 3 or 4 (depending on the measurement instrument), and τ is the period for every cycle. A typical voltage trace and its corresponding instantaneous power trace for one period of excitation are shown in Fig. 5**c**. The actual power that the PNG delivers is not P_i but the area under the P_i curve. Several cycles should be considered for every external load, and the average power should be reported.

The instantaneous power can be obtained in various ways, namely by $V_{out} \times I_L$, $Z_L I_L^2$, $Z_L V_{out}^2$. A good research paper should always state which one of the methods has been employed in calculating power. It should be noted that reporting power from $V_{oc} \times I_{sc}$ is a incorrect practice because it considers two independent measurables obtained from two different circuits, and their product, a number in Watts, has little relevance to the PNG performance.

Let us now clarify the abovementioned matters with examples using the PZT and PVDF devices and then discuss the literature. The voltage generated by both PNGs are recorded using an electrometer and an oscilloscope. Both PNGs are placed in series with variable resistors. The voltage (or current) across different resistive loads is measured and plotted in Fig. 6 for both PNGs. The voltage for the PZT device is low for low external load values. It then increases as the load increases until the open-circuit condition is reached. The average power generated by the PZT device is obtained using the procedure explained above, Eq. (5), and is presented in Fig. 6a. The power shows a clear maximum peak at an external load of 190 kΩ. The measurements are also conducted using the oscilloscope. The power obtained from oscilloscope data follows exactly those obtained from the electrometer because the internal impedance of the oscilloscope is substantially larger than that of the PMN-PT device. Note that the external load in the case of using an oscilloscope is always in parallel configuration with the 1 MΩ input resistance. In the case of the PVDF device, Fig. 6b, the maximum power point is obtained at 3.8 GΩ. Note that the maximum power point is obtained only using an electrometer because the internal impedance of the PVDF device is much larger than the input resistance of the oscilloscope. Therefore, the oscilloscope measures only a limited part of the power curve and cannot capture the maximum achievable voltage, thereby the maximum achievable power.

The values obtained for power for the device still cannot serve as comparison metrics because the devices used have different areas and piezoelectric layer thickness. According to Eq. 1**,** the voltage generated by the PNG depends on both device area and film thickness. Hence, power should be normalised to the area and volume of the active material. The areal and volumetric power densities are the comparison metric between various PNGs.

Now let us explore some possible *incorrect* ways to calculate power for the PVDF-based PNG. Eight different power values have been obtained using a variety of approaches, as shown in Fig. 7**a**. We used data from measurements with either a low impedance oscilloscope and a high impedance electrometer. Three power values are related to measurement with the electrometer. An *average* power, as described above, is calculated and plotted as the reference. *Instantaneous* power, which is obtained from the peak voltage of every excitation, clearly overestimates the actual power. The power calculated from the oscilloscope

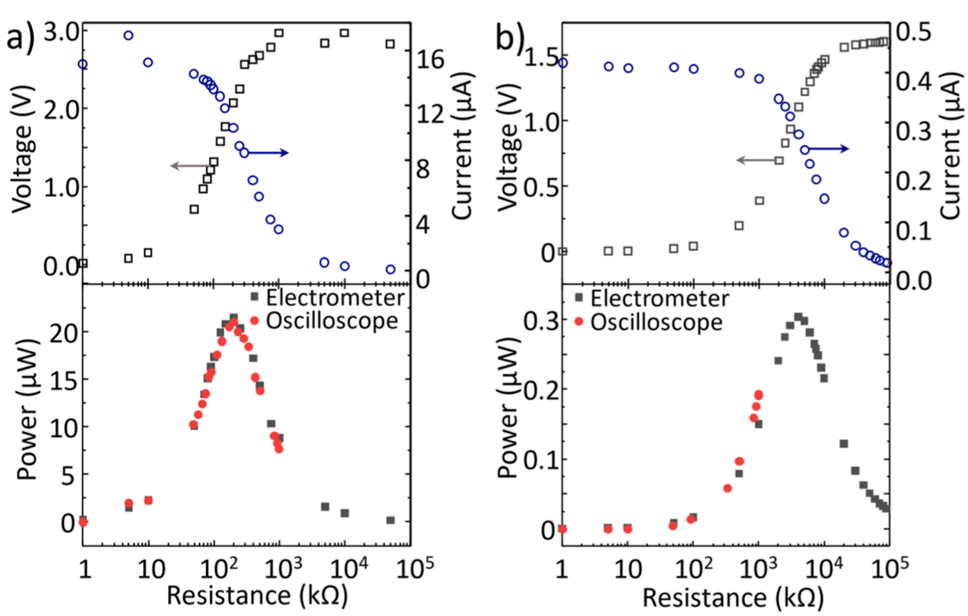

Fig. 6. Voltage-current measurements and power calculations for a) PZT and b) PVDF-based PNGs. Average power is calculated using Eq. 5, with data obtained independently from an electrometer and an oscilloscope. Power obtained from oscilloscope is calculated by taking the input impedance of the Oscilloscope into account (see the discussion leading to Eq. 4).

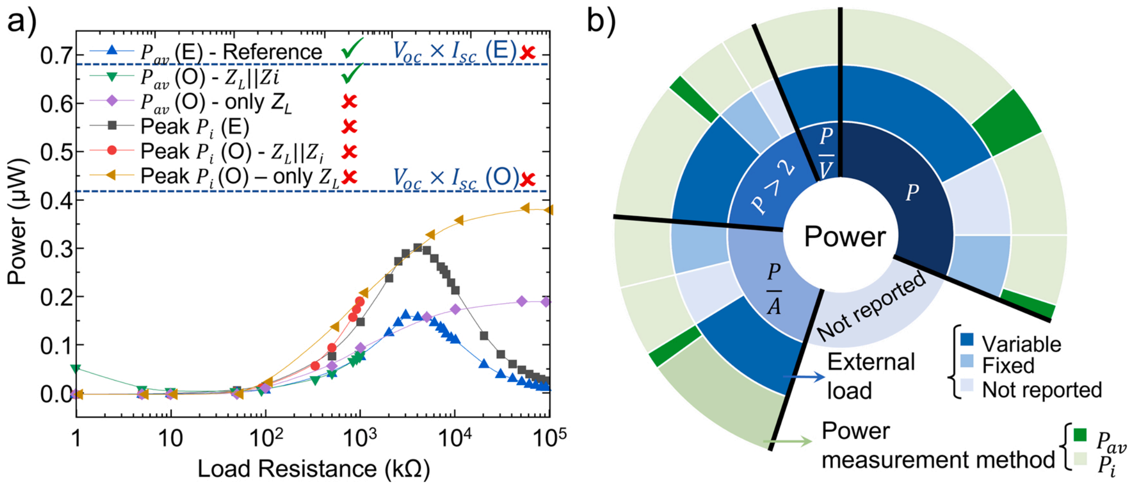

Fig. 7. a) Various correct and wrong methods of reporting power for a PNG (in this case, for PVDF-based PNG). The correct and wrong methods are indicated with green tick and red crosses. Eight different methods are typically used in the literature, of which only two are correct. The Reference data, $P_{av}(E)$, is the average power obtained from data collected using an electrometer. $P_{av}(O)$-$Z_L||Z_i$ is calculated from data obtained using an oscilloscope with taking the input impedance of the oscilloscope into account. $P_{av}(O)$-only Z_L is calculated by ignoring the input impedance of the oscilloscope, and is wrong. Obtained. Peak P_i values are calculated by taking the only the peak value for voltage (or current) into account, which over estimates the actual power. The values calculated from $V_{oc} \times I_{sc}$ (obtained using electrometer or oscilloscope) overestimate the actual power and are not correct. b) Sunburst overview of the literature assessment showing only a tiny fraction of papers (1.3%) correctly reporting power.

measurements is even more prone to misinterpretation because the impedance of the oscilloscope is a limiting factor. In this case, the average power over the equivalent load (Eq. 5) is the correct power. Note that even the average power obtained overestimates the actual power that the PNG delivers.

For the sake of the completeness, the value for the product of V_{oc} and I_{sc} for either case, although irrelevant to the actual power, is also given on the plot as a dashed line. In either case, the values are substantially larger than the *real* power value.

Now it is time to assess the reported power in the literature, a summary of which is given as a sunburst plot in Fig. 7b. The inner circle shows the distribution of the papers reporting power (of any sort, correct or wrong). Five categories are identified; papers that do not report any form of power, papers reporting only power, areal power or volumetric power, and papers reporting more than two power number, for example areal and volumetric. It is observed that nearly 31.3% of the papers reported a power value, while 21.3% reported areal power, and 6% reported volumetric power. 15% of the papers have reported two power metrics, while only 2.4% reported all three power values relevant to PNG performance. Note that nearly 24% of the papers have not reported any form of power. The inner middle ring of the plot indicates whether the calculated power is obtained using and external load. Note that maximum power point is obtained when the external load is systematically varied. It is observed that of all the papers that have reported power, 54% have used a variable load, 19.7% have used a fixed load, and 26.3% have not reported the load condition. The outer circle of the sunburst plot shows the distribution of methods used in calculating power. Of those papers reporting power, only 10% have obtained power by integration and reported the time-average power, whereas 44% have reported instantaneous power using one of the conventional formulas ($V_{out} \times I_L$, $Z_L I_L^2$ or $Z_L V_{out}^2$). It worth noting that 46%, hence a majority, of the papers have not indicated how the power was obtained. Nevertheless, we have counted those papers as reporting instantaneous power. It is clear that there is a tendency in the literature to overestimate the power by reporting the maximum instantaneous power instead of the time-averaged power. In addition, when using an oscilloscope, the equivalent resistance of the load and input resistance of the oscilloscope terminal is rarely used as the actual external load (Eq. 4).

As shown in Fig. 7b, only a limited number of investigated papers in our survey have provided sufficient experimental details so that the work could become reproducible by others. The power metric which should be reported in each paper is the average power normalised by the active area (areal power density) and volume of the device (volumetric power density); See Eq. 1. Publications discussing PNGs should be preferably reporting all three power values. In our analysis, only two papers (out of 80) have reported all three power values. However, these papers do not report an average power.

A flowchart is developed to determine how many publications are addressing the criteria for reliable reporting of power. The flowchart discards the publication if a particular criterion is not fulfilled. As shown in Fig. 8, only 1 out of the 80 papers has correctly reported a power metric. This is a low number, which indicates that there is need to improve in the reporting of data for the field to develop and succeed. Otherwise, as the research community there is a waste on limited resources and a potential to endanger the fate of the PNGs as a field of

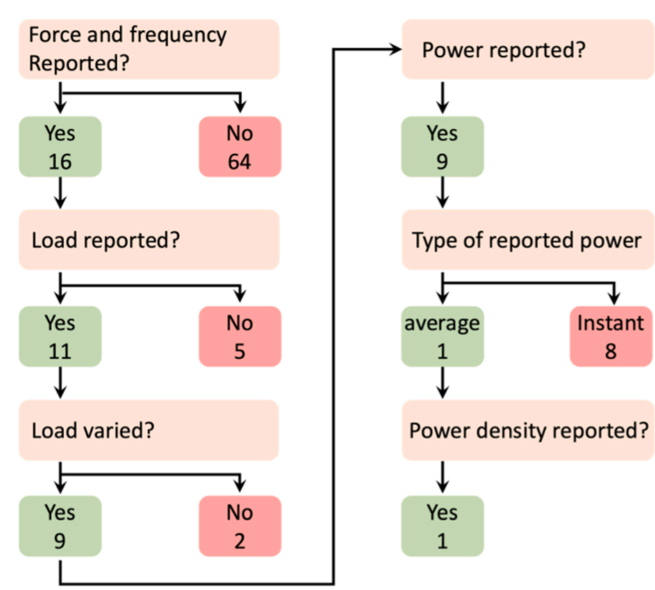

Fig. 8. The flowchart retrieves the number of papers reporting at least one power metric.

research. This finding strongly suggests that there is an urgent need to develop a 'standardised experimental protocol' that should be followed by all the researchers in the energy harvesting field.

4.7. Useful electrical power from PNGs

Upon the mechanical excitations, PNGs produce an alternating voltage or current, as shown in Fig. 5c, where the polarity of the voltage alters with time. Typical electronic circuits require a direct current (DC) voltage source. Therefore, the PNG must be accompanied by a voltage rectifier circuit to supply the consumers with both positive and negative half-cycles. Our literature review shows that full-wave voltage rectifier bridges employing silicon p-n junction diode are the most used (27.5%), followed by silicon Schottky diode (6.25%) and active rectification (1.25%). The circuit diagram of the commonly used rectifying circuits is given in Fig. 9a-c.

The rectifying diode bridge is the most used circuit due to its simple implementation. However, for any forward-biased p-n junction diode, there is a voltage drop of ~ 0.7 V, resulting in a ~1.4 V loss in the generated voltage by the PNG. This voltage loss is highly significant for a piezoelectric energy harvester. The voltage loss for a Schottky diode is nearly half that of a p-n junction diode and amounts to 0.3–0.4 V. Hence, replacing the silicon p-n junction diodes with Schottky diodes partially mitigates the voltage loss problem and reduces the loss from ~1.4 V to ~ 0.6–0.8 V. However, the higher leakage current of the Schottky diodes is their major drawback and has a negative impact on the overall energy efficiency of the harvesting system. The associated leakage current and voltage efficiency should therefore be considered and detailed – usually available in the manufacture datasheet. In addition to passive rectifying solutions based on diodes, it is also possible to realise actively controlled rectifiers using Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), Fig. 9c. These so-called active or synchronous voltage rectifiers guarantee a rectified wave shape on output voltage terminals by actively turning on and off the MOSFETs in the circuit and are an alternative to conventional diode bridges. An integrated comparator detects the polarity of the voltage and accordingly turns on and off the corresponding MOSFET switches. The advantage of this method is that is significantly reduces the voltage drop to 0.1–0.2 V due to the low resistance of MOSFETs in their *on* state, which can be as low as 10 mΩ. Reports claim at least double the efficiency (92%) in the rectifying stage in comparison to standard rectifying diode bridges. [15] The drawback, however, is that it is a more complicated circuit and cost. We now clarify the issue with the losses from the rectifying element using the PVDF PNG. The peak voltage of the PNG (at a load of 1 MΩ, using an electrometer for the measurement) for the case of the p-n junction diode is 0.5 V, while the voltage obtained from the Schottky diode rectifying bridge is 1.15 V and 1.5 V for active rectification using commercially available LT4320 (from Linear Technology).

Until now, we have described the AC-DC conversion stage. After rectification, a voltage regulation stage usually takes place. The voltage regulation stage often employs a DC-DC converter, which essentially changes the DC current originating from a source, from one voltage level to another, based on the requirements of the apparatus being supplied. Commercially available and highly efficient DC-DC solutions with sub-microwatt operation losses, such as the ADP5091/ADP5092, can be adapted to incorporate a low loss full-wave bridge rectifier and enable energy harvesting from piezoelectric devices. Furthermore, step-up or step-down converters, such as the LTC1474 from Linear Technology, are usually used in energy harvesting from piezoelectric films to bring, for example, a high input voltage from a piezoelectric element down to a low voltage, or vice-versa - to the electronic load.[16,17] A step-up converter is often called a boost converter, which essentially is a DC-to-DC power converter that, as the name suggests, increases the voltage from its input to its output - at the expense of stepping down the current. These converters are often accompanied by complex adaptive control algorithms to further improve energy harvesting efficiency at the regulation level.[18,19].

The output power of a piezoelectric film is generally low, due to its low volume. The energy needs to accumulate in an efficient storage medium before being fed to a specific load. Capacitors are among the preferred choices to accumulate charge from constantly oscillating piezoelectric sources [21–23] since they enable rapid access to the

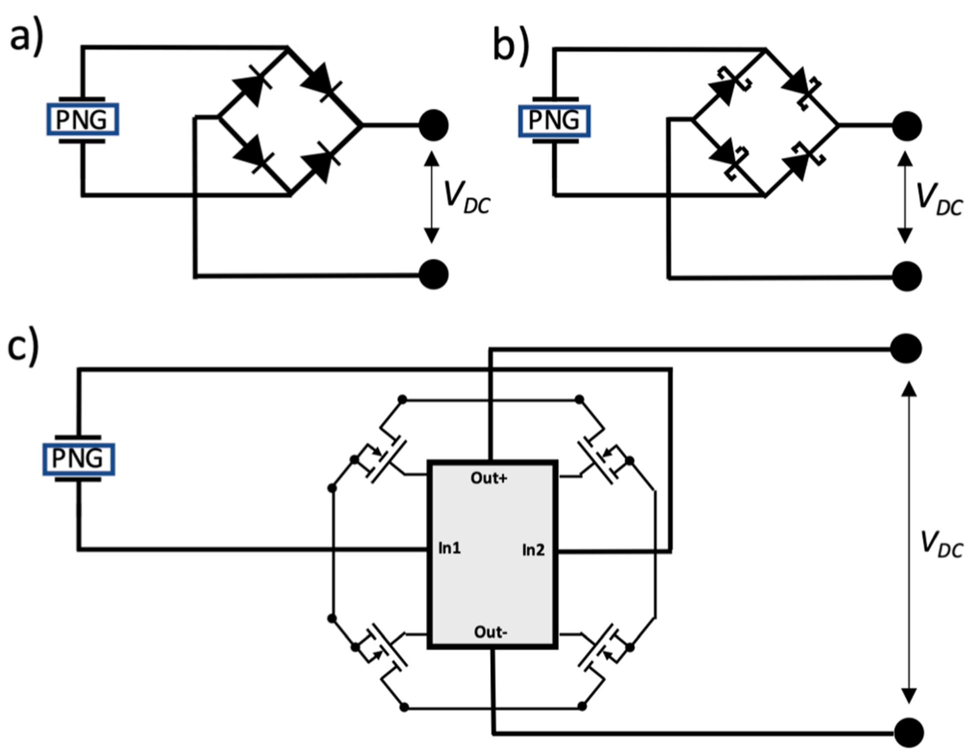

Fig. 9. Schematic circuit diagrams of the circuits used for rectifying the voltage signal generated by the PNGs.

accumulated charge v and do not need a least amount of voltage to begin charging. Intermittency is, however, a debilitating factor for capacitors and likely the most favourable point to their competitors, e.g., batteries. Rechargeable batteries do not suffer from intermittency or input signal suspension but do have a limited number of charging cycles, below 1000, [23] which is important in the area of piezoelectric energy harvesting. This limitation is a key enabler for the recent research in supercapacitors, where the charging cycles move up to 10^6. Yet, the intermittence issue still holds and represents significant power losses in a matter of a few days. [16].

Depending on the piezoelectric input characteristics and external load requirements, and complementing the already discussed power management units in this section, there are other commercially available all-in-one power management units such as, for example, the LTC3588, LTC3108 and MAX17710 from Analog Devices, [24,25] which could be used as Plug-and-Play or even optimised, such as adjusting the low-frequency operation regime, [25] to allow a more efficient end usage of piezoelectric energy.

4.8. Efficiency

The term *efficiency* has been used in a vague form in the PNG literature. To clarify this statement, let us first define the term efficiency. A variety of efficiencies are defined for mechanical to mechanical, mechanical to electrical and electrical to electrical energy conversions. The mechanical-to-mechanical efficiency, η_{mm}, is a measure of absorbing the mechanical vibrations by the PNG defined as absorbed mechanical energy divided by the applied mechanical energy. The mechanical-to-electrical, η_{me}, efficiency is defined as the amount of electrical energy produced by the PNG divided by the input mechanical energy. The electrical-to-electrical efficiency, η_{ee}, is defined as the amount of stored electrical energy in a capacitor (or battery), which is the available energy to feed to electronic devices divided by the amount of energy that is produced by the PNG. The overall efficiency,η_{PNG}, is defined as $\eta_{PNG} = \eta_{mm}\times\eta_{me}\times\eta_{ee}$. Several review papers have already been published in which various efficiencies and estimation methods have been discussed in detail; the reader should consult, for example, the review papers from Uchino. [9] Nevertheless, a brief treatment of the efficiency is provided here.

To have a more accurate look at the PNGs, consider the following electrical model of a PNG with emphasis on its transducing functionality, as shown in Fig. 10. On the left, the mechanical part of the PNG is modelled, where the voltage source acts as the input mechanical energy. Due to mechanical loss of the system, a part of mechanical energy is dissipated as heat in the resistor. The remaining part of the mechanical energy is stored as potential energy in the structure, analogous to the stored energy in a compressed spring. The energy is stored in form of electric charge and magnetic flux in the capacitor and inductor. The transducing nature of the PNG is indicated by the two mutually coupled inductors. The transducing ratio is M:N, and is conceptually tightly coupled with electromechanical properties of the material, namely piezoelectric charge (d_{ij}) and voltage (g_{ij}) constants. It should be noted that not all of the stored mechanical energy can be transformed to the electric energy (second winding in the transformer) as the result of mechanical impedance mismatch. A fraction of the transformed electrical energy will be dissipated in form of heat, representing electric loss in electrode contacts, wires, etc. and the rest will be stored in the capacitor. By interfacing an electrical energy consumer (load), a part of the stored electrical energy will be reflected due to electrical impedance mismatch and the rest will be delivered to the consumer.

With the explanation given above, one can unambiguously define the following parameters as criteria of efficiency for PNGs:

I. The electromechanical coupling factor

$$\kappa^2 = \frac{\text{stored electrical energy}}{\text{input mechanical energy}} = \frac{\text{stored mechanical energy}}{\text{input electrical energy}} \tag{6}$$

II. The energy transmission coefficient

$$\lambda_{max} = \text{MAX}\left(\frac{\text{output electrical energy}}{\text{input mechanical energy}}\right) = \text{MAX}\left(\frac{\text{output mechanical energy}}{\text{input electrical energy}}\right) \tag{7}$$

III. The efficiency

$$\eta_{PNG} = \eta_{mm}\times\eta_{me}\times\eta_{ee} = \frac{\text{output electrical energy}}{\text{consumed mechanical energy}} = \frac{\text{output mechanical energy}}{\text{consumed electrical energy}} \tag{8}$$

Our literature shows that a large number of papers, 83.8%, do not report any efficiency. Of the remaining 16.2% that report an efficiency value, it is unclear which efficiency is being reported. The reported values for efficiency in the literature vary from values as high as 90% to as low as 0.2%. These numbers are primarily meaningless as it is not clear how they have been obtained and which efficiency they specify. There is clear lack of consistency in the definition of efficiency. The issue regarding efficiency calculation needs careful and immediate attention and we refer the interested reader to the paper published by Uchino. [9] The efficiency estimation heavily relies on a proper measurement, which is the focus of this review to provide a standardised measurement protocol.

Generally, PNGs are not efficient devices and their η_{PNG} is typically low unless they are intentionally tuned to operate at a resonant frequency. Nevertheless, the paper reporting PNGs should report at least one (ideally two) efficiency parameter, namely η_{me} (and η_{mm}).

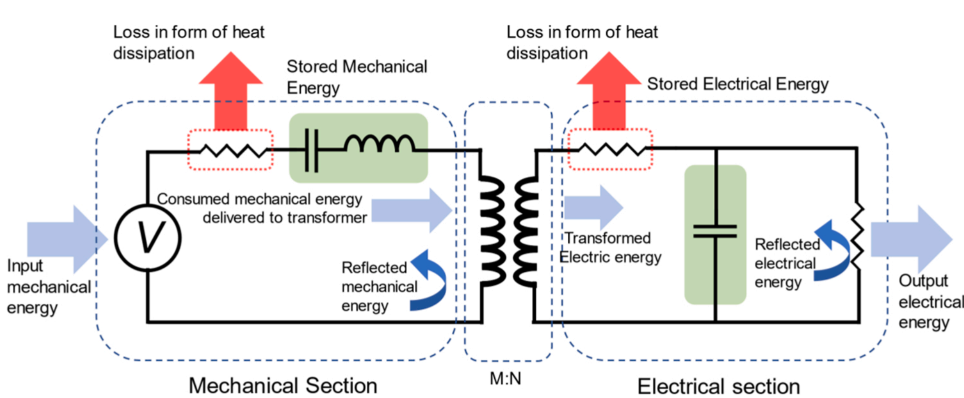

Fig. 10. Schematic circuit diagrams of the PNGs as an energy transformer and its corresponding flow of energy.

5. Standardised data reporting protocol

We hope the reader is convinced that there is a lack of a standardised data reporting protocol in the PNG field. Such a protocol will enable an easier reproducibility of results from different labs and also enables identifying promising material or device candidates for further investigations. We suggest four groups of information encompassing 21 entries, as summarised in Table 1**,** that must be reported in every energy harvesting paper.

Below we have provided further clarification as to why these values must be reported:

- First and foremost, details of the *preparation conditions of the active materials* must be reported in any papers dealing with PNGs. The data should provide enough details about the starting materials, solvents, precursors, their supplier, the purity and report the details of any purification process. Moreover, details of material synthesis must be given. Particularly for the (nano)composite class of materials, details regarding the particle sizes, size distribution, stoichiometry of the particles, weight fraction, and mixing conditions must be provided. Providing details of mixing, baking, curing, synthesis and film processing conditions is vital. Descriptions such "ambient laboratory conditions" bare no information since the ambient condition in our own laboratory in Bath, which is among the wettest cities in the UK, is very much different from Yazd, which is one of the driest cities in Iran. Hence, as a matter of good research practice, relative humidity and temperature of the lab should be measured and reported because they, particularly humidity, can affect the preparation process and the final results. These details are needed for the sake of reproducibility of results by other groups.
- *Piezoelectric constant*: For novel materials, particularly for (nano) composites or polymer ceramic composites, the values of piezoelectric constants highly depend on various experimental parameters such as particle size and stoichiometry, as well as the film microstructure (agglomeration versus uniform dispersion). Hence, for this class of materials, the relevant piezoelectric constants (d_{ij}) must be measured and reported. For more conventional and commercial piezoelectric materials, the piezoelectric constants are usually known or can be found in the literature. Nevertheless, it is recommended that the authors measure the piezoelectric constant of the material that is used in their study. If that is not possible, the authors must explicitly state the most acceptable values for the piezoelectric constants for their material from reliable sources.
- *Relative Permittivity*: For (nano)composites or polymer ceramic composites, the piezoelectric constants can widely vary and the relative permittivity at constant stress should be reported for piezoelectric and poled ferroelectric materials. For this class of material, the dielectric loss (or the imaginary part of the permittivity) is also important, and it is highly recommended to measure and report the value of loss permittivity. For a high performance PNG, a low-loss piezoelectric is required. For more conventional piezoelectric materials, the permittivity is usually known or can be found in the literature. However, loss permittivity often depends on the device fabrication process and it is therefore recommended that the authors measure the piezoelectric constant and loss permittivity of the material that is used in their study.
- *Mechanical properties*: It is recommended that the authors measure and report the mechanical properties of particularly newly developed materials, e.g., the Young's modulus and elastic constants. It should be made clear if the reported elastic constants are at conditions of constant electric field (c_{ij}^E) or dielectric displacement (c_{ij}^D).
- *Device fabrication conditions* should be accurately reported. Report all relevant temperatures, pressures, humidity, and other details relevant to the fabrication of the device. For example, humidity and substrate temperature can substantially affect the microstructure of polymer films.
- The *active device area & thickness* of the piezoelectric active layer must be known so that others can further process, investigate, reproduce, and benchmark the research data.
- *Internal impedance* should be measured as a function of frequency or at least at the mechanical excitation frequency to enable the identification of the optimal external load to maximise the power. Care should be taken that a proper instrument is used for the impedance evaluation. Piezoelectrics have typically very large internal impedance, and therefore an instrument which can reliably measure in high impedance regime, typically in hundreds of GΩ, should be used.
- *Poling conditions* must be reported. Note that in an unpoled polycrystalline piezoelectric, as in nearly 100% of the cases with PNG device, the net macroscopic polarisation of the piezoelectric is zero. Hence unpoled PNG should not produce a significant voltage upon excitation. Reporting poling condition is therefore vital since it provides that condition to properly optimise and investigate the power generation by the materials.
- *Type of force* must be specified (cyclic, impact, strain or stress), and the amount of the applied *force* (N) and its *frequency* (Hz) must be reported. Note that experiments involving finger tapping or other quantitative methods and assigning an arbitrary number to the excitatory force (or pressure) should be strictly avoided. Experiments such as finger tapping, are useful only for the sake of application demonstration, not for material evaluation. A *fatigue test,* although not a requirement, is recommended. At least several tens of thousands of cycles should be reported. It is advised to design or employ an experimental setup that allows controlling of the applied frequency, for instance, using a function generator. It is recommended to report the force and frequency of the fatigue test. Considering the limited time and resources in academic labs, 10^5 cycles seem to be a reasonable number of cycles for a fatigue test.
- For the electrical measurements, it is of crucial importance to report the measurement method for the electric parameters, particularly V_{OC} (V) and I_{SC} (μA), which must be reported. The *input impedance* of the measuring instrument must be reported. Using a measuring instrument with input impedance lower than that of the PNG must be avoided.

Table 1
Parameter checklist that is recommended to be reported with papers dealing with nanogenerators.

	Must be reported	Recommended
Material		
Material preparation conditions	✓	
Piezoelectric constant	✓	
Relative Permittivity	✓	
Mechanical properties		✓
Device		
Fabrication conditions	✓	
Area (cm^2)	✓	
Thickness (μm)	✓	
Internal Impedance (Ω)		✓
Poling conditions	✓	
Mechanical input		
Type of Force	✓	
Force (N)	✓	
Frequency (Hz)	✓	
Fatigue test		✓
Electrical output		
Experimental conditions	✓	
Measuring instrument	✓	
V_{OC} (V)	✓	
I_{SC} (μA)	✓	
Power (P_{av})	✓	
Areal power density (μW/cm^2)	✓	
Volumetric power density (μW/cm^3)	✓	
Efficiency %		✓

- All PNG papers must report *power* (μW), *areal power density* (μW/cm^2), and *volumetric power density* (μW/cm^3). Power must be obtained by integrating the instantaneous power signal over one period of excitation. Moreover, the power must be obtained from the experiment wherein the external load is varied. The latter must be done in all PNG reports regardless of the knowledge of the internal impedance of the PNG. In reporting V_{oc}, I_{sc} and power values, special attention must be paid to the internal impedance of the measuring instrument. Moreover, it should be practiced to report a statistical average of the power for the PNGs obtained from a number of measurements on different devices to ensure good reproducibility.
- *Efficiency* of the devices must also be reported. Arguably reporting η_{PNG} is an involved process. Nevertheless, it is straightforward to report η_{me}. For the experiments involving 33-mode, as in impact, the applied force can be measured with a pressure sensor, while for the experiments involving 31-mode, as in the case of bending, the force can be measured using a strain gauge sensor. Data from the sensors should be used to calculate η_{me} Ideally, PNG related publications should also contain rectifying circuits and report the amount of stored energy in a capacitor in a certain period of time. It should be noted that the choice of the capacitor highly depends on the rectification circuit, the frequency of the excitation and the RC time of the circuit. Hence, it is only recommended that the authors report the energy stored in a capacitor and give a total efficiency of the device under study. Obtaining the other efficiency parameters namely η_{mm} and η_{me} from the measurements is straightforward and it is recommended to report them.

6. Conclusion

It is shown that the majority of the literature on piezoelectric energy harvesters does not fully report the relevant material properties, device parameters, experimental conditions, or implement correct measurement procedures. The lack of information and the inconsistency in data reporting makes it difficult to effectively compare materials investigated by the community and identify the promising candidates for an alternative energy source. A 'universal data reporting protocol' is suggested to enable more coherent data reporting and quantitative experimental practices, which will enhance the reproducibility and thereby enable further material optimisation towards reaching piezoelectric energy harvesters with higher efficiencies.

CRediT authorship contribution statement

Morteza Hassanpour Amiri: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Rose Fatscher**: Validation, Formal analysis, Data curation, **Rebecca Taylor:** Validation, Data curation, Formal analysis. **Paulo R.F. Rocha:** Formal analysis, Investigation, Writing – original draft. **Chris R Bowen:** Formal analysis, Investigation, Writing – original draft. **Kamal Asadi**: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2022.108073.

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