Piezoelectric generators enable maintenance-free power supply for integrated electronics in smart system applications. The majority of publications consider the aspect of power transfer electronics; however, the influence of the transducer materials was rarely described. Recently, material characteristics received increased attention from the ceramics community. We set the focus of the present paper to commercially available piezoelectric ceramics. Different figures of merit are derived from system analysis using electromechanical modeling. They allow for the description of typical load scenarios and commercial piezoceramics. Derived rules are expected to be helpful for guiding ceramic engineers and system designers to succeed in improved generator solutions.

I. Introduction

Recent developments in sensing technology, electronics, and wireless communication together with the progress in the harvest of electrical energy from sustainable sources, such as sunlight, heat, and mechanical vibrations, enable a new generation of smart structures and systems. Application scenarios include wireless, self-powered sensor nodes, which are capable of reporting on operating conditions and monitoring “life experience” to account for the current state of health. Growing markets are seen in energy and environmental management, building management, process control, condition monitoring, logistics, and asset tracking.

Wireless sensor networks require a flexible and maintenance-free power supply that works for decades. The use of solid-state generators has proved to be a competitive approach. In comparison with other energy converters, the piezoelectric generator features a high-energy density at relatively low mechanical strain–stress levels. Furthermore, mechanical vibration energy is available at almost all locations allowing for the general implementation of piezoelectric power supply.

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A Survey on Piezoelectric Ceramics for Generator Applications

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Historically, piezoelectric generators made of piezoceramic have existed since 1959 (Table I). An electric spark generator for the ignition of flammable or explosive gas mixtures was the first application, where a relatively long longitudinally poled piezoceramic bar is mechanically stressed by a hammer stroke. Because of the piezoelectric effect, a high open-circuit voltage of more than 10 kV is generated. If the generated voltage exceeds the breakdown voltage of the gas, an electric spark occurs thereby igniting the gas (see Fig. 1).

In 1980, the application of a piezoelectric generator in combination with a low-power electronic was reported for the first time. A piezoelectric transducer is used to monitor the pressure level in tires of cars and trucks. While driving with low pressure levels, the rubber of the tire and the piezoelectric transducer are more prone to stress. The amount of energy converted increases and allows for sending a telegram to a receiver.

In 2003, Enocean GmbH began commercializing wireless light switches for building automation. The mechanical input energy is taken from the user while operating the light switch. A piezoelectric bending transducer generates sufficient electrical energy to send a message up to 300 m.

We conclude that the performance of piezoelectric ceramics allows for the implementation of wireless, self-powered sensor nodes either as a part of smart structures and systems or as a more general maintenance-free, self-sufficient operation of low-power electronic through the complete life cycle.

Of course, product developments are based on the optimum selection and combinations of subassemblies. The main focus of the present paper is directed to the multifarious correlations between the characteristic values of commercial piezoceramics and their effective implementation in generator architectures.

Section II reports on the individual modules of a piezoelectric generator. Section III illustrates the details of the piezoelectric energy conversion. Section IV summarizes the commercial materials basis, Section V considers the electronic, and Section VI ends up with the conclusions.

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II. Operating Principle of a Piezoelectric Generator System

A piezoelectric generator is divided in five major modules: mechanical energy source, mechanical transformer, piezoelectric transducer element, generator electronics as well as intelligent
energy and storage management (Fig. 2). These modules are considered in the following sections.

(1) Mechanical Energy Sources
A piezoelectric generator must be driven dynamically; hence, the achievable output power is proportional to the driving frequency. For understanding the influence of the material properties, which is our motivation, it is more convenient to use energy quantities instead of power.

We classify the mechanical energy sources in terms of energy forms and drive modes. Three generalized mechanical energy forms are available: translational, rotational, and acoustic energy. In practice, piezoelectric materials are usually driven under translational loads. Alternatively, the shear case is also possible. Rotational energy is not directly usable.

Concerning mechanical drive modes, two principles are distinguished:

1. Stress-driven mode: An applied mechanical stress leads to a specific strain value depending on the material’s Young’s modulus. Parallel loading paths to the piezoelectric material must be avoided. Otherwise, the stress energy is separated depending on the stiffness ratio and electrical boundary condition, see Section III. Stress-driven load cases can be resonant or nonresonant. The piezoelectric accelerometer sensor may serve as an example.

2. Strain-driven mode: The generator is forced to follow an external strain, caused by an “infinite” stress. For example, considering a large bridge with a small attached surface-mounted flat generator, like a Macro Fiber Composite (MFC), the generator follows the deflection of the bridge, completely.

In both modes, the generator is assumed not to react on the external driver. Practical cases are sometimes more complex. This is especially true if the stiffness of the generator is influenced by the behavior of the piezoelectric material. In other words, stiffness of the structure and stiffness of the piezoelectric material are connected in parallel and establish a secondary load path.

Depending on electrical boundary conditions, the stiffness and hence the mechanical energy in the piezoelectric materials vary; see Section III/(1). The effect can be monitored by resonant frequency shifts and damping effects, which are directly related to change in stiffness and energy distribution. Change in vibration amplitude can often be observed as is typical for resonant generators.

(2) Mechanical Transformers
Mechanical transformers have two functions: the transformation of nontranslational into translational energy and the matching of the mechanical impedance.

Typically, the mechanical sources produce only a limited stress level and the piezoelectric materials are mostly stiff. This implies the coupling of mechanical sources of high impedance with piezoelectric materials of low mechanical impedance. Piezoelectric polymers represent an exception.

Mechanical transformers are known from actuator developments, e.g., lever arms, bending structures, C-blocks, rainbows, THUNDERS, recures, telescope, moonie, and cymbal structures.

Mechanical impedance matching enables an optimized energy transfer from the source to the transducer. This ensures a higher mechanical, and hence a higher electrical converted energy. It should be noted that mechanical energy transformation and impedance matching are always accompanied with losses of transferred energy. Typically, a certain amount of mechanical input energy is needed to deform the mechanical structure elastically. This energy is stored recoverably but is not used to stress the transducer to generate electrical energy. Additionally, real losses like friction occur, but their contribution is comparably low.

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**Table I. Historical Review of Piezoelectric Generators**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1880</td>
<td>Discovery of the piezoelectric effect</td>
</tr>
<tr>
<td>1950</td>
<td>General use of piezoelectric generator claimed</td>
</tr>
<tr>
<td>1959</td>
<td>Piezoelectric spark igniters claimed</td>
</tr>
<tr>
<td>1972</td>
<td>U.S. patent about a gas ignition device as shown in Fig. 1</td>
</tr>
<tr>
<td>1980</td>
<td>First possible application using piezoelectric generators in combination with low-power electronics</td>
</tr>
<tr>
<td>2003</td>
<td>EnOcean starts commercializing wireless light switches</td>
</tr>
<tr>
<td>2009</td>
<td>Diversification of research objectives and markets</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** A micro section of piezoelectric spark generator from a pocket lighter is shown. The acceleration (1) and retaining (2) spring is loaded by the human finger. Reaching a defined stress, a simple mechanic releases the energy stored in the acceleration spring and a hammer (3) hits the piezoceramics (4).

**Fig. 2.** Block diagram of a piezoelectric generator. Each column shows one of the five major modules with some typical examples.
(3) Piezoelectric Materials
The three most common piezoelectric material groups are single crystals, ceramics, and polymers (Table II).

A deeper view into the crystal structure of single crystals and ceramics proposes that 20 of the 32 crystallographic point groups are piezoelectric due to unsymmetrical lattice. Furthermore, 10 of them are polar and are called pyroelectric. A subgroup has switchable polarization and is called ferroelectric.

The superposition of the piezoelectric and the ferroelectric effects increases the electromechanical performance. This behavior is well known from ferroelectric piezoceramics with a perovskite structure such as lead–zirconate–titanate (PZT) and BaTiO$_3$, but is also nonlinear. We always consider the linear approximation in the present paper. For further interest in nonlinear effects, Half is recommended.

The tailoring of piezoelectric and ferroelectric material characteristics by compositional variations and the microstructure is well known. In addition to being one of the best-known ceramics, PZT is also commercially available in large amounts and for an affordable price.

Hard PZT ceramics are characterized by reduced hysteresis, low depolarization, and low losses, and therefore they are used for high-power ultrasound transducers and sensors with higher temperature stability. Soft PZT materials commonly exploit the ferroelectric effect for high strain and high piezoelectric voltage constant $g$. Typical application areas are low-frequency, high-strain actuators and sensors with high sensitivity.

Today, PZT materials for generator application, like gas ignitors, play a secondary role in R&D activities. The materials are optimized for high mechanical stress loads without depolarization and high voltage output (high $g$-constant), respectively. Two examples are the impact-type Sonox$^\text{TM}$ P5$^{24}$ (see Fig. 1) and the squeeze-type Sonox$^\text{TM}$ P41$^{24}$. Sometimes, piezoceramics for sensor applications are specified as a possible candidate for generator applications. However, tailored ceramic materials for piezoelectric generators, especially designed for the use with electronics, are not commercially available. Therefore, the aim of this paper is to evaluate commercial high-performance piezoelectric ceramics for their possible use in generator applications.

(4) Power Transfer Electronics
Dynamically stimulated piezoelectric generators produce an alternating current (ac) output, which is not directly usable by electronic loads. Usually, a direct current (dc) output is needed to power electronics. Rectification, filtering, and an optimum power transfer are essential. Generally, power transfer circuits for piezoelectric generators are composed of up to four different power electronic components (Fig. 3).

Circuit design and layout, both depend on the topology used. Typical standard topologies are provided by the power electronic literature. The power transfer electronic is aimed to match the electrical impedances of the generator and the load. In order to improve the amount of harvested energy, additional active electronics may be helpful. dc–dc converters, such as step-down and step-up converters, inverter, and charge pumps, are used as standard components in electronic design. The extremely low output current of the piezoelectric generators limits the design option for the dc–dc converters, which are normally used to transfer higher currents ($10 \text{ mA}$–$10 \text{ A}$). To handle the very low current of a piezoelectric generator, the inductance or the switching frequency must be increased. Both approaches cause higher losses resulting from the resistance of the inductor and the higher on-site power due to higher switching frequency of the transistor, respectively.

A step-down dc–dc converter working in a discontinuous conduction mode is proposed as the solution of choice. Advantages arise from a smaller inductor and a comparably low switching frequency. However, the discontinuous mode is less efficient. Alternatively, dc–dc converters with a relatively low inductor and switching frequency working in a continuous conduction mode under intermittent duty cycle can also solve problems.

A nonlinear technique called Synchronized Switch Harvesting on Inductor (SSHI) as an alternative power transfer electronic is described in Guymor. It can be understood as an energy-level-triggered dc–dc converter in discontinuous conduction mode. The idea behind SSHI is to work under open-circuit conditions until the maximum voltage is reached. Then, short circuiting is carried out by switching on an inductor, which starts the charge and power transfer. A practical self-powered implementation showing a high on-site power and low efficiency is cited.

Despite many activities in R&D, a few self-powered dc–dc converters providing the lowest acceptable current in the 100 $\mu$A range are commercially available. One example, the LT1934 is used in the wireless light switch for building automation, showing an efficiency of approximately 50%–75% depending on the load current in the range of 100–1000 $\mu$A. This implies that the piezoelectric generator must be roughly doubled in size to provide the same amount of energy, but the output energy is well adjusted and regulated in the voltage level to the load.

Additional power transfer electronics consume a certain amount of energy, which has to be delivered by the generator. The efficiency of relatively small piezoelectric generators can have an adverse balance due to the on-site power consumed by the power transfer electronics, and therefore the output power can be negative (see Fig. 4).

(5) Intelligent Energy and Storage Management
An intelligent energy management and storage technology is needed to ensure reliable energy supply. This should be considered as a part of the generator system in order to maximize the energy output by switching the energy flow to empty storage units. Furthermore, controlled and reliable wake-up and shutdown routines are required in accordance with the available energy. This is necessary to increase the performance and ensure the operation of the generator.
A typical topology for a possible intelligent energy and storage management is shown in Fig. 5. The first energy path is used to power up the microcontroller, which manages the energy. This path must be powered up first and put to sleep at last. After turning on the energy management microcontroller, the incoming energy must be transferred to the load and to different storage elements, characterized by individual charge-up and discharge times.

The reason for this is that the wake-up time should be as low as possible. The charge time of a small capacitor storing enough energy for a few working cycles of the load needs less time than to charge-up a super capacitor or a lithium ion secondary cell. The highest potential for reducing on-site power is the usage of low-power electronics and slim software code for the microcontroller.

Power transfer, intelligent energy/storage management are often considered as one module. Here, in this paper, they are discussed separately due to their different functionality and system relevance.

III. Piezoelectric Generator Effect

The direct piezoelectric effect used for piezoelectric generators was discovered by Jacques and Pierre Curie in 1880. By applying a mechanical load to piezoelectric elements, the energy is split into mechanical and electrical energy. We will consider the operation conditions under which electrical work can be performed by a loaded piezoelectric generator. Let us start with the three electrical loading conditions. They comprise:

1. Short-circuit conditions: A charge is generated proportional to the mechanical load. In turn, the strain is proportional to the stress load although higher than in case 2. There is no counter-acting electric field.
2. Open-circuit conditions: A voltage is generated proportional to the mechanical load. The strain is proportional to the stress load but lower than in case 1. The reason for this is the generation of an internal electric field acting in the opposite direction of the mechanical load and stiffens the generator.
3. Load circuit conditions, i.e. a voltage and charge performing an electric work are generated simultaneously. The strain is proportional to the stress; the strain level depends on the voltage and charge output level, respectively, but lies between short- and open-circuit conditions.

The first two cases are typically used in sensors, whereas the latter case depicts the piezoelectric generator effect.

Considering piezoceramics like PZT and BaTiO$_3$, the piezoelectric effect is superimposed by the nonlinear ferroelectric effect. In this paper, the electromechanical behavior is assumed as linear when considering large signals.

(1) Energy Density

The piezoelectric generator is stimulated by an external mechanical vibration. The total energy provided is split into mechanical and electrical energy portions, i.e. the elastic deformation of a solid body and the free electric surface charge generating an electric field. This electric field can drive the free electric surface charge as a current through a load to perform electric work. Simultaneously, the electric field decreases. For a continuously alternating stimulation, a permanent electric work is performed.

For a better understanding of the piezoelectric generator effect, we consider a theoretical working cycle as visualized in Fig. 6. Starting at point 1 and applying a mechanical stress $T_1$ to a piezoelectric material under open-circuit condition leads to a strain $S_1$. The slope describes the compliance $s^T_1$; see also the line from point 1 to point 2 in Fig. 6.

The superscript $D$ denotes operation under a constant electric displacement field, e.g. open-circuit conditions. Vice versa, the superscript $E$ indicates the regime with a constant electric field, e.g. short-circuit conditions. The projection of strain and stress into quadrants II and IV describes the piezoelectric behavior. The external electric displacement field $D_2$ remains zero but the electric field strength $E_2$ increases by $d(e^T s^D)$. The constants $d$ and $e$ are the piezoelectric charge constant and the permittivity,
The constitutive piezoelectric equations\(^{30}\) can be written as hybrid four terminal network equation (Eq. (A1)). The signs are defined by the direction of the arrows in Fig. A1. The admittance matrix Y (Eq. (A2)) and the inverse transmission matrix B (Eq. (A3)) used for electromechanical and analytical modeling, respectively. The electromechanical modeling allows the use of piezoelectric material properties including electrical and mechanical components and sources in circuit simulation tools, e.g. SPICE. The transformation among the different matrix equations does not provide additional information; however, it allows an easier approach to the requested information.

\[
\begin{bmatrix}
S \\
D
\end{bmatrix} = \begin{bmatrix}
S^E & -d^E \\
d & -e^E
\end{bmatrix} \cdot \begin{bmatrix}
T \\
E
\end{bmatrix} = [Y] \cdot [T] \quad (A1)
\]

\[
\begin{bmatrix}
T \\
D
\end{bmatrix} = \begin{bmatrix}
1/s^E & d/s^E \\
d/s^E & -(s^E \cdot e^E - d^E)/s^E
\end{bmatrix} \cdot \begin{bmatrix}
S \\
E
\end{bmatrix} = \begin{bmatrix}
e^E & e^E \\
e^E & -e^E
\end{bmatrix} \cdot \begin{bmatrix}
S \\
E
\end{bmatrix} = [Y] \cdot [S] \quad (A2)
\]

\[
\begin{bmatrix}
E \\
D
\end{bmatrix} = \begin{bmatrix}
-1/d & s^d/d \\
e^d/d & -(s^d \cdot e^d - d^d)/d
\end{bmatrix} \cdot \begin{bmatrix}
T \\
S
\end{bmatrix} = \begin{bmatrix}
-1/d & 1/e^d \\
1/g^d & -e^d/e^E
\end{bmatrix} \cdot \begin{bmatrix}
S \\
E
\end{bmatrix} = [B] \cdot [S] \quad (A3)
\]

The transition from geometrically independent to geometrically dependent quantities, see Table A1, may apply.

**Table A1. Correlation of Physical Variables**

<table>
<thead>
<tr>
<th>Geometrical independence</th>
<th>Geometrical dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain (S)</td>
<td>Displacement (\xi)</td>
</tr>
<tr>
<td>Electric displacement (D)</td>
<td>Force (F)</td>
</tr>
<tr>
<td>Electric field strength (E)</td>
<td>Charge (Q)</td>
</tr>
<tr>
<td>Energy density (W)</td>
<td>Power (P)</td>
</tr>
<tr>
<td>Energy (E)</td>
<td>Voltage (V)</td>
</tr>
</tbody>
</table>

The working cycle is approximated by the SSSH technique.\(^{27}\) Generally, the efficiency can become complex if energy dissipation (real part) and storage (imaginary part) are considered separately. For piezoelectric materials, the storage is higher than losses. Therefore, the efficiency of the working cycle, shown in Fig. 6, can be written as:

\[
\eta = k^2 = \frac{W_{el}^D - W_{el}^S}{W_{el}^D} = \frac{W_{el}^D}{W_{el}^D} \quad (3)
\]

The definition of efficiency is the same as for the square of the coupling coefficient.\(^{31}\)

The ratio of mechanical and electrical energy \(k^2\) in Eq. (3) depicts a material constant. A high-efficient piezoelectric generator material can be selected by a proper set of material constants defining a very high value of the coupling coefficient \(k\); see the known Eq. (4).

\[
k^2 = \frac{d^2}{e^2 s^2} \quad (4)
\]

For piezoelectric generators, it is more advantageous to provide a maximum of electrical energy output by a given volume independent of the efficiency. For this case, another figure of merit applies.

It should be noted that piezoelectric generators are driven dynamically. The energy approach presented here does not include the influence of the frequency. Considering the frequency behavior, power density, which is defined as energy density cycles per time interval, must be used instead of energy density.
For piezoelectric generators, the electrical energy output as well as the electrical energy density of the considered material should become a maximum. The valid figures of merit depend on the stimulation mode of the piezoelectric generator and up rate different material data. In Sidebar A, the constitutive piezoelectric equations are presented.

Considering a piezoelectric generator driven under a stress load, the appropriate figure of merit can be derived from Eq. (A3) in Sidebar A.

\[
W_{el}^T = \frac{1}{w_{el}^T} T^2 = \frac{d^2}{e^T} T^2
\]

For both exceptional electrical loading cases, short circuit, i.e. \( E = 0 \), and open circuit, i.e. \( D = 0 \), the Eqs. (9) and (10) shown in Table III, can be derived. The strain \( S \) in the stress–load condition is set equal in the Eq. (A3). Equation (5) can be obtained by replacing \( D \) and \( E \) in Eq. (2) using the Eqs. (9) and (10).

\[
W_{el}^D = \frac{1}{w_{el}^D} D^2 = \frac{d^2}{e^T} S^2
\]

The derivation of Eq. (6) follows similarly to Eq. (5), but under strain-drive conditions. \( W_{el}^s \) and \( w_{el}^s \) are the electrical energy density and the piezoelectric energy density constant under stress load, respectively. Table IV summarizes the relations for this load case.

In the case of strain-driven mechanical energy sources, compliance becomes important. A stiffer, i.e. less compliant piezoelectric material leads to a higher energy output. The reason for this is the high mechanical stress forced by the strain energy source. Therefore, the mechanical energy applied to the generator is comparatively high. This leads to a higher amount of energy converted even if the material efficiency is low.

It is essential to keep in mind that the highest efficiency does not necessarily mean the highest energy output. This can be seen by the different values for energy density constants \( w_{el}^s \) or \( w_{el}^D \) and coupling coefficient \( k \). See also Fig. 13 in Section V.

In discussing energy transfer and efficiency, three issues must be taken into considerations.

1. The piezoelectric generator material should be able to absorb huge amounts of mechanical energy. Therefore, the compliance \( s \) must be adapted to the mechanical source. Considering stress- or strain-driven sources, a high or low compliance is essential, respectively (see Tables III and IV).
2. The piezoelectric charge constant \( d \) represents the coupling between mechanical input and electrical output. A high value for piezoelectric coupling is essential in order to obtain large energy transfer as well as high efficiency.
3. The piezoelectric generator material should be characterized by a low ability to transmit electric fields. This means a low polarization under electric field load, represented by a low permittivity.

All these requirements are expressed in the well-known Eq. (4) for the coupling coefficient. In this equation, the square of the piezoelectric charge constant \( d \) plays the key role, but the compliance \( s \) and the permittivity \( e \) should also be taken into account.

### IV. Material Survey

Currently, more than 200 different piezoelectric ceramics from more than 14 suppliers are commercially available. Most of these materials are based on PZT solid solutions.

Furthermore, there are ongoing research activities in the optimization of PZT materials, development of lead-free piezoelectric ceramics, and the special structural design of piezoelectric materials such as ZnO nanowires. All these new developments are not considered here. We focus on commercial piezoceramics with fully documented values.

The properties of a piezoelectric material are defined by the elastic, dielectric, and piezoelectric tensor components. They are represented by the compliance \( s \), the permittivity \( e \), and the piezoelectric charge constant \( d \), respectively. The materials data used in following sections are taken from the datasheets provided by different vendors.

In this analysis, we consider only material properties at room temperature assuming that they are constant under the generator load conditions, e.g. temperature profiles and depolarization effects will not be considered here.

One result is that the investigated materials data in the diagram (Fig. 7) are correlated to each other linearly and are located along certain lines. These lines are labeled as the “PZT lines.” Understanding this correlation between permittivity, \( e \), and piezoelectric charge constant, \( d \), requires a deeper view into the structural properties of the lattice. Both materials data depend on the mobility of the ions in the lattice and are therefore linearly related to each other.

The statistical analysis of the material data encompassing more than 200 different piezoelectric materials shown in Fig. 7, is presented in Table V. The compliance range is comparatively low, whereas the permittivity and piezoelectric charge constant vary by one order of magnitude.

More specifically, six commonly used standard materials are assessed in the following sections. These ceramics correspond to PZT 4, 5A, 5H, 8, BaTiO\(_3\), and KNN. They are labeled in the derived diagrams and are listed in Table VI. All other materials are marked by a data point. The selected materials cover the whole interesting variation range of piezoelectric materials data. Because of limited availability, noncommercial ceramics have

### Table III. Equations for Stress-Driven Piezoelectric Generators

<table>
<thead>
<tr>
<th>Property</th>
<th>Material constant</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain</td>
<td>Elastic constant</td>
<td>( S^D = s^DT )</td>
</tr>
<tr>
<td></td>
<td>Compliance</td>
<td>( S^E = s^ET )</td>
</tr>
<tr>
<td>Electric displacement</td>
<td>Piezoelectric charge constant</td>
<td>( D = dT )</td>
</tr>
<tr>
<td>Electric field strength</td>
<td>Piezoelectric voltage constant</td>
<td>( E = g^TT = d/e^T T )</td>
</tr>
</tbody>
</table>

### Table IV. Equations for Strain-Driven Piezoelectric Generators

<table>
<thead>
<tr>
<th>Property</th>
<th>Material constant</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>Elastic stiffness</td>
<td>( T^D = e^DS )</td>
</tr>
<tr>
<td></td>
<td>( T^E = e^FS )</td>
<td>(12)</td>
</tr>
<tr>
<td>Electric</td>
<td>Piezoelectric charge</td>
<td>( D = e^FS = d/s^D S )</td>
</tr>
<tr>
<td>Electric field</td>
<td>Piezoelectric field constant</td>
<td>( E = hS = d/(e^T s^D) S )</td>
</tr>
</tbody>
</table>
been excluded in this study. The next two sections present more detailed material analyses, where we differentiate between stress- and strain-driven modes and the directions of the acting mechanical and electric fields \((d_{33}, d_{31}, d_{15})\).

### (1) Stress-Driven Scenario

Regarding the piezoelectric stress energy density constant \(w_{33}^T\), most of the materials data are located close together forming a piled cloud (Fig. 8). There are only a few data points, which are separated in both directions, to lower or to higher \(w_{33}^T\). Points in Fig. 8, which are located closer to the origin of the diagram—among them BaTiO\(_3\) and KNN—are of minor interest, because the energy density is low. Present lead-free materials are characterized by lower energy density \(W_{33}^T\). It should be noted that the correlation between the piezoelectric stress energy density constant \(w_{33}^T\) and energy density \(W_{33}^T\) is inverse (Eq. (5)).

Few data points were found to be located distant from the origin. One example is a single crystal based on PMN–PT, having \(w_{33}^{T,\text{PMN-PT}} = 1.4 \times 10^{10} \text{ J/m}^3\) in Fig. 8. In addition, there are a few tables and diagrams that are not included in the text, but they are important for a complete understanding of the material properties and their analysis. Here are some key points:

#### Table V. Statistical Evaluation of the Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Minimum</th>
<th>90% range</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permittivity</td>
<td>(\varepsilon_{11}^T/\varepsilon_0)</td>
<td>—</td>
<td>127</td>
<td>500–5000</td>
<td>6500</td>
</tr>
<tr>
<td></td>
<td>(\varepsilon_{33}^T/\varepsilon_0)</td>
<td>4.86</td>
<td>200–5000</td>
<td>59.7</td>
<td></td>
</tr>
<tr>
<td>Compliance</td>
<td>(s_{11}^T)</td>
<td>(10^{-12} \text{ m}^2/\text{N})</td>
<td>7.19</td>
<td>8–20</td>
<td>59.7</td>
</tr>
<tr>
<td></td>
<td>(s_{33}^T)</td>
<td>(10^{-12} \text{ m}^2/\text{N})</td>
<td>6.94</td>
<td>8–25</td>
<td>86.5</td>
</tr>
<tr>
<td></td>
<td>(s_{55}^T)</td>
<td>(10^{-12} \text{ m}^2/\text{N})</td>
<td>11.5</td>
<td>25–55</td>
<td>57.8</td>
</tr>
<tr>
<td>Piezoelectric charge constant</td>
<td>(d_{33})</td>
<td>(10^{-12} \text{ C/N})</td>
<td>2.3</td>
<td>100–1000</td>
<td>2250</td>
</tr>
<tr>
<td></td>
<td>(d_{31})</td>
<td>(10^{-12} \text{ C/N})</td>
<td>7.99</td>
<td>160–1000</td>
<td>1160</td>
</tr>
<tr>
<td></td>
<td>(d_{53})</td>
<td>(10^{-12} \text{ C/N})</td>
<td>6.42</td>
<td>40–400</td>
<td>21600</td>
</tr>
<tr>
<td>Piezoelectric energy density constant</td>
<td>(w_{33}^T)</td>
<td>(10^{10} \text{ J/m}^3)</td>
<td>1.4</td>
<td>6.5–50</td>
<td>1430</td>
</tr>
<tr>
<td></td>
<td>(w_{31}^T)</td>
<td>(10^{10} \text{ J/m}^3)</td>
<td>3.16</td>
<td>4–30</td>
<td>1860</td>
</tr>
<tr>
<td></td>
<td>(w_{33}^T)</td>
<td>(10^{10} \text{ J/m}^3)</td>
<td>0.00412</td>
<td>0.21–2.1</td>
<td>1.74</td>
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<tr>
<td></td>
<td>(w_{33}^T)</td>
<td>(10^{10} \text{ J/m}^3)</td>
<td>0.0171</td>
<td>1–30</td>
<td>58.5</td>
</tr>
<tr>
<td></td>
<td>(w_{33}^T)</td>
<td>(10^{10} \text{ J/m}^3)</td>
<td>0.00809</td>
<td>0.5–4</td>
<td>4.17</td>
</tr>
</tbody>
</table>

#### Table VI. Standard Piezoelectric Material in Comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Minimum</th>
<th>90% range</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compliance at constant electric field strength</td>
<td>(s_{11}^T)</td>
<td>(10^{-12} \text{ m}^2/\text{N})</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Piezoelectric charge constant</td>
<td>(d_{33})</td>
<td>(10^{-12} \text{ C/N})</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Piezoelectric energy constant</td>
<td>(w_{33}^T)</td>
<td>(10^{10} \text{ J/m}^3)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Material</td>
<td>Symbol</td>
<td>Unit</td>
<td>Minimum</td>
<td>90% range</td>
<td>Maximum</td>
</tr>
<tr>
<td>BaTiO(_3)</td>
<td>1620</td>
<td>1900</td>
<td>5.55</td>
<td>8.55</td>
<td>11.5</td>
</tr>
<tr>
<td>KNN</td>
<td>938</td>
<td>496</td>
<td>8.2</td>
<td>16.3</td>
<td>24.8</td>
</tr>
<tr>
<td>PZT4</td>
<td>1475</td>
<td>1300</td>
<td>12.3</td>
<td>18.8</td>
<td>25.1</td>
</tr>
<tr>
<td>PZT5A</td>
<td>1730</td>
<td>1700</td>
<td>16.4</td>
<td>20.7</td>
<td>24.1</td>
</tr>
<tr>
<td>PZT5H</td>
<td>3130</td>
<td>3400</td>
<td>16.5</td>
<td>20.7</td>
<td>24.1</td>
</tr>
<tr>
<td>PZT8</td>
<td>1500</td>
<td>1200</td>
<td>11.8</td>
<td>14.2</td>
<td>16.5</td>
</tr>
<tr>
<td>Bandurak PZT8</td>
<td>1500</td>
<td>1200</td>
<td>11.8</td>
<td>14.2</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Fig. 7. Materials data of more than 200 different commercially available piezoelectric materials. Each single point represents a material described by its three characteristic values (compliance \(s^T\), permittivity \(\varepsilon^T\), and piezoelectric charge constant \(d^T\)). The best-fit lines are shown. The gray net surface depicts the theoretical limit \((k = 1)\).
number of ceramic materials showing an interesting material property combination. It should be considered worth investigating these combinations before starting a complete new material development.

The location of the data points in Fig. 8 depends on the relative directions of polarization, and the mechanical and electric fields, which is represented by the characteristic tensor components $d_{33}$, $d_{31}$, and $d_{15}$. In comparison, a $d_{31}$-mode-driven piezoelectric transducer has the lowest energy density and is, therefore, less efficient. An interesting fact is that shear mode ($d_{15}$) enables a higher energy density than the $d_{33}$-mode. The reason is the typically higher piezoelectric charge constant $d_{15}$ compared with $d_{33}$ used quadratic in Eq. (5). The typically higher relative permittivity $e_{11}$ compared with $e_{33}$ is of minor effect.

Despite the wide range of variation of the piezoelectric charge constant $d$ and the piezoelectric voltage constant $g$, the variation range of the resulting product, the piezoelectric stress energy density constant $w^T$, is relatively low. We find the energy density values of commercial PZT-based piezoelectric materials in the same range. Both properties, $d$ and $g$ constant, can be tailored, but not independently.

It is clearly demonstrated that different piezoelectric materials have similar energy densities, but they differ with respect to the piezoelectric voltage constant $g$ and piezoelectric charge constant $d$ enabling a high open-circuit voltage or high short-circuit charge output, respectively.

Proper material selection enables a better electrical impedance matching to the load. This can be a substantial advantage, compared with the additional use of complex power transfer circuits. Moreover, this can be of great importance when considering technologies where the thickness of the piezoelectric layer mainly influences the value of the output voltage. This is discussed more detailed in the Section III.

(2) Strain Driven Scenario

When comparing stress-driven piezoelectric generators, the study considered more than 200 commercial materials located as a band in the diagram of Fig. 9. For the majority of the materials under consideration, the variation of energy density and the variation of piezoelectric strain energy density constant $w^S$, were found to be low.

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**Fig. 8.** Piezoelectric charge constant $d$ vs. piezoelectric voltage constant $g$ for more than 200 different materials, each represented by a point, is shown. Additionally, the piezoelectric stress energy density constant $w^T$ is visualized as contour lines.

**Fig. 9.** Piezoelectric charge density constant $e^E$ vs. piezoelectric electric field constant $h^D$ for more than 200 different materials is shown. Additionally, the piezoelectric strain energy density constant $w^S$ is visualized as contour lines.
The quadratic influence of the piezoelectric charge constant in Eq. (6) is nearly completely compensated by compliance in combination with its permittivity. The values for \( w_3^2 \) for five of the six materials considered vary minimally (Table VI). For BaTiO\(_3\), the values for \( w_3^2 \) are deviated from the other figures. It is quite interesting to see the ferroelectric soft material PZT 5H and the ferroelectric hard material PZT 8 bearing nearly the same value for \( w_3^2 \), i.e. \( w_3^2 \approx 1.1 \times 10^{10} \, \text{J/m}^3 \) or \( w_3^2 \approx 6.2 \times 10^{10} \, \text{J/m}^3 \). Taking into consideration only the piezoelectric charge constant \( d \), one would expect that the energy densities of the two materials are quite different with PZT 5H showing the higher value.

In strain-driven generators, compliance plays a key role for energy density considerations. As an example, the comparably stiff lead-free material KNN, characterized by a low piezoelectric coupling, shows a high piezoelectric strain energy density constant \( w_3^2 \) due to its ability to absorb a high amount of mechanical energy.

Materials with a comparable low stiffness, e.g. single crystals based on PMN–PT, suffer from low mechanical input energy, even when they are more efficient in energy transforming.

Considering the relative directions of polarization, and the mechanical and electric fields \( (d_{33}, d_{31}, \text{and} \, d_{13}) \) the \( d_{31} \)-mode is the most energized. In comparison with the stress-driven scenarios, the \( d_{31} \)-mode has a lower energy density, due to higher compliance. The \( d_{33} \)-mode again shows the lowest values for piezoelectric strain energy density constant \( w_3^2 \).

From the present investigation comprising commercial PZT ceramics, the highest value of \( w_3^2 = 30.5 \times 10^{10} \, \text{J/m}^3 \) was identified.

(3) Technological Aspects

The piezoelectric layer’s thickness plays a key role in the design of the generator. It defines the open-circuit voltage, which is proportional to the layer thickness. Given the device volume and the layer thickness, the charge output can be derived. This output, in turn, is proportional to the electrical active cross section.

There are several manufacturing technologies for piezoceramics ready to be used\(^{33} \) (Fig. 10).

By varying the layer thickness and the cross section, a piezoelectric generator can be specifically designed for high-voltage or high-current applications carrying the same volume. Thus, the corresponding electrical output impedance can be matched to the electrical load impedance by device design avoiding complex power transfer circuits. The maximum achievable electrical output power, defined by the material properties, will not be influenced.

Optima can be found for specific mechanical load values and output requirements. For applications requiring a load voltage, for example, of 3.3 V, several technologies including sputtering, sol-gel, thick film, well known for its relative thin piezoelectric layers, cannot be used directly. The reason is that an open-circuit output voltage larger than 3.3 V cannot be reached. Other technologies, e.g. solid fabrication, well known for its relative thick piezoelectric layers, are usable but less powerful (Fig. 11).

For layers that are either too thin or too thick, additional active power transfer circuits may increase the output power. However, power transfer circuits suffer from on-site power. This poses the issue of whether the generator system can be more efficient with or without power transfer electronic.

It should be noted that a limited number of piezoceramic materials are compatible with a specific technology. Furthermore, processing may influence the material properties and they may differ from the properties of bulk ceramics given in the datasheets.

At times, there are technological limits in the reduction or increase of layer thicknesses. Two examples are tape casting in combination with the co-firing of stack transducer and sputtering, respectively. In both of these cases, optimal electrical impedance to the load cannot be obtained. By choosing a different material characterized by a high charge output or a high open-circuit voltage, the technological limit can be extended to ensure optimal electrical impedance matching.

V. Piezoelectric Generator and Electronics

In this section, the aspects of electronics are considered. For this purpose, a complete transition from geometrically independent to geometrically dependent physical values is more practical. To operate with time-independent quantities, it is more convenient to use velocity, current, and power rather than displacement, charge, and energy (Table A1).

Figure 12 shows a block diagram of a simple piezoelectric generator. Assuming that the diodes and capacitors are ideal, i.e. the forward voltage, backward current, and equivalent series resistance (ESR) are zero and the leakage resistance \( (R_{\text{leak}}) \) is infinite.

(1) Resistive Load

Considering only a variable resistive load without the blocks 1 and 2 (in Fig. 12), the electrical condition of the piezoelectric generator varies from short circuit (low resistance) to open circuit (high resistance). A small window exists in between these two states where electrical work can be performed. For low resistor values, the mechanical input power is high, while the output power and the efficiency are low. Under a high resistive load, the output power and the efficiency are low.

Figure 13 illustrates that the resistor value for maximum output power is not the same for maximum efficiency. It should also...
be noticed that the stiffness, and hence mechanical input power variation depend on the electrical conditions, represented by the compliance $s_E$ and $s_D$, respectively. Figure 14 portrays strain-driven piezoelectric generators under variable load resistor electrical conditions where the behavior is different. The mechanical input power changes in the opposite direction, as more force and hence more energy is needed to induce a stiffer material to the same deflection point. An interesting result occurs when a stiff but less-efficient piezoelectric material like KNN can produce a relatively high electrical output power compared with the other materials.

Power and efficiency are both influenced by the electrical load. Electrical output power and efficiency can be increased by optimized impedance matching.

(2) Charging a Capacitor

Charging a capacitor is an important issue for a piezoelectric generator system, due to the task of separating, filtering, and storing the energy (see Fig. 12 without the block 3).

In Fig. 15, a generalized charge-up cycle is illustrated. At low-voltage levels, the piezoelectric generator acts under a short-circuit condition, e.g. high currents. The input power is relatively large due to the larger compliance $s_E$. The electrical output power and efficiency are low.

When the storage capacitor reaches the open-circuit voltage of the piezoelectric generator, the output power and efficiency returns to a low level. The mechanical input power is low due to the smaller compliance $s_D$.

VI. Conclusions

Market analysis shows a broad offer of commercial piezoceramics usable in generator applications. Material selection for a generator depends on the type of mechanical energy source, the mechanical transformer, the electrical load, and the usable fabrication technology. Ceramic performance data must be evaluated in the context of the considered system. Depending on the mechanical load conditions, different figures of merit are valid.
We state, that the distribution of mechanical and electrical energy in a stressed piezoelectric generator is defined by the properties of the piezoelectric material used. The relation cannot be changed by system design. It is the demanding task of the system designer to adjust the mechanical source and electrical load of the generator by a process of impedance matching to achieve the lowest loss of harvested electrical energy.

As a general consideration, the overall system efficiency of a piezoelectric generator is estimated to be 25%. This estimation assumes the efficiency of the piezoceramic of approximately 50% (coupling coefficient k² = 70%) and a 50% electrical energy transfer rate from the generator to the system. While this sounds less, the efficiency of other solid-state generators is lower (commercial solar cell <20%, thermal electric generator <10%), which opens up a secure perspective for the piezoelectric generator principal.

![Fig. 16. The capacity of capacitor to be charged is adjusted with regard to always reaching the same energy level. The normalization to maximum achieved values is used.](image-url)
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