Polymer Power: Dielectric Elastomers and Their Applications in Distributed Actuation and Power Generation

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ABSTRACT

In the past decade, dielectric elastomers have emerged as promising multifunctional smart energy-transduction materials in several actuation, sensing, and electric power generation applications. As actuators, dielectric elastomers have demonstrated strains (over 300%) and specific energy density (over 3.4 J/g) larger than that observed in any other field-activated smart material. In generator mode, dielectric elastomers have been shown to generate electricity from mechanical motion with high specific energy densities (0.4 J/g) and predicted high efficiencies (80–90%). In addition to superior performance, dielectric elastomers have two features that distinguish them from other energy-transduction materials: They are made from low cost materials that can be easily fabricated in large-area sheets and they are very compliant. This allows good impedance matching where strain in the material result from human body motion, combustion, or from wind or ocean waves. These characteristics suggest relevance to power generation in rural areas or other areas where there is not reliable central power. Two case studies—a shoe-based or “heel strike” generator and a polymer engine (in which an expanding polymer chamber replaces a conventional piston-cylinder arrangement)—are used to illustrate the promise of these materials for energy transduction.

Keywords: Dielectric elastomer, electroactive polymer (EAP), artificial muscle, smart structure, polymer engine, distributed actuation and power generation, rural energy, distributed energy, energy harvesting

1. INTRODUCTION

Electroactive polymers (EAPs) are an emerging transducer technology that offers many advantages over other smart materials or more conventional electromagnetic technology. Typically, polymers are low in cost, compatible with a variety of fabrication techniques, and able to withstand a wide range of environmental conditions. Polymers can be compliant enough to easily deform under applied loads, yet rugged enough to resist wear and fatigue over a large number of cycles.

In particular, dielectric elastomer are a particular type of EAP actuated by an electric field. This type of field-activated EAP has shown tremendous promise for a variety of applications as actuators, sensors, and electrical power generators. These rubbery polymer transducers can undergo large strains and convert a large amount of energy per unit mass or volume. Silicones and acrylics are the two classes of polymers that have best demonstrated exceptional performance as energy transducers. In fact, the maximum strains and energy densities demonstrated in these dielectric elastomers exceed those of any field-activated material, including single-crystal piezoelectric ceramics and magnetostrictive ceramics. These materials can also operate over a wide range of temperatures and humidities.

The combination of good performance as both actuator and generator (high strain, high energy density, high efficiency) with the desirable properties of polymers (low-cost fabrication in large area films, high strain and compliance, good durability, good environmental tolerance) suggest a range of potential applications. In particular, there are possibilities for distributed power generation in rural areas and other regions that lack a reliable power infrastructure. This paper discusses such applications of dielectric elastomers and offers case studies of devices that have already been demonstrated: a shoe generator and a polymer engine.

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2. DIELECTRIC ELASTOMER ACTUATORS

Dielectric transducers are based on the electromechanical response of an elastomeric dielectric film with compliant electrodes on each surface. Actuators based on dielectric elastomer technology operate on the simple principle shown in Fig. 1. When a voltage is applied across the compliant electrodes, the polymer shrinks in thickness and expands in area. Simply put, the opposite charges on the two electrodes attract each other, while the like charges on each electrode repels the other. Using this simple electrostatic model, we can derive the effective pressure $p$ produced by the electrodes on the film as a function of the applied voltage as

$$p = \varepsilon_r \varepsilon_o E^2 = \varepsilon_r \varepsilon_o (V/z)^2,$$

where $\varepsilon_r$ and $\varepsilon_o$ are the permittivity of free space and the relative permittivity (dielectric contact) of the polymer, respectively; $E$ is the applied electric field; $V$ is the applied voltage; and $z$ is the film thickness.

A comparison of the maximum performance of these acrylic and silicone elastomers with those of other electrical actuator technologies\(^2\) shows that dielectric elastomers excel in several measures of performance. Like other electric-field–activated materials such as piezoelectrics, they are relatively fast and energy efficient. Their maximum strains (up to 380%) and specific elastic energy density (3.4 J/g) are far greater than that of any other field-activated material—including the vastly more expensive single-crystal piezoelectric ceramics\(^3\). This outstanding performance is all the more remarkable because these acrylic and silicone elastomers are commercially manufactured and optimized for applications other than use as electroelastomers. The use of commercially available low-cost materials allows dielectric elastomers to potentially serve as low-cost, large area transducers for actuation or power generation.

The fundamental actuation mechanism can be applied to actuation in a number of different configurations; these include planar configurations (diaphragms, stretched-film actuators, etc.), rolled configurations (multifunctional elastomeric roll actuators), and surface deformation configurations\(^4\). The design flexibility allows dielectric actuators potentially to be applied to a wide variety of applications (Fig. 2). Some of these applications hold relevance to rural settings, but their effectiveness compared with alternatives have not yet been fully established. For example, low-power, low-cost pumps can be used in individual homes for fluid transport. Linear actuators can be used in prosthetic devices or in robots that may handle unexploded ordnance such as landmines. The advantages of dielectric elastomers for each of these applications are listed in Table 1 with details available in Kornbluh et al.\(^4\).

\[\text{Figure 1. Principle of operation of dielectric elastomer actuators.}\]

\[\text{Figure 2. Configurations and representative applications of dielectric elastomer actuators.}\]
The energy output of a dielectric elastomer generator for a single cycle of stretching and relaxation is related to the changes in capacitance of the dielectric elastomer layers as
\[ E = \gamma \varepsilon_0 \varepsilon \varepsilon_{\text{max}} \ln \left( \frac{A_i}{A_f} \right) \]  

where \( A_i \) and \( A_f \) are total capacitances of the dielectric elastomer layers in the stretched and unstretched states, respectively, and \( E_{\text{max}} \) is the maximum electric field across the polymer, \( \varepsilon_0 \) is the constant film volume, \( \varepsilon \) is the dielectric constant of the dielectric elastomer material and \( \varepsilon_0 \) is the permittivity of free space (constant). \( \gamma \) is the efficiency of power transduction, which includes the electromechanical coupling in the material, as well as the efficiency of the conversion electronics.

Thus, if we know the area change of the dielectric elastomer film during a wave cycle, we can determine the energy output. The basic concept can be applied in several different ways to produce electrical power from mechanical work. Each of these configurations leads to different engineering devices, as discussed in the sections that follow.

### 3.2. Dielectric Elastomer Generator Applications

To date, our work in dielectric elastomer generators has focused on small amounts of power. Typical power generation has ranged from 1 to 50 W. There are many potential generator applications for dielectric elastomers at these smaller power levels. Table 2 lists some potential applications along with the potential advantages and disadvantages of the competing technologies. From Table 2 it can be seen that dielectric elastomers have potential advantages over both competing electromagnetic technologies as well as other smart materials for almost all applications listed.
We also note from the recent advances in polymer electronics, including fluorescent lights, conventional cathode ray tube monitors, room ionizers for particle filtering, and electrical power and clean fuels are not readily available. Small to medium amounts of distributed energy can be generated larger amounts of power. The economics of large area dielectric elastomeric generators for larger amounts of distributed energy, which range from 100 W to 1 kW (in comparison with conventional internal combustion engines, electric motors, or renewable sources such as hydrothermal energy, wind turbines, or solar energy), have not yet been evaluated. In addition to the efficiency and cost of energy generation, economics of distributed energy storage and distribution methods will also likely influence the viability of applying new technology for rural needs. Practical considerations may limit the specific outputs and efficiencies of dielectric elastomeric generators in each application.

At this early stage of dielectric elastomer generator research, only a few power generation devices based on dielectric elastomers have actually been built and tested. In the following sections we describe two such devices: a shoe-based or “heel strike” generator and a polymer engine. We also discuss wind and wave power devices, although such devices have not yet been realized. These specific examples can help illustrate the potential advantages, as well as the technical challenges. It may be noted that while the polymer engine concept discussed uses dielectric elastomers to generate electrical energy, it has benefits even as a source of pure mechanical energy compared to a conventional small IC engine.

### 3.2.1. Heel Strike Generator

Wireless communications is attractive for much of the world because it eliminates the need for costly infrastructure and provides a backup system in emergencies. However, wireless devices are often mobile and thus require batteries. Batteries can be a cost-prohibitive factor for some and for all they can pose issues in disposability due to their toxic content. Thus, a technology that could reduce the need for batteries can make telecommunications and personal computing devices more widely available. Such devices are also important for the developed world as they offer.

<table>
<thead>
<tr>
<th>Generator Application</th>
<th>Competing Technologies</th>
<th>Dielectric Elastomer</th>
<th>Potential Disadvantage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine-driven generators</td>
<td>Electromagnetics</td>
<td>Higher energy density, lower cost, good low speed performance, higher temperature performance</td>
<td>Electronic cost and weight (very small engines)</td>
<td>Electronics are probably not an issue for large engine applications</td>
</tr>
<tr>
<td>Shoe generators</td>
<td>Electromagnetics, piezoelectrics</td>
<td>Low cost, good mechanical load matching eliminates much mechanical complexity; lightweight; high energy density</td>
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<td>Demonstrated 0.8 J energy/ stroke generation in heel-size device (not including electronics)</td>
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<tr>
<td>Parasitic energy harvesting for remote sensors</td>
<td>Electromagnetics, piezoelectrics</td>
<td>Good mechanical load matching to some available energy sources enables simpler designs; lower cost, Recyclable</td>
<td>Electronic cost an issue for some applications</td>
<td>Remote sensing can eliminate wires and potentially reduce cost for a number of applications, but power sources are currently limited</td>
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<td>Wave or wind energy</td>
<td>Electromagnetics</td>
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<td>Needs coupling to a high strain mode for effective conversion</td>
<td>Water compatibility can be achieved with protective layers</td>
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As noted previously, dielectric elastomers also have a large potential advantage in terms of using lower-cost materials and fabrication techniques. The extent to which this advantage can be exploited depends to a large extent on the application and considerations such as cost of electronics for distributed low-power units. We note, however, that successful low–medium power, high-voltage devices are already being used in widespread applications; examples include fluorescent lights, conventional cathode ray tube monitors, room ionizers for particle filtering, and electrostatic speakers. We also note from the recent advances in polymer electronics that successful low–medium power, high-voltage devices are already being used in widespread applications; examples include fluorescent lights, conventional cathode ray tube monitors, room ionizers for particle filtering, and electrostatic speakers. Also note from the recent advances in polymer electronics that, if translated to higher voltages, may make it possible to couple large area distributed actuators of generators with integrated flexible electronic circuitry.

Some of the applications in Table 2 may hold relevance in developing rural areas where distribution costs are large and electrical power and clean fuels are not readily available. Small to medium amounts of distributed energy can be delivered in the form of several “individual” lightweight, inexpensive polymer power units. For example, one 14-inch black and white TV has a power requirement of 20 W and that of a compact fluorescent lamp (CFL) ranges from 5 to 30 W. A small rural telecommunications center continuously powering two laptop computers, one phone/fax machine, one inkjet printer, and four CFLs has an estimated power requirement of approximately 110 W. In response to these requirements, several pedal or hand-powered sources as well as fuel-powered portable generators that use conventional battery or electromagnetic technology are currently being developed around the world. Dielectric elastomer generators may offer a low-cost, lightweight, portable power source to some of these application areas of relevance to rural populations.

Dielectric elastomers are also inherently scale-invariant in their operation and can theoretically also be used to generate larger amounts of power. The economics of large area dielectric elastomer generators for larger amounts of distributed energy, which range from 100 W to 1 kW (in comparison with conventional internal combustion engines, electric motors, or renewable sources such as hydrothermal energy, wind turbines, or solar energy), have not yet been evaluated. In addition to the efficiency and cost of energy generation, economics of distributed energy storage and distribution methods will also likely influence the viability of applying new technology for rural needs. Practical considerations may limit the specific outputs and efficiencies of dielectric elastomeric generators in each application.

### Table 2. Potential applications of dielectric elastomer generator technology.

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greater convenience and reduce disposal issues. It is worth noting that the Freeplay wind-up radio\textsuperscript{8}, originally developed for the poorest regions of the world, have sold well in the wealthiest and most developed areas as well.

A heel strike boot generator developed by SRI (Fig. 4) investigated ways to harvest otherwise wasted energy from walking\textsuperscript{9}. The demonstrated recovered energy on the order of 1 W per boot can be used to supplement battery power charge small devices such as handhelds or cell phones, as an emergency backup source of power, for specialized onboard boot functions such as massaging or, in the future, to enhance walking and other mobility performance. The approach used by SRI exploited the fact that dielectric elastomers are rubbery materials that closely match the impedance and stiffness properties of the heel of a boot, thus causing no discomfort to the person wearing the boot. Attractive levels of power from boot generators can be achieved with compact, lightweight polymers that are low in cost and well suited for boots (unlike, for example, brittle ceramic piezoelectrics).

Using the boot generator device, we showed several important results. First and perhaps foremost, we demonstrated that EAPs can function as powerful generator materials. Generator energy densities as high as 0.4 J/g were recorded, a value we believe, based on the available literature, to be the highest ever recorded for any material. A second important result was the demonstration of high energy output, up to 0.8 J/step, in a heel strike generator. Previous shoe generators had produced outputs of a few tens of millijoules.

The boot generator, because it is a small self-contained device that needs to output low voltage (in order to recharge batteries), poses significant challenges in the design and implementation of power-conversion electronics. Further, unlike piezoelectric devices, dielectric elastomers require an initial bias voltage be applied. We successfully addressed the initial generation of the high bias voltages by developing a variety of circuits that can use battery power and step-up or pump-up the charge to the needed voltages. We also demonstrated efficient (70–80\%) step-down of high voltage in a breadboarded circuit. The challenge of developing efficient and compact step-down circuits is particularly difficult because of the lack of commercially available low-power, high-voltage transistors—the result of existing market forces and not technical obstacles.

In addition to heel strike generators as an inexpensive source for human-derived power, several other possibilities that can use motion or extension in a dielectric elastomer from human movement are listed in Fig. 5. As in the case of a heel strike generator, the expected power levels from these dielectric elastomer generators is relatively small. As noted previously, hand- or leg-cranked generators based on electromagnetic technology are already widely used in devices such as portable radios or flashlights (e.g., Ref. 8).
3.2.2. Polymer Engine

In recent years, SRI has demonstrated that a new type of power source, polymer engines, can potentially overcome existing technology limitations of small internal combustion engines for portable power. Polymer engines use polymers to form a gas expansion chamber that replaces the piston-cylinder chamber of a conventional engine (Fig. 6). The polymers are typically elastomers capable of high strains and good environmental tolerance. Silicones, similar to those used as dielectric elastomer transducers, are good candidates. A mechanical output can be obtained by coupling to the expansion of the polymer chamber. Using expanding combustion chambers made of dielectric elastomers operated in the generator mode, the device can simultaneously provide both mechanical and electrical output. In this way, the polymer engine can replace the popular portable electric generator combination of a conventional piston-cylinder engine coupled to an electromagnetic generator.

![Diagram of polymer engine](image)

**Figure 6.** Principle of operation of polymer engine/generators.

There are potential advantages of the polymer engine over other small fuel-burning power generators (such as small internal combustion engines coupled to electromagnetic generators or micro fuel cells):

- **Efficiency.** Polymer engines can achieve higher efficiency in many ways: much lower heat loss, elimination of piston-cylinder leakage, and reduced mechanical losses. All three phenomena are regarded as reasons why small engines achieve only about 6% efficiency compared with that of large engines—up to 30 to 40%\(^\text{11}\).

- **Lighter weight and higher power density.** Polymers are much lower density than metals (1 g/cm\(^3\), versus 2.7 to 8.0 g/cm\(^3\) for metals). Dielectric elastomer engines also have fewer parts as they eliminate the entire separate generator subsystem (see Fig. 6).

- **Low cost.** A variety of polymers that can sustain high temperatures can be used as the basis for the combustion chamber. In addition, tight tolerances and expensive lubricants are not required for the piston-cylinder interface, thereby reducing the cost of manufacturing.

- **Ability to run on multiple fuels such as kerosene, natural gas, or gasoline (including “dirty” fuels) without damaging the combustion chamber.** A conventional piston-cylinder engine is relatively intolerant to particulate matter due to the sliding piston-cylinder interface. Polymer engines also offer the potential of being rugged and shock tolerant. Most fuel cell membranes are “poisoned” by dirty fuels.

- **Ability for one component to provide both mechanical and electrical power simultaneously.** This feature is useful in several rural home applications where collocated mechanical power is required for pumping water from a well, but electrical power may be required, for example, to power a lights and telecommunication devices.

- **Quieter.** Commercially available portable generators that are commonly used in places with unreliable centralized electric power are typically very loud and operate at frequencies that are especially sensitive to human hearing. Since polymer engines produce larger amounts of energy per stroke and are efficient even at low frequencies, the noise signature can be much smaller than electromagnetic alternatives.

These advantages are quantified in Table 3. Many of these advantages have already been demonstrated in some preliminary proof-of-principle generators. However, much work remains in developing this promising concept into a practical portable power source that can be readily used in commercial applications.

3.2.3. Ocean and Wind Powered Generators

Dielectric elastomer electrical energy generation is well suited to applications where electrical power must be produced from relatively large motions. The high compliance and large elongation capabilities of the dielectric elastomer material suggests a good impedance match to motions produced by wind and waves, allowing direct operation from these sources without gearing.
Table 3. Performance of various existing power subsystems with projected polymer engine specifications. The operation duration assumes that all systems produce an output of 20% electrical and 80% mechanical energy.

<table>
<thead>
<tr>
<th>System</th>
<th>Efficiency (%)</th>
<th>Non-fuel Power Density (W/g)</th>
<th>Quiet?</th>
<th>Range of Fuels?</th>
<th>Relative Duration of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer Engine</td>
<td>24</td>
<td>3.8</td>
<td>Yes</td>
<td>Yes</td>
<td>8</td>
</tr>
<tr>
<td>Metal Engine + Generator</td>
<td>5.7</td>
<td>1.7</td>
<td>No</td>
<td>Yes</td>
<td>1.8</td>
</tr>
<tr>
<td>Fuel Cell + Motor*</td>
<td>12</td>
<td>0.04</td>
<td>Somewhat</td>
<td>No</td>
<td>1</td>
</tr>
</tbody>
</table>


Conventional windmills are often miles removed from the urban centers where the demands for electricity are high. In addition, in order to have high efficiency wind turbines, the blades are often very large, making the structural foundation very expensive since they have to support large structural and aerodynamic loads. An alternative approach uses dielectric elastomers to generate highly distributed, parallel, low-cost, localized power where the emphasis is on simply capturing more wind rather than in improving the efficiency with which this wind energy is converted to electric power. For example, fluttering flag sail designs can be used to block wind with a dielectric elastomer fabric (Figure 7), thus directly straining it. These highly distributed power generators are much smaller; they can be located in more populous areas without significantly affecting their aesthetic appeal, and thus minimize distribution costs. Since the generators are not rigid, they could be strung across a valley or even across existing structures such as fences without the need for expensive towers from traditional wind turbines, for example.

A similar approach can also be used to couple a dielectric elastomer to ocean waves to generate electricity. It is estimated that the average energy in waves breaking along the world’s coastlines is about 65 MW per mile. While it is difficult to harness even a small fraction of this energy, an alternative can be to capture large areas of wave motion rather than building a large, centralized wave-based generator. One possible configuration, shown in Fig. 7, involves anchoring one end of a dielectric elastomer tether to a float. Initially, dielectric elastomer generators may produce only a small amount of power; however, it may be sufficient to power remote ocean sensors (such as for tsunami warning systems or seabed pipeline sensors) and additional systems that need ocean-based localized power. The critical advantages of dielectric generators in these applications are low cost, simplicity (eliminates all moving parts and the need for rotary motion and seals), corrosion resistance, as well as inherent relative immunity from high loads imposed by storms and unpredictable situations that have, in some cases, destroyed larger, rigid power generators.

4. SUMMARY AND DISCUSSION

Dielectric elastomer transducers have a number of unique characteristics that suggest a wide range of applications as actuators and generators. As actuators, they are applicable in a wide variety of commercial applications due to their use of inherently low-cost materials to produce high strains and energy densities. As generators, these characteristics coupled with good impedance matching make them attractive materials for producing distributed electrical energy. We have so far demonstrated two generator concepts based on dielectric elastomers—one harnessing the energy from human walking, and another from the combustion of fuels. These examples show that dielectric elastomer generators may hold promise for addressing the need for distributed power transduction in remote environments where centralized power is unavailable or unreliable.

![Image 7](image7.png) Dielectric elastomer generators operating from wind or wave energy to produce localized electrical energy.
The distributed power transduction may be in the form of personal power (for charging cell phones, GPS systems etc.), or in the form of a localized self-contained off-grid power station as shown in Fig. 7. However, many technical and economic challenges must be carefully examined to enable the technology to succeed: availability and cost of electronics for driving the relatively high voltages but low power of the dielectric elastomer, lifetime, and environmental tolerance. The cost of individual electronics units for storage and conversion of these small amounts of distributed power is also a challenge that has not yet been fully addressed, and will need to be overcome (possibly with distributed flexible electronics [Ref 1]) before this approach becomes commercially viable.

**ACKNOWLEDGMENTS**

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11. D.S. Paul, “Quiet, small, lightweight, heavy-fueled mini generator sets for power needs of soldiers and unmanned ground vehicles,” 2002. (Available at http://www.asc2002.com/manuscripts/F/FO-05.PDF.) Also, for example, information on the performance of a small Cox engine, the commercially available industry standard often used for MAVs, can be found at http://www.aero.ufl.edu/~issmo/mav/Morris/morris.htm.