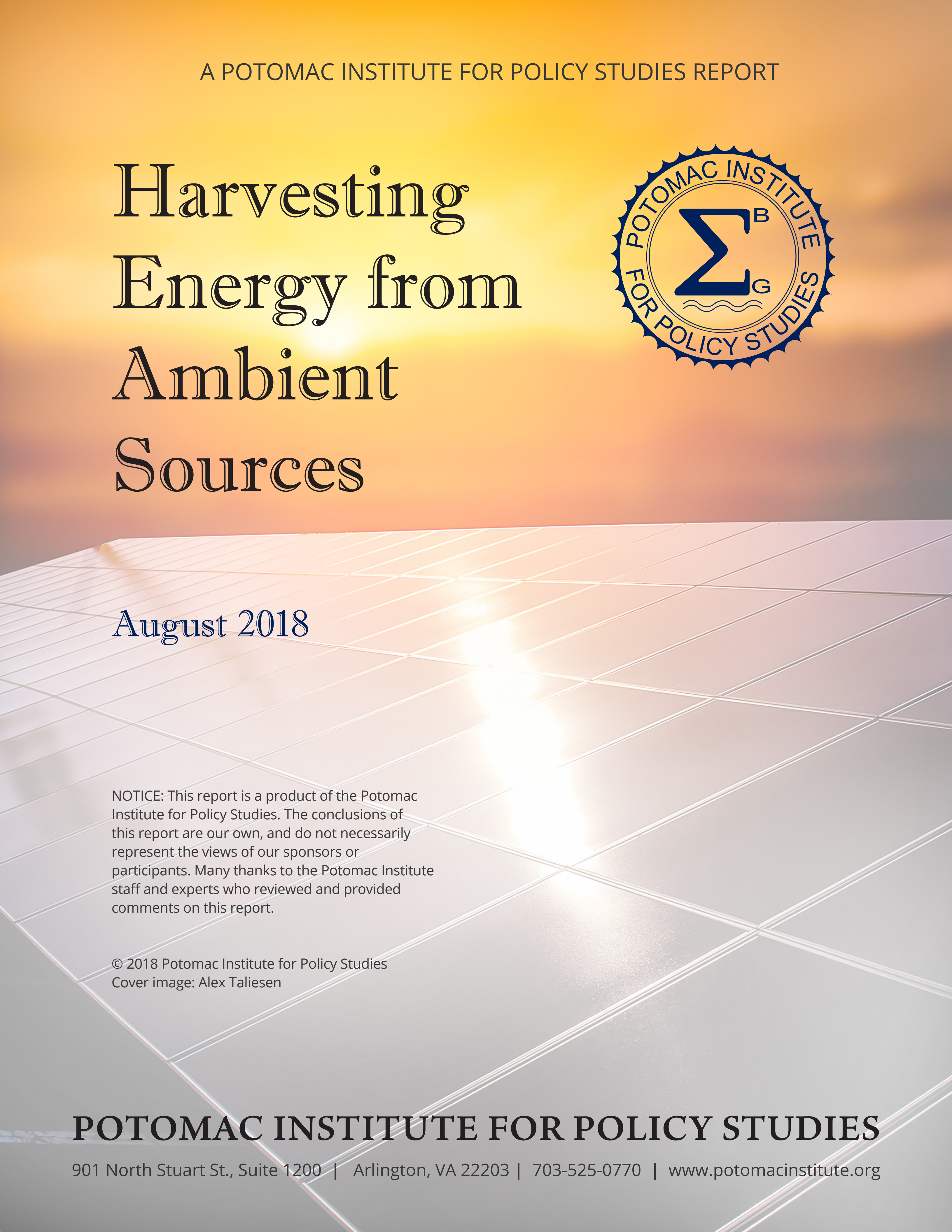
Harvesting Energy from Ambient Sources

Potomac Institute for Policy Studies



A POTOMAC INSTITUTE FOR POLICY STUDIES REPORT

Harvesting Energy from Ambient Sources

August 2018

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Background

Stand-alone sensors located in remote or hard-to-reach areas are becoming increasingly common and are critical components of early-warning systems that detect building and bridge stresses, air pollution, forest fires, pending landslides, worn bearings, and airframe vibrations.[1] These sensors combine in the thousands to serve as low power wireless sensor networks that are at the heart of numerous industrial, medical, and commercial applications. As the size of these systems continues to decrease, on-board energy storage space decreases and device lifetimes shorten.[2] Batteries with improved energy densities are an ongoing research goal, but the amount of energy available is finite and low, limiting the system's life span. Furthermore, conducting battery maintenance on such a large-scale network would be extremely expensive and arduous.[3]

Ambient energy harvesting technologies would eliminate the need to run expensive power cables to remote locations or replace expensive primary batteries.[4] Energy harvesting technology captures and converts the small amounts of readily-available energy in the environment into usable electrical energy.[5] Sensors relying on energy harvesting would offer unlimited operating lifetimes with little maintenance requirements. Such technology would enable monitoring and control at remote locations, especially in sensitive ecological settings.[6] Energy harvesting can also be scaled to support larger systems, such as building lighting, medical devices and equipment, and even satellites.[7]

The core component of all energy harvesting devices is the transducer/harvester, which collects and converts energy from the source into electrical energy.[8] Currently, the main energy sources being explored and utilized are:[9]

- Solar energy: Energy from sunlight
- Mechanical energy: Energy from vibration and mechanical stress/strain
- Thermal energy: Energy from furnaces, heaters, friction sources, and body heat
- Radio frequency (RF) energy: Energy from wireless and broadcast networks like WiFi, 2G, 3G, 4G and Digital TV.

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The general structure of these devices is shown in Fig. 1.

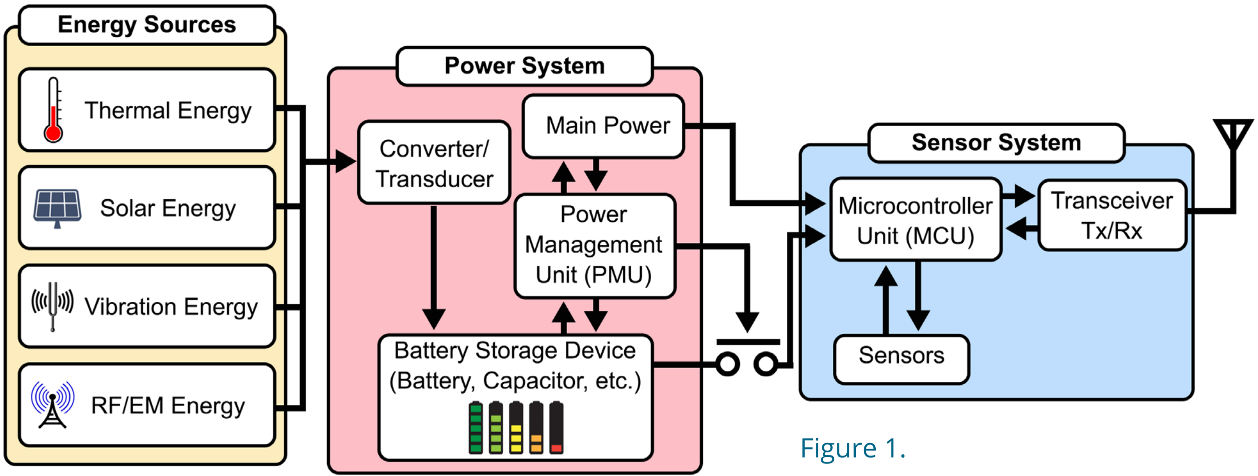

Figure 1.
A general block diagram of ambient energy harvesting devices.[10]

The reliability, predictability, and output power of these sources vary and are important factors that must be considered (Table 1).[11]

TABLE 1. THE ADVANTAGES AND LIMITATIONS OF DIFFERENT AMBIENT ENERGY SOURCES.[12]

Energy Sources	Overall Efficiency	Output Power	Available Condition	Reference
Solar (outdoors)	6%–35%	1350mW	Daytime with sunlight	I 0,22,25,82
Solar (indoors)	3%–7%	621 μW	Daytime or indoor lighting	
Vibrations (human motion)	10%–30%	0.84 m μW–4.13mW	Body motion (swing, shock, walk)	83,84,96
Vibrations (machine motion)	20%–40%	200 μW–40 mW	Mechanical motion (vibration, rotation), moving parts	36,38,39,85,97
Wind	7%–20%	0.77mW–439mW	Windy regions rotation parts	31–33,86
Thermal (human)	0.8%–4%	0.5mW–5mW	Temperature gradient	87,88
Thermal (industry)	1%–7%	3mW–50mW	Need cooling parts	
RF–GSM station	5%–15%	1 mW	Line of sight, 0–100 m	66,89
RF–TV station	2%–10%	16 μW–54 μW	Line of sight, 0–4 km	69,89
RF–WiFi station	5%–25%	I0nW–0.1 μW	Line of sight, 0–10 m	90,91
RF–AM station	0.02%–5%	0.5 μ,W–2.39 mW	0m–20km	73,79

Energy harvesting systems can be constructed with three topologies that differ in their reliance on energy storage systems (Fig. 2).[13] *Autonomous harvesting systems* can fully satisfy energy needs from ambient sources without employing batteries. While lifetime and performance aren't limited by storage inefficiencies, they can only operate when the energy source is available. They can never consume more than what can be delivered, and they should be designed to operate at maximum performance to avoid the loss of excess energy. The second topology, *autonomous hybrid harvesting systems*, describes devices that collect energy for system operation and the recharging of storage. This arrangement dramatically increases operational lifetime, potentially achieving 0% deadtime operation. The third topology, *battery-supplemented harvesting systems*, uses batteries as the main sources of energy and relegates the harvesting device to a secondary role. Such a setup enables the device to operate in environments where secondary storage has been depleted and ambient energy is not available for harvest.

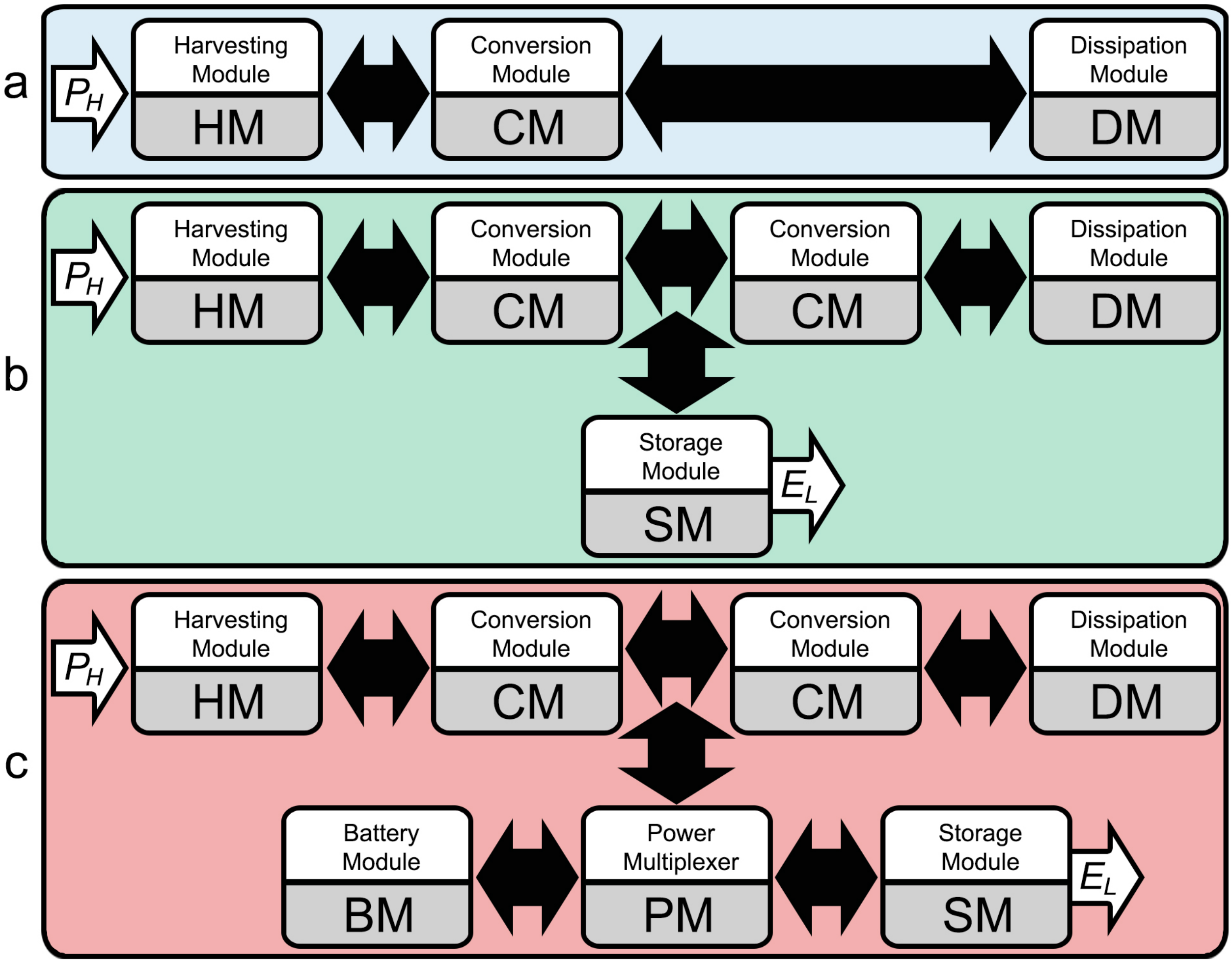

Figure 2.

Energy harvesting systems may be (a) autonomous, (b) autonomous hybrids, or (c) battery-supplemented.[14]

Technology Analysis

SOLAR

Light energy can be converted to electrical energy via photovoltaic cells, which capture and convert incident light to electricity.[15] This can be performed via a variety of system architectures, which vary based on materials used, device complexity, cost, conversion efficiency, and stage of development (Fig. 3).[16] Since sunlight is only available during the daytime and is weather-dependent, solar power is typically used in tandem with a battery or supercapacitor.[17,18]

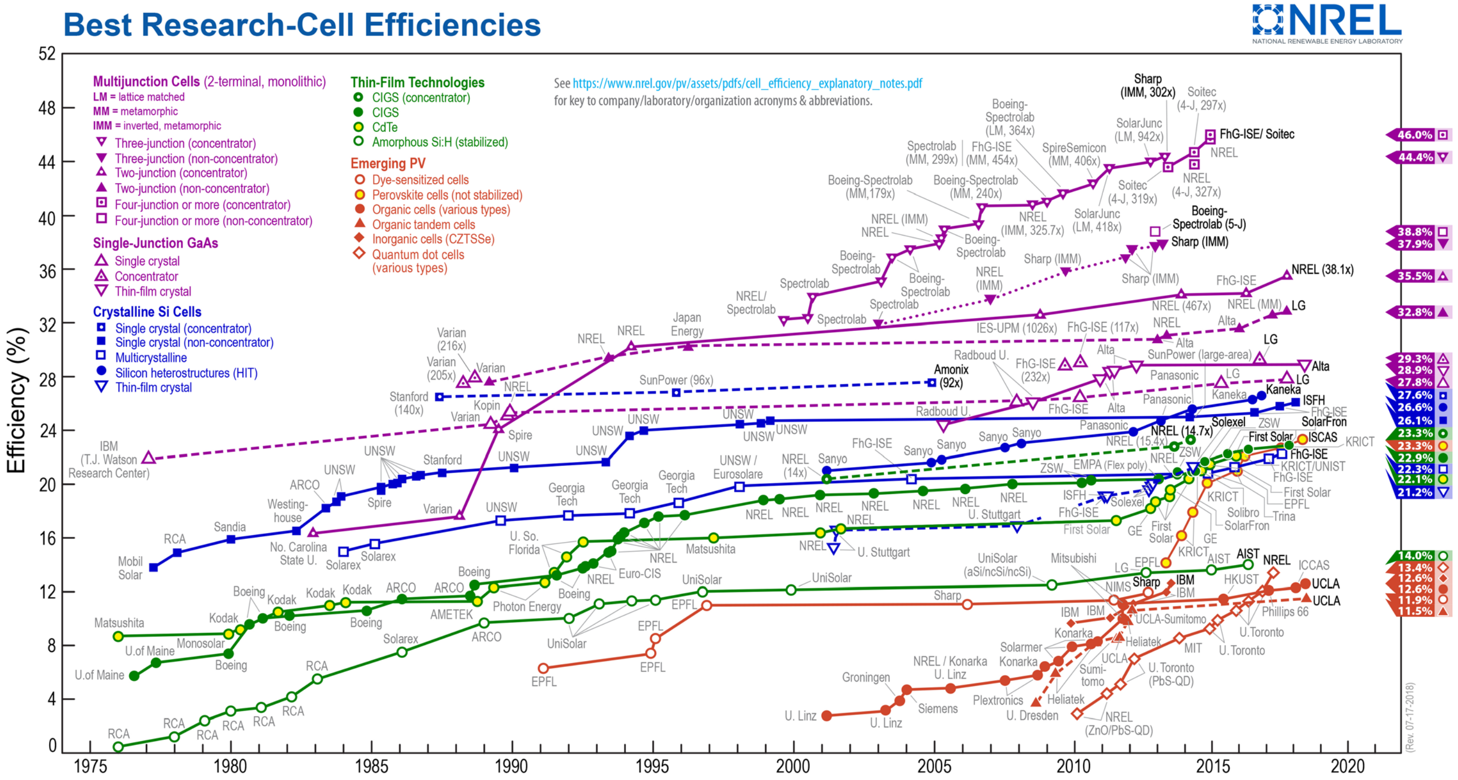

Figure 3.

Efficiencies of various photovoltaic architectures as a function of year.[19]

93% of all photovoltaic cells produced in 2017 were composed of either polycrystalline or single crystal silicon.[20] Silicon is widely-available in the Earth's crust and has a theoretical maximum photoefficiency close to the maximum theoretical efficiency for single-junction solar cells.[21] In these devices, incident light forms electron-hole pairs in the depletion region, which is composed of heavily doped n-type silicon.[22] Charge separation is instantaneous, with electrons migrating to the layer of n-type silicon and holes migrating to the layer of p-type silicon. Photocurrent is generated when the accumulated electrons travel through the load and recombine with holes in the p-type silicon region. These cells operate with efficiencies close to 24%.[23]

These photovoltaic cells can generate sufficient power to sustain a microsystem.[24] Small silicon-based solar cells are frequently used in consumer and industrial applications, including toys, watches, calculators, street lighting controls, portable power supplies, and satellites.[25] Other technologies include a wireless heliometer sensor node powered by sunlight that produced a maximum of 260 mW and a solar harvester-supercapacitor tandem unit that generated over 350 mW of power on sunny days and approximately 40 mW on cloud days.[26] Indoor use is also possible, with a 2 mm diameter photovoltaic cell located 2 meters away from a 100 W incandescent bulb being capable of producing a few microwatts of power.[27] These devices typically utilize power management modules that can efficiently acquire and manage power generated by photovoltaics, including Maxim's MAX17710 and Texas Instruments' bq25504.[28]

An alternative commercially available photovoltaic scheme is the multi-junction solar cell, which can exhibit efficiencies of over 50%.[29] These materials are capable of surviving the extreme temperature fluctuations and radiation exposure experienced in space and are therefore the predominant type of solar panel used to power long-term space missions.[30] However, their high cost relative to silicon has to-date limited their terrestrial applicability.[31] These devices are composed of a range of materials in an effort to accurately capture the solar spectrum, including gallium arsenide, gallium indium phosphide, and germanium.[32] In a standard arrangement, the top layer of the cell is composed of a material that enables the absorption of high-energy photons (Fig. 4).[33] Lower-energy photons pass through and are absorbed by subsequent layers.

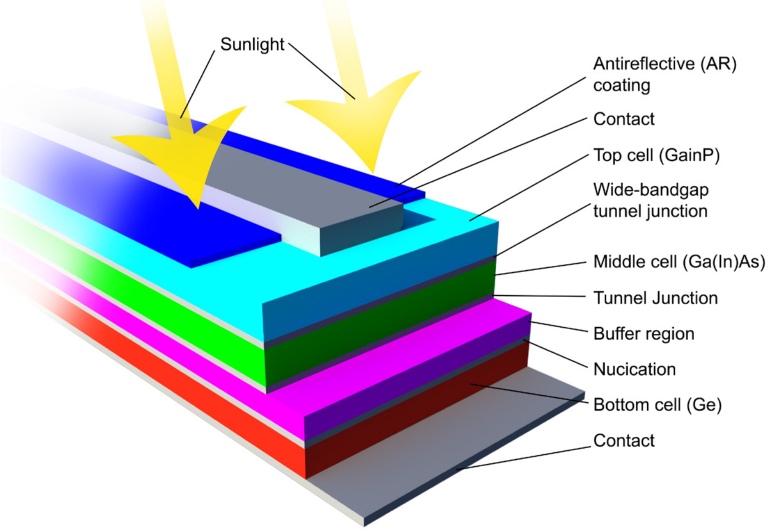

Figure 4.
The operating scheme of a multi-junction solar cell.[34]

THERMAL

Thermal energy can be converted to electricity via thermoelectric generators (TEGs), which convert thermal gradients in the environment to electrical energy.[35] Temperature differentials between opposite segments of a conducting material result in heat flow, and consequently charge low, since mobile high-energy carriers diffuse from high to low concentration regions (Fig. 5).[36,37] Thermoelectric devices are composed of thermopiles, which consist of n- and p-type materials electrically joined at the high-temperature junction. This arrangement allows heat flow to carry the dominant charge carriers of each material to the low-temperature end, establishing a voltage difference. The generated voltage and power are proportional to the temperature differential and the Seebeck coefficient of the thermoelectric materials.

A good thermoelectric material should have a large Seebeck coefficient that is usually present in semiconductors, high electrical conductivity like metals, and poor thermal conductivity as in glasses.[39] These features are not easily combined into a single material. Current top performing thermoelectric materials are based on bismuth telluride and lead chalcogenides (Fig. 6). In an effort to address issues related to the scarcity of tellurium and the toxicity of lead, tellurium- and lead-free materials have been developed. However, few of these materials function in operational temperatures relevant to the human body.[40,41] Polymeric materials such as poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) and polyaniline (PANI) also show promise for use in flexible devices, but suffer from poor electrical conductivity.[42]

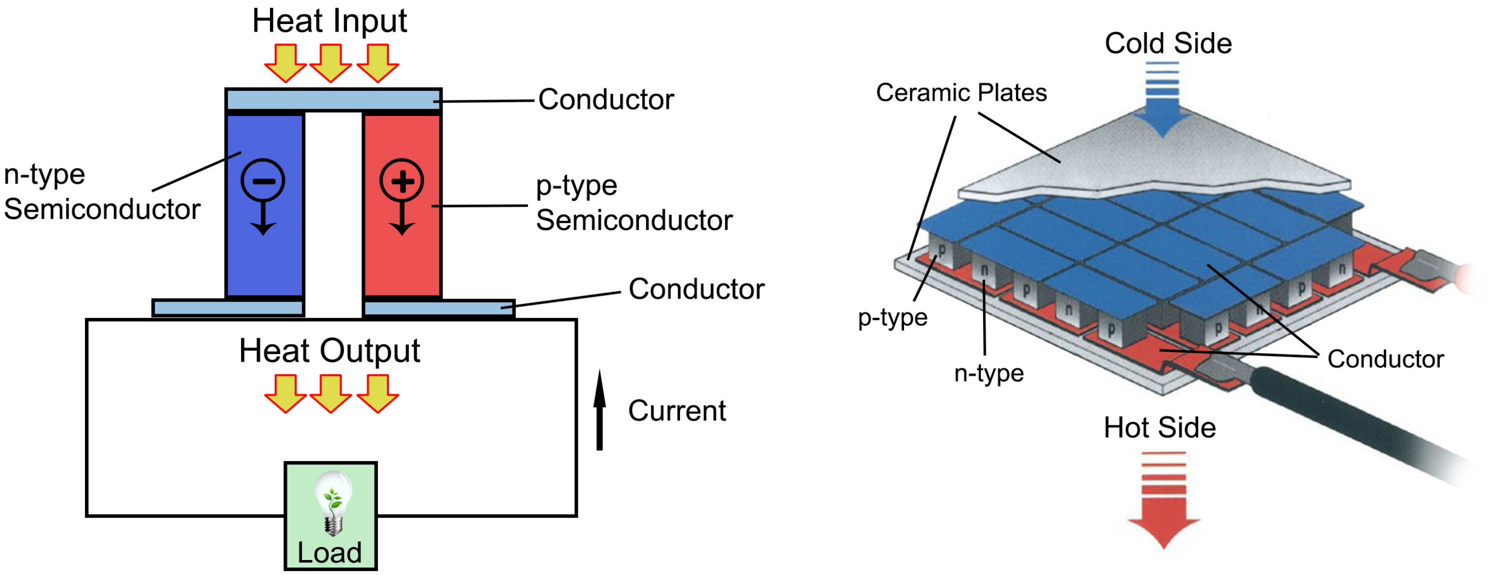

Figure 5.

A diagram of a thermoelectric generator.[38]

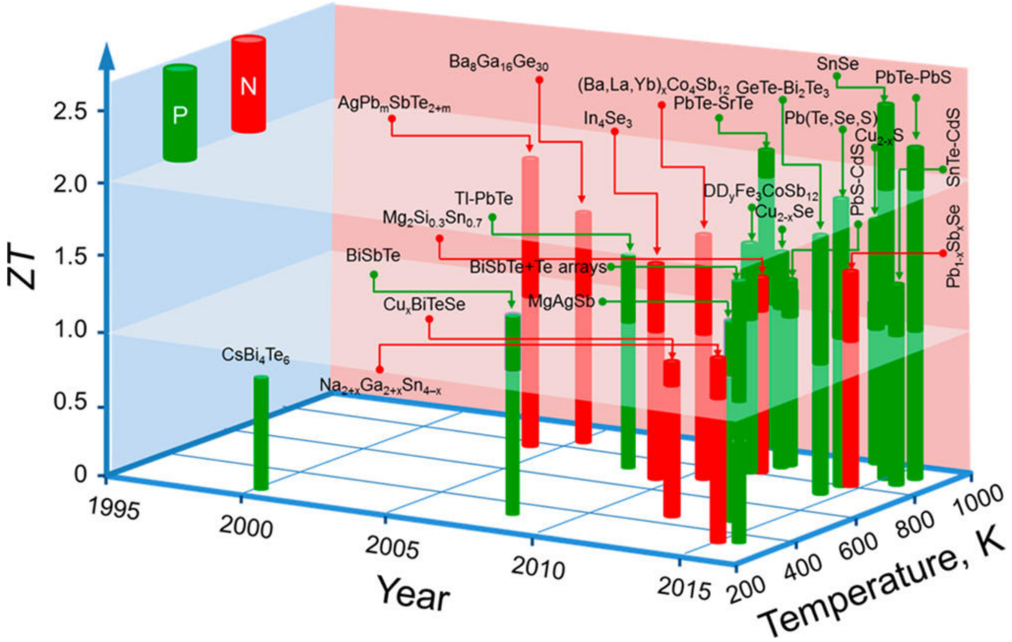

Figure 6. Current state-of-the-art thermoelectric materials as a function of operating temperature and year discovered. A higher value of ZT corresponds to better thermoelectric performance.[43]

Thermoelectric harvesters are characterized by long lifetimes, stationary components (and are therefore quiet), high reliability, and low (5-6%) efficiencies.[44] However, emerging thermoelectric materials combined with improved modules have achieved efficiencies over 10%. A variety of geometries for thermoelectric devices are currently under development, including flat bulk, cylindrical bulk, thin- and thick-film, and flexible.[45] Microfabricated devices have been designed to function in environments with 5°C temperature differences, such as the human body. For example, a 700 mm² device has achieved a power density of 0.14 μW/mm², while a 1.12 mm² device has produced 0.60 μW/mm². Recently, researchers at Pacific Northwest National Lab developed a thermoelectric generator that can exploit the small temperature gradients that are common in the environment, such as those at the ground-air, water-air, skin-air interfaces.[46]

Thermoelectric modules are currently incorporated into several portable devices. Wristwatch manufacturers Seiko and Citizen have produced two models that are powered by the body's thermal energy.[47] Under typical operating conditions, the Seiko Thermic and Citizen Eco-Drive Thermo watches produce 22 μW and 13.8 μW of power, respectively. Other thermoelectric-powered portable technologies include a pulse oximeter (powered by a thermoelectric generator that produces 30 μW/cm²) and a network of body sensors (powered by a 100 μW thermoelectric generator that is placed on the most convenient part of the human body to obtain maximum possible body heat).

An alternative thermal energy generation scheme relies on pyroelectrics, which convert temperature changes to electrical energy.[48,49] In this device, temperature changes force positive and negative charges to migrate in opposite directions, establishing an electrical potential.[50] However, power can only be generated when the external temperature is actively fluctuating, severely limiting the use of this technology.

MECHANICAL

The conversion of mechanical to electrical energy relies on a mechanical-to-electrical energy generator (MEEG), which has several variations (Table 2).[51] One design of a MEEG relies on a piezoelectric material, which generates a voltage in response to applied mechanical strain (Fig. 7).[52] Specifically, strain/deformation of a piezoelectric material causes charge separation, producing an electric field and a voltage drop proportional to the applied stress.[53] Typically, this device relies on an oscillating system that employs a cantilever-beam structure with a mass at the unattached end. Such a design provides higher strain for a given input force. Importantly, the voltage produced varies with time and strain, and relatively high voltages and power densities could be produced.

The current leading piezoelectric materials were discovered in the 1950s and include lead zirconate titanate (PZT) and barium titanate.[55] However, their incorporation into devices has been limited due to their characteristic brittleness and toxicity. Inclusion in polymer-ceramic composites improves the mechanical properties, but at the loss of piezoelectric properties. Piezoelectric polymers, such as polyvinylidene fluoride (PVDF) and a copolymer of vinylidene fluoride trifluorethylene (P(VDF-TrFE)), offer moderate piezoelectric properties but can be easily formed into curved structures, greatly improving their commercial viability.

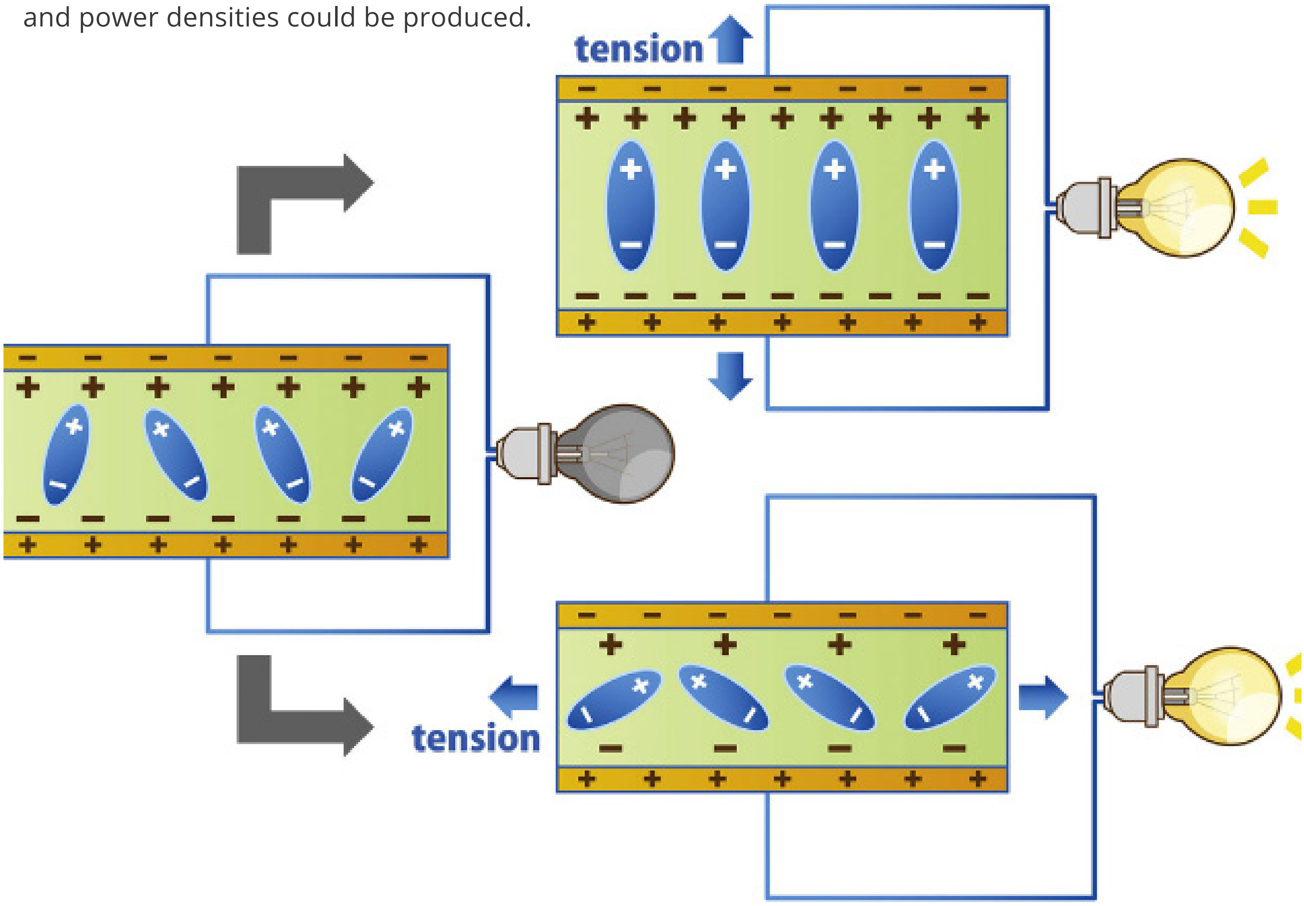

Figure 7.

The piezoelectric effect for energy harvesting.[54]

An alternative MEEG design is based on electromagnetic-energy harvesting, where a magnetic field converts mechanical energy to electrical energy.56 Here, a coil attached to an oscillating mass traverses a magnetic field, inducing a voltage according to Faraday's Law because it travels through a varying amount of magnetic flux. Unfortunately, the output voltage is too low for most applications and must be increased via a transformer, by increasing number of coil turns, or by increasing the magnitude of the magnetic field.

A third MEEG scheme relies on electrostatic energy harvesting, which is dependent upon the changing capacitance of vibration-dependent varactors.[57] A variable capacitor is initially charged and, as vibrations separate its plates, mechanical energy transforms into electrical energy. This technology is advantageous due to its compatibility with integrated circuits and capability to produce higher and more practical output voltage levels.

Human power is an excellent source of mechanical energy.[59] Several commercially available flashlights and radios can be powered by winding. Researchers at MIT found that the most reliable and exploitable energy source occurs at the foot during heel strikes when running or walking. A piezoelectric shoe insert takes advantage of this, producing 330 $\mu W/cm^2$ while an average person is walking. Additionally, the motion of the heart, lungs, and diaphragm is capable of generating 1.2 $\mu W/cm^2$.[60] However, the miniaturization of this technology is a significant challenge that needs to be overcome to facilitate commercial adoption. Other human-powered MEEG-technologies include battery-less remote controls (where the force used to press a button is sufficient to power a wireless radio or infrared signal), and floor tiles (where the kinetic energy generated by the footsteps of crowds power ticket gates and display systems).[61]

TABLE 2. COMPARISON OF MECHANICAL ENERGY HARVESTING TECHNIQUES.[58]

	Electromagnetic	**Piezoelectric**
Complexity of process flow	Very High	High
Energy density	24.8 mJ cm-3	35.4 mJ cm-3
Current size	Macro	Macro
Problems	Very low output voltages	Low output voltages

RF

RF energy harvesting captures and converts energy from ambient RF sources, including AM, FM, TV, GSM, CDMA, 3G, 4G, ISM, and WiFi (Fig. 8).[62] Ambient RF energy is typically available throughout the day and is independent of weather conditions, but is characterized by low power densities and strength that rapidly decreases with increasing distance from the source.[63,64] Other important factors to consider for the conversion of RF energy into electrical energy include source power, antenna gain, and energy conversion efficiency.[65] Typical RF-to-DC conversion efficiencies are between 50 and 75%.

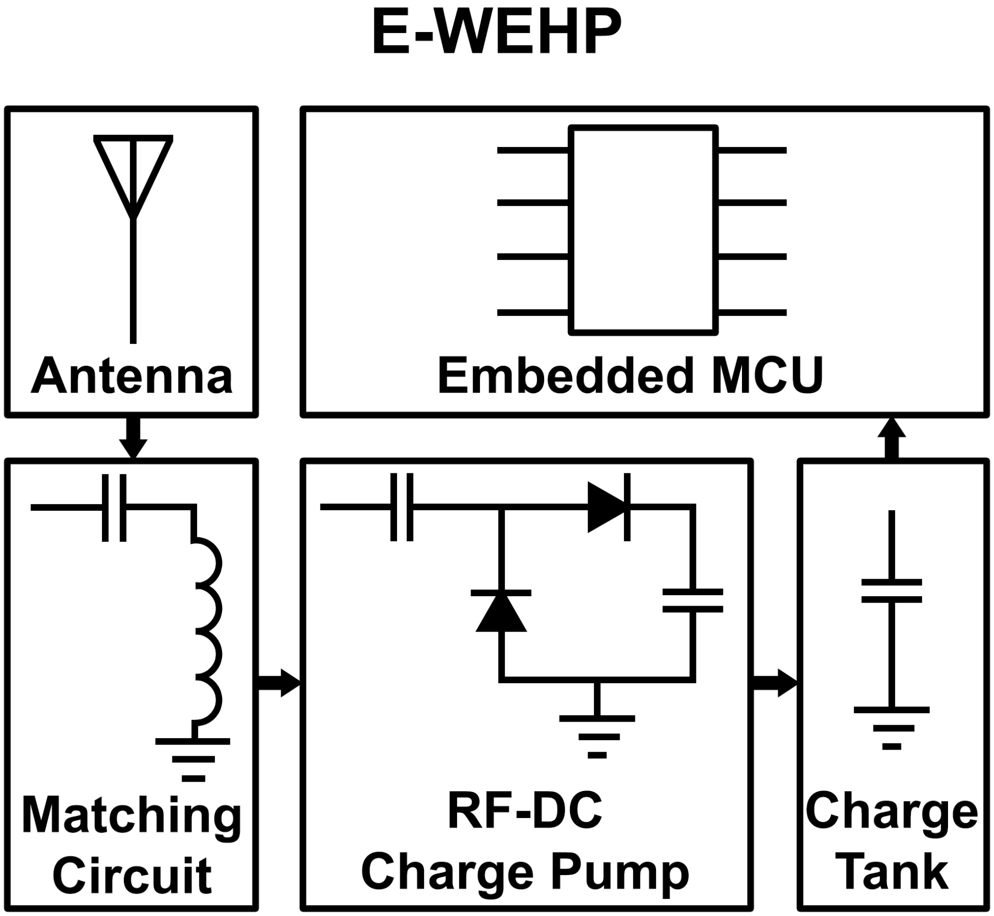

Figure 8.
A block diagram of a RF energy harvesting device.[66]

The technology implemented in RF energy harvesting devices must be carefully selected to ensure appropriate function and overall compatibility.[67] For example, a highly sensitive device capable of harvesting the UHF digital TV band would need to use a high-gain broadband antenna. Meanwhile, a single-stage rectifying circuit could be used to maximize the RC-DC conversion efficiency of a dual-band cell/WiFi energy harvesting device that's capable of collecting power from multiple bands. And an energy harvester designed to power wearable electronics should utilize an antenna geometry that can be folded or otherwise miniaturized to reduce overall size.

Broadcast stations are particularly attractive ambient RF sources, especially those broadcasting AM signals.[68] RF signals in the AM band has several advantages over those in the UHF, FM, cellular, and WiFi bands, including high penetration ability, low attenuation inside building materials, and non-reliance on line of sight signal propagation. Additionally, there are numerous high-powered commercial AM stations throughout urban and rural landscapes. However, large antennae are typically required to capture the signal. For example, a 62.8 m wire antenna was required to produce 2.39 mW of power in a device located 50 m from the AM station.

Other examples of products powered by RF energy harvesting include a RFID tag that was powered by a TV station 10 km away and a sensor that produced 16 μW of power from a TV station located 6.4 km away.[69] These devices typically employ one radio for RF harvesting and communicating with other sensor nodes in the network.[70] Additionally, a Multistage Villard Voltage Multiplier (MVVM) circuit can be utilized to increase the output power to required power levels.

ENERGY STORAGE

As noted earlier, several energy harvesting device topologies include an energy storage module to allow for continuous operation despite an immediate inability to harvest energy. The predominant energy storage technologies currently in use are batteries and supercapacitors. Important specifications to consider for choice of battery include energy density, internal resistance, depth of discharge, self-discharge, and tolerance to overcharging.[71] Operating conditions are also particularly important factors that should be weighed. Lithium-ion batteries will likely be the current battery of choice for most energy harvesting devices due to its relatively high operating voltage, capacity, temperature range and cycle capacity (Table 3). Current battery technologies are limited by the cycling capacity, which restricts the number of charge/recharge cycles that can be achieved. The overall efficiency of a battery is typically between 60 and 80%, but efficiencies tend to decline over time due to chemical corrosion of the electrodes.

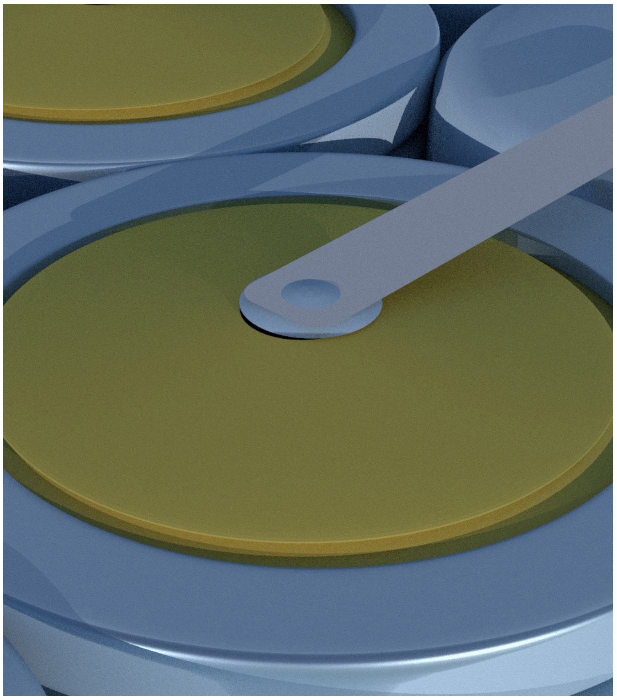

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TABLE 3. PARAMETERS OF VARIOUS COMMERCIALLY AVAILABLE BATTERY TYPES.[72]

Type	Rated Voltage (V)	Capacity (Ah)	Temperature Range (°C)	Cycling Capacity (-)	Specific Energy (Wh/kg)
Lead-Acid	2	1.3	−20–60	500–1000	30–50
MnO$_2$Li	3	0.03–5	−20–60	1000–2000	280
Li poly-carbon	3	0.025–5	−20–60	-	100–250
LiSOCl$_2$	3.6	0.025–40	−40–85	-	350
LiO$_2$S	3	0.025–40	−60–85	-	500–700
NiCd	1.2	1.1	−40–70	10,000–20,000	50–60
NiMH	1.2	2.5	−20–40	1000–20,000	60–70
Li-Ion	3.6	0.74	−30–45	1000–100,000	75–200
MnO$_2$	1.65	0.617	−20–60	-	300–610

Supercapacitors offer numerous advantages over batteries and standard capacitors, including high power densities, high charge/discharge efficiencies (up to 98%), fast charging processes, a wide range of operating temperatures, and a large number of charge/discharge cycles without diminishing performance (500,000-1,000,000).[73]

However, supercapacitors suffer from a self-discharge rate of 50-60% per month, which severely decreases device lifetime. Fortunately, this could be compensated for with fast charging. Several supercapacitors are currently commercially available (Table 4).

TABLE 4. PARAMETERS OF VARIOUS COMMERCIALLY AVAILABLE SUPERCAPACITORS.[74]

Supercapacitor	Life Cycle (-)	Specify Energy (Wh/kg)	Operating Temperature (°C)	Cell Voltage (V)
Maxwell PC10	500,000	1.4	−40–70	2.50
Maxwell BCAP0350	500,000	5.1	−40–70	2.50
Green-cap EDLC	>100,000	1.47	−40–60	2.70
EDLC SC	1,000,000	3–5	−40–65	2.70
Pseudo SC	100,000	10	−40–65	2.3–2.8
Hybrid SC	500,000	180	−40–65	2.3–2.8

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Market Analysis and Technology Forecast

The global energy harvesting market was valued at $1.28 billion in 2016 by Inkwood Research (Fig. 9). The market is expected to see significant growth in the coming years, with a CAGR of 22.21% between 2017-2024. By 2024, the global energy harvesting market is expected to be valued at ~$6 billion. Within the United States, the energy harvesting market was valued at ~$80 million in 2017 (Fig. 10). The market is expected to double in value by 2024, reaching ~$200 million by 2026.

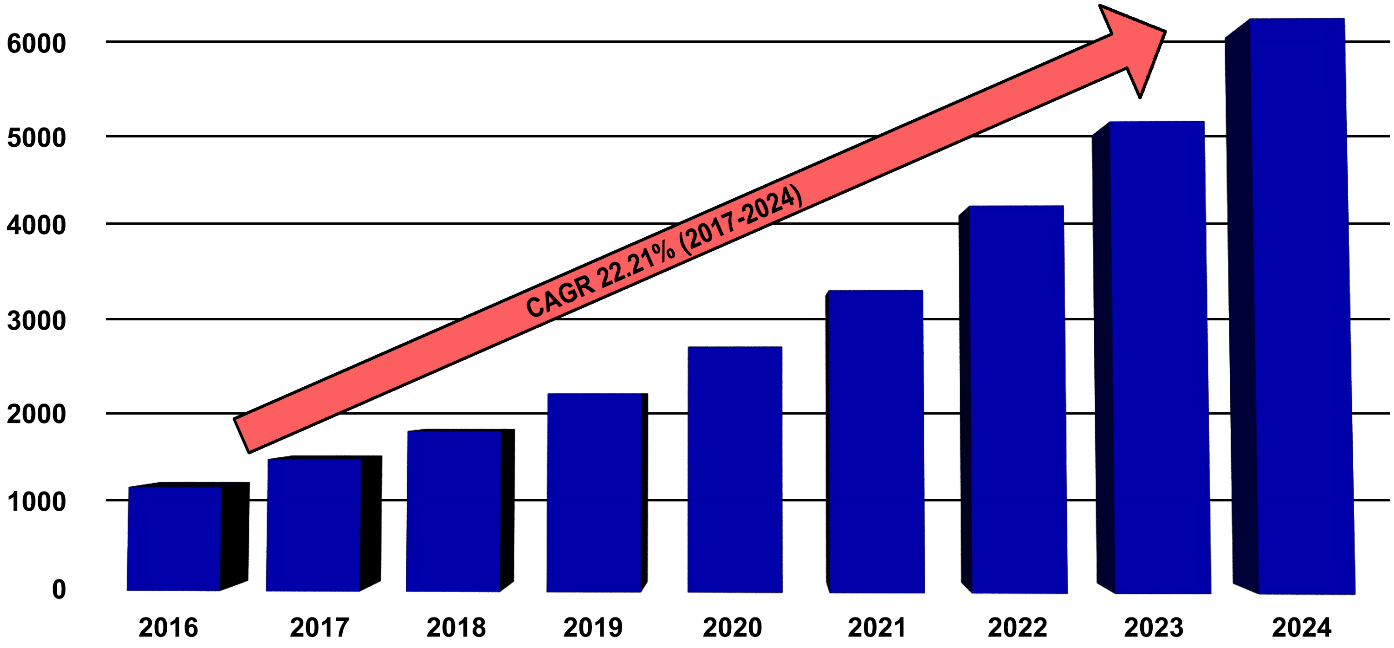


Figure 9.

Global energy harvesting market in 2016. Projections from 2017-2024.[75]

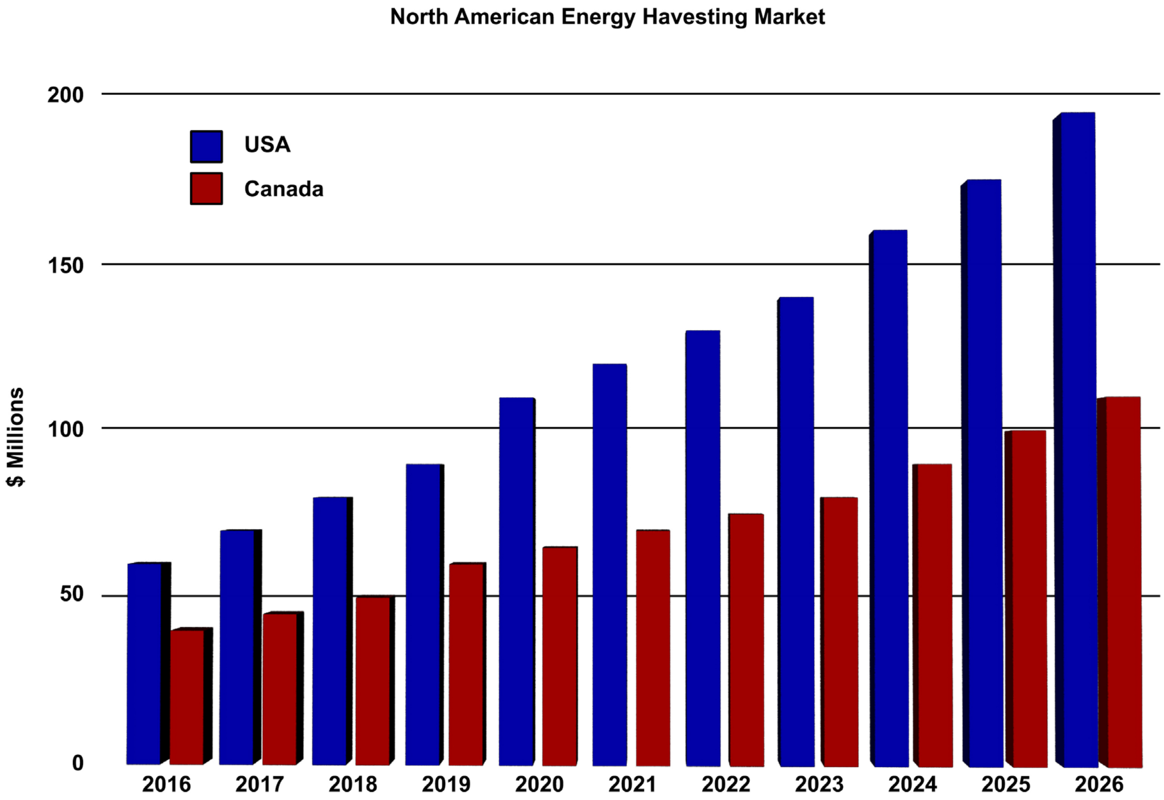


Figure 10.

Global energy harvesting market in 2016. Projections from 2017-2024.[76]

Within the energy harvesting sub-industries, significant market growth is expected in the piezoelectric, solar and thermoelectric harvesting sectors.[77] RF harvesting technology is still in the research and prototyping phase. Below, market analysis and forecasting is provided for each sub-industry.

SOLAR ENERGY HARVESTING

The solar energy harvesting market spans low-energy harvesting devices to higher-energy panels for buildings and energy grids. The solar photovoltaics (PV) market has seen significant growth in recent years, as cost per watt has decreased (Fig. 11). Within the PV market, a significant majority of the global annual energy production is dominated by devices made of polycrystalline silicon (Multi-Si), followed by single crystal silicon (mono-Si)-based devices (Fig. 12). Thin-film devices make up a much smaller share of the market.

A 2017 report from the National Renewable Energy Laboratory provides forecasts on photovoltaic capacity (Fig. 13). The projections account for baseline trends, as well as trends factoring in the SunShot program. SunShot is a program run by the Department of Energy aimed at propelling growth in the solar energy sector. Projections for SunShot and SunShot with Low Storage Cost show significantly higher growth compared to the baseline scenario (ATB Mid). NREL estimates that by 2030, PV deployment will peak at just under 55 GW/year, stabilizing between 20 GW/year to 40 GW/year in the subsequent years.[78]

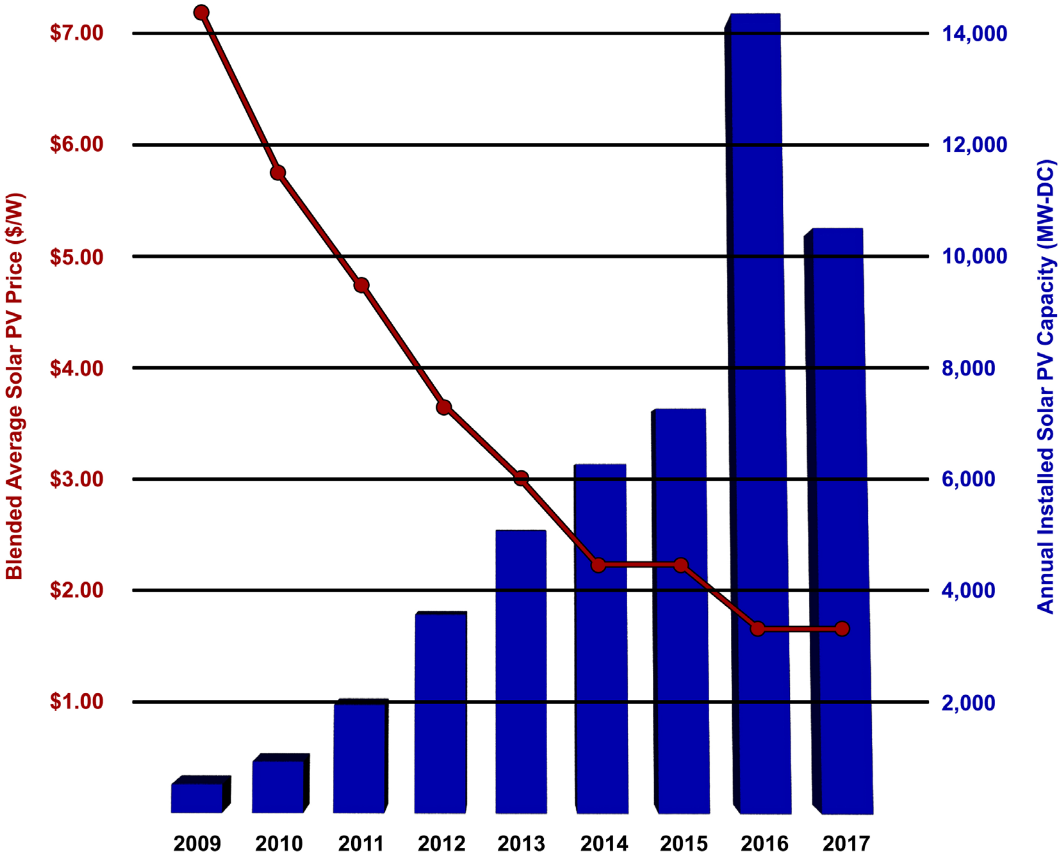


Figure 11.

Trends in solar PV prices and solar PV installations.[79]

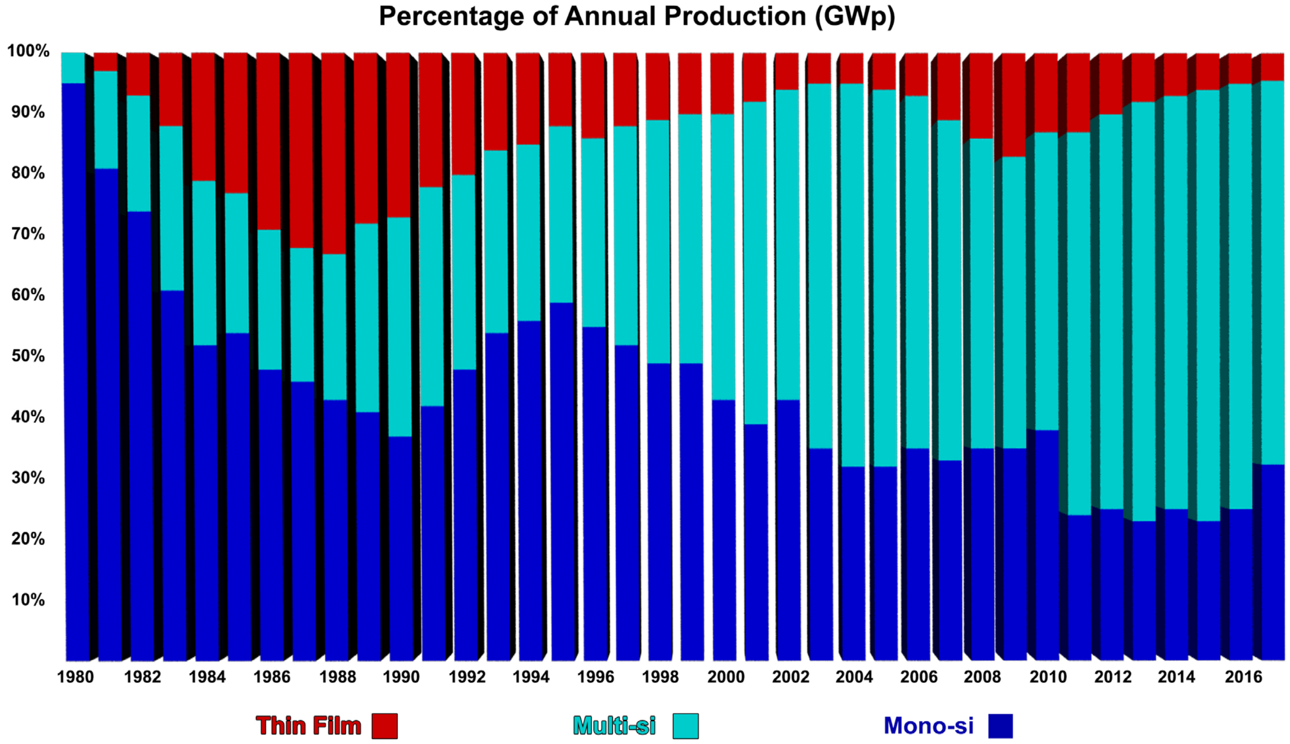


Figure 12.

Trends in percentage annual production by photovoltaic material type.[80]

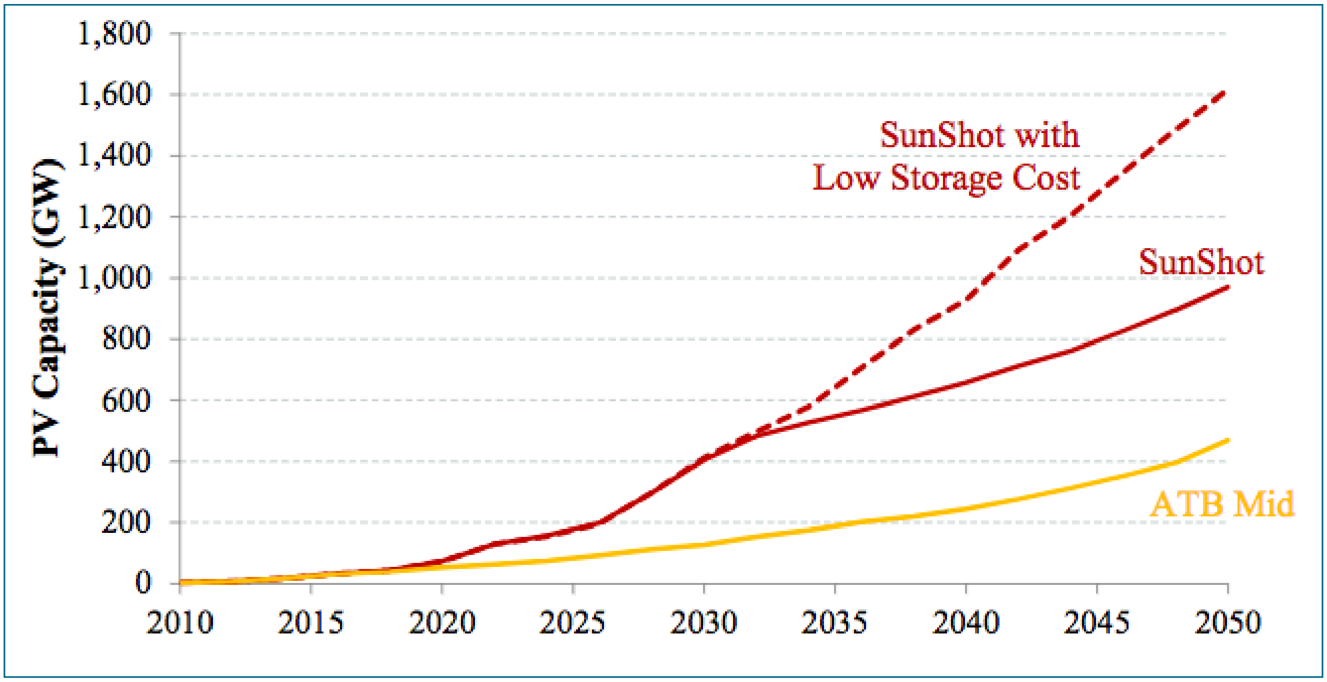


Figure 13.

Forecast of PV capacity in the U.S.[81]

Within the solar industry, the global portable solar charger market was valued at $16.89 billion in 2017.[82] North America is projected to see significant growth in this sector, with market value growing to $33.36 billion by 2023.[83] The primary consumers for portable solar chargers right now are the military (45% of market value) followed by transportation and individual customers.

There are various companies active in the solar energy harvesting space, focusing either on materials development or integration of harvesting devices into products.

Devices

Solar Application Lab, a Dutch company, develops solar cells of any size that are capable of energy generation even when partially shaded or if light falls at an angle.[84] Their flagship product is the Dutch Solar Cycle, an electric bicycle powered by solar discs that use nano inverters to harvest solar energy. The company professes that their product can be tailored to a variety of products and are open to partnerships on products that can use their nano inverter technology.

Sol Chip, an Israeli company, offers a variety of solar harvesting products. The Sol Chip Pak provides non-stop power using solar cells, a rechargeable battery and advanced power management circuitry for small scale devices like wireless sensor networks.[85] The Sol Chip Comm is a maintenance-free solar-powered wireless tag that can power, control and wirelessly connect a wide variety of sensors to the cloud.[86] It has numerous applications for outdoor wireless sensors such as environmental monitoring, smart cities and surveillance.

Walty, an Italian-Spanish startup company, has developed a “solar-powered” computer capable of generating electricity, purifying water and providing internet services.[87] It is powered by photovoltaic panels, that harness solar energy and convert it into electricity through an internal 140 kwh battery. It is capable of distilling 5,000 liters of safe drinking water each day and providing wireless internet access over an 800-meter radius. Prototypes are being tested around rural Africa, with demonstrations in rural Ghana.

Materials

Heliatek, a German company, develops solar films made of ultra-thin layers of organic molecules that are deposited on a flexible PET film.[88] They tout their pioneering low-cost mass production ability as giving them the advantage of high throughput, high yield and low costs. The main application of their product is for solar panel installations on building windows, rooftops and automobiles.[89]

Eight19, an X company, develops organic photovoltaics (OPV) based on printable organic semiconductor materials.[90] They state that their OPVs can be used for a multitude of applications including wireless powering of devices by harvesting indoor light and for providing outdoor off-grid power.

GCell, a UK company, sells Dye-Sensitized Solar Cells (DSSC) that can be integrated into an electrical device using a rechargeable battery or super capacitor for energy harvesting.[91] Their solar cells are flexible, thin, lightweight and designed specifically for indoor energy harvesting.

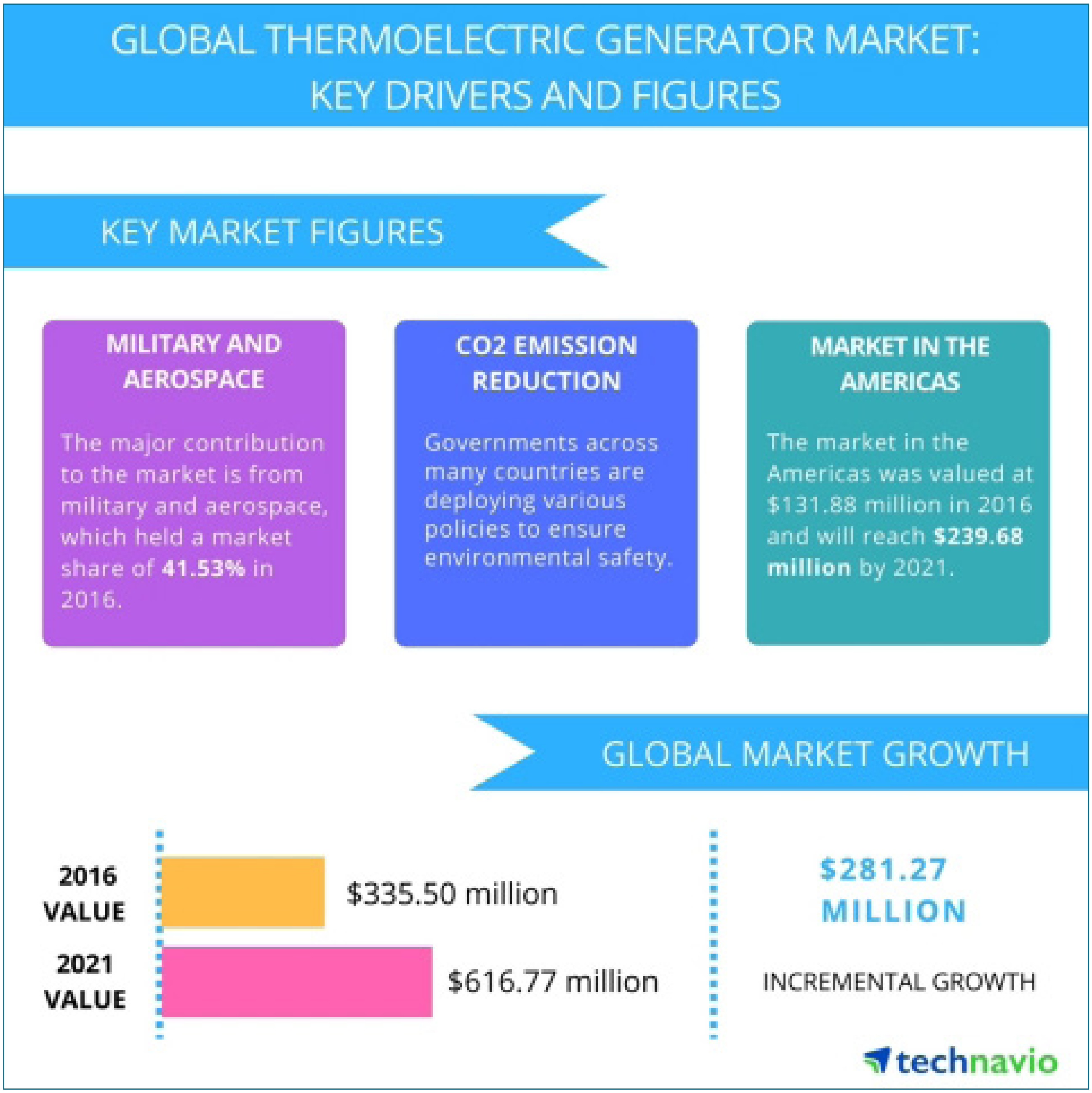
Alta Devices, a company based out of California, develops thin-film solar cells made out of gallium arsenide.[92] Their thin-film solar cells have a variety of applications and can be integrated into UAV's, automobiles, IoT devices and wearables.

Ubiquitous Energy, another company based out of California, has developed the first truly transparent solar technology. Their thin-film solar cells harvest light energy in the ultraviolent and infrared band, allowing the cells to maintain up to 90% visible transparency.[93] These solar cells can be deployed on a variety of surfaces like windows or mobile screens to harvest light energy.

Saule Technologies, a Polish company, develops thin-film solar cells made from halide perovskites for solar energy harvesting technology.[94] They tout several advantages to their products including low-cost of production and specifications such as semi-transparent, lightweight and ultra-thin materials. Current applications of their technology are primarily geared towards outfitting windows in buildings with solar cells. They license their technology to a variety of countries including the U.S.

THERMOELECTRIC ENERGY HARVESTING

The market value of the thermoelectric generator industry was estimated to be ~$330.5 million in 2016 (Fig. 14). Projecting forward, the market value is expected to climb up to ~$616.77 million by 2021. The biggest contributor to the total market share in 2016 was the military and aerospace industry, with a share of 41.53% of the total industry.



GLOBAL THERMOELECTRIC GENERATOR MARKET: KEY DRIVERS AND FIGURES

KEY MARKET FIGURES

MILITARY AND AEROSPACE

The major contribution to the market is from military and aerospace, which held a market share of **41.53%** in 2016.

CO2 EMISSION REDUCTION

Governments across many countries are deploying various policies to ensure environmental safety.

MARKET IN THE AMERICAS

The market in the Americas was valued at $131.88 million in 2016 and will reach **$239.68 million** by 2021.

GLOBAL MARKET GROWTH

Figure 14.

Key insights for the global thermoelectric generator market.[95]

A primary market driver for growth in thermoelectric generators (TEG) is government regulations on fuel efficiencies in automobiles. Since a vast majority of fuel energy in vehicles is lost as waste heat, harvesting energy from waste heat can significantly improve fuel efficiency. However, technical limitations and the high cost of thermoelectric materials and generators have prohibited widespread adoption of waste heat recovery technology.

However, recent breakthroughs in materials science have contributed to industry growth in this area. A recent advancement from Michigan State University was pivotal in driving down costs of thermoelectric materials. Professor Don Morelli's identified tetrahedrites as low-cost compounds that function as highly-effective thermoelectric materials.[96] Shortly after discovery, researchers at Michigan State University entered into an exclusive partnership with Alphabet Energy for the commercialization of tetrahedrites.[97]

Alphabet Energy is a startup company based out of California that is working on developing advanced thermoelectric generators.[98] Their goal is to develop materials with conversion efficiencies of 10% or more and functional capability at 800ºC. In 2014, they introduced a thermoelectric generator called the E1 that converts exhaust from diesel- or gas-fired engines or gensets into electricity.[99] The E1 converts exhaust heat from large industrial engines to electricity. The TEG is capable of generating up to 25 kWe on a standard 1,0000 kW engine.[100]

Alphabet Energy announced a nonexclusive partnership with Borla, a pioneer and leading manufacturer of stainless-steel performance exhaust systems, to develop a next generation exhaust system that incorporates thermoelectric waste heat recovery.[101] Furthermore, Alphabet Energy, in partnership with Lawrence Berkley National Laboratory, was given a $2 million grant from the California Energy Commission to "create a cost-effective thermoelectric waste heat recovery system to reduce both energy use in the industrial sector and electricity-related carbon emissions."

Several other startup companies are active in this field. Thermoaura, a company based out of New York, develops and sells thermoelectric materials. They specialize in offering customizable thermoelectric nanocrystals in nanopowder form that can be used in the creation of thermoelectric cells.[102]

Otego, a German company, develops innovative TEGs capable of providing energy supply for wireless sensors, actuators and IoT devices.[103] Their TEGs are sugar-cube sized and detect small differences in temperature and convert heat directly into electric power. Otego mass produces TEG's through a novel in-house production process that can print the electrical conductor tracks on extremely thin plastic films at the speed of newspaper printing.[104]

TEGma, a Norweigian startup, is developing thermoelectric power modules that can be used across many industries.[105] Their patented power module technology claims to have higher power density than "state-of-the-art modules" with increased reliability. At the moment, they are partnering with several shipping companies on installing waste heat recovery modules for ship exhaust systems.

MECHANICAL ENERGY HARVESTING

Piezoelectric energy harvesting devices are expected to see the most significant growth in the mechanical energy harvesting sector.[106] The market value of the piezoelectric energy harvesting industry is estimated by IDTechX to be ~$145 million in 2018 (Fig. 15). Projecting forward, the market value is expected to climb up to ~$650 million by 2022. The broader market for piezoelectric materials is significantly larger, with an estimated value of ~$20 billion in 2016 (Fig. 16). This market is expected to see major growth, with an estimated value of ~$48 billion by 2021.

Piezoelectric Energy Harvesting Devices

Several companies sell piezoelectric energy harvesting products. PICeramics, a German company that specializes in piezoelectric technology, sells two products: the P-876 DuraAct Patch Transducer and the E-821 Electronic Module for Energy Harvesting. The P-876 is a multi-use device that can function as an actuator, sensor or energy generator.[108] The E-821 uses piezo actuators for energy generation and is adaptable to customer application on request.[109] It can provide autonomous power supply and has applications for devices such as wireless sensor networks.

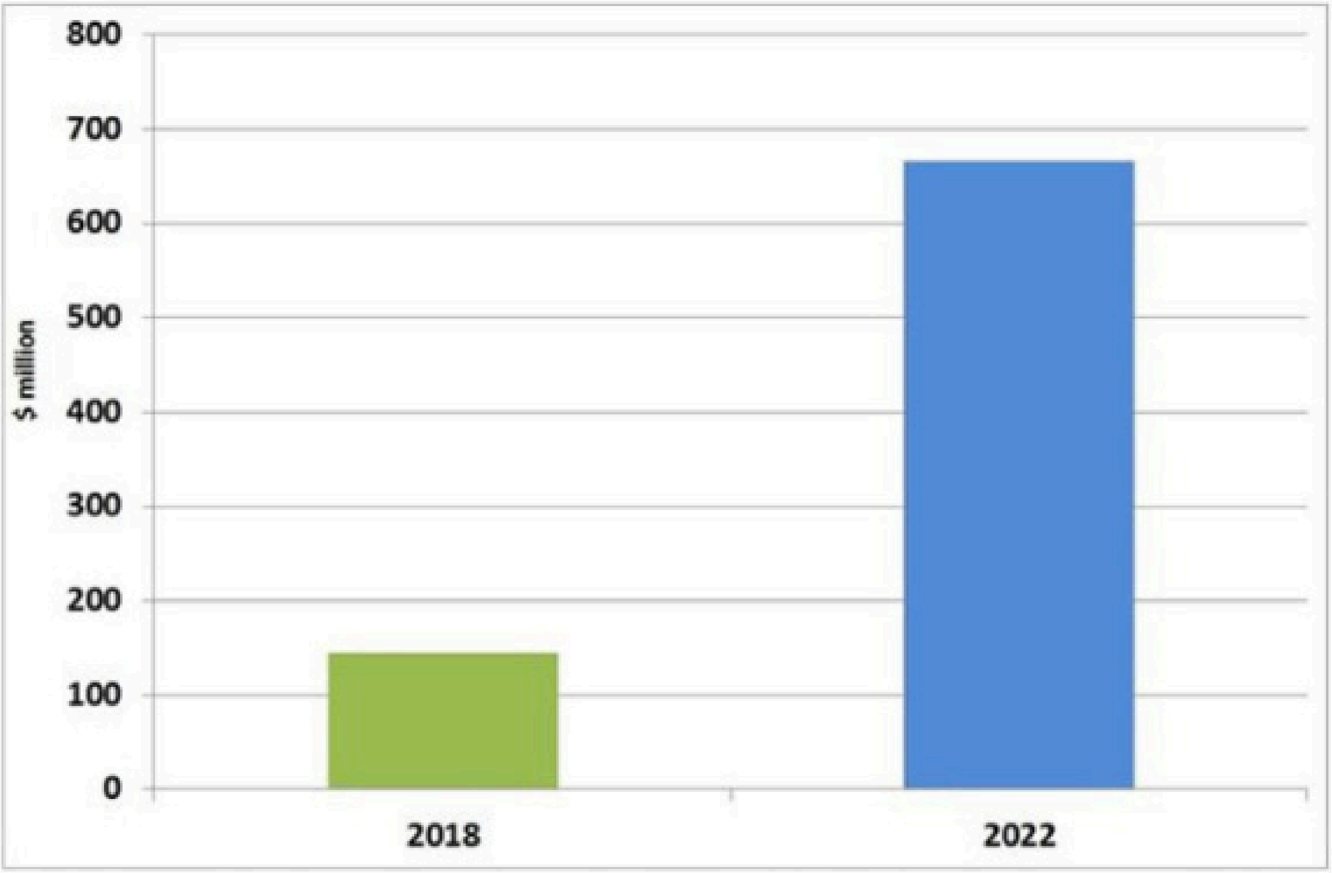
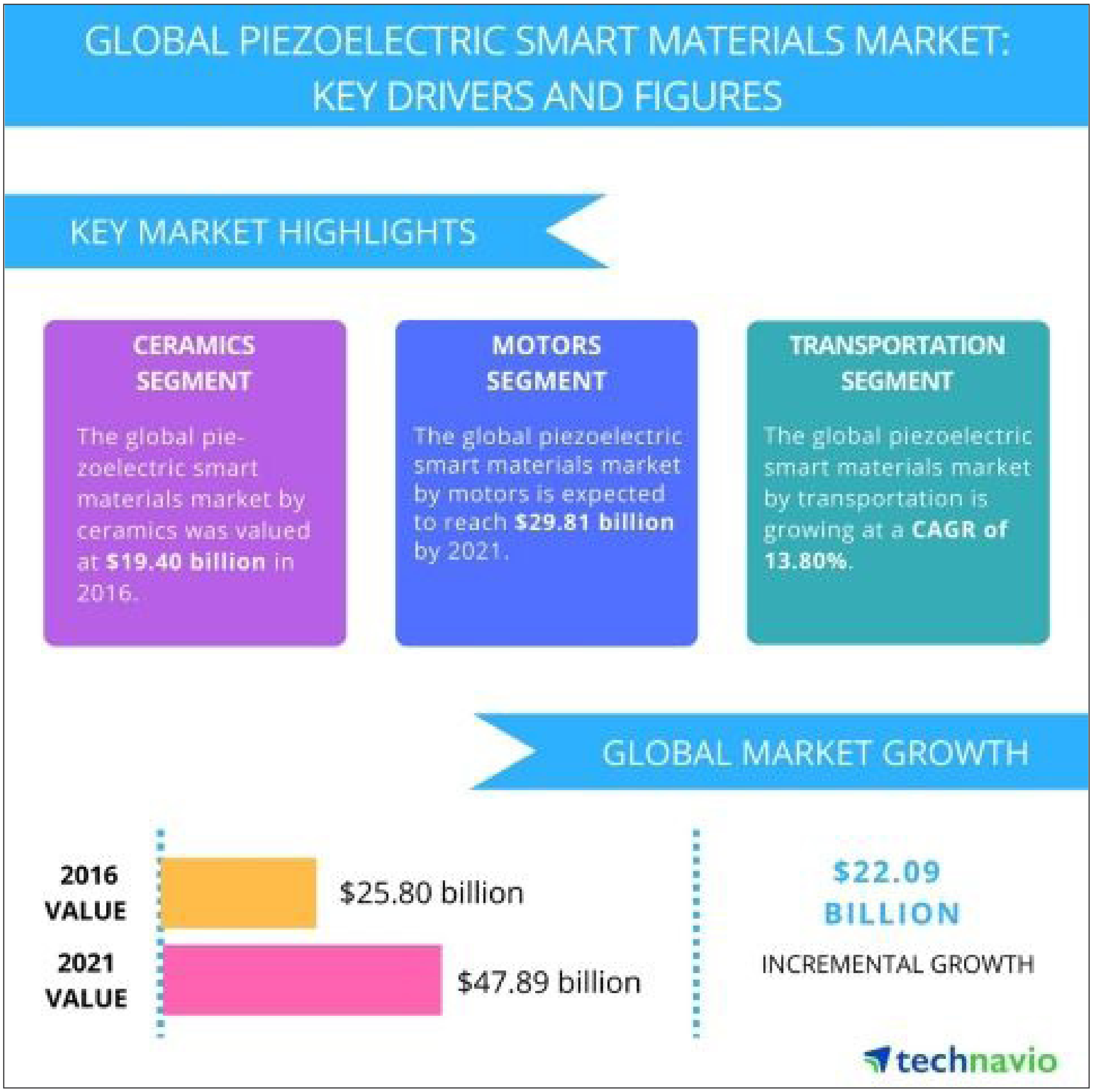


Figure 15.

Estimated piezoelectric energy harvesting market in 2018 and projection for 2022.[107]



GLOBAL PIEZOELECTRIC SMART MATERIALS MARKET: KEY DRIVERS AND FIGURES

KEY MARKET HIGHLIGHTS

CERAMICS SEGMENT

The global piezoelectric smart materials market by ceramics was valued at **$19.40 billion** in 2016.

MOTORS SEGMENT

The global piezoelectric smart materials market by motors is expected to reach **$29.81 billion** by 2021.

TRANSPORTATION SEGMENT

The global piezoelectric smart materials market by transportation is growing at a **CAGR of 13.80%**.

GLOBAL MARKET GROWTH

Figure 16.

Key insights for the global piezoelectric materials market. [110]

Mide's Volture PPA products are energy harvesters that use piezoelectric materials to convert vibration energy into usable electrical energy.[111] Their products can be used to charge batteries, supercapacitors or for directly powering remote sensory systems.

MicoroGen Systems, a U.S. based company, develops piezoelectric energy harvesters that can power wireless sensor systems.[112] Their technology provides life-long ultra-low power to wireless sensor networks, that can be configured and scaled to the needs of the customer. 8Power, a

UK based company, offers similar vibration energy harvesting technology that can power wireless sensor networks.[113]

The startup Pavegen has developed "smart tiles" that generate power using the piezoelectric effect. Each foot stomp on the tile is capable of producing one to seven watts of energy.[114] The tiles are functionally capable of powering LED lighting and sensors for data collection.

Non-Piezoelectric Mechanical Energy Harvesting Devices

Several companies are developing products that harvest kinetic energy that include non-piezoelectric harvesting methods. Bionic Power, a company based out of Vancouver, makes wearable technology that harvests kinetic energy for charging batteries.[115] Their products are slated to undergo multi-unit field trials with the U.S. Army, U.S. Marine Corps and Canadian Forces this year.

SolePower is another company that is developing wearable technology capable of producing power. Their "smart boots" generate power form the kinetic energy of heel strikes.[116] The technology uses captures linear motion using links and gears that spin a permanent magnetic generator. The generated power is then stored in a battery capable of powering mobile devices.[117]

Smalle Technologies, a company based out of Barcelona, develops generators that can convert the mechanical energy of sea waves into electricity to power off-shore devices.[118] Their flagship product is the eForcis. It is a wave power generator specifically designed for AtoN and ODAS buoys.[119]

RADIO FREQUENCY (RF) ENERGY HARVESTING

The exact value of the RF energy harvesting market is unclear, as there are few well-established companies in this sub-industry. A consumer market for RF energy harvesting devices is largely non-existent.[120]

Powercast, a company based out of Pittsburgh, is one of the market leaders in RF energy harvesting technology.[121] Their technology relies on two components: a RF energy transmitter that operates in the ~913MHz band and a receiver chip embedded in a device which converts the energy into DC to charge batteries or directly power a device. Their most recent product is the PCC114 chip, which has a significantly smaller footprint (1 x 0.6 x 0.3 mm) and volume than their previous products.[122] Devices can be powered using Powercast's PowerSpot transmitter, which is capable of transmitting an intentional RF source up to 80 feet to a receiver.

A similar technology is licensed by Ossia, a company based out of Washington State. Ossia's flagship product is Cota, a receiver and transmitter that can be embedded in any device for seamless wireless power transmission. Ossia does not sell products directly and instead license their technology to brands and manufacturers. Their product operates in the 2.4 GHz band, allowing for greater control over power transmission.

Another company active in this space is Energous, whose flagship product WattUp promises wireless charging for devices such as mobile phones, tablets and wearables.[123] However, Energous has recently faced criticism from investors over poor performance and failing to meet expectations.[124]

Researchers at University of Washington (UW) recently demonstrated a battery-free cell phone that is powered entirely by harvested energy from radio waves and light.[125] The phone is capable of transmitting and receiving calls and receiving user input via buttons. The prototype uses 3.5 microwatts of power, drawing energy from a base station that was 31 feet away. The UW research team is now commercializing this product and technology through a startup called Jeeva Wireless.[126]

A major limitation to RF harvesting technology is the reliance on a transmitter. Ideally, a RF energy harvester should tap into abundant ambient radio waves propagated in our environment. There are several companies and academic groups that are developing prototype technologies that push beyond the limitations of traditional RF harvesters. They are working on developing energy harvesting devices that tap into ambient radio waves present in our environment without the need for a transmitter.

Teratonix, a startup launched out of Carnegie Mellon University, is developing energy harvesters that use a metal-semiconductor-metal (MSM) ultrahigh speed diode. This technology enables their energy harvesters to simultaneously harvest energy from all available radio frequencies (TV, FM radio, 3G, 4G and WiFi) (Fig. 17).

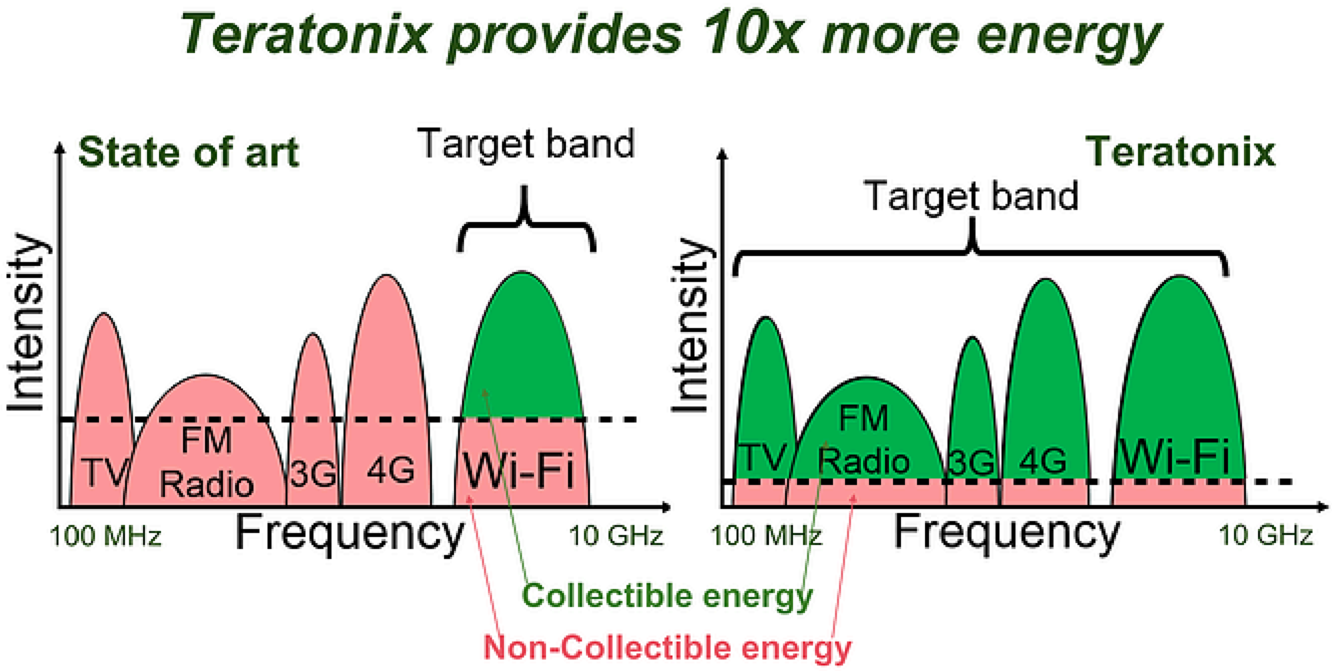


Figure 17.

Energy harvesting capability of Teratonix vs. current state of the art.[127]

Drayson Technologies, a UK based startup, is also developing technology capable of harvesting energy from wireless and broadcast networks like 4G, WiFi. Their flagship product is FreeVolt, a RF energy harvester that uses a multi-band antenna and rectifier to harvest energy from ambient radio waves.[128]

Nikola Labs, a startup launched out of Ohio State University, has a flagship product called INDRA. INDRA is a miniaturized chip that functions an efficient RF-to-DC circuit (Fig. 18). Nikola Labs recently demonstrated their technology by designing an iPhone 6 case that captured waste RF transmissions and used them as an energy source to power the device.[129]

Jennova, a company based out of Tennessee, offers transmitter-free RF energy harvesting designs that can be incorporated into their client's energy harvesting needs. [130]

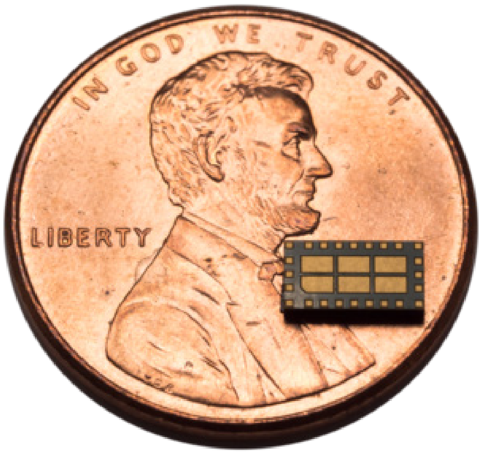


Figure 18.
Size reference for the INDRA chip designed by Nikola Labs.[131]

TECHNOLOGY FORECAST

Improved Thermoelectric and Piezoelectric Materials

The search continues for materials that exhibit excellent piezoelectric or thermoelectric characteristics. Importantly, these materials should be free of elements that are toxic and of low-earth abundance.[132] Of paramount interest is the search for new materials with intriguing physical properties, in addition to the optimization of known systems. The most recent state-of-the-art approaches to these efforts range from manipulating band structures and microstructures to altering composition designs via alloying.

Thermoelectric polymers are attractive targets due to their low thermal conductivity and high flexibility.[133] For example, a polymer-based thermoelectric generator capable of being wrapped around hot water pipes was developed by researchers at Georgia Tech. However, current p- and n-type semiconducting polymers offer thermoelectric efficiencies that are far lower than those of solid-state compounds, motivating continued discovery efforts.

An alternative scheme for converting solar heat to electricity relies on the isothermal expansion of sodium.[134] Currently under development, the device produces electricity by thermally driving a sodium redox reaction at electrodes on opposite sides of a solid electrolyte. The resulting potential difference could then travel through an external load. This process shows promise for improved conversion efficiencies and heat utilization.

Also at Georgia Tech, researchers in Alper Erturk's laboratory are developing nonlinear piezoelectric-based energy harvesters.[135] These emerging technologies allow for the capture and up-conversion of wideband energy inputs, a significant improvement over current state-of-the-art devices that require the excitation frequency of ambient sources to match the resonance frequency of the harvester. For example, a recent design achieved output that was an improvement of nearly 700% over linear piezoelectric-based harvesters.

Improved Photovoltaic Cells

Researchers around the world are developing alternative photovoltaic designs to replace silicon-based and multi-junction designs in a bid to reduce costs and improve processability and efficiencies. One scheme, called dye-sensitized solar cells, relies on a combination of quantum dots, light-absorbing dyes, and titanium dioxide nanoparticles to capture sunlight and generate electricity.[136] While these photovoltaic cells are lightweight, mechanically robust, and easy to manufacture, they suffer from conversion efficiencies that are far lower than silicon. Current research efforts into this technology is seeking to develop new dyes and solid-state light absorbers that will hopefully improve efficiencies.

Solar cells based on organic lead halide perovskite materials were discovered in 2012 and currently exhibit efficiencies over 20%.[137] Efficiencies over 27% have recently been achieved with a perovskite-silicon tandem solar cell.[138] Perovskite-based solar cells can be manufactured using solution-based techniques, which are far cheaper than the processing protocols required for silicon-based solar cells.[139] However, these cells rapidly degrade upon exposure to moisture. Additionally, the presence of lead is undesirable due to lead's known toxicity.

A third design called organic thin-film solar cells utilizes two layers of semiconducting polymeric materials sandwiched between a transparent and a reflecting electrode.[140] This design enables the utilization of roll-to-roll processing, which is low-cost and can rapidly achieve economies-of-scale. Organic thin-film photovoltaics, however, suffer from low, single-digit efficiencies that must be improved prior to commercialization.

In an alternative scheme, researchers at the University of Missouri and Idaho National Lab developed a flexible solar film composed of an array of nano-antennae tuned to specific frequencies of light.[141] A current is then induced upon being struck by incident light. This device could theoretically achieve efficiencies approaching 90%.

Improved Radio Frequency Harvesting

The advent of technologies that enable harvesting energy from a broad range of RF signals without the need for dedicated transmitters is a major breakthrough in this field. Future applications of this technology will rely on several other developments, particularly improved hardware, wireless interference mitigation and faster source selection.[142] As highlighted in the market analysis section, the technology from Teratonix shows great promise as it can harvest radio signals across a broad range. Their proprietary ultra-high-speed diode is 100x faster than other devices on the market and their harvester is 10x more effective in converting weak RF-radiation into DC-power.[143]

Improved Energy Storage

The storage of energy generated via ambient energy harvesting requires a charger capable of capturing and transferring intermittent low-energy bursts to a rechargeable battery.[144] However, maximum battery life, capacity, and energy content of a Li-ion battery is achieved by adopting a constant current, constant voltage charging scheme. Unfortunately, current charging schemes are incompatible with energy harvesting devices because they require a continuous, steady energy source. The development of an alternative charging circuit that is compatible with intermittent low-energy bursts is therefore critical to the development of energy harvesting devices.

Additionally, new battery technologies are actively being developed to improve portability and lower costs.[145] Researchers are aiming to replace the anodes currently in lithium-ion batteries with metallic lithium, which should drastically increase energy densities. However, studies have not been able to prevent the formation of dendritic growths out of the lithium anode, which short-circuit the battery and decrease its lifetime. An alternative design that uses an anode with a lithium peroxide surface, called a lithium-air battery, is theorized to display five times the energy density of traditional lithium-ion batteries.[146] Similar designs replace the lithium component of the anode with aluminum, zinc, or sodium.[147] Research into these designs, however, needs to overcome challenges associated with the rapid corrosion of the anode and cathode.[148]

Emerging Applications

Devices powered by ambient energy harvesting are being widely explored for use in the medical and fitness communities.[149] For example, researchers are utilizing RF energy harvesting to recharge the batteries in pacemakers and implanted transcutaneous electrical nerve stimulation (TENS) devices. Scientists at MIT and Harvard have developed a chip powered by sound to monitor the biological activity in the ears of individuals with impaired hearing or balance. In a collaborative venture, three British universities developed a piezoelectric energy harvesting device that attaches to the knee and generates power from walking or running. And researchers at Riga Technical University produced a mechanical energy harvesting device that requires magnets to be sewn into the sleeves and coils into the pockets of a jacket. A current is then generated by swinging the arms past the pockets.

DARPA's Near Zero Power RF and Sensor Operations (N-ZERO) program is seeking to develop ambient energy harvesting-powered sensors that remain dormant until awakened by an event of interest.[150] These technologies would be able to continuously and passively monitor the environment, exploiting the energy in signal signatures to detect notable events while ignoring noise. In late 2017, researchers at Northeastern University developed a device capable of remaining dormant until sensing energy in the infrared region of the electromagnetic spectrum, such as the energy emitted by vehicles in exhaust fumes.[151]

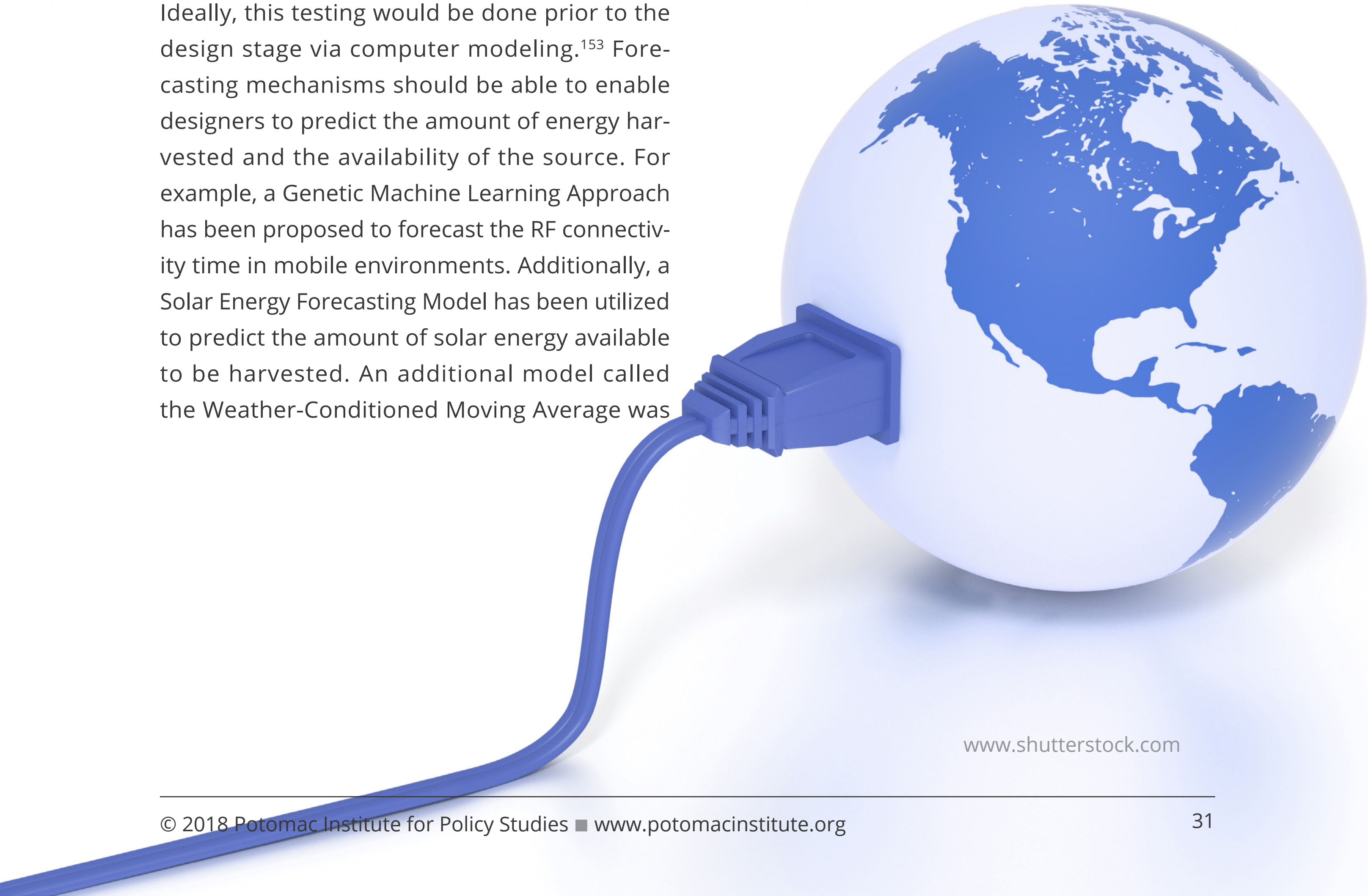
Testing of Energy Harvesting Devices

The development of metrological techniques for energy harvesting devices is critical to enabling innovation, market development, and the standardization of performance metrics.[152] However, the production of these protocols has been hindered to the complexity of energy harvesting devices and the broad possible means of measuring performance. Importantly, these measurements need to be related to actual conditions of use and should be performed under realistic conditions that consider complex vibrational environments, non linear behaviors, degradation, lifetime, and effects of harsh environments.

Ideally, this testing would be done prior to the design stage via computer modeling.[153] Forecasting mechanisms should be able to enable designers to predict the amount of energy harvested and the availability of the source. For example, a Genetic Machine Learning Approach has been proposed to forecast the RF connectivity time in mobile environments. Additionally, a Solar Energy Forecasting Model has been utilized to predict the amount of solar energy available to be harvested. An additional model called the Weather-Conditioned Moving Average was employed to make up for deficiencies in accommodating frequent weather changes.

The Development of a Generic Energy Harvester

A generic energy harvester would be capable of harvesting energy from multiple sources, possibly eliminating the need for energy storage systems.[154] One key challenge that needs to be overcome to enable this technology is the development of advanced power management techniques. However, researchers are developing composite materials that can generate electricity from stray AC magnetic fields while simultaneously converting mechanical vibrations into electricity.[155]



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