ObservatoryNANO

BRIEFING No.17

ENERGY

SEVENTH FRAMEWORK PROGRAMME

THERMOELECTRICITY FOR ENERGY HARVESTING

Thermoelectricity (TE) is the conversion of heat into electricity (Seebeck effect), or of electricity into heat or refrigeration (Peltier effect). The use of the Seebeck effect could allow heat to be saved which would be otherwise lost. Although the conversion efficiency is very low, it has been enjoying renewed favour for several years, and novel research and development leads have been investigated, such as new materials and the structuring of matter at the nanoscale. This combination has led to active investigations worldwide, but without achieving the decisive breakthrough, which will give TE a prominent place among energy harvesting technologies. The most promising applications of TE, in the context of energy saving, concern thermal engine heat recovery (particularly in transport applications), and human body heat scavenging to power portable devices. TE for energy harvesting has several barriers to overcome: low conversion efficiency; toxicity; and low availability of chemical elements constituting part of the most interesting thermoelectric materials. In this context, the main challenges for nanotechnology are to demonstrate high efficiency improvement, and to display low cost implementation in thermoelectric materials.

Need for thermoelectric energy harvesting

Thermoelectricity (TE) is a promising source of electric power, thanks to its ability to locally scavenge energy by converting a heat flow in electricity, when placing a thermoelectric device in a persistent thermal gradient. Even with a modest conversion yield, this would have huge benefits. As a consequence, many applications are being imagined for local electricity production by the TE effect, thanks to local heat leakages. Since this energy is available anyway, it is possible to estimate the interest of this solution depending on the price of the TE device vs. benefits like reduction in local energy requirements. The other main features of these devices are: the lack of mechanical parts allowing for silent and clean functioning; their small size and light weight properties; their reliability; and their low maintenance.

The major barrier to mass commercialisation of this technology is the poor performance. A good thermoelectric material must have a high Seebeck coefficient (high conversion of heat to electricity) to produce the required voltage, a high electrical conductivity to reduce thermal noise, and a low thermal conductivity to reduce thermal losses. These properties are measured by the 'Factor of Merit', also known as "ZT factor". Investigation of new semiconducting materials displaying higher ZT factors is very active worldwide. At present TE materials are stuck to a ZT value around 1 and below. A broad consensus estimates a ZT factor would allow for large scale TE development.

Box 1: Nanotechnology for thermoelectricity

Following a theoretical forecast[1] published in 1993, electronic properties of matter, like quantum confinement of electrons and holes in low dimensionality materials, would induce a dramatic increase of ZT factor. This could be achieved by using nanomaterials, or by structuring bulk matter at the nanoscale. In the last 15 years, many experiments attempted to apply this concept with varied structures[2]: superlattices; quantum wells; and nanowires amongst others. To measure thermal conductivity of such nanostructures is a real challenge, and much progress has been achieved over the last few years. However, even if improved ZT factors are obtained, many questions have been raised about capability of nanomaterials to really enable TE devices.

Background

Nanotechnology has been identified as the main enabler of thermoelectric efficiency improvement and thus potentially highly beneficial energy applications. However, on one hand, the increase of the Seebeck coefficient generally leads to a decrease of the electrical conductivity. On the other hand, the increase of the electrical conductivity leads to an increase of the electronic contribution to the thermal conductivity and then to an increase of it. The improvement of nanotechnology process techniques offers possibilities to enhance the materials performances. But up to now progress remains insufficient to enable efficient energy harvesting devices. Moreover, important issues remain to be solved, namely long term nanostructure stability under high temperature and gradients.

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Impacts

Economic/Industry

The current thermoelectric market consists mainly of consumer cooling applications and some niche applications. The consumer market which is expected to grow steadily over the coming years, is the largest market segment, making up 35% of the total existing market. The total market is estimated at €175-200 million, according to sources listed below:

- €175 million, MicroPower Global[3]
- €175 million, ENECO[4]
- €200 million, Phononic Devices[5]
- €200 million (expected to grow to €300 by 2015), Rusnano [6]

If a ZT over 2 can be obtained, the total market could increase by a factor of between 10 and 100. [7]

There are currently 15 projects concentrating on thermoelectrics funded under 7th FWP (Seventh Framework Programme). This has resulted in an upsurge of collaboration between European Universities and the thermoelectrics industry.

An impact can already be seen in the automotive industry, where exhaust heat can be recovered via TE devices. The market potential here is significant, since around 40% of the energy produced by internal combustion engines is currently lost in heat through the exhaust. The automotive industry is also well known for being an enthusiastic adopter of new enabling technologies. The potential market size for waste heat recovery in the transportation sector is estimated at €7 billion[4]. Other automobile applications include:

- Power generation;
- Heated and cooled seats; and
- Battery thermal management.

Specific industries (such as steel plants, gas liquefaction, or waste incinerators) could make use of the proximity of cold and hot sources. The temperature of the waste heat generated by steel industry furnaces is 200-450°C and for waste incinerators around 500-700°C[8]; capturing the heat and converting it into electricity would greatly improve the overall efficiencies, and environmental impact, of these industries.

TE could allow for the harvesting of heat emitted by human body enabling the development of new mobile uses. The difference between the body temperature and the ambient temperature is sufficient for powering devices with a low power consumption; an energy harvesting estimate from temperature difference of human body is 25 µW/cm².

Box 2: TE for refrigeration

At present the only mass applications of thermoelectricity has been within coolers, utilising the Peltier effect. Several companies produce such Peltier modules for varied applications; for example car seat cooling systems are commercialised by Amerigon, a US based company. Chinese plants also produce millions of refrigeration systems for water or fridges and the German company, Micro-Pelt, develops thin film Peltier modules.

In aeronautics, the use of TE devices on the outer surface of aircrafts could power distributed devices like sensors, and suppress the need for some of the wires currently used to feed them, leading to a reduction in aircraft weight, and therefore a reduction in oil consumption. A study conducted by the Frost & Sullivan consulting company forecasts a leading role of thermoelectrics in energetically self-sufficient sensor systems.

Technology readiness levels

Although optimistic announcements forecast short time to market (2-3 years) for TE generators in automotive applications, higher delays seem more realistic. Low conversion efficiency and high production costs mean TE energy recovery solutions remain too expensive (several €/W). Demonstrators already exist, but market entry for TE energy harvesting will only arise when approximately a 0.25€/W rate is reached (***Figure 1***). Historically, semiconductor costs decrease with volume and TE should follow this trend. Nanotechnology is a potent candidate to increase efficiency, but its impact on ZT factor has to be improved, and its implementation at industrial level remains problematic. As a consequence, roadmaps foresee mass production only after the year 2020.

Societal Impact on European Citizen

Energy use reduction is the central application for TE waste heat recovery systems. These devices have a very low impact on the environment; they are totally passive, clean, and they operate without any additional energy supply. Their use in cars and public transport systems would reduce oil consumption within the limit of a few percents. Increased gasoline and diesel prices are a good market driver for seeking more sustainable and efficient technologies.

TE could provide all this and simultaneously contribute to CO_2 emission reductions in Europe. Additionally, TE generators could enable autonomous

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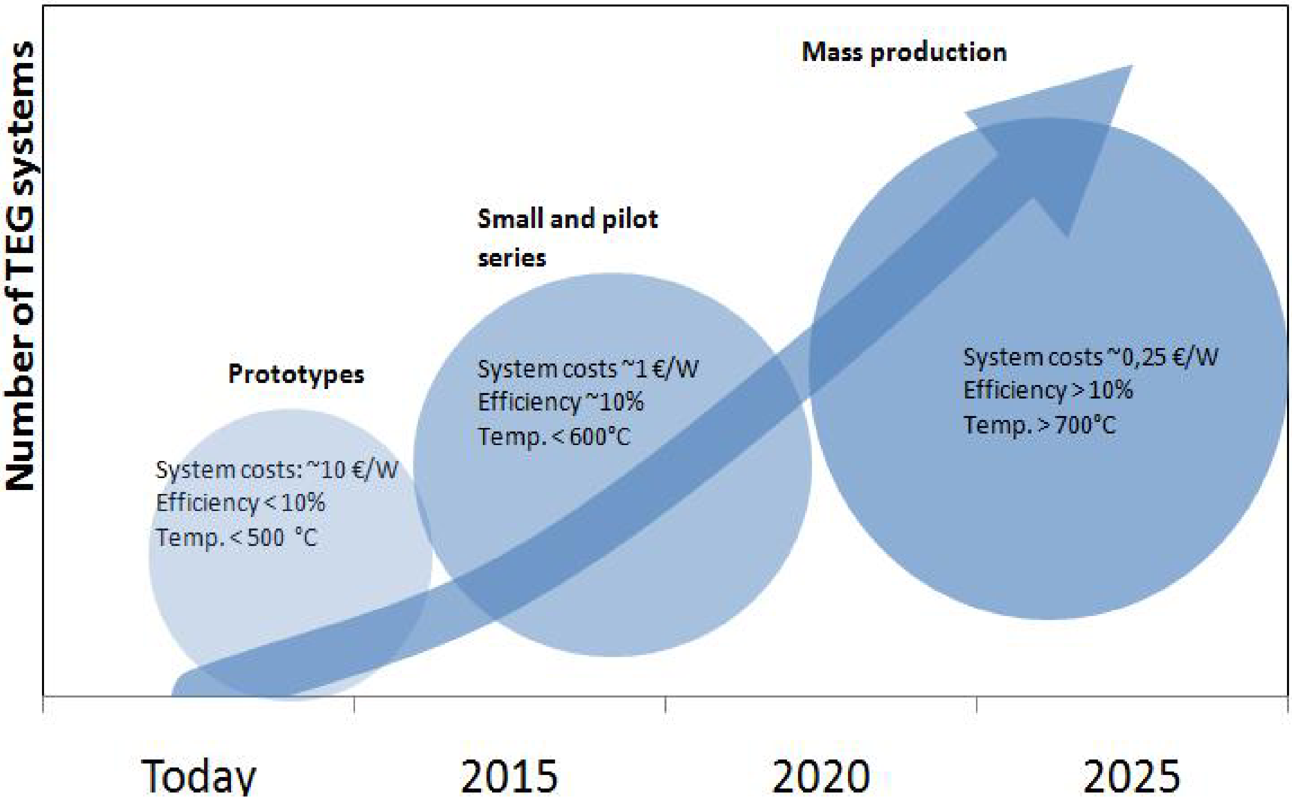

Figure 1*: Market requirements roadmap for Thermoelectric Generator systems. Picture adapted from [9]*

and wireless devices, which would possibly offer new uses and habits, and limit the requirement for electricity storage devices. Recently, a system for autonomous sensors supplying has been developed by three European companies (**Box 3**).

EHS Impacts

Friends of the Earth emphasises the need for taking into account the energy and resource consumption during manufacturing of the energy saving technologies and materials as well as the energy saving during use[9]. Several common efficient thermoelectric materials, like lead and cadmium, are known as toxic compounds and current solutions use compounds that contain tellurium, which is also harmful to the environment. Commercialisation of such compounds is unlikely in Europe, and many studies aim at replacing these compounds by others. Nanostructuring of less toxic but less efficient compounds is expected to improve their performance, and thus enable sustainable materials for TE. The situation is slightly different in United States, where lead alloys, for example, are still considered to be suitable for use in TE devices. For this reason, the environmental impact of future TE devices worldwide is not totally clear at this point.

Future TE devices based on nanotechnology will possibly involve nanostructured or matrix-bound nanomaterials. While manufacturing procedures should be controlled in order to avoid exposure during nanomaterial synthesis or inclusion, potential for nanoparticle release during use of final TE applications and subsequent exposure to humans or the environment is considered to be very low.

Challenges

Recent advances have suggested the possibility of overcoming classical limitations and improving the thermoelectric materials significantly. Currently, TE suffers from low efficiency (around 5%) and material problems at high temperatures. The efficiency can be improved by maximising the material's electrical conductivity and minimising its thermal conductivity. However, it is impossible to optimise everything at the same time, so the result is always a compromise between these two. Nanotechnology is expected to aid the optimisation and improvement of the ZT factor.

Typical barriers to commercialisation and the broader use of TE products are cost and efficiency, thus making them more useful in niche applications where other factors are more important. Low availability of the chemical elements needed in TE devices could also be an issue. Research on new, cheaper and more abundant materials is required. The architecture and design of TE devices play also an important role in commercialisation, especially in the consumer markets. One unique aspect of TE devices is that there are no direct substitutes for them. When the technological and economical problems are solved, TE devices will dominate the market of energy harvesting via temperature difference.

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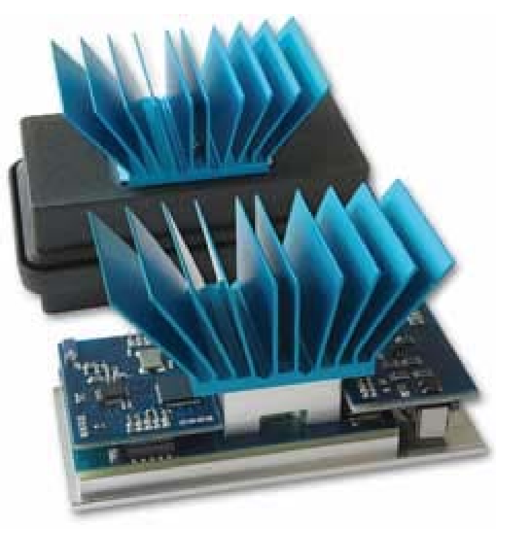
EU Competitive Position

More than 300 research laboratories in the world currently work on thermoelectric materials. About 100 are located in Europe (including 35 in Germany and 15 in France), 160 in Asia (mainly in Japan and China) and 75 in the USA. This quite well-balanced R&D situation is not replicated within the industrial sector with only a few European companies producing thermoelectric devices: Micropelt, Laird, Beakon Technologies and Termo-Gen.

There are currently over 1000 patents concerning thermoelectrics in Europe[11]. Most of the patenting activity comes from Germany, which accounts for over half of the patents. For example, the large chemical company BASF has 29 patents in the field of thermoelectrics. It is also interesting to note that the patenting activity has been increased in recent years. This could be due to the renewed research interest in thermoelectric materials. Even so, Europe lags behind the USA in patent applications but is well positioned in second place along with Japan and South Korea.

For the last three years, the automotive industry has increasingly invested in R&D projects on thermoelectricity. In the USA, the DoE subsidises three consortia gathering car companies and laboratories. In Europe, the FP7 program finances large projects including German, French, Italian, and Swedish car and part manufacturers. For instance, the HeatReCar project is focused on developing a TE device which could produce up to 3kW in a combustion engine vehicle. In Germany (BMW, VW, Daimler, Opel) and in France (Renault, Valeo) specific programmes are lead by car and truck manufacturers.

Box 3: An autonomous temperature sensor



Three European companies (MicroPelt, STMicroelectronics and ARaymond) have developed a wireless temperature sensor, embedding a thin film TE harvester and a storage device, continuously supplying the sensor. This system, dedicated to thermal solar devices, was displayed at Hannover Messe in 2011.

Summary

- Thermoelectricity is the conversion of heat into electricity allowing for the capture of heat which would be otherwise lost.
- New fundamental focus on nanostructured materials has greatly increased research activity in this field.
- Thermoelectricity has several technological issues to overcome related to low conversion efficiency and the durability of materials at higher temperatures.
- Cost is the largest barrier for commercialisation.
- Improvement of ZT factor with nanotechnology could make thermoelectricity a multibillion-dollar market in the future.
- European research is active and well positioned; however, more emphasis and investment is from the industry perspective.
- Drivers for commercialisation of thermoelectricity are based on achieving better efficiencies in thermal engines and thereby reducing CO_2 emissions in Europe.

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