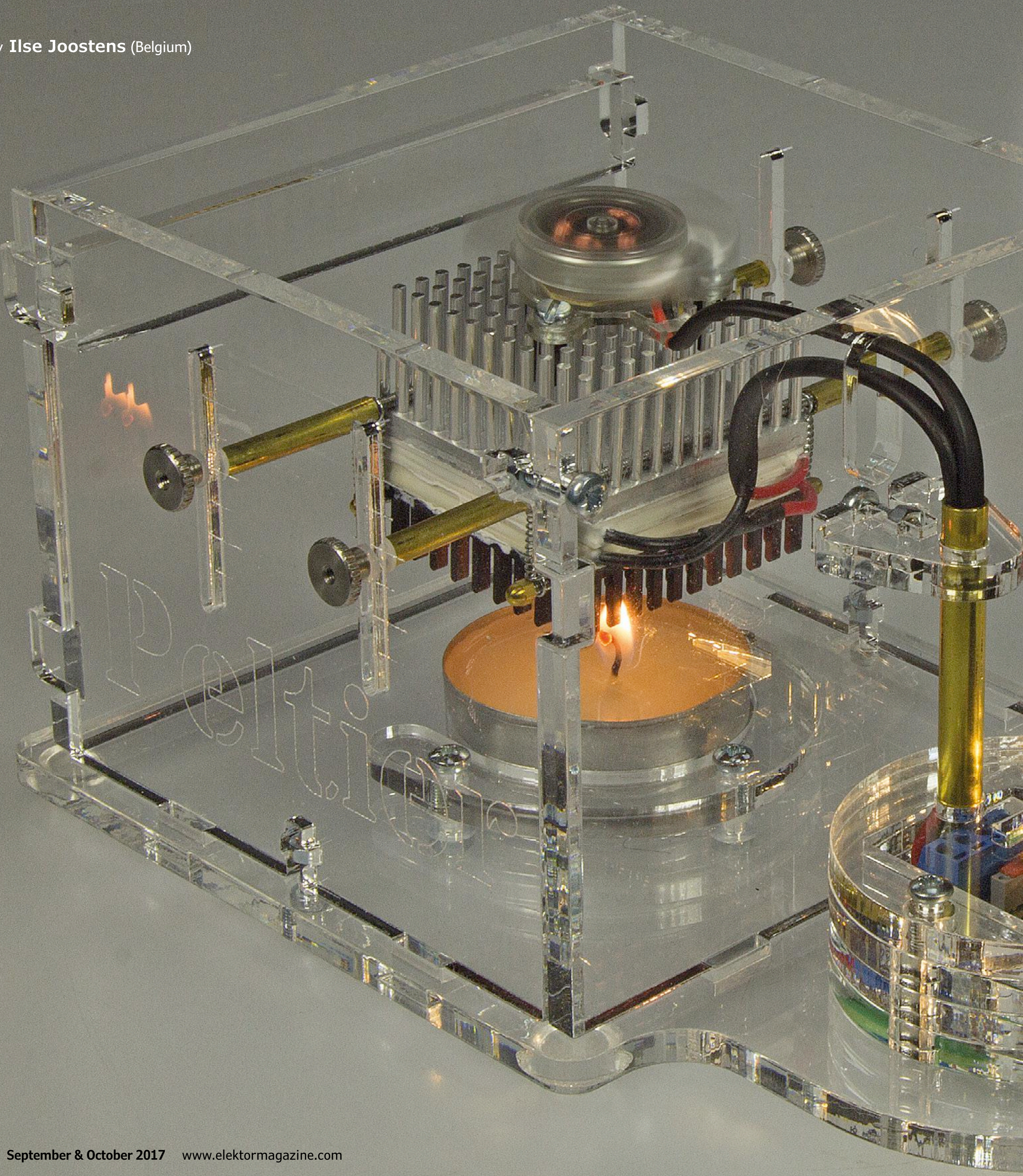
Candle2light

By **Ilse Joostens** (Belgium)



Luminous efficiency booster

The advent of the Internet of Things has also boosted research into alternative energy sources which allow energy to be converted into electricity by means of a variety of physical processes. The project described here converts heat from a candle flame into electrical energy, so that you can read your favorite books by candlelight.

PROJECT INFO

Peltier module
alternative energy
step-up converter

entry level
→ intermediate level
expert level

2 hours approx.

Parts kit,
soldering iron,
needle-nose pliers

€100 / £90 / $115 approx.

Before electric lighting became commonplace in the early twentieth century, candles and oil lamps were the main forms of lighting. The oldest candles ever found were made from whale fat and originated from the Han dynasty in China. Until about 1850 candles were made from natural substances – primarily animal fat, with beeswax reserved for more expensive candles. With the advent of commercial petroleum extraction, paraffin was increasingly used to make candles. Unlike animal fat, paraffin produces a nearly smokeless flame.

Low efficiency

The average power generated by the flame of a modern candle is approximately 80 W. Candles generate mainly heat, with a luminous efficacy of just 0.16 lumen/watt. The efficiency is a factor of 100 worse than a traditional oil lamp, which itself is hardly a sterling example of efficiency.

Compared to the candles used for lighting, the tea light candles used in this project have a thinner wick and generate much less heat. Depending on the sort of paraffin used in the candle, the power is about 32 W.

We thought there must be a way to improve this. Many things are possible with modern, energy-efficient high tech electronics, so why not use electronics to boost the light output of a candle? Tea lights are very inexpensive, especially in large quantities, and with this approach we can create a light source that is not dependent on batteries or AC power.

From theory to practice

The thermoelectric generator for this project consists of two 40 x 40 mm TEC1-12706 Peltier modules (**Figure 1**) connected in series. They are clamped between two heat sinks by springs. This assembly is mounted above a tea light holder and can be adjusted in height.

The bottom heat sink measures 40 x 40 x 10 mm and is intended to distribute the heat from the tea light evenly over the full surface of the Peltier modules. The top heat sink, which is twice as high and therefore has much lower thermal resistance, is cooled by a fan to keep the cold side of the Peltier modules as cool as possible

Finally, a DC/DC boost converter raises the output voltage from the Peltier modules to a level suitable for operating a USB LED lamp.

The fan is also powered by the electrical energy from the Peltier modules. At first this may appear counterproductive, but the amount of energy actually available for the USB lamp is at least the same or even more with the fan than without it. In addition, the fan reduces the risk of over-

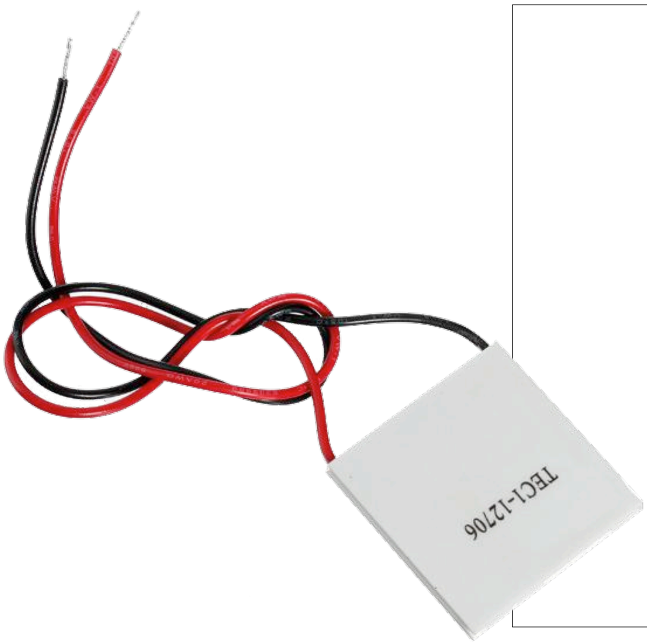


Figure 1. The TEC1-12706 Peltier module.

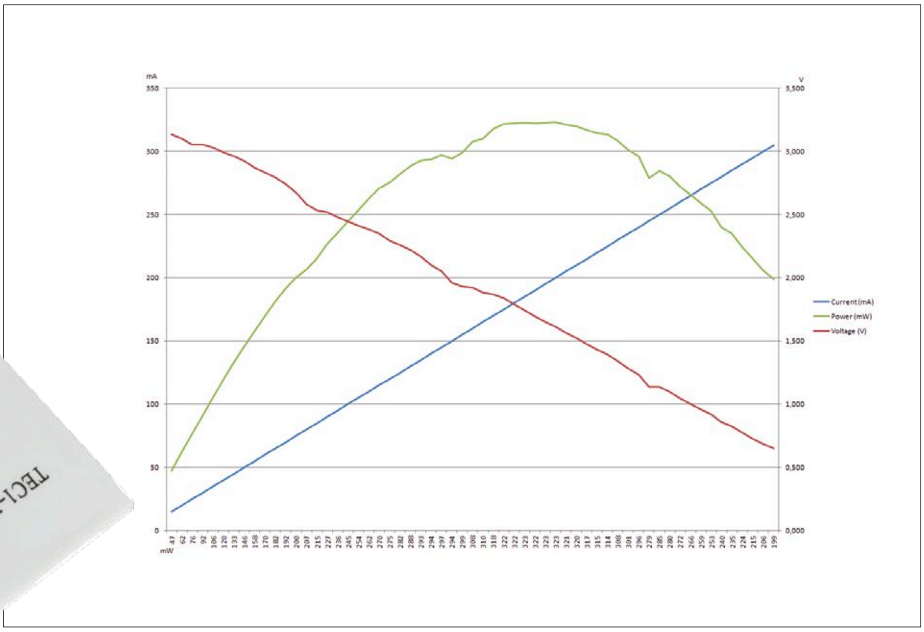


Figure 2. Measuring voltage, current and power. The maximum power point is clearly evident.

Features

- Converts candlelight into electrical light
- Works for 4 to 5 hours with a single tea light
- Attractive transparent housing (two versions available)
- Complete parts kit available, including LED lamp and tea lights

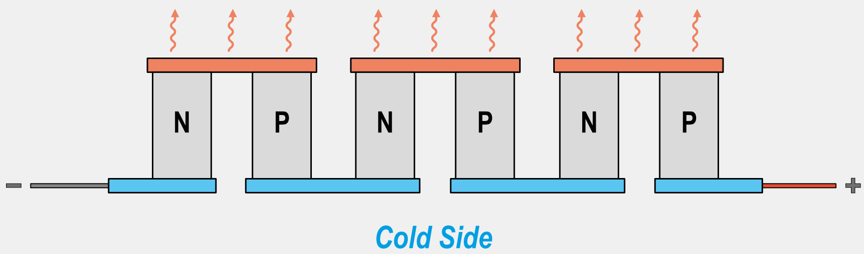
heating the Peltier modules. The internal elements of the TEC1-12706 are soldered using a bismuth solder alloy with a melting temperature of 138°C, so it is important to keep the module temperature well below that temperature.
To make measurements during the development of this project, we loaded the Peltier modules with a wire-wound potentiometer and measured the output voltage with increasing load, and then plotted the readings on a chart (**Figure 2**). The fan was connected to an external 3.3 V power supply so that it would not influence the measurements. The candle flame (with as large a flame as possible) was about 5 to 10 mm (0.2 to 0.4 in.) below the bottom heat sink, at which point thermal equilibrium was reached. The measured output voltage of the Peltier modules with no load was approximately 3.2 V. Since Peltier modules (like many other alternative energy sources) act as voltage sources with high internal resistance, the output voltage drops with increasing load. We also plotted the output power (voltage times current), which clearly showed that the maximum power of approximately 320 mW was reached at an output level of about 1.6 to 1.7 V. That is the maximum power point (MPPT). With a weaker candle flame, the open-circuit voltage is closer to 2.2 V and the output power at the maximum power point is approximately 180 mW. Without a fan the maximum achievable power is only 80 to 100 mW.
The theoretical efficiency of a thermoelectric generator is about 5 to 8%, which means it should be possible to get 1.6 to 2.6 W from a tea light with 32 W output. In practice it is a lot lower because we cannot harvest all the heat from the candle and because the Peltier modules used here are actually intended for cooling and are not optimized for use as thermoelectric generators. Real thermoelectric generator modules (which have type numbers starting with “TEG1”) can handle much higher temperatures, but they are also much more expensive.

The circuit

Our initial idea was to build the circuit (**Figure 3**) entirely with through-hole components in order to make home assembly easy. Unfortunately, many attractive ICs are now only available in SMD packages, and if we had used “normal” electrolytic capacitors instead of compact SMD MLCC capacitors the board

The Seebeck effect

Anyone with a professional or personal interest in electronics is probably familiar with the operating principle of a thermocouple. Thermopiles, which consist of a large number of thermocouples connected in series, are less well known. They are used for very precise measurement of small temperature differences. Some well-own applications are contactless infrared thermometers and fever thermometers. But they are not used in infrared cameras, which instead work with microbolometers (which have a completely different operating principle).
The Baltic/British physicist Thomas Johann Seebeck discovered in 1821 that a closed loop made from two different metals deflected a compass needle when the joints between the two metals were at different temperatures. He called this the “thermomagnetic effect,” not realizing that an electric current was flowing in the loop. The Danish physicist Hans Christian Ørsted ultimately recognized what was actually happening and coined the term “thermoelectricity.”
Thirteen years later, the French watchmaker Jean Athanase Peltier discovered that the Seebeck effect is reversible. When he passed an electric current through a loop made from two different metals, one joint became warmer and the other joint became cooler. Practical applications of the Peltier effect had to wait for the emergence of the semiconductor industry in the mid-twentieth century. The effect occurs not only with different metals, but also with semiconductors – something that Jean Athanase Peltier never could have known.
A Peltier module is a solid-state semiconductor heat pump which uses electrical energy to transport heat from one side to the other against the temperature gradient. The module consists of two plates of a thermally conductive but electrically insulating ceramic material (usually aluminum oxide, Al_2O_3) which act as substrates, with blocks of semiconductor material sandwiched between the two plates. These semiconductor blocks consist of normal n-doped and p-doped bismuth telluride interconnected by PCB tracks on the ceramic substrates. On the cold side the current flows from the p material to the n material, and on the warm side from n to p (with conventional direction of current flow).
Due to the poor efficiency of Peltier modules, they are mainly used for cooling in applications where little cooling capacity is necessary and the available space is limited. Some examples are cooling the sensor chips of digital cameras, and of course cold boxes.



Basic structure of a Peltier module.

The effect is also reversible, which means that a Peltier module can generate electricity if it is heated on one side and cooled on the other side. In that case it is called a thermoelectric generator (TEG).
Thermoelectric generators are often used as energy sources for satellites, and formerly (mainly in Russia) to supply electricity for unmanned facilities in remote locations. In those applications the heat source consists of a radioactive isotope (usually plutonium 238, curium 244 or strontium 90), which produces heat by radioactive decay. Currently research is being carried out on automotive thermoelectric generators (ATEGs) to convert heat from internal combustion engines into electricity for the onboard electrical system.

would have been a lot bigger. In the end we therefore opted for SMD, despite our original idea.

The circuit is built around an LTC3105, which is a 400 mA step-up DC/DC converter with integrated maximum power point control. That feature makes this IC ideal for our application. The LTC3105 can start up with an input voltage as low as 250 mV and is used in many energy harvesting applications.

The circuit is largely copied from the example application circuit in the LTC3105 data sheet. Resistor R1 (100 kΩ) sets the maximum power point to approximately 1 V. That is intentionally lower than the actual maximum power point with a strong candle flame. It means we lose about 50 mW (270 instead of 320 mW) with the candle flame at maximum power, but with this setting the converter starts up more easily right after the tea light is lit, when only little energy is available.

It would be possible to add maximum power point tracking by sensing the temperatures of the heat sinks and feeding this information back to the LTC3105. However, we decided not to do this because it would increase the complexity and the energy gain of about 20% is not all that large. In addition, the maximum power of the tea light is only reached for a limited time during the 4 to 5 hour burning time of a standard tea light.

The ceramic MLCC capacitors used here are very compact, especially compared to electrolytic capacitors, with capacitance up to 10 μF in a 0805 package. A disadvantage of the X7R dielectric in these capacitors is that the capacitance decreases with increasing voltage on the capacitor. It's a bit like pouring water into a flower vase with an inward taper – the pressure on the bottom of the vase increases as the water level rises, but it takes less and less water to raise the level. The effect is significant: at 3.3 V the loss of capacitance is already 20%. For this reason we boosted the capacitance of output capacitor C4 to 22 μF, instead of the 10 μF we originally chose for the design. That value is only available in the 1206 package.

The LED lamp used here draws a current of 55 mA at 5 V. That corresponds to a power of 275 mW, which is a lot more than the figure of 0.15 W in the product spec, and in any case it is too much for our thermoelectric generator. At 3.3 V the current consumption drops

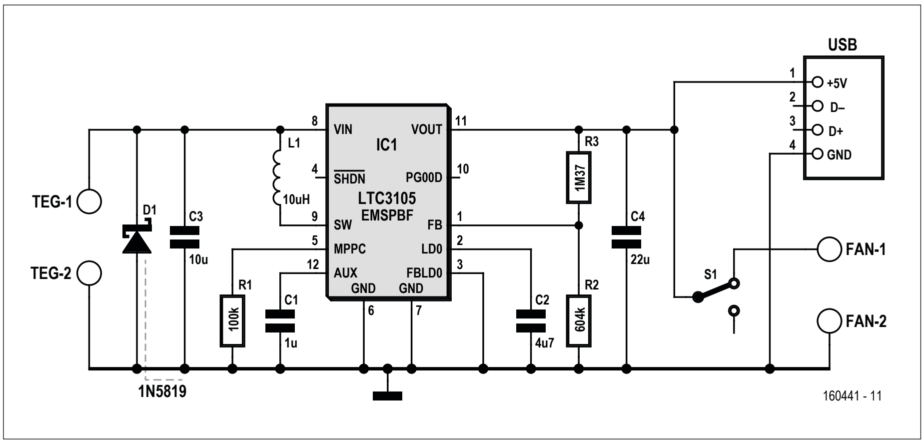


Figure 3. The components of the converter circuit fit on a tiny PCB.

ONDERDELENLIJST

Resistors

Default: 1%, 0.125W, SMD0805
R1 = 100kΩ
R2 = 604kΩ
R3 = 1.37MΩ

Capacitors

Default: 10V, X7R MLCC
C1 = 1μF, 10V, 0805
C2 = 4.7μF, 10V, 0805
C3 = 10μF, 10V, 0805
C4 = 22μF, 10V, 1206

Semiconductors

D1 = 1N5819HW-7-F SOD-123
IC1 = LTC3105EMS#PBF
TEC1,TEC2 = TEC1-12706 40x40mm

Miscellaneous

L1 = 10μH 850mA, shielded WE-MAPI (Würth 74438335100)
K1, K2 = 2-way PCB screw terminal block, 3.5mm pitch
K3 = USB Type A connector, vertical (Würth 614004185023)
S1 = slide switch, SPDT, On-On (Würth 450301014042)
1x USB reading lamp, type Jansjö (IKEA 702.912.32)

Mechanical parts

1x heatsink 40x40x20mm aluminum, Fischer Elektronik ICK S series (Farnell 1850058)
1x heatsink 40x40x10mm aluminum, Fischer Elektronik ICK S series (Farnell 1850047)
2x threaded rod M2x118mm
2x threaded rod M2x51mm
4x acorn nut M2 (Microschroeven.nl MD-DopMoer -M2 - ME)
4x knurled thumb nut high type M2 stainless (Fabory 51830020001)
4x tension spring 0.5x3.5x12mm (Fabory 17902053012)

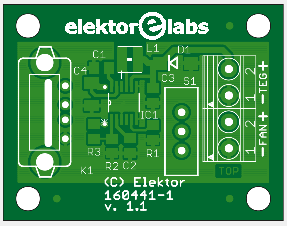


Figure 4. The double-sided converter PCB.

Figure 5. The assembled converter board.

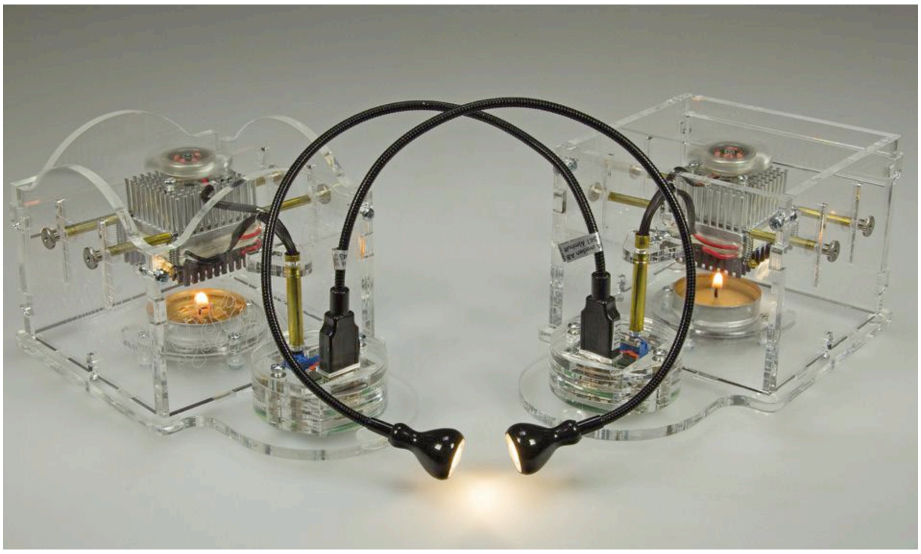
4x brass tube, diameter 4x0.5mm, length 26mm
8x flat washer, nylon, M2
1x fan transparent plastic, open, diameter 35mm, for VGA card (4894462470268)
3x machine screw M3x6 slotted/cheese head (M36 CSSTMCZ100)
Heat-shrink tubing, diameter 3mm 1:2 ratio
Heat-shrink tubing, diameter 1.6mm 1:2 ratio
1x pouch silicone-base thermal paste
5x self-adhesive rubber foot (TME RI-RBS-12)
14x machine screw M3x12 galv. steel Pozidrive DIN 7985A
3x machine screw M3x16 galv. steel Pozidrive DIN 7985A
13x hex nut M3 steel DIN 934
7x spacer 3mm polyamide
4x flat washer M3 plastic DIN 125A
3x corrugated washer M3
1x brass tube diameter 6x0.5mm, length 45mm
2x standoff 15mm M3 F/F
Enclosure clear acrylic 5mm extruded, laser cut

to just 39 mA, corresponding to a power of about 130 mW. The light output is 30% lower at that point, but there is still enough light to read a book. We therefore decided to limit the output voltage of the DC/DC converter to 3.3 V. At a voltage of 3 to 3.3 V, the power consumption of the fan is approximately 95 to 120 mW. Together with the USB lamp, that is just within the capacity of the thermoelectric generator. You should bear in mind that with a relative weak candle flame the output voltage of the converter can drop to about 3 V.
There is also a slide switch for switching off the fan. That can come in handy when you temporarily want more light with a relatively weak candle flame. With the fan switched off there is more energy available for the USB lamp, but this does not last long because the temperature of the top heat sink will rise, reducing the temperature difference between the two sides of the Peltier modules and thus reducing their output power. If you want to switch off the fan for an extended length of time, you must be careful to avoid overheating the Peltier modules, so you should adjust the distance between the bottom heat sink and the candle flame.
Also please note that the circuit is not suitable for charging mobile phones, even if the output is adjusted to 5 V, because it simply cannot supply enough energy. It would take several days to charge a phone battery, and even then only if the phone is completely switched off. Otherwise it would consume more power than the charger can deliver. In some YouTube videos you can see that the charging indicator of the phone is triggered, but that does not mean that it is effectively being charged.

Construction and use

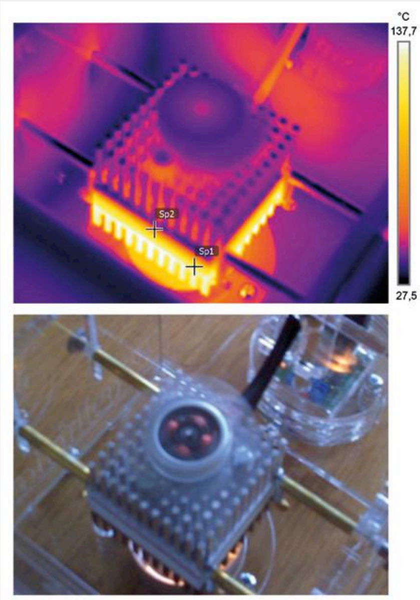
Start with the converter board (**Figure 4** and **Figure 5**). Mount the USB connector, the slide switch and the terminal blocks on the pre-assembled board. If you want to test the board, you can connect the TEG+ and TEG– terminals through a 10 Ω resistor to a 2 V power source (if necessary, you can use a 1.5 V AA battery). The measured voltage on the fan terminals should then be 3.3 V when the slide switch is in the On position. The measured voltage on the TEG+ and TEG– terminals should be at least 1 V, depending on the output load, which means that the MPPT function of the DC/DC converter is working.
The next task is to assemble the thermoelectric generator. Screw the long threaded rods between the pins of the top heat sink (**Figure 6**). Do not simply push them down between the pins. Then place the Peltier modules on the heat sink. Pay attention to the orientation, and apply only a thin layer of thermal paste.
Finally, place the bottom heat sink on top of the stack and secure this assembly temporarily with two strips of packing tape applied crosswise (**Figure 7**). Insert the short threaded rods, and then use needle-nose pliers to fit the four tension springs over the threaded rods. Next, mount the fan and fit the small hardware (**Figure 8**).

Romantic candlelight and bright LED light — a perfect combination



Thermal characteristics

We used an infrared camera (FLIR type E40) to examine the Candle2light in operation; the result is shown in the figure (top photo: infrared; bottom photo: visible light). The temperature difference between the bottom and top heat sinks (with the Peltier modules clamped between them) is clearly visible in the IR photo, and the rotating fan makes a significant contribution to this. Less clearly visible is that the outside of the enclosure also gets rather warm, but you can determine this for yourself by cautiously touching it with your finger.



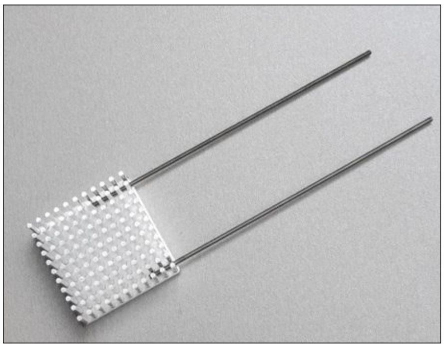


Figure 6. Carefully screw the long threaded rods between the pins of the heat sink.

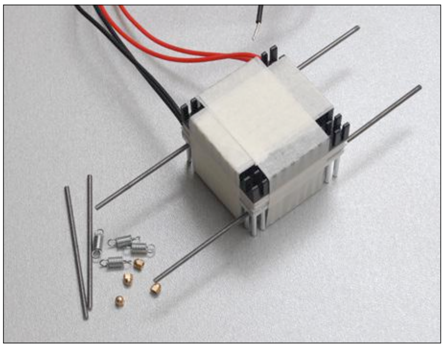


Figure 7. The assembly is temporarily held together by packing tape.

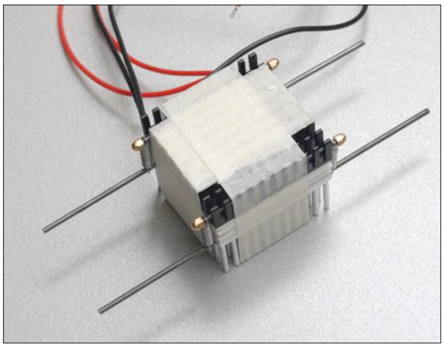


Figure 8. Springs clamp the heat sinks firmly against the Peltier modules.

Now it's time to assemble the transparent (PMMA) enclosure, which is available in two versions. The enclosure also acts as a wind screen for the candle flame. Mount the thermoelectric generator in the enclosure, and mount the converter board. Finally, connect the USB lamp to complete the construction (**Figure 9**).
Using the vertical slots in the enclosure, adjust the height of the thermoelectric generator to position the bottom surface approximately 15 mm (⅝ in.) above the candle flame. Put the slide switch for the fan in the On position, then light the candle and place it in the holder.
The USB lamp should start to light up weakly after a few minutes. Wait another one or two minutes while the lamp brightness increases, then give the fan a slight push in the clockwise direction. It should now start turning. If it doesn't, wait a little while and then try again. If it still does not turn, check the position of the slide switch. The fan needs a push to get started because it is actually intended for 12 V operation, and we are using outside its specifications. At full speed a fan of this sort would draw too much power and would disturb the candle flame, not to mention the noise level.
When the fan starts turning, the USB lamp will flicker a bit because the thermoelectric generator is not yet able to supply enough power and the fan causes a bit of disturbance. This effect will go away after a few minutes, depending on how strongly the candle is burning. It usually takes a while for the flame to reach full strength, because the pool of melted paraffin is small at first.
During use you can occasionally adjust the height of the thermoelectric generator, depending on the flame from the tea light. The height is not especially critical; a distance of about 10 to 20 mm (⅜ to ¾ in.) between the flame and the generator is usually satisfactory. For safety reasons, you should never leave the Candle2light operating unattended. ◀

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Figure 9. The enclosure is available in two versions.