A fridge that takes only 0.1 kWh a day?

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There is no mistake in the title. This article describes an inexpensive fridge that is 10 to 20 times more energy efficient than an average fridge on the market. It also demonstrates that the biggest limitations are our habits and mediocre attitudes, not technology or cost.

My dream is to live a near-zero emission life. Step by step I come closer to bring this dream to reality. After all, the rainforest here at Mt Best is so beautiful and so unique that I hesitate to disturb it with any kind of pollution.

Insulating and double-glazing my RAL home reduced my winter energy requirement to about 20 Watt per square meter of floor area. I do not like “star ratings”. I think they are misleading and promote ignorance rather than understanding of energy efficiency.

Reflective solar heating (described in issue 88 of Renew) nearly halved my heating energy (and the firewood) needs in winter. However, to achieve a near-zero emissions I needed to find a clean renewable source of energy to replace the firewood altogether. The system of choice became a geothermic storage heat pump system that will be described in my next article. However, since I generate my own electricity from wind and sun, I needed to save some energy to run the heat pump.

For almost 2 years I tolerated the fridge that I did not like a little tiny bit. The list of things I did not like about it is too long to mention here. If I could eliminate this fridge, I would have enough energy to run the heat pump…

Chest fridge

Comparing the energy consumption of various refrigeration devices available on the market I noticed that well-designed chest freezers actually consume less electricity than fridges of comparable volume, even though freezers maintain much colder temperatures inside. While chest freezers typically have better thermal insulation than fridges, there is another reason for their efficiency.

Vertical doors in refrigeration devices are inherently inefficient. As soon as you open a vertical fridge door – the cold air escapes, simply because it is heavier than the warmer air in the room. When you open a chest freezer – the cool air stays inside, just because it’s heavy. Any leak or wear in a vertical door seal (no seal is perfect) causes significant loss of efficiency. On the other hand, even if you leave the chest freezer door wide open, the heavy cool air will still remain inside. Have you ever wondered why chest freezers in supermarkets have their doors either wide open or not thermally insulated?

Designing refrigeration devices with vertical doors is clearly an act against the Nature of Cold Air. Shouldn’t we cooperate with Nature rather than work against it?

I become really curious just how efficient a chest fridge can be. After contacting some leading fridge manufacturers and discovering that no one has ever made and tested a chest fridge, I decided to make my own test. I bought a good chest freezer and turned it into a fridge.

Turning a chest freezer into a chest fridge

The main difference between a freezer and a fridge is the temperature maintained inside. Freezers maintain sub-zero (freezing) temperatures down to -25^{o} C, while fridges operate somewhere between $+4^{o}$ and $+10^{o}$ C.

Hence, turning a freezer into a fridge meant changing the temperature control. Rather than interfering with mediocre thermostat of the freezer, I decided to install an external thermostat to cut the power off when the temperature of my choice has been reached.

For my research I bought a Vestfrost SE255 chest freezer with 600a refrigerant and a $40 battery-powered thermostat equipped with digital temperature display and an internal 5A/240V latching relay. The main feature of the latching relay is that it consumes battery power only during actual switching so that the thermostat equipped with it is a true micro-power device and its 2 AAA batteries last for many months.

Connection diagram (Fig 1.) is really simple. Thermostat relay cuts the power to the freezer, much like a light switch cuts the power to a lamp. Thermistor (the temperature sensor) is placed inside the freezer at the end of a thin 2-wire flexible cable. I used the freezer drain hole to pass the thermistor cable inside the cooling compartment. An alternative is to insert it from the top via the chest door. If the thermistor is left near the bottom of the chest fridge – the minimum fridge temperature is controlled by thermostat. If the thermistor is located near the top of the cooling compartment – the thermostat will control the maximum temperature there. The best position for thermistor is somewhere in the middle.

It took me about 30 minutes to make all connections. The most time consuming part was removing the thermistor from inside the thermostat (I cut it out from the circuit board using wire clippers) and soldering it at the end of a thin 2-wire flexible cable. I protected the thermistor from moisture and mechanical damage using shrink-wrap tubing and a tiny bit of silicone.

The external thermostat can be installed anywhere on the fridge or outside it. I have decided to place it on the wall behind the fridge, so that the temperature display was easy to read at the eye-level.

I have also removed the interior light bulb, rated 15 Watts, because I avoid using energy wasting devices as a matter of principle. I will consider installing a LED interior illumination if I find a reason for opening my fridge in the dark.

When I finished my connections I had a chest fridge with a digital temperature display and a temperature control at my fingertips.

Performance

I set the thermostat to +7° C and switched on the AC power via energy measurement gadget called Sparometer. After about 2 minutes my thermostat displayed +6.5° C and the power to the freezer was cut off. The temperature continued to drop down to about +4° C. I thought that there was something wrong with the digital display, because everything happened too quickly. I took another thermometer and to my surprise, it confirmed readings of the thermostat.

I watched the system for a few hours and then decided to move the content of my old fridge to the new one that I have just made. Since I have never had a chest fridge – it took me some time to arrange baskets and their content inside. I placed the most frequently used items in top baskets that slide on top edges of fridge walls. It turned out to be a very practical idea. Not only they are very handy there, but also I can take out the entire basket, rather than taking out one item at a time (a typical case with a vertical door fridge).

In the first 24 hours my new chest fridge took 103 Wh (0.103 kWh) of energy. About 30% of this energy was consumed during the initial power up and re-arranging of the fridge content. The room temperature varied from 21°C during the day to 15°C at night. The fridge interior temperature was kept between +4° and +7° C. The fridge compressor was working only for about 90 seconds per hour. When the thermostat intervened – the fridge consumed ZERO power. The only active part was a battery powered temperature display.

Results of my experiment exceeded all my expectations. My chest fridge consumes as much energy in 24 hours as a 100W light bulb does in just an hour. Not only it is energy efficient. I have never seen a fridge that was SO quiet. It only works 90 seconds or so every hour. At all other times it is perfectly quiet and consumes no power whatsoever. My wind/solar system batteries and the power sensing inverter simply love it. With my new chest fridge I have power to spare and I can use it to warm up my house in winter with a heat pump. I wonder why no one has ever thought of a chest fridge controlled by a digital thermostat…

What performance can I expect from my chest fridge during hot summer days? In principle, the energy consumption should be proportional to thermal losses of the fridge, which in turn are proportional to the temperature difference between the inside and outside of the fridge. A vertical door fridge has large additional losses caused by opening the door and the associated loss of cold air.

The power consumption data for my chest fridge was measured for average 5°C internal and about 18°C average ambient temperature (13°C difference). If the average ambient temperature rose to 31°C, the temperature difference will double to 26°C. This in turn should double the thermal losses and hence the energy consumption. In this case I expect my fridge to work about 3 minutes per hour.

In reality, doubling the temperature difference causes slightly more than doubling of the energy consumption, due to the reduced thermal efficiency of the fridge heat pump (compressor system). The larger the temperature difference between the heat source and the heat sink, the less efficient is the heat pump.

Fortunately for those who rely on solar power, in hot summer months there is also more solar energy to power the fridge...

It is obvious that a truly energy efficient fridge does not cost any more money than a mediocre one. It actually costs less. It also has extra features, such as a digital temperature display that gives you full control over the temperature settings. So - WHY mediocre fridges are being made? Why people continue to buy and use energy wasting devices? Does anyone care?

Nearly every household on Earth has a fridge that totally wastes at least 1 kWh of energy a day (365 kWh a year). Some fridges waste 3kWh each day. How much reduction in greenhouse emissions can we achieve by banning just ONE inefficient household device in just ONE country? How many politicians debating for how many years will it take to achieve such a ban? Rather than waiting for someone to do something I would like to volunteer to supply modified chest freezers and/or freezer modification kits to environmentally conscious people of Australia. Let's do something in the right direction right now.

Note: Design details of my electronic thermostat have been published in Renew magazine issue 93 (2005). The copy of this article is attached below.

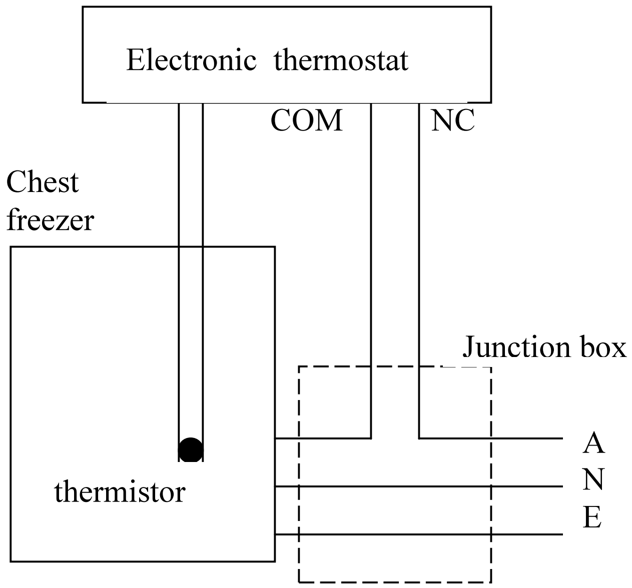

Fig. 1. Wiring diagram of the chest freezer turned into chest fridge. The junction box is not required if all connections are made inside the fridge service compartment. Active (A) connection passes via latching relay terminals inside the thermostat.

Fig 2. Fully installed chest fridge with thermostat on the wall. Note energy measuring gadget at the bottom left.

My fridge-to-freezer thermostat

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Since I published my article about my 0.1 kWh/day chest fridge in the issue 90 of *Renew* I keep receiving daily inquiries from all over the world about the thermostat that I used to convert my chest freezer into an ultra efficient fridge. Apparently, my article has been posted and discussed at quite a number of Internet Forums and attracted attention of some academics and researchers, some of whom contacted me directly.

This article aims to answer those inquiries in public. It describes details of the thermostat system that I had to design myself, because I couldn't find a ready-made unit that was able to meet all my requirements.

The Jaycar QT7200 thermostat (described in issue 92 of *Renew*) that I tried first in November 2004, failed after about 6 weeks of use. Its relay contacts fried up, because they were not rated for inductive load of any kind to begin with. I had to disconnect it in a hurry when the relay begun to produce bright and loud plasma arcs that illuminated my kitchen at night.

Although, in essence, the thermostat function is very simple, design of a really good freezer-to-fridge thermostat system is not quite trivial. There are some unexpected problems and challenges that only become apparent when one aims to design a system that works really well.

Let's begin by outlining general requirements for the freezer-to-fridge thermostat.

Thermostat requirements

1. Reliability. Fridges need to be very reliable household devices, simply because our health depends on their reliability. Excessive temperature fluctuations due to any malfunctioning of the thermostat accelerate food spoilage and introduce the associated health risks. The thermostat should work unattended for years if not for decades.
2. Safety. The 240V power supply to the fridge should be well insulated from all low-voltage electronic components of the thermostat.
3. Zero 240V power consumption during the standby period (when the fridge compressor is off). This requirement is very important in the situation, when the fridge is powered by an inverter that has a power-sensing feature. Using zero-standby-power appliances allows inverter users to save up to 0.4 kWh per day just by allowing their inverter to enter the standby (sleep) mode at every opportunity.
4. Hysteresis. The number of fridge compressor starts per hour should be kept as low as possible, not only to conserve energy, but also to minimize the compressor wear.
5. The thermostat should be easy to install and should not require any modifications to any freezer, so that a new freezer warranty is not compromised in any way.
6. The thermostat should be simple and easy to construct from readily available low cost components

Zero-standby-power challenges

From my experience with failing Jaycar QT7200 thermostat illuminating my kitchen with plasma arcs it became obvious that a 240V relay used to switch the fridge compressor on and off should be properly rated for inductive load.

The general trend in modern industry is to replace electro-mechanical relays and contactors by solid-state semiconductor relays. In our case, however, this clashes with the requirement 3. Solid-state relays have significant capacitance when off. This means that when they are connected in series with a motor (a resistive/inductive load) they allow a small current to flow through the motor windings, even when everything is off. This current causes a continuous power loss of about 0.5 Watt as measured with my Vestfrost freezer compressor. Since semiconductor switches and relays cannot meet the zero-standby-power requirement, we have to consider them unsuitable for our application.

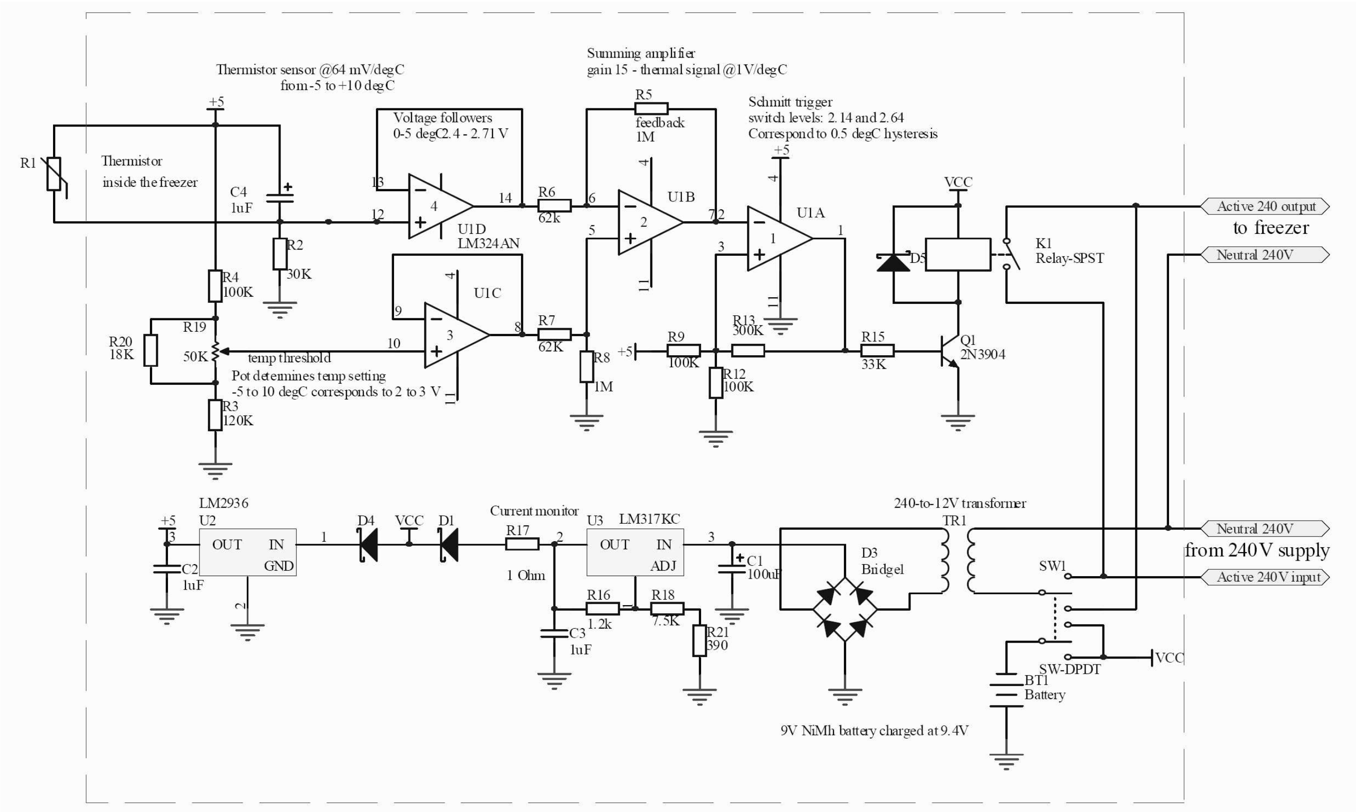

Fig 1. Schematic of the zero-standby-power freezer-to-fridge thermostat. AC supply earth connection (not shown) must be carried from the AC power supply wire to the freezer supply wire.

Hence, we need to settle for a properly rated relay. After experimenting with a few brands and designs, I decided to use OMRON G6RN-1A DC12 relay. In addition to its ability to handle small inductive load, and low-energy switching, it has about 7kV insulation between its 12V coil and its 240V contacts, which I consider essential from the safety point of view. A number of them work for 6 months now in thermostats that I built with no signs of any deterioration in performance.Due to the zero-standby-power requirement, all electronics of our thermostat, including the temperature-sensing system, need to be powered from a battery-based power supply. Since we also require our system to work unattended for years (or decades) we have another challenge to meet: design of a UPS (Uninterrupted Power Supply) that can work for many years unattended. The battery in this UPS needs to be charged when the fridge compressor is turned on.

The design

The schematic of the system that I currently use, after making several not-so-interesting mistakes and attempts, is depicted in Fig 1. It is a result of a compromise between the minimal possible power consumption, simplicity and the cost of components. The temperature sensing system consists of thermistor R1 (BC 2322 640 54103, 10kΩ @25ºC) interfaced with an op-amp. The LM324 quad op-amp chip that I selected has quite low power consumption (<0.7 mA) and can operate from single voltage power supply, which greatly simplifies the design.

U1C and U1D serve as buffers, to minimize the power consumption taken by the temperature measurement and comparison system down to negligible values. U1B is a summing amplifier. U1A is a Schmidt trigger with easy to adjust hysteresis (by changing R13), set here at approx 0.5ºC. The diagram is annotated to be easier to read. Capacitor C4 prevents radio signals that appear on the long thermistor R1 cable from interfering with functioning of the system.

The switch SW1 addresses the issue of powering the system down (the center-off position) and allows the thermostat to operate in two modes: powered by mains 240V (“SW1 up”, in which case battery can be removed) and from the battery (“SW1 down”, the zero-standby-power mode). The “SW1 up” mode also addresses the issue of the initial charging of the battery.

Note the use of the micro-power LM2936 as a 5V regulator. Typically used LM7805 would by itself consume 5 times more power than the entire circuit and would prevent the entire system to become classified as micro-power. Using LM7805 would make battery discharge cycles 5 times deeper and hence requiring 5 times larger capacity battery for sustained operation, not to mention a bigger transformer to keep it charged. It is interesting to note, that the system in Fig 1 will work correctly even if LM2936 is removed and bypassed (pin1 pad connected to pin3 pad). This is due to the fact that all key voltages in the system are proportional to the LM324 supply voltage.

In “SW1 down” mode, the battery is charged when the freezer relay and hence the compressor are on, which, for my Vestfrost fridge, is between 1 and 2 minutes per hour. The rest of the time, the thermistor circuitry is powered up by the battery, so that it does not draw any current from the 240V supply.

During the system operation, the nominal 8.4V NiMh battery voltage varies between 9.2V and 9.4V, so that in practical terms the battery remains fully charged and hence can operate for many years.

Fig 2. The printed circuit board of the thermostat is double-sided and has insulating solder masks to maximize the circuit safety and reliability. The 240V part contains only 2 pins and they are well insulated from the rest of the circuit.

When choosing the transformer, we need to be aware of its magnetizing current specifications and choose the one with the minimum magnetizing current, if possible. In my design I used a cheap 2VA transformer with built-in thermal fuse and the magnetizing current <20mA. Since the battery charger section (transformer TR1 and LM317 regulator) only work 1-2 minutes per hour, their optimization was not attempted.

Fig 3. Inside the thermostat. The thermostat enclosure is waterproof. Top: transformer surrounded by soldered and double-insulated wires. Bottom: the 9V NiMh battery. Cables are intentionally left longer so that the assembled pcb can be removed for inspection without disconnecting it from any part of the circuit.

Installation

The thermostat system described above is designed to be installed on a power extension cable that delivers power to the freezer. No freezer modification is needed. The well-sealed thermistor, soldered at the end of a thin cable of sufficient length, needs to be inserted into the freezer interior. This is best achieved using a freezer draining hole.

Temperature measurement

I deliberately omitted temperature measuring and display from my design in order to keep the design as simple as possible (one IC design). What helped me in this decision was an abundance of the fancy temperature measuring gadgets available on the market. Personally I use the “dual thermometer” from Jaycar for less than $20 with its temperature sensor well sealed with silicone. It measures 2 temperatures: one inside the fridge and one in the room outside it.

The weak point

The design above has one weak point. When the 240V power is not available and the fridge interior temperature rises, the 60mAh battery will power the relay coil up for about 4 hours and then will go flat. This time can be extended by using a larger capacity battery.

I have doubts if this issue requires attention, because my view is that if the power goes down for many hours, the content of any fridge, no matter how advanced, will need a very careful inspection and manual intervention. When the power is restored, my system will require switching to the "SW1 up" mode for a day or so, so that the battery becomes fully recharged.

Fig 4. The thermostat at work. Bottom wires are 240V in-out wires entering the enclosure via rubber grommets. The end of the top wire connects to thermistor R1. Switch SW1 is equipped with a waterproof boot. The potentiometer shaft end is accessible for easy temperature adjustment. A bit of a good tape or a drop of silicone can be used to cover the potentiometer shaft if the full waterproofing is required.

Living with the chest fridge

My Vestfrost freezer-turned-fridge with the thermostat described in this article maintains the pre-set fridge interior temperature with the accuracy of approximately ±1.5°C. The minimal fluctuations in temperature help to minimize the food spoilage. For example, one of my test jars contained some yogurt that was still edible 6 months after its expiry date. Have you ever tried to store half a jar of yogurt in a fridge for 6 months?

Please contact the author (tom@mtbest.net) for prices and availability of the kit in your part of the world.

Other published designs

The thermostat design published in the Silicon Chip magazine (June 2005, Australia) has been designed to draw about 60Wh per day continuously from a 240V source. This power draw comes from the 240V "plugpack" and the triac relay. Implementing this thermostat to a Vestfrost freezer-to-fridge conversion, would cause my 0.1 kWh/day fridge power consumption rise by about 60%. People who relay on Solar Power would incur another waste of 200-400Wh per day, because the mediocre thermostat would prevent their inverter from ever entering the standby (sleep) mode. In their case, the amount of wasted power would be equivalent of running at least TWO (and up to 4) additional Vestfrost fridges equipped with my thermostat. Surely, they would enjoy experiencing the difference, wouldn't they?