New Zealand's Next Top Engineering Scientist

Could New Zealanders save enough electricity via energy efficiency improvements in homes to avoid New Zealand requiring an additional power station being constructed?

Group ID: 1302

Introduction

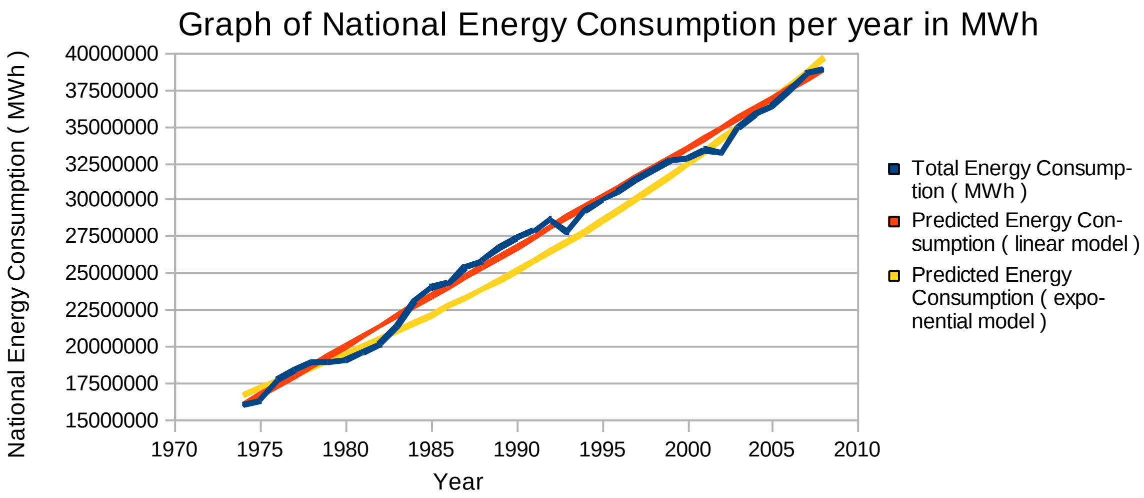
This is an investigation into how New Zealanders could save enough electricity by improving energy efficiency in homes, to avoid additional power stations being constructed. The energy conservation requirements and energy usage details will be covered, followed by the potential solutions. We will be mainly looking at heating in homes, as it is one of the largest sectors of energy consumption. There will be a focus on insulation and heat pumps, but there will be other potential solutions mentioned, developed with mathematical models.

How much energy does each household need to save?

In order to avoid an additional power generator, we simply must not exceed our current electrical capacity at any point in time. We have assumed that this means that we cannot use more power then we currently do, thus allowing some degree of freedom in how much power is available. To keep below our current usage, we have to prevent the demand increasing by improving the energy efficiency of houses to counteract the increases in the industrial and commercial sectors.

Thus, as we cannot allow usage to increase any further, we must reduce the energy requirements of the residential sector by the same amount as the increase in demand in the commercial and industrial sectors. To achieve this, we have modelled the power consumption of the nation as a whole, and of the residential sector. We then used these models to calculate the rate of increase of energy consumption by the commercial and industrial sectors.

The amount of energy required by New Zealand each year was calculated to follow a linear mathematical model using data from the New Zealand Energy Data file for 2009, provided by the ministry for economic development. The mean increase in energy requirements was calculated to be 673,900 MWh per year[1]. The energy requirements could also be modelled by an exponential distribution, increasing by 2.57% each year, but a linear model is a more accurate representation.



[1] New Zealand Energy Data File, 2009. Ministry of Economic Development, p 119

Linear Model: y=15,947,000+67,400×(x-1974)

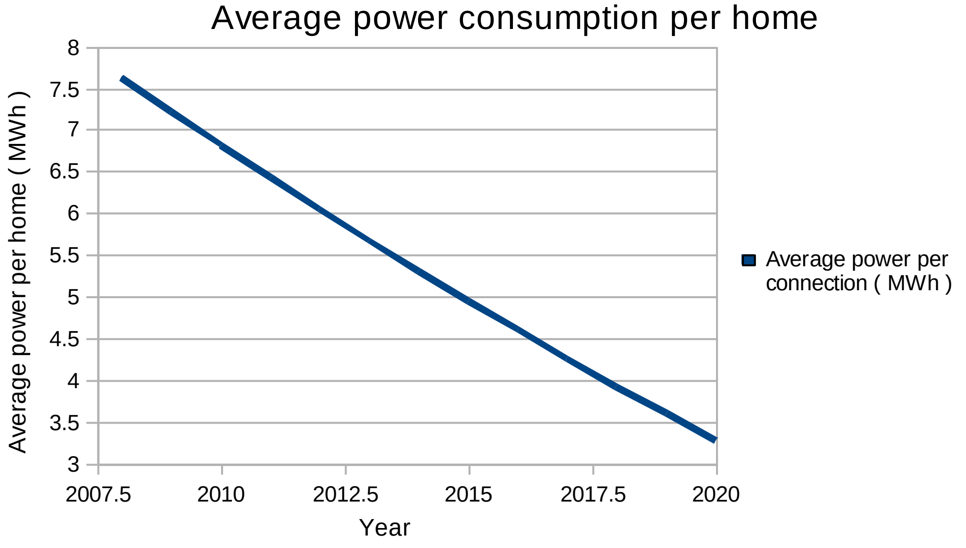
Exponential Model: $y=15{,}947{,}000*1.026^{x-1974}$

Using a linear model for the national power consumption, we then calculated a model for the energy consumed by the residential sector, again using data from the *New Zealand Energy Data file* (Ministry of economic development), and thus predicted a model for the amount of energy consumed by the commercial and industrial sectors. The energy consumption of these sectors was found to increase by 530,000 MWh annually, meaning that the residential sector has to reduce its consumption by 530,000 MWh annually to maintain the current level of energy consumption.

We then modelled the number of homes connected to the national grid by using data from the *New Zealand Energy Data file* and, using a linear model for the number of homes connected to the grid, calculated the required demand for electrical energy required by each house.

We have assumed that the amount of electricity required by the industrial and commercial sectors continues to increase at its current rate. We then calculated the amount of electrical energy which would need to be conserved by the residential sector to prevent any new power plants being constructed. We then converted this into the amount of electrical energy which each house would be able to use each year.

Year:	Maximum Energy available to homes (MWh)	Number of homes connected to national grid	Average power per connection (MWh)
2008	12417000	1628176	7.63
2009	11889411.76	1647504.76	7.22
2010	11361823.53	1666833.53	6.82
2011	10834235.29	1686162.29	6.43
2012	10306647.06	1705491.06	6.04
2013	9779058.82	1724819.82	5.67
2014	9251470.59	1744148.59	5.3
2015	8723882.35	1763477.35	4.95
2016	8196294.12	1782806.12	4.6
2017	7668705.88	1802134.88	4.26
2018	7141117.65	1821463.65	3.92
2019	6613529.41	1840792.41	3.59
2020	6085941.18	1860121.18	3.27



Thus, we have calculated that New Zealand can meet its energy requirements with the current power generators if we limit the amount of electricity consumed by each household according the formula below:

$$\text{Average Power Consumption Per House} = \frac{12417000 - (years - 2008) \times 530{,}000}{1628176 + (years - 2008) \times 19{,}400}$$

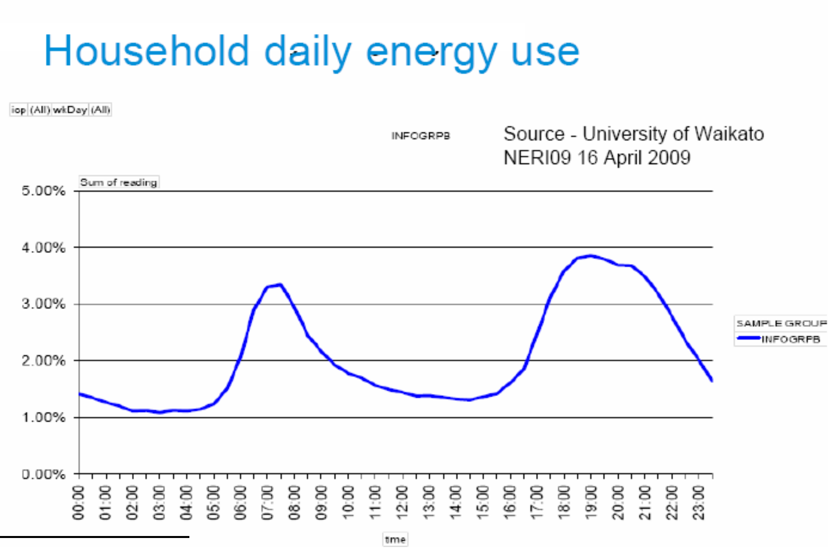
This means that to avoid the need for an additional power plant in 2010, every household in New Zealand would need to reduce their electrical energy consumption by 0.4 MWh, or by 5.5%. This level of reduction in consumption could be easily achieved, but it cannot be continued indefinitely. For example, by 2020, each home would have to reduce its energy consumption by 57%.

It is worth noting at this point that it is infeasible to achieve any significant change in energy requirements by improving residential electrical usage alone. Eventually, the amount of electricity demanded by the commercial and industrial sectors would be too large to be offset by greater efficiency in the residential sector. It is impossible to sustain the increase in demand for electrical energy in the industrial and commercial sectors by increasing the efficiency of the residential sector.

Household electricity usage in New Zealand

The average hourly usage of electricity for the last is approximately 55000MW (2 s.f.)[2]. However, this is not constant. The demand fluctuates during the day and has peaks and troughs relating to consumer demand. It peaks during the morning when the population wakes up, and during the evening, when everyone arrives home from work. This is mainly due to heating electricity costs, such as stoves, water, showers, heat pumps, etc. The required capacity of our energy grid is determined by the peak demand. By targeting energy reduction at peak times, the required maximum capacity of our power grid can be reduced.

The potential amount of energy that can be conserved is 19% based on the electricity usage data in 18/09/09[3].

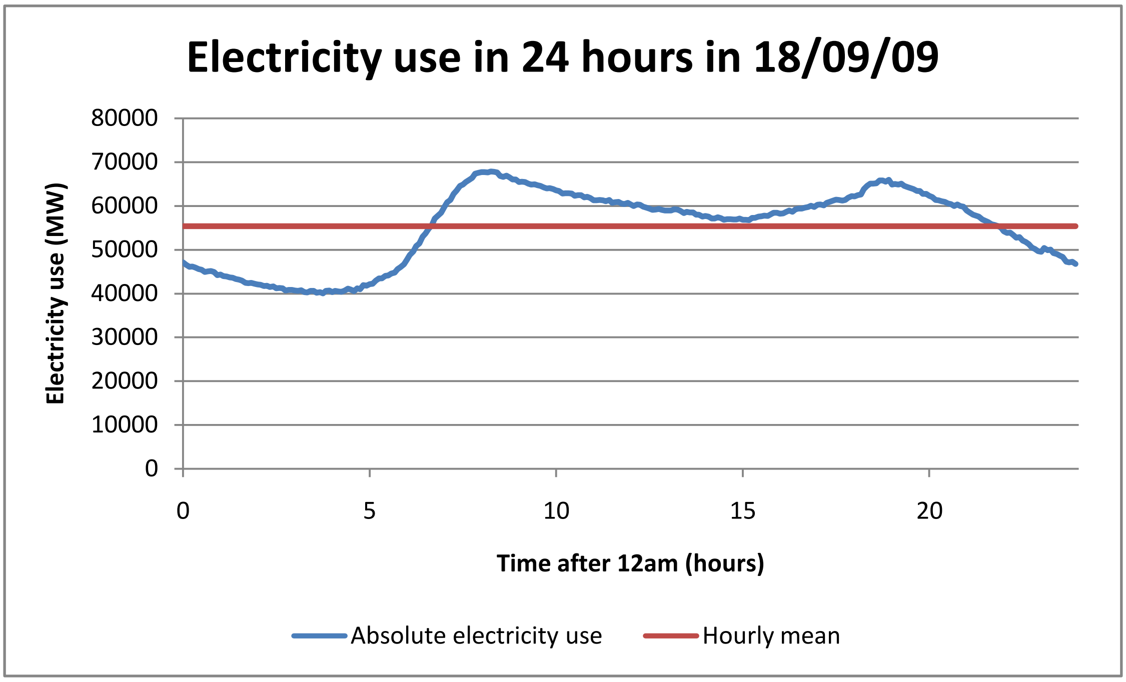


2 http://www.systemoperator.co.nz/n1944,download=true.html
3 http://www.systemoperator.co.nz/n1944,download=true.html

$$Maximum\ Percentage\ potential\ capacity\ reduction = 100 \times \frac{Peak - average}{Peak}$$

$$= 100 \times \frac{68000 - 55000}{68000} = 19\%\ (2\ s.f.)$$

The difference between the graph above and graph below is that one considers only households, while the other is for all of New Zealand, including industry, etc. This means that the fluctuations are lower. Furthermore, the one below is only based on 1 day, whereas the one above is an average.



Effectively, there are two requirements which must be met in order to avoid an additional power plant. The main limiting factor is that the total output of New Zealands generators must be greater than the demand at any given time. This means that during the peak usage period, the energy consumption by the population cannot exceed the energy produced by the generators. The most effective way to reduce this consumption is to improve the efficiency of the devices used during the peak periods, of which the major culprits are heating, lighting and appliances, or switch unnecessary appliances such as fridges.

One particularly useful method which could be used to reduce the appearance of peaks in energy consumption is heat retention. If homes are better insulated, then they will retain heat better and for longer, which would reduce the amount of energy required to heat a home. This would effectively spread out the peak. Another way this can be achieved is by using smart appliances, such as heaters which will start during the night when energy demand is low, and heat the house so that it is comfortable when people wake up. This would effectively shift the energy consumption from the peak period into the low period, reducing the maximum capacity required by the national grid.

Modelling heat losses in the average New Zealand house:

(1) A box house made of one material, heat transfer only through conduction:

Newton's law of cooling (convection):

$$\frac{dQ}{dt} = A \times U \times (T_{env} - T_{house})$$

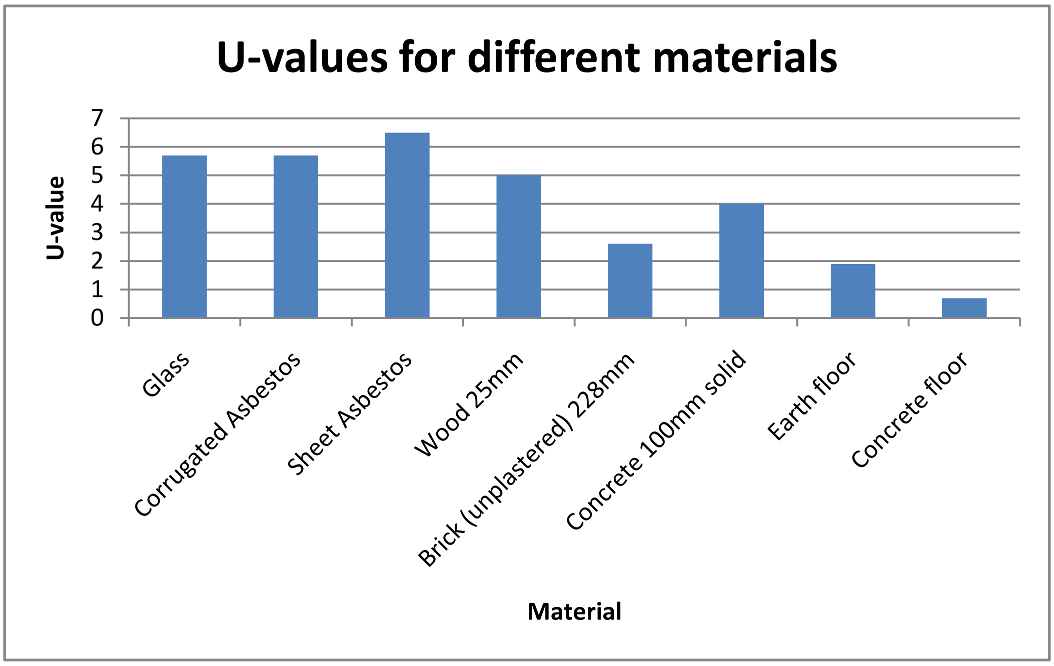
Power to maintain the temperature of the house:

$$\frac{dQ}{dt} = A \times U \times (T_{env} - T_{house})$$

$$U = \frac{1}{R}$$

	U-value
Glass	**5.7**
Corrugated Asbestos	**5.7**
Sheet Asbestos	**6.5**
Wood 25mm	**5.0**
Brick (unplastered) 228mm	**2.6**
Concrete 100mm solid	**4.0**
Earth floor	**1.9**
Concrete floor	**0.7**

Source: http://www.tombling.com/heaters/heatloss.htm



For example if I were to make my house completely out of 25 mm wood I would theoretically lose twice as much energy (via conduction) than if I made my house completely out of brick.

(2) A house made of two materials in series, heat transfer only via conduction

$$U = \frac{1}{R}$$

$$\frac{dQ}{dt} = A \times \frac{1}{R_T} \times (T_{env} - T_{house})$$

$$R = \frac{L}{kA}$$

$$R_T = R_1 + R_2$$

$$\frac{dQ}{dt} = A \times \frac{1}{R_1 + R_2} \times (T_{env} - T_{house})$$

E.g.

A house is made of two materials pink batts and wood in series. The pink batts have an R-value of 2.2, the wood has an R-value of 0.2. Calculate the rate of heat loss.

$$\frac{dQ}{dt} = A \times \frac{1}{2.2 + 0.2} \times (T_{env} - T_{house})$$

$$\frac{dQ}{dt} = 600 \times \frac{1}{2.4} \times 10 = 2.5\ kW$$

Implications:

Substantial reductions in heat loss can be made by putting to insulating materials in series, such as wood and then an insulator like pink batts.

(3) A house made of two materials in parallel, heat transfer only via conduction

$$\frac{A}{R_T} = \frac{A_1}{R_1} + \frac{A_2}{R_2}$$

$$\frac{dQ}{dt} = \left(\frac{A_1}{R_1} + \frac{A_2}{R_2}\right) \times (T_{env} - T_{house})$$

For example:

A house is made glass and brick. The brick has an R-value of 6 the glass has an R-value of 3. The house is by surface area 2/3 bricks, 1/3 glass. Calculate the rate of heat loss:

$$\frac{dQ}{dt} = \frac{600}{3} \times \left(\frac{2}{6} + \frac{1}{3}\right) \times 10 = 1.3kW$$

Despite the fact that the glass has half the surface area of the brick it transmits the same amount of energy to the environment. The important implication of this is any weak point (poor insulator) in the house can act as a ‘thermal bridge’ allowing the thermal energy to be lost to the environment. Therefore there is little point improving one aspect of the insulating properties of a house and neglecting another property.

$$A_1 = 0.5A, A_2 = 0.5A$$

$$\frac{dQ}{dt} = \frac{A}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \times (T_{env} - T_{house})$$

(4) Impact of variations environmental and house temperature

$$Percentage\ of\ energy\ saved\ by\ reducing\ the\ temperature\ of\ the\ house = 100 \times \left(1 - \frac{T_{env}' - T_{house}'}{T_{env} - T_{house}}\right)$$

For example if the temperature of a house is 20°C and the environmental temperature 10°C then changing the internal temperature of the house to 15°C will reduce the heat energy consumption of the house by 50%.

$$100 \times \left(1 - \frac{T_{env}' - T_{house}'}{T_{env} - T_{house}}\right) = 100 \times \left(1 - \frac{10 - 15}{10 - 20}\right) = 50\%$$

(5) Radiation into the house from the sun

Power per meter square of direct sun rays:

$$\frac{P}{A} \approx 100Wm^{-2}$$

(http://en.wikipedia.org/wiki/Sunlight)

$$\frac{dQ}{dt} = \epsilon \times A(roof) \times 120Wm^{-2}$$

$$A = 200\ m^2$$

Corrugated iron roof:

$$\epsilon_{absorb} \approx 0.3$$

$$\frac{dQ}{dt} = 0.3 \times (100 \times 100) = 3kW$$

Implications:

A substantial amount of energy could be harnessed from the sun. This could be harnessed by used by circulating the hot air in the roof around the house or installing a solar water heating system.

Unfortunately this would be difficult to harness during a winters day. Moreover thermal radiation would be lost from the roof as the surface is at a higher temperature than the environment.

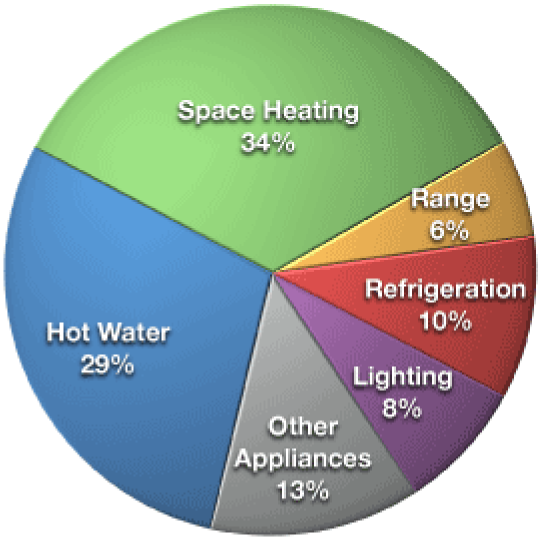
Assumptions:

We simplified heat loss in a house down into basic components. The temperature of the house was assumed to remain constant and similarly the temperature of the environment was assumed to remain constant. We ignored drafts and other forms of convection in the house. We also ignored thermal radiation emitted from the house.

Evaluation:

The problem with this model is that it is difficult draw anything but vague conclusions. The uncertainties are large because every house is different. Some are made of bricks, some are made of wood, and some are made of cardboard. A major factor in the amount of thermal energy lost is the surface area of the house, this was highlighted in the model, but is difficult to predict for any individual house.

Potential solutions to reduce energy consumption



Pie chart showing energy consumption in an average New Zealand household.
Source: http://www.energywise.govt.nz/

Space Heating

Space heating is the largest area of energy consumption in the average New Zealand household, accounting for 34% of electricity usage. The main areas of wastage of electricity are heat loss and inefficient heating.

Heat loss

The major components of heat loss in houses are:

- air leakages (due to gaps between doors and doorframes and windows and window frames)
- trapped heat in the roof cavity (air in the roof cavity is heated by the sun and heat rises from living areas and becomes trapped in the roof cavity, where it is of no use)

Air leakage accounts for 15-25%[4] of heat loss/wastage in an average home. This often occurs in older houses or those poorly constructed, with gaps between doors and windows and their frames. These gaps allow air flow in and out of the house, allowing heat to escape. These spaces need to be sealed to prevent leakage. However that means there is no way for fresh air to enter the house and stale air to be expelled. One method of providing ventilation is a system of air ducts and fans, with fresh air pumped into the living areas and bedrooms and stale air out of the bathrooms and kitchen. This has the added benefit of removing water vapour and airborne, odour causing bacteria from their main sources – the kitchen and bathroom. The air pumped out of the house is warmer than that pumped in, so a heat exchanger can be used to transfer up to 85%[5] of the heat.

This method could be improved by pumping air from the roof cavity into the house and fresh air from outside into the roof cavity, rather than pumping air directly from outside into living areas. The roof cavities of houses often contain air that is both warmer and drier than that in the rest of the house; as the air in the roof cavity is heated by the roof which is heated by the sun as well as receiving rising heat from the rest of the house. Essentially the roof cavity becomes a reservoir of warm, dry air. This warm, dry air will reduce heat loss from the house by directly increasing temperature of the air as well as reducing moisture in the air.

Efficiency of heating

The efficiency of heating can be greatly improved by using heat pumps rather than regular electrical heaters. The heat pumps, moving heat from a cold reservoir to a hot reservoir have a range in efficiency of 250% to 500%[6] (in New Zealand) and a COP range of 2.5 - 5[7]. Regular heaters have a maximum efficiency of 100%[8], as they depend on the conversion of electrical energy to heat energy, rather than the transfer of heat energy from one area to another. This means that about $500 can be saved per year (with 8 hrs of use per day for 6 months of the year). The price range is approximately $1300 - $4600 with the range in installation cost of $800 - $1500 depending on location[9]. This means the heat pump will have paid for itself in 4-12 years, however the reductions in energy usage could be up to 80%[10] of that used for an electrical heater.

Note: Heat pumps must be used correctly and for the same heating effect as electrical heaters to produce energy savings. Issues stemming from incorrect or excess usage:

- People may use heat pumps for longer, or at higher temperatures than they would use an electrical heater because it is less expensive. Thus reducing the energy savings.

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4 http://www.nzs.com/new-zealand-articles/lifestyle/power-saving.html

5 http://www.newscientist.com/article/mg12917595.400-the-house-that-came-in-from-the-cold-houses-designed-withenergy-efficiency-in-mind-are-more-pleasant-to-live-in-less-harmful-totheenvironmentand-need-not-be-expensive-to-build.html

6 http://www.energywise.govt.nz/how-to-be-energy-efficient/your-house/heating-and-cooling/heat-pumps

7 http://www.energywise.govt.nz/how-to-be-energy-efficient/your-house/heating-and-cooling/heat-pumps

8 http://www.energywise.govt.nz/how-to-be-energy-efficient/your-house/heating-and-cooling/heat-pumps

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10 http://www.energywise.govt.nz/how-to-be-energy-efficient/your-house/heating-and-cooling/heat-pumps

- Some people that previously used heating such as wood or coal burning fires are converting to heat pumps, thereby increasing the number of people relying on electricity for heating
- People that did not previously use air conditioning or fans in the summer months begin using their heat pumps to reduce the temperature in the house, thereby increasing energy use in the summer months. (although this point would have little effect on whether a new power station would be required as the energy usage in summer is well below the peak usage in winter)
- Poor installation reduces efficiency
- The heat pump requires annual servicing and regular replacement of the filter to ensure efficiency is maintained

Humidity also poses a barrier to efficient heating as it means heating is less efficient as the water vapour must be heated as well as the air. Non electrical dehumidifiers could be an effective solution as they remove moisture from the air without using more electricity. Air recirculation of air from the roof cavity also reduces moisture in the air.

Hot Water

Around 29% of the energy used by a household goes into heating water. This makes the heating of water a major target in increasing efficiency. In the heating of water there are several arenas of energy wastage:

- the heating of the water
- the use of the hot water

Heating Water

There are two main ways of heating water used in New Zealand, hot water tanks (which se electricity) and gas heating systems (for which efficiency is not a concern). The efficiency of an internally heated hot water tank can be improved using insulation, for example padding the hot water tank with polystyrene. Otherwise hot water tanks that are heated using heat pump technology can be used – which will greatly increase the efficiency of heating.

Using gas for water heating country wide would completely remove the electrical energy demand for heating. However gas is a non-renewable resource and the economic cost of converting the entire country to gas would be huge.

The solar water heating system is a third way to heat water. It involves water being pumped through thin pipes in an insulating box with a glass front. In essence the box acts like a mini greenhouse and the water absorbs heat energy through convection as it is pumped through, therefore requiring less, if any, further heating in a hot water tank before use. The energy reductions may be great in summer or on warmer sunny days in winter however issues arise or extremely cold or overcast days.

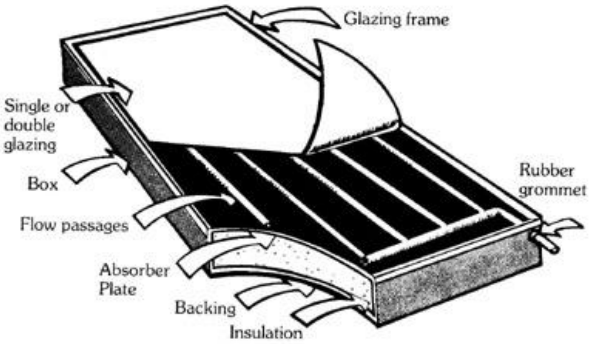

Image courtesy of Missouri Department of Natural Resources

Recycling hot water

The energy used to heat water is largely wasted. For example, water is heated for showers and dishwashers, used, and then discarded while still retaining the majority of its heat energy. These wastages could be reduced by re-circulating the hot water, pumping it through a heat exchange system that pre-heats fresh water. The fresh water would then require less energy to reach the desired temperature. Another solution could be to reduce the volume of hot water used, by using cold water where possible. For example in washing machines or even dishwashers; this could save up to 90%[11] of the running cost of the appliance. The issue is that new innovations would be required to allow the effectiveness of the appliances to be maintained without the hot water.

Appliances

There are already numerous initiatives to encourage production and purchase of more efficient appliances such as the efficiency rating given to most household appliances. Fridges, for example, now have an energy usage 50% of what they used 10 years ago[12].

Despite the increasing efficiency of appliances; their energy wastage can be reduced by turning them off while not required.

Lighting

Lighting is a major area of inefficiency. The common incandescent light bulb converts approximately 5% of the energy supplied to it into light, while the other 95% is converted to heat[13]. This may not be an issue in winter where heating is required anyway, however in summer it is pure wastage, possibly even meaning more energy is used to cool the house down in compensation for the heat produced. On the other hand in newer houses light bulb sockets are mounted into the roof, meaning that the heat energy produced is lost into the roof cavity – where, in summer it is not a further problem but in winter, it must be re-circulated to be of use. Current solutions to this inefficiency include the eco-friendly light bulbs. These

[11] http://www.nzs.com/new-zealand-articles/lifestyle/power-saving.html
[12] New Zealand's energy outlook to 2030, pg 110
[13] http://www.rightlight.govt.nz/efficient-light-bulbs/lighting-efficiency.html

CFL light bulbs fit the regular sockets and are around 80%[14] more efficient than the standard incandescent light bulb.

Construction

The shape and orientation of houses can be used to reduce heat loss and thereby increase effectiveness of space heating in houses. For example a dome shaped house, without the protruding corners increasing its surface area and trapping heat, is less susceptible to heat loss and requires less energy to heat. Other areas of heat loss are windows and lack of insulation of walls, floors and roofs.

Windows

Heat conducting and radiating through windows account for approximately 25-30% of heat loss[15]. Windows need to be glazed, to prevent radiation. It is possible to double, triple and quadruple glaze windows. The gaps between the sheets of glass or polyester can also be filled with argon. Argon is a better insulator than air as it is less conductive, thereby reducing heat loss. The outer face of the inner pane of glass can be coated with a low-emissivity coating containing silver oxide or copper oxide, which reduces heat loss by radiation by 80%[16]. Furthermore, windows need to be facing the sun (North-facing in the southern hemisphere), to allow solar energy to heat up the house. The windows on the non North-facing side of the house should be smaller and better insulated than the North-facing windows, to ensure more heat is let in than let out. After dusk, when heat is no longer being radiated into the hour, thick insulating curtains or shutters could be used to reduce heat loss through the windows.

Insulation

To prevent heat loss homes need to be insulated as much as possible. Approximately 10% of heat is lost through floors, and if a home is not insulated, up to 30-35% can be lost through the roof, and 18-25% can be lost through the walls[17]. Mineral fibre and cellulose fibre are useful for the insulation of floors and carpet can also make a large difference. Foam insulation is a possible solution in walls and roofs. Full insulation having a sum effect of reducing heating costs by 42%[18].

Solar panels

Solar panel could be installed on the roofs of houses to harness solar energy and convert it into electrical energy. This electrical energy could be used to heat water, or run home appliances. This would reduce the amount of electricity drawn by the house from the grid.

Conclusion

If we wish to build no more power plants in New Zealand over the next ten years, while allowing industrial and commercial growth to continue at its current rate we would have to half household electricity consumption by 2019. If we wish to do this only by reducing household consumption we must take fairly dramatic action. It is unlikely that people will have the motivation to do so unless there is some substantial incentive. Legislation from the government dictating that no more power plants can be built may be effective at achieving

[14] http://www.rightlight.govt.nz/efficient-light-bulbs/lighting-efficiency.html
[15] http://www.nzs.com/new-zealand-articles/lifestyle/power-saving.html
[16] http://www.newscientist.com/article/mg12917595.400-the-house-that-came-in-from-the-cold-houses-designed-withenergy-efficiency-in-mind-are-more-pleasant-to-live-in-less-harmful-totheenvironmentand-need-not-be-expensive-to-build.html
[17] http://www.smarterhomes.org.nz/design/insulation/
[18] http://www.smarterhomes.org.nz/design/insulation/

this sole aim, it would force up prices and ensure that market forces made people reduce their energy consumption. However this would be politically unpopular and probably hamper economic growth. Other solutions include extending the subsidy program for energy efficient homes, offering to offset the cost of insulating a home. But the fundamental problem is once we have picked the low hanging fruit (such as insulating in roofs and walls with Pink Batts) we must use the more costly solutions such as installing solar panels or double glazing. We feel that this it is simply not possible to rely on household energy efficiency saving only in order to prevent a new power station being built.

As detailed above, it is possible to reduce the electrical energy consumption of the average household by 52%. This means that it is possible to prevent any increase to the national demand for electrical energy before 2017, assuming that the demand generated by industry and commerce continue to increase at the current rate, thus meaning that it is possible to avoid installing an additional power plant before 2017. Beyond this date, however, it is not possible to offset the demand generated by the industrial and commercial sectors with improvements to the efficiency in the commercial sector.

Limitations:

In this report, we have assumed that the rate of increase in demand for electricity from the industrial and commercial sectors is constant. We have also assumed that the rate of increase in the number of homes connected to the national grid is constant. We have also assumed that there are no difficulties in installing energy saving systems in homes, and that there are substantial improvements in energy saving technology occur. We have also assumed that none of the existing power stations need to be decommissioned, and that there are no technical problems with existing power stations or power lines.

Our estimate of potential energy savings over the next 10 years.

Energy Use	Percentage usage in an average NZ household	Possible reduction	Energy saving (percentage of NZ electricity consumption)
Space Heating	34%	70%	23.8
Water Heating	29%	40%	11.6%
Other Appliances	13%	5%	0.65%
Refrigeration	10%	5%	0.5%
Lighting	8%	80%	6.4%
Flattening off demand	100% (includes everything)	10% (off peak consumption)	10%
		Total	52.95%

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