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*Article*

# Does Energy Efficiency Reduce Emissions and Peak Demand? A Case Study of 50 Years of Space Heating in Melbourne

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**Abstract:** This paper examines the relationship between space heating energy efficiency and two related but distinct measures; greenhouse mitigation, and peak demand. The historic role of Melbourne's space heating provides an opportunity to assess whether improvements in energy efficiency lead to sustained reductions in energy consumption or whether rebound factors "take back" efficiency gains in the long run. Despite significant and sustained improvements in appliance efficiency, and the thermal efficiency of new building fabrics, the per-capita heating energy consumption has remained remarkably stable over the past 50 years. Space heating efficiency is bound up with notions of comfort, sufficiency and lifestyle, and the short-run gains from efficiency become incorporated into a new set of norms. It is this evolution of cultural norms that reconciles the contradiction between the short-run gains from efficiency measures, with the efficiency rebound that becomes evident over the long-term. The related, but distinct peak demand measure can be influenced by efficiency measures, but energy efficiency measures will not alter the requirement for large-scale conventional energy to provide affordable and reliable winter heating.

**Keywords:** energy efficiency; space heating; peak demand; greenhouse emissions

## 1. Introduction

Energy efficiency is a key component of climate change policy, and is promoted as a low cost means to reduce greenhouse emissions [1–3], and reduce peak demand [4–7]. Energy efficiency is a key component of the "soft energy path", originally articulated by Amory Lovins [8] in 1976 as a solution to energy supply concerns and declining resources, then later adopted as a solution to climate change. Such is the power and intuitive appeal of the idea of energy efficiency that it has been almost universally adopted as a key plank of the "sustainability project" by environmental NGOs, green parties, and large sections of Government.

Yet Jevon's Paradox, or the energy efficiency rebound effect, suggests that some, or all, of the gains of energy efficiency are "taken back" in the long-run [9–11], and has been extensively debated within the literature [12,13]. Further, advocacy of energy efficiency and energy transformations based on broad-brush theoretical analyses can easily overlook the practicalities of delivering reliable and affordable heating.

The most common explanation for the failure to reduce energy is that we haven't tried enough; therefore the solution should be increased regulation and greater stringency, along with greater support for efficiency programs [11]. However, a historical examination shows that an improvement in efficiency of Melbourne's space heating has in fact been sustained and significant, yet energy demand continues to grow. An examination of the specific case of Melbourne's space heating over a 50-year time-scale provides an opportunity to reconcile the contradiction between the short-run gains from efficiency at a household level, with the irrefutable increase in aggregate energy consumption over the long run. This paper attempts to reconcile this contradiction, and briefly offers a way forward.

## 2. The Relationship between Energy Efficiency and Notions of Comfort, Sufficiency, and Lifestyle

The energy efficiency of heating appliances has shown a significantly improving trend over the last 50 years, and building fabrics over the last 20 years; a modern gas furnace or heat pump in a recently constructed 6-star home in Melbourne typically needs only 6% of the energy as a typical home *circa* 1960 to maintain a square metre of living space at a given temperature. However a combination of rebound and lifestyle factors including larger homes and larger heated areas, lower per-household occupancy rates, higher expectations of comfort, and an increase in the relative affordability of energy (see Table 1), has led to the result that per-capita heating consumption has remained remarkably stable over the last 50 years. The per-capita greenhouse emissions attributed to space heating fell as a natural consequence of fuel shifting to fuels with a higher H/C ratio, but has flattened over the past 20 years due to the saturation of gas heating. Most of the appliance efficiency and greenhouse gain has occurred as a result of technology and fuel switching, outside of specific energy efficiency policy measures. In contrast, building regulations have driven most of the building fabric improvement.

A reasonable question would be whether the rebound and lifestyle effects would have happened anyway, and that therefore, efficiency gains have prevented per-capita energy use from being *even higher*. Indeed, critics of Jevons would argue that this is in fact what happens [14]. Yet consider whether home owners on average incomes would still be building "McMansions" if homes were uninsulated, leaky, and still relied on open fires? Nevertheless, all energy efficiency observational studies are bedevilled by the same limitation; the counterfactual cannot be observed.

Intuitively, one would expect to observe inflection points in the per-capita energy use following the large-scale transfer from oil and briquettes to more efficient gas heating from the late 1970s (see Figure 1), the introduction of mandatory insulation in 1991 and minimum building performance standards from the early 2000s. However the stubbornness of the per-capita energy use is striking in the context of significant and sustained improvements in building and appliance efficiency (see Figure 2).

Notions of comfort, sufficiency, and lifestyle are bound up within the interactions between people, energy, appliances, buildings, affordability, and social values. The rebound posited by this paper is not predicated solely on a simple short-run causation, such as a tendency for householders to adopt a higher indoor temperature following the installation of insulation, but rather, on a set of complex interactions, some of which only become apparent when viewed a multi-decadal time scale. For example, the notions of sufficiency and comfort of elderly people living modestly, whose lifelong habits were formed during the Great Depression, may be quite different to that of the contemporary, affluent "environmentally aware" person, maintaining year-round comfort in a large "energy efficient" home filled with "energy efficient" appliances. In addition, adequate heating is considered an essential service in Melbourne, and is a factor in reducing the risk of thermal illness in vulnerable people, such as those with chronic illness [15].

Nearly all energy efficiency advocacy assumes that technical efficiency can be isolated from these complex interactions, such that a simple linear model describes the relationship between efficiency and greenhouse abatement. Yet it is clear that the short-run gains from efficiency are assimilated and new norms emerge, resulting in a far more complex long-run relationship. The conclusion is that the capacity for energy efficiency to effect a net reduction in greenhouse emissions and peak demand is far more limited than frequently asserted, and therefore distracts from other efficacious greenhouse mitigation measures, and avoids the more challenging social debates around population, sufficiency, and comfort.

**Figure 1.** Victorian space heating annual energy consumption 1960–2010. Source: author calculated estimates based on ABARE [16], assume space heating proportion of total residential energy: electricity 10% [17], gas 75% [18], wood, briquettes 75%, heating oil 100%.

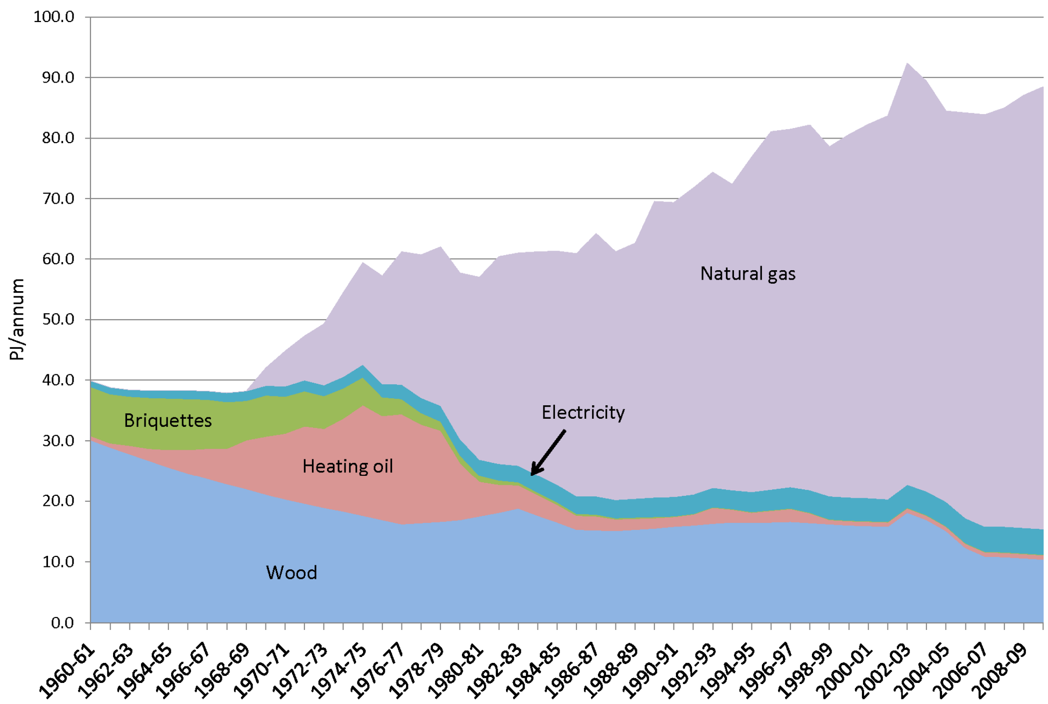
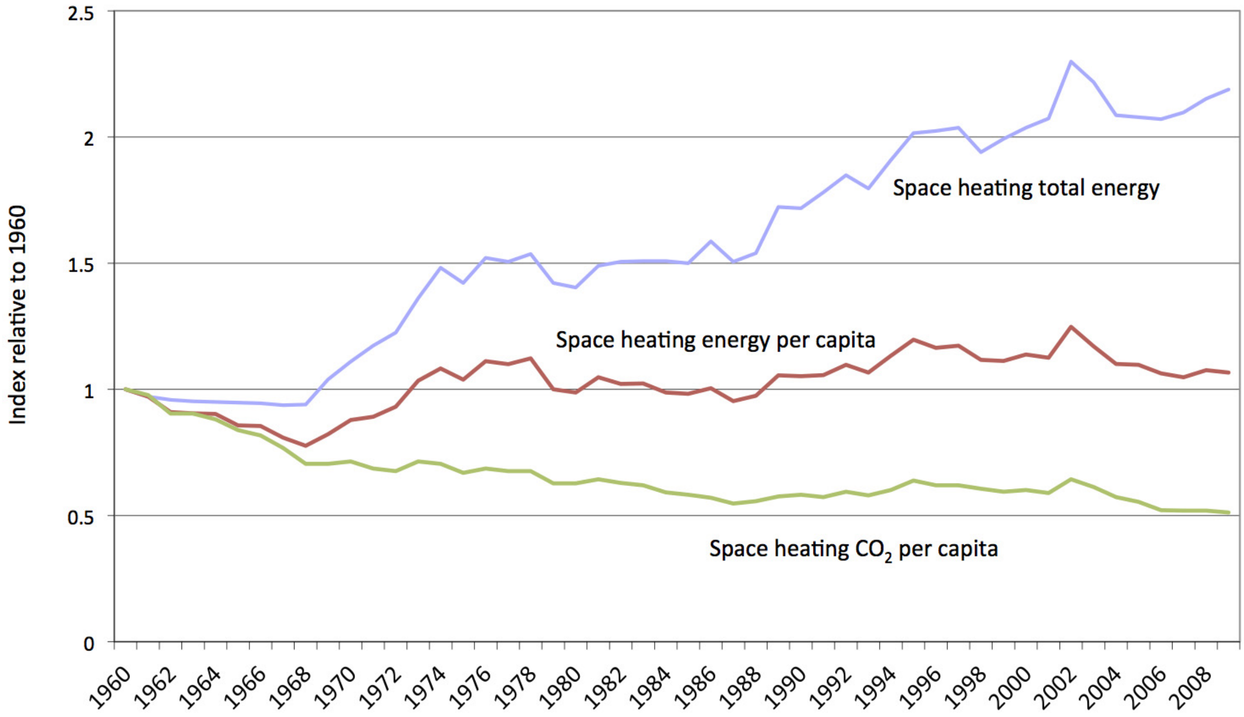


**Figure 2.** Historic space heating energy use in Melbourne. Source: author's calculations using ABARE energy data [16]—refer Figure 1, population [19], emissions [20]. Note: per-capita figure subject to year-to-year climate variability, data and proportion uncertainties.




## 3. Defining the Energy Efficiency of Space Heating

If one defines the "energy efficiency" of space heating as the energy required to maintain a single individual's thermal comfort, then it could be shown that developing "more efficient" heating appliances (see Figure 3) and "more efficient" building fabrics (see Figure 4) is to miss the point; better to encourage smaller homes, more occupants per household, encourage people to wear heavier clothing indoors, promote an attitude of sufficiency, and adopt a discretionary approach to the use of standardized technical measures of thermal comfort for heating system design (such as ANSI/ASHRAE Standard 55, which defines technical measures for "acceptable" comfort conditions).

For example, the average number of persons per household in Australia has declined from 4.5 in 1911, to 3.5 in 1960, and 2.6 in 2006, with a projected 2.3 in 2026 [21], while the average floor area of new residential buildings increased by 37% from 1984 to 2002 [22]. Shove [23] notes that average winter temperatures in British homes have been rising steadily over the last thirty years, from around 17 to 21 °C, and that comfort-related patterns of human behaviour and lifestyle have changed dramatically over the last century, with a global convergence of indoor climates. Indeed, there appears no imminent limit to the evolution of thermal comfort; consider the recent proliferation of the patio radiant heater permitting outdoor "lifestyle" living to continue through winter [24], and requests for air-conditioned garages [25].

It is possible to construct a new home in Melbourne requiring little active heating, but in the context of greenhouse abatement, this doesn't tell us much about the overwhelming majority of households in the vast expanses of Melbourne's suburbia who have established homes. The rate of new home construction relative to the existing building stock is of the order of 2 per cent per annum, with a net demolition rate of around 0.2 per cent [17]. Even new home constructors confront many trade-offs in architectural design *versus* energy consumption, such as glazed area and outlook, ceiling heights, and orientation, while more compact blocks limit opportunities for solar passive design. Indeed, the urban expansion of large freestanding dwellings in Melbourne, driven by population growth, is projected to continue indefinitely [26]. As of 2007, Melbourne's population was 3.8 million, with projections under the ABS "medium level scenario" of 5 million in 2026 and 6.8 million in 2056 [27]. And despite rising energy costs, the average home buyer continues to be driven by floor area rather than energy efficiency [28].

**Figure 3.** Indicative historic improvement in the efficiency of heater appliances 1900–2010. Note: for consistency, heat pump includes average thermal efficiency HHV (high-heating value) of electricity sent out (est. 25%) in Victoria [29]. Source: [30–32].

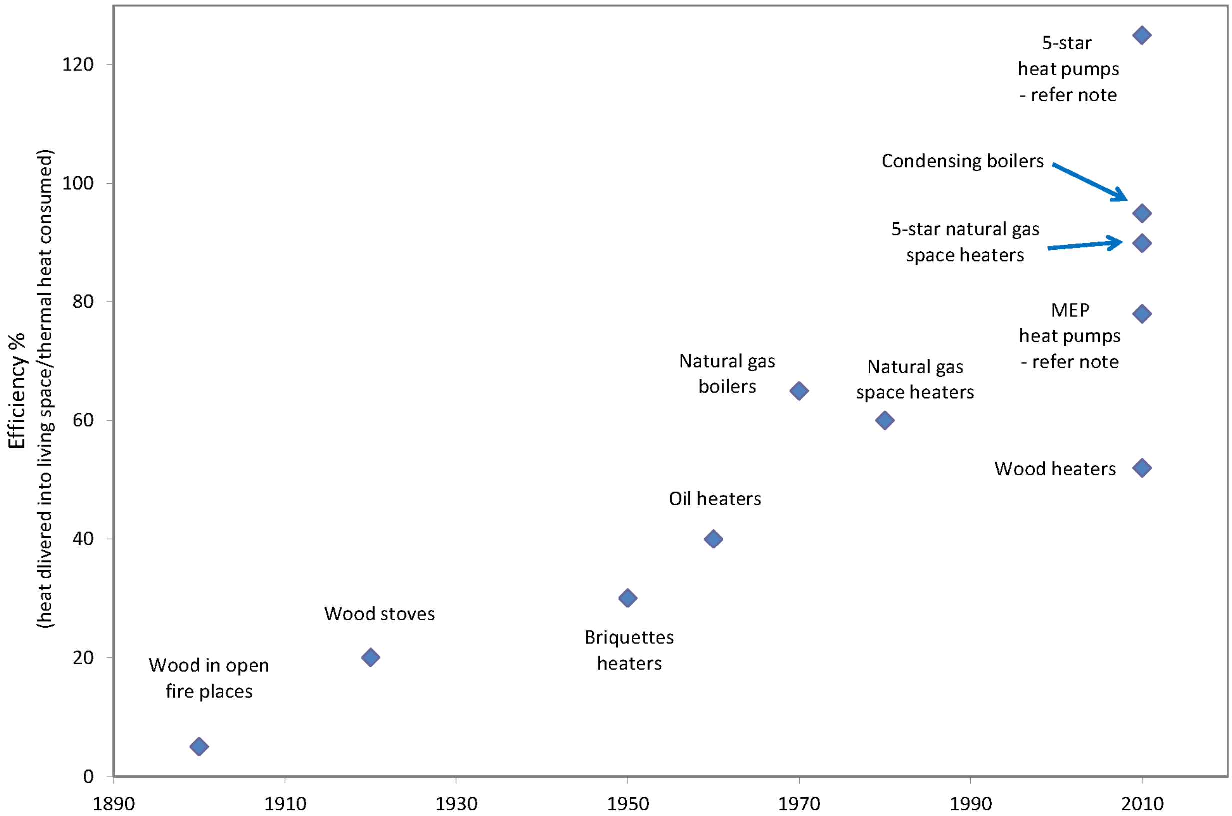
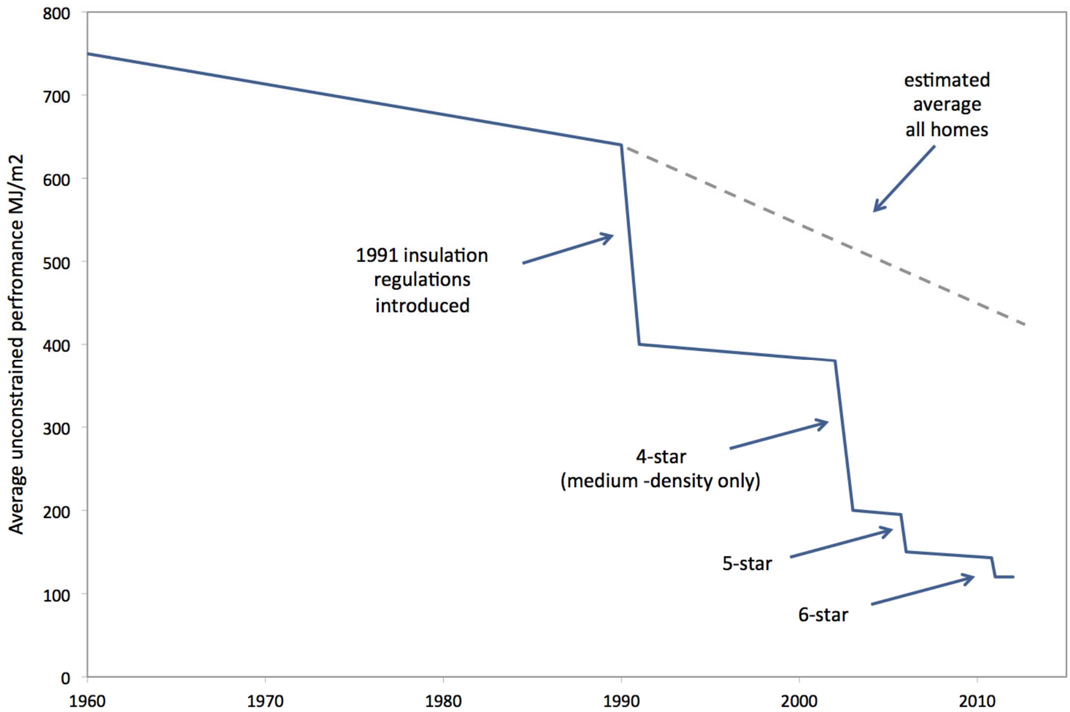


**Figure 4.** Average thermal performance whole-of-house Victorian new housing 1960–2011. Source: Energy Efficient Strategies [33], author estimates for average based on new construction weighted data assuming 0.2% demolition rate of older stock, and average 1.2% annual improvement due to insulation, sealing and renovations such that pre-1991 stock averages 490 MJ/m$^2$ by 2010, consistent with [48].




## 4. Residential Space Heating in Melbourne

### *4.1. Historic Overview*

Up to the Second World War, wood burnt in open fireplaces was the main method of heating houses in Melbourne, and slow combustion stoves using coke were used for a while in the post-war years [34]. At the start of the 1960's, briquettes and wood were the main sources of heating [16]. Beginning around 1962, heating oil started being used for heating, largely displacing briquettes. It was during this time that Victoria saw the first oil central heaters, but single-room heaters, usually located in a modestly sized living area, continued to be the main heating appliance. Many of these heaters required at least 30 minutes before providing adequate heat, and were often the only warm area in a home during winter. Rooms usually had wall vents to permit adequate ventilation for wood heaters and flueless heaters. These vents also increased the heating load during winter, but were eventually removed from new construction following the standardisation of flued or external heaters.

Up until 1969, Melbourne used town gas, produced from a number of feedstocks, including carbonization of black coal, residual oil, refinery gas and LPG, and Lurgi gas produced from brown coal [35]. From 1960 to 1970, the gas price had been stable at around 0.28 cents/pence per MJ [18], with an average consumption per domestic consumer of 13 GJ (120 therms) in 1952, which rose steadily to 22 GJ (205 therms) 1970. Following the development of the Gippsland Basin, natural gas was introduced in 1969, and one million appliances were converted from town gas [35], with natural gas immediately starting to displace oil and briquette heating. The price of gas dropped significantly in real terms over the next 4 years. Although oil continued to grow until 1975, the shift from oil heating was eventually rapid, dropping from 17.5 PJ/annum in 1977 to 3.9 PJ/annum in 1982, representing an 88 per cent decline over 5 years in response to a sharp increase in heating oil price [36]. The consumption of gas per consumer rose rapidly to 36 GJ in 1974, but slowed during the 1980s, recording 52 GJ in 1990. Firewood also gained in popularity for a number of years, peaking in 1992 [37].

Developments in ductwork, including the introduction of Vulcan "Sidewinder" flexible duct in the early 1970s, simplified the installation and decreased the relative cost of central heating, and together with the relative low cost of gas, drove growth in central heating. The early duct was wrapped in glass-wool blanket and encased in a sleeve, with an insulation rating of around R0.5. During the 1980s, further developments in "interlock" compressible flexible duct, then wire-glued duct, further reduced production costs, leading to ongoing decreases in the relative cost of central heating. This was accompanied by incremental improvements in gas furnaces and the development of plastic ductwork fittings and registers, which displaced the more expensive sheet metal fittings and provided improved air sealing and therefore efficiency [32]. The growth drew in larger number of contractors, which contributed, to a competitive market. The availability of affordable systems and gas brought comfort to the masses; the installation of a thermostatically controlled central heater brought respite from Melbourne's winter for a large proportion of the community. By the 1990s, there was a large-scale change-over from glass-wool ductwork insulation to polyester fibre, with typical R-values in the range R0.4 to R0.6, which rose to R0.6 to R1.0 by the early 1990s, with R1.0 now standard for heating in Victoria, with some installations now requiring R1.5.

During the 1970s, the government-owned Gas and Fuel Corporation took a pro-active role in promoting energy efficiency, including promoting and financing ceiling and wall insulation, and overseeing gas and ducted heating systems [38]. Research by the corporation was revealing differences between actual *versus* predicted energy savings, however insulation was still deemed cost-effective [39]. In 1991, Victoria was the first Australian state to introduce minimum residential thermal insulation requirements, which required insulation to be installed in the ceilings and walls. These regulations lifted rated house efficiency from 1 to 2.2 stars, resulting in a modelled average performance improvement from 640 MJ/m$^2$ down to 400 MJ/m$^2$ [40]. In 1994, at least 70% of Victoria homes has ceiling insulation installed [41]. From 2003, the Australian Building Codes Board introduced minimum energy performance requirements into the Australian Building Code (BCA), which have been ratcheting towards greater stringency, with 5 stars modelling to 150 MJ/m$^2$ [40] with the current requirement 6 stars [42] modelling to 120 MJ/m$^2$.

Minimum energy performance standards (MEPS) and energy labelling for gas heaters were developed by the Australian Gas Association, and have been a required part of the gas certification scheme for gas ducted heaters in Australia since the early 1980s [43]. Gas appliances are already near their theoretical maximum efficiency, with commercially available condensing units available with a seasonal operating efficiency of up to 95%; 5-star (>90% eff.) ducted units make up a quarter of current sales, with 60 per cent of sales attributed to 3 and 4-star units, with the minimum efficiency set at 70 per cent. In contrast, the average efficiency of ducted units in the 1970s was 60% [32]. Ductwork is now commercially available with a system efficiency of up to 90% [32].

**Table 1.** Melbourne inflation-adjusted energy prices and Australian average male weekly earnings index relative to 1960. Sources: [18,36,44,45].

| | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 |
|---|---|---|---|---|---|---|
| Gas | 1.00 | 0.70 | 0.39 | 0.32 | 0.32 | 0.45 |
| Electricity | 1.00 | 0.75 | 0.60 | 0.58 | 0.55 | 0.83 |
| Heating oil | 1.00 | 0.76 | 3.08 | 1.78 | 3.27 | 3.28 |
| Earnings | 1.00 | 1.42 | 1.79 | 1.78 | 2.07 | 2.45 |

The substantial stock of gas furnaces and ductwork, with many installed in the 1970s permits ongoing incremental improvements in energy efficiency as appliances and fittings are replaced. The shift to gas represented a substantial efficiency gain over earlier heating, and since the 1970s, the sales-weighted efficiency of gas heaters has been rising steadily. Given that gas heaters are already close to their efficiency ceiling, further long-term structural gains in appliance efficiency gains will come through the use of electric heat pumps given that they can operate with a COP (coefficient of performance) of greater than 3. Single-phase air conditioners and heat pumps have been covered by MEPS since 2004, with the current Australian MEPS at an EER of 3.1 [46].

The efficiency improvement of Australian heating appliances has been unexceptional and has followed international trends. However, the one area in which Australia has led is in the development of single-piece blow-moulded plastic ductwork fittings, which provide a substantial improvement in ductwork leakage relative to sheet-metal fittings. These were introduced in the 1980s due to their lower cost, and eventually achieved market dominance in domestic heating systems.

### *4.2. Current Trends in Melbourne Space Heating*

Figure 5 provides the "main heater type" from ABS survey data in 2005, and in the intervening 7 years, space heating has continued to be dominated by gas heating with a gradual shift from non-ducted to ducted. Table 2 provides an estimate of the stock of the two dominant heating sources in Melbourne; gas ducted and non-ducted. There are currently two trends in the Melbourne space heating market. Firstly, the shift to on-slab construction, driven by the energy efficiency requirements in the Building Code of Australia, has reduced the use of under-floor gas ducted heating, being replaced with ducted heating through ceiling grilles. And secondly, there has been a shift towards wall mounted heat pumps (so called "splits"), also driven by the trend towards on-slab construction, a contractor preference due to the relative ease with which these appliances can be installed, the cash-and-carry sales model of electrical bulk stores, and the fact that they can also be also used for refrigerated air conditioning in summer at no additional capital cost.

**Figure 5.** "Main heater type" Victoria in 2005. Source: [41].

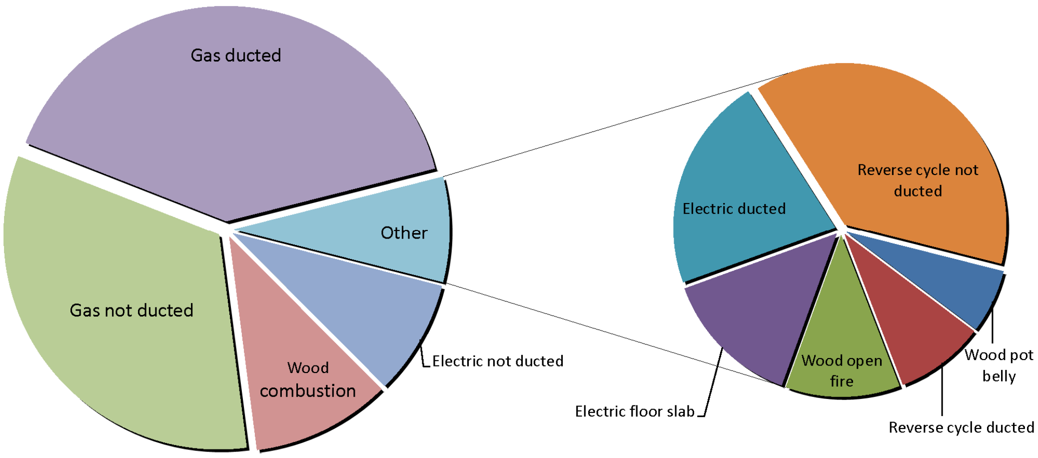



**Table 2.** Victorian gas heater estimates for 2011. Source: author's calculations based on [32,41,47].

| | Non-ducted gas | Ducted gas | Total gas |
|---|---|---|---|
| Estimated appliances | 662,000 | 890,000 | 1,552,000 |
| Average unit power | 10 $kW_{gas}$ | 20 $kW_{gas}$ | |
| Assume annual run-time | 800 hours | 800 hours | |
| Annual energy consumption per appliance | 29 GJ | 58 GJ | |
| Total annual energy consumption | 19 PJ | 52 PJ | 71 PJ |
| Total annual greenhouse emissions @63.6 kg $CO_2$-e/GJ | 1.2 Mt $CO_2$-e | 3.3 Mt $CO_2$-e | 4.5 Mt $CO_2$-e |

### *4.3. Moreland Household Energy Efficiency Retrofit Modelling*

Moreland Energy Foundation [48] conducted a study on potential energy efficiency retrofits on fifteen "typical" Melbourne homes built before the 1990s. The study consisted of detailed on-ground surveys, leakage tests, billing data assessment, and the use of "FirstRate5" house energy rating software to model possible building shell upgrades. No actual upgrades were undertaken, but modelling showed that comprehensive building shell upgrades could lift the modelled average star rating from 1.3 to 4.3. Most of the potential energy savings in potential building shell upgrades could be achieved at an average cost per household of $7,000. The magnitude of actual savings relative to the modelled savings remains unknown since the upgrades weren't actually undertaken.

### *4.4. Gas Heating Ductwork Retrofit Field Study*

In a field study on replacement ductwork for pre-1990s gas ducted heating systems in Melbourne, consisting of ten homes, an average measured energy reduction of 30% was achieved, with an average cost of $1,500 to $2,000 per home [32]. The study measured the actual heat flow into the living space and ductwork leakage, both pre and post ductwork replacement. The study found substantial energy losses through ductwork leakage due to failing ductwork and joins, and thermal losses through inadequate duct insulation. The study results broadly correlated with similar studies conducted in the United States (for example Francisco *et al.* [49], Treidler and Modera [50], Jump *et al.* [51]).

Most clients commented on the improved thermal comfort and shorter warm-up times of the retrofitted systems, which was due to improvements in airflow due to lower leakage and improved installation. The study did not include a follow up of energy bills.

The study probably represents the high-end of available energy savings since the retrofit was conducted carefully using compliant materials, and installed with attention to detail. A key challenge for regulators is maintaining compliance with regulations and standards, given the difficulties in assessing quality. For example, it is not always obvious to a householder or building inspector whether the correct R-value insulation batt has been installed and whether it has been installed correctly. Traditionally, building compliance has focussed on structural integrity, safety, licensing and insurance, rather than the more amorphous measure of thermal efficiency.

## 5. Rebound of Space Heating Efficiency Measures

### *5.1. The Emergence of Jevon's Paradox*

Beginning firstly with Jevons [52], then rediscovered by Brookes [53] and Khazzoom [54], the rebound postulate suggests that increased efficiency firstly lowers consumption thereby lowering costs, but by becoming cheaper, encourages more demand. If the subsequent demand is large enough, no savings really occur, and we have a paradox [55].

### *5.2. The Definition of Rebound*

Despite a general agreement within the energy efficiency literature that some rebound occurs, there is no standard definition or classification [13]; however the classification by Greening [56] provides a convenient reference: "direct", "indirect" and "economy-wide" rebound. In the context of space heating, direct rebound is the tendency for consumers to make greater use of appliances with higher efficiency. For example, a householder may be inclined to use a higher thermostat setting, wear lighter clothing, heat larger areas, or use the heater for longer hours when they have a more energy efficient home or heating appliance. Indirect rebound describes the mechanism by which the energy savings from the use of an efficient appliance is used to purchase other discretionary goods which themselves consume energy, for example the fuel savings from the use of an efficient heater might contribute to an overseas holiday. The "economy-wide" rebound attempts to capture all of the complex interactions within the community that may result from efficiency gains.

The primary concern of Jevons was the depletion of British coal in the nineteenth century, while the re-emergence of Jevons by Brookes and Khazzoom was during a period of concern over oil supply security. Since the contemporary use of energy efficiency is driven by concerns with greenhouse emissions, this paper has used the metric of "per-capita energy" since this provides the most direct route to measuring the aggregate greenhouse emissions–if all the efficiency gains were to be "spent" on improving comfort or larger homes for example, then the efficiency has not contributed to greenhouse abatement at all. Hence, this paper uses rebound as the greenhouse abatement that would otherwise occur, but is "taken back" through "spending" the efficiency gain. No attempt is made to measure the indirect rebound.

### *5.3. Space Heating Rebound Studies*

Household space heating is one of the most commonly studied areas of energy efficiency rebound. The potential "energy savings" from improved energy efficiency are commonly estimated using basic physical principles and engineering models. However, the energy savings that are realised in practice generally fall short of these theoretical engineering estimates [10,55,57,58].

Disputes over the size and importance of rebound effects can result from different choices for system boundaries, measures, and time frames [56]. Nearly all rebound studies are, by necessity, observational, rather than control studies with randomization since it is mostly not practical nor economic to case-control households. There are broadly five types of observational studies of relevance to rebound investigation: engineering estimate, before/after, cross-sectional, matching, and integrated studies. In addition, there are a range of design issues, including the choice of time and spatial scale. Nearly all government energy efficiency programs are based on theoretical engineering estimates, some of which include a small provision for a fixed proportion of rebound (for example the Victorian VEET white certificate scheme includes an explicit 20% rebound and the UK Department of Energy and Climate Change incorporates a 15% rebound for domestic insulation).

In a meta-review analysing the impact of rebound of space heating efficiency measures, Somerville [58] analysed 19 papers from a variety of peer-reviewed, government, and expert sources from the U.S. and Western Europe. The studies included temperature measurement, billing data, and a range of statistical measures in an attempt to measure the actual energy savings in response to efficiency measures. With one exception, none of the studies exceeded 2 years of observations. The exception was a longitudinal study that examined the affect of occupant behaviour on 2 homes with improved insulation, compared with 2 standard homes used as a control. Most of the studies showed some difference between actual and predicted energy savings, with a range of between 10% and 50%.

Similarly, in an evaluation of 9 econometric estimates of rebound for space heating in the OECD, Sorrell [57] found that the range of estimates was between 1.4% and 60%, with a "best guess" of 10 to 30%, noting that the evidence for direct rebound effects is relatively robust to different datasets and methodologies. Maxwell [12] similarly concludes that assertions that rebound effects are generally small (for example; Lovins, Schipper) are not supported by the empirical evidence.

"Backfire" is the condition in which a given improvement in energy efficiency leads to higher energy consumption than if the efficiency measure wasn't undertaken, but Sorrell [57] suggests that backfire is more likely restricted to "pervasive" industries (for example; steel making), rather than household consumer appliances such as space heating.

### *5.4. Short-Run Studies* versus *Long-Run Observations*

Importantly, most of the rebound studies relate to short-run direct rebound, and attempt to capture the difference between the theoretical engineering estimate, and the actual energy use. In particular, there is a focus on capturing the behavioural response of household occupants after having energy efficiency measures installed. None of the studies attempts to capture the long-run impacts on efficiency at a community-wide level, or the evolution of comfort, sufficiency and lifestyle.

It is this contrast, between the readily apparent short-run gains of efficiency, such as demonstrated by the studies in sections 4.3 and 4.4, with the irrefutable increase in aggregate energy over the long run, which is at the heart of disputes over rebound; despite significant and sustained efficiency improvements, space heating energy consumption in 2010 was around 2.2 times that used in 1960. Indeed, it is for this reason that Smil [10] and Alcott [9] note that on a global scale, despite the desirability of energy efficiency and the need to live within ecological limits, the evidence is unequivocal; secular advances in energy efficiency have not led to any decline in aggregate energy consumption.

### *5.5. Estimating the Long-Run Rebound*

An estimation of rebound requires knowing what the energy consumption would have otherwise been in the absence of efficiency measures. Since the counter-factual cannot be observed, there is a need to make assumptions about whether the rebound and lifestyle factors would have happened anyway, leaving a conclusion that will always be subject to debate. A further consideration is that it cannot be assumed that historic trends will continue indefinitely or that elements of the rebound, such as house size or comfort conditions, will not approach saturation. The purpose of this paper is not to establish a decisive figure for rebound, but to draw attention to the significance of the long-run rebound. Alternatively, the question could be re-framed as: what efficiency gain would have been necessary to force the per-capita trend away from unity, given that a greater than ten-fold improvement has evidently not been sufficient? As Table 3 demonstrates, the long-run steadiness of the per-capita energy use is not due solely to the inertia of the existing building stock, but that gas use for new "energy efficient" housing remains stubbornly high.

**Table 3.** Household gas use 1960 to 2006. Note 1: since the early 1970s, space heating has typically constituted 75% of household gas use, however in 1960, the proportion was substantially less. Note 2: 2012 included for comparison of load and efficiency but gas data not available.

| | Estimated annual thermal load ($MJ/m^2$) | Typical gas space heater efficiency (%) | Comparative efficiency to 1960 | Average annual gas use (all uses) (GJ) |
|---|---|---|---|---|
| 1960—average all homes [18] | 750 | 35 | 1.0 | 15 (see note 1) |
| 1975—average all homes [18] | 700 | 60 | 1.8 | 40 |
| 1990—average all homes [18] | 640 | 70 | 2.3 | 52 |
| 2003 *constructed homes only* [59] 4-star | 200 | 75 | 8.0 | 54 |
| 2006 *constructed homes only* [59] 5-star | 150 | 80 | 11.4 | 41 |
| 2012 *constructed homes only*, 6-star | 120 | 90 | 16.1 | (see note 2) |

### *5.6. Targeting the "Impact" Directly*

The so-called IPAT identity provides a useful concept for discussing the drivers of emissions [60]:

$$Impact = Population \times Affluence \times Technology \quad (1)$$

The environmental impacts (e.g., emissions) are the product of the population, affluence (income per capita) and the level of technology deployed (emissions per unit of income). A variation on the identity is referred to as the Kaya identity, and is expressed as:

$$CO2\ Emissions = Population \times (GDP/Population) \times (Energy/GDP) \times (CO2\ /Energy) \quad (2)$$

Of the right-hand side terms in the IPAT identity, the *technology* component is targeted because technological variables seem easier to manage than human behaviour [61], and the *population* and *affluence* elements are largely quarantined from environmental policy. Yet the interdependence of the right-hand elements ensures that any attempt to isolate technology will result in limited net gain in the net impact; for example, improvements in efficiency can lead to increased productivity and therefore affluence.

By way of illustration, it could be argued that the contemporary phenomenon of the "McMansion" (see [62]) is only possible because the average wage earner can now afford to heat an expansive home during winter. Viewed through this alternate and controversial lens, energy efficient heating becomes one of the key drivers of the unconstrained expansion of suburbia, and therefore as much a part of the problem if the objective is building sustainable cities; without a constraint on the overall impact, energy efficiency reduces the barriers to the evolution of comfort and "lifestyle".

One solution is to target the left-hand side term directly through emission caps or Pigouvian taxes [9]; given limits on emissions, the desire to maximise welfare will drive adjustments, with little or no need for policy intervention. The principle of a CO2 cap is to permit the *Energy/GDP* (energy efficiency) and *CO2/Energy* (emission intensity of energy) factors to find their own optimums to satisfy the capped *CO2 Emissions*. Indeed, policy interventions for household energy efficiency, beyond for example, community support programs or manifest market failures, would become redundant and possibly increase the overall cost of abatement. Under a capped emission scenario, energy efficiency becomes one of a number of alternative approaches to meeting an abatement target rather than an objective in itself.

## 6. Winter Peak Loads Due to Space Heating

### *6.1. Conservation Load Factor*

The relationship between energy efficiency measures and the impact on peak demand is not well understood [63], and while energy efficiency programs can lead to reductions in peak demand, measurement of these impacts has not been a priority [64].

The concept of "conservation load factor" (CLF) describes the peakiness of a load, and is a dimensionless number of typically between 0 and 1. A figure of greater than 0.8 represents a temporally "flatter" load, such as a refrigerator, while a figure below 0.2 represents a peaky load, such as exhibited by air conditioners in mild climates. The implication is that a given reduction in energy consumption will provide either a large reduction in peak demand (air conditioner) or a low reduction in peak demand (refrigerator). Koomey *et al*. [65] introduced it as a means of assessing supply and demand-side investment decisions for electrical generators.

In an Australian context, the CLF has been applied to potential energy efficiency strategies [63, 66], however most of the analysis has been applied to electric demand, and mostly to air conditioning, and rely largely on modelling rather than *ex post* analyses. The most thorough analysis in Australia is from the University of Technology, however it doesn't provide a detailed analysis of winter gas heating demand.

### *6.2. Peak Demand of Gas Furnaces*

Gas furnaces are usually on/off appliances, meaning that the appliance runs at full power until the thermostat senses that the indoor space has reached the preset temperature, at which point the appliance switches off (note: modern appliances can have multiple preset gas flow rates, but the principle remains). When a furnace is switched on in the morning or evening, it will operate at 100% duty cycle until it reaches the preset thermostat temperature setting, hence the "peak load" of the appliance is fixed irrespective of the run-time. It is therefore difficult to formulate a relationship between the Melbourne-wide peak demand, and energy efficiency measures. What matters is the number of heaters that are simultaneously running, and their rated power. The demand peak occurs twice daily in Melbourne during winter–typically around 7:00 in the morning, and around 18:00 in the evening (see Figure 6).

In theory, the size (or power rating) of the gas furnace will not alter the total furnace energy consumption for a given heat load, but a smaller furnace will require a longer run-time to deliver a given quantity of energy. The benefit of a smaller furnace (other than cost) is that the instantaneous load on the gas network is reduced. Under steady-state conditions, a smaller furnace can maintain comfort in a home with an efficient building fabric with an acceptable run-time. However a home that has been allowed to cool down requires a significant quantity of energy to raise the temperature of the interior living space, regardless of whether or not the building fabric is efficient. This tends to mitigate against the selection of a smaller furnace by heating contractors, leading to the risk that modelled reductions in peak demand as a consequence of building fabric improvements may be overstated.

To illustrate the complexity of formulating a relationship between energy efficiency and peak load, consider four cases in Table 4 in conjunction with Figure 7, which assume that the peak morning demand occurs between 6:30 and 7:30. These simple examples are formulated to illustrate the challenge in formulating a relationship between efficiency, energy consumption and peak demand, but there are many other possible real-world examples that could demonstrate other elements.

**Figure 6.** Typical winter gas demand in Victoria, excluding large industrial use, based on AEMO "INT271" dataset. Data source: AEMO [67].

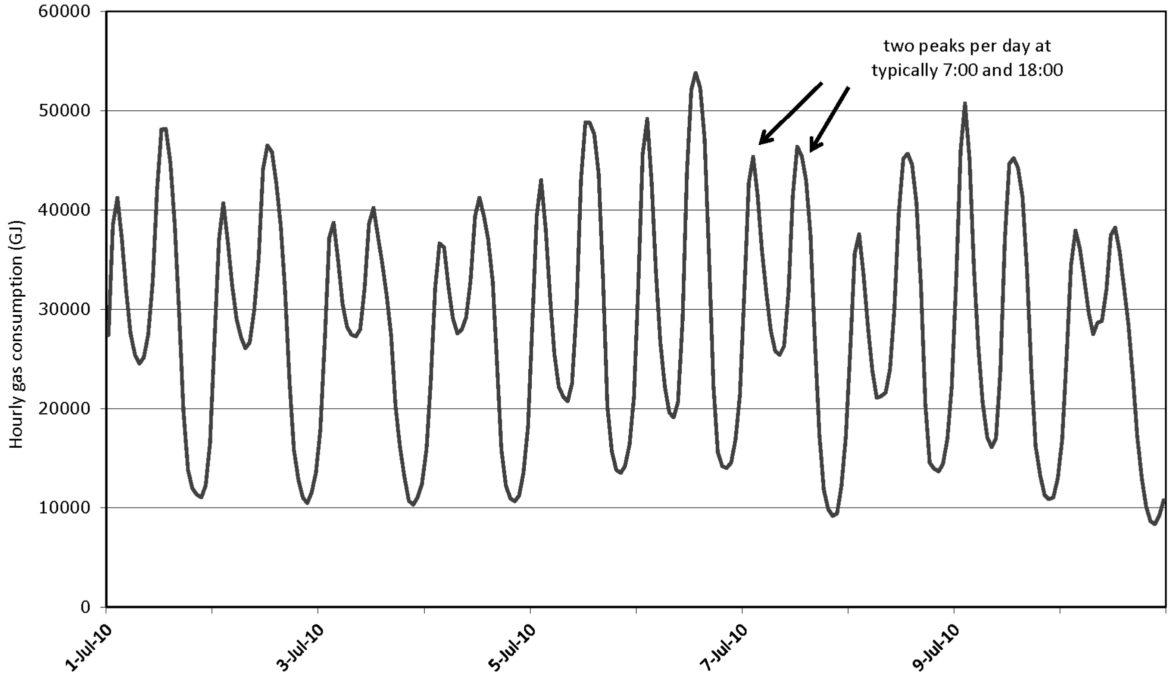
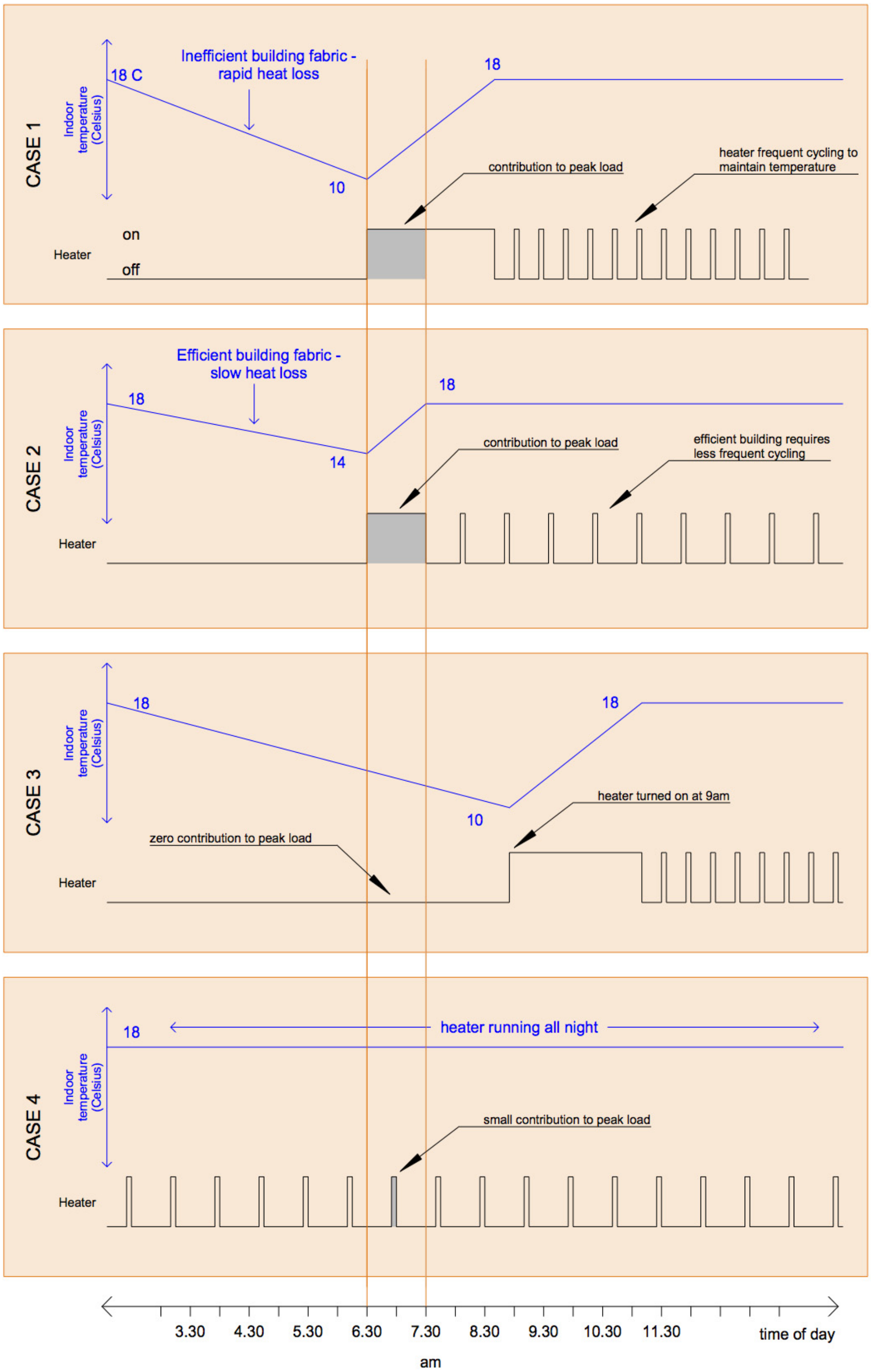



**Table 4.** Four examples linking energy efficiency and peak demand.

| | |
|---|---|
| Case 1 | The building fabric is inefficient leading to a substantial nighttime heat loss, requiring a long furnace run-time in the morning to bring the temperature up to the thermostat setting. Given that the furnace initial run time is two hours, no reasonable energy efficiency measures will have any effect on the peak hour, unless they can reduce the run-time to below one hour. |
| Case 2 | The building fabric is relatively effective in containing heat within the living space. When the heater is switched on at 6.30, the heater runs at 100% duty, but unlike case 1, only runs for one hour instead of two. Despite the highest building fabric efficiency of the four cases, it is the only example in which a further improvement in efficiency would lead to a reduction in peak demand, since the run time coincides with the "peak hour", therefore any reduction in heater run-time would lead to a reduced peak load impact. |
| Case 3 | The heater is not turned on until 9:00, so the building fabric efficiency is irrelevant from a peak demand perspective. Therefore any measures to influence building or equipment efficiency will have no effect on peak demand. |
| Case 4 | In this case, the heater is left running all night, maintaining a constant temperature throughout the night. Given that the heater only needs to cycle to maintain the temperature during the peak hour, this home would only make a small contribution to peak demand. Any efficiency measures would have only a minor effect on peak demand. Given that the temperature is maintained all night, the total energy consumption will be greater than what it would otherwise be if it started in the morning. In this case, an *increase* in energy consumption causes a *decrease* in peak demand. |

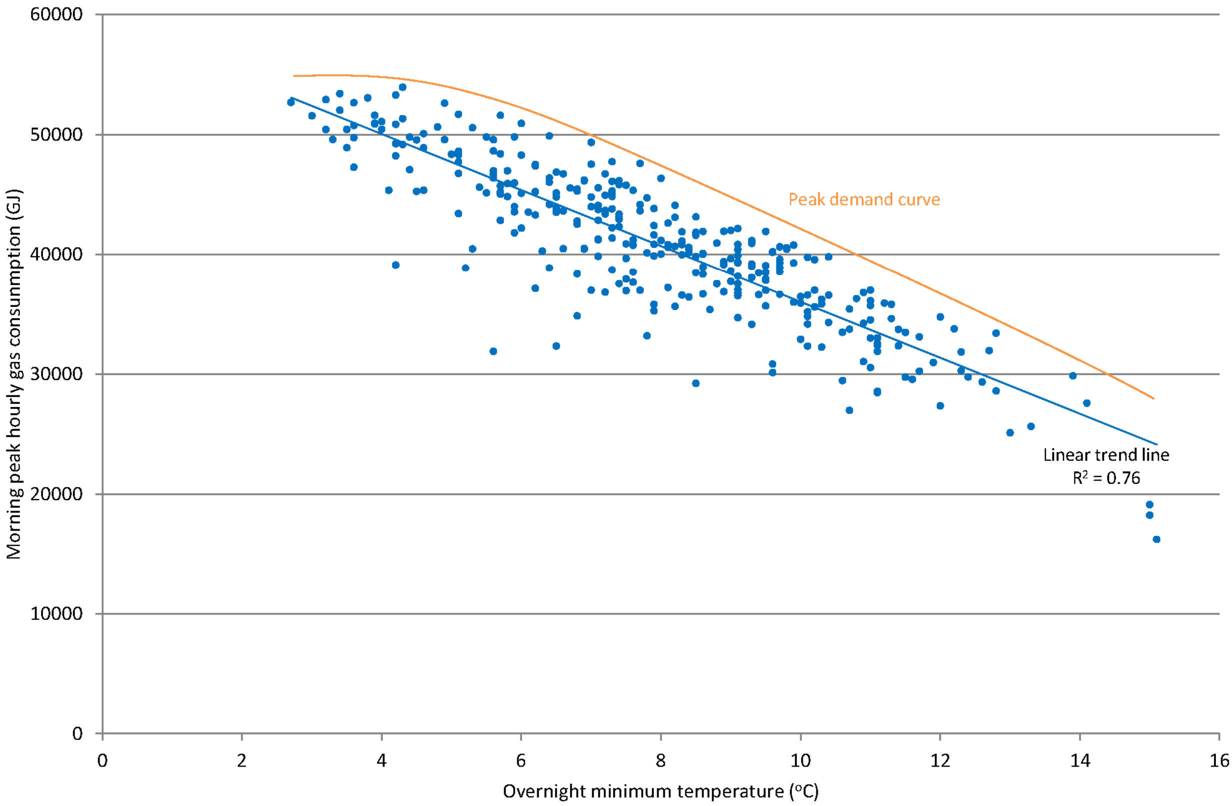
**Figure 7.** Illustration of relationship between energy efficiency and peak demand with peak hour between 6:30 and 7:30.




## *6.3. Heater Load Saturation and the Threshold Temperature*

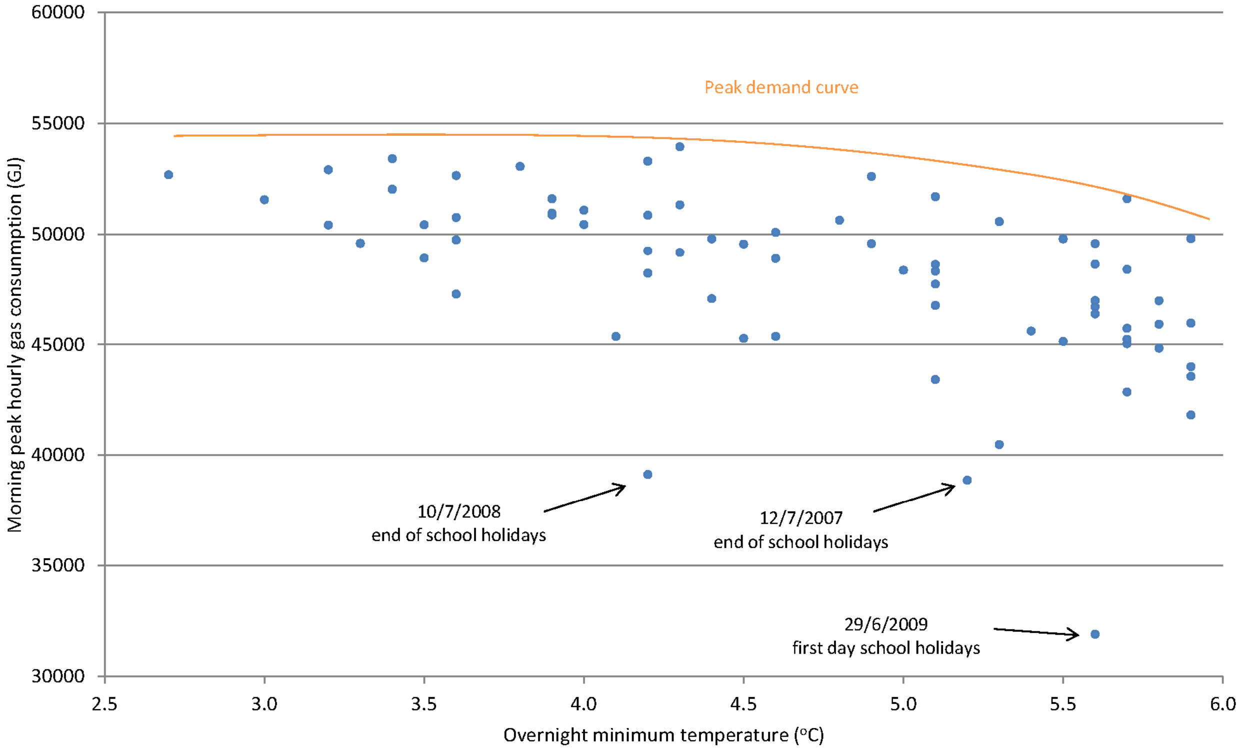
Figure 8 plots the Victorian peak morning demand for June, July and August for the years 2007 through to 2011 against the minimum overnight temperature for BOM station 86071 (note that station 86071 is city-based and typically slightly warmer than many suburban areas). The data is based on the AEMO "INT271" dataset, which excludes large industrial and power generation gas consumers on tariff D using daily metering (see AEMO–Technical Guide to the Wholesale Market [68]). Consumption by residential and small and medium enterprises typically comprises around 60 per cent of Victorian winter peak load, and 50 per cent of annual consumption. In order to avoid confounding, only weekdays were plotted to remove variations from weekend activity and householder behaviour. According to AEMO [69], Melbourne and Geelong make up 81% of Victorian peak gas demand. It is noteworthy that the morning peak typically occurs one hour later on weekends, probably as a result of people arising later on weekends. The evening peak shows a typically higher demand, but displays a less reliable relationship between temperature and demand, probably as a result of greater light industrial and commercial loads.

**Figure 8.** Morning peak gas consumption *versus* minimum overnight temperature 2007 to 2011. Data source: "INT271" from AEMO [67], Bureau of Meteorology.




There is a clear linear fit between the temperature and peak demand with a negative slope, with a regression R-squared of 0.76 indicating a strong relationship between the temperature and peak demand. However, visual inspection of the data shows that there may be a flattening of the peak demand curve at lower temperatures. To further investigate this, another graph was constructed for only the data points below 6 °C (see Figure 9).

**Figure 9.** Morning peak gas consumption *versus* minimum overnight temperature 2007 to 2011 for temperatures below 6 °C. Note different y-axis scale to Figure 8.




The clear linear trend that is apparent in Figure 8 has mostly abated at lower temperatures, and with the exception of some outliers, most of the data points are concentrated within a boundary of 45,000 to 54,000 GJ/hour. The three most significant outliers occur at the beginning or end of school holidays, suggesting that the holidays provide an opportunity for families to sleep in, and thereby run their heating systems later than the usual 7:00 morning peak hour.

A possible explanation for the levelling off of the peak demand curve is that below a given *threshold temperature*, a large number of Victorian heaters are running at 100% duty cycle throughout the peak-hour. Since the heaters cannot "work any harder", then regardless of how much colder the morning, the aggregate demand on the gas network will not substantially increase, hence the heating load is *saturated*. The result is a large number of heaters exhibiting the characteristic shown in case 1 in Figure 7 and Table 5. The implication is that a marginal increase in energy efficiency, even if it leads to a marginal reduction in energy consumption, may not lead to a commensurate reduction in annual peak load. Together with an aversion to under-sizing of heaters, this has important implications in the event of a large scale shift to electrical heating.

Table 5 shows the linear trend results for the five years studied. Interestingly, the trend line appears to be flattening over successive years, such that at 14 °C, there appears to be an average year-on-year growth of 3.2%, but at low overnight temperatures, the growth is close to zero. It is not clear why the year-on-year trend exhibits this behaviour, however some causes may include:

1. Given that most of the demand growth is from new buildings, the increased thermal efficiency of the new building fabrics may result in a flatter trend than the existing housing stock, such that at

lower ambient temperatures, new buildings tend to maintain a higher indoor temperature. This may be lowering the "threshold temperature" and limiting peak demand growth.

2. Householder behaviour of new buildings may differ from the average resulting in a flatter trend. For example, if new homeowners have a greater tendency to leave heaters on overnight, the morning peak may be flatter.

**Table 5.** Linear trend results for morning peak demand (GJ/hour) *versus* minimum overnight temperature for 4 °C and 14 °C.

| | Trend equation (GJ/hour) | *t* = 4 °C | *t* = 14 °C | $R^2$ |
|---|---|---|---|---|
| 2011 | 58,857–2212 *t* | 50,009 | 27,889 | 0.85 |
| 2010 | 58,555–2158 *t* | 49,923 | 28,343 | 0.67 |
| 2009 | 60,017–2377 *t* | 50,509 | 26,739 | 0.76 |
| 2008 | 59,154–2334 *t* | 49,818 | 26,418 | 0.77 |
| 2007 | 59,045–2447 *t* | 49,257 | 24,787 | 0.77 |

### *6.4. Testing the Saturation Hypothesis—The Home Insulation Program*

The Australian Government home insulation program (HIP) provides an opportunity to test the hypothesis that improving the efficiency of relatively inefficient building stock may reduce energy consumption but may not lead to a commensurate reduction in peak demand. It also provides a convenient check on the realistic, rather than theoretical impact of large-scale energy efficiency programs.

The program was announced in February 2009 with the aim of installing ceiling insulation into 2.2 million homes, and providing support for employment during the global financial crisis [70]. The Department of Climate Change suggested that the program might provide a reduction of up to 40 per cent in heating costs [70]. The scheme was terminated in February 2010 with ceiling insulation installed in over 1 million Australian homes. There were 279,344 Victorian homes insulated [71], which is 13% of Victoria's 2.1 million households, which began at a cost of $1,600 per home, but was reduced to $1,200. Most Victorian homes already had insulation [41], and given that the program was only permitted to fund homes with inadequate insulation [72], the targeted funding should have been able to deliver the most effective energy outcomes. Hawke [70] also identified non-compliance with the relevant Australian Standard (AS4859.1:2002) and varying quality of installation.

Given that most of the Victorian homes were insulated in the period from mid 2009 to early 2010, a comparison of winter demand between 2009 and 2010 should provide an indication of the effectiveness of the scheme in reducing peak demand and energy consumption, and indeed, one analysis suggested that a reduction of 1.0 to 1.5 PJ per annum in gas consumption may have occurred [71]. Of interest is that the large scale "Green Loans" program ran concurrently with the HIP program, which provided energy efficiency assessments to 360,000 homes Australia-wide. However, the uptake of a loan was of the order of 1% [73], suggesting that the program would have had no discernable effect on aggregate energy consumption.

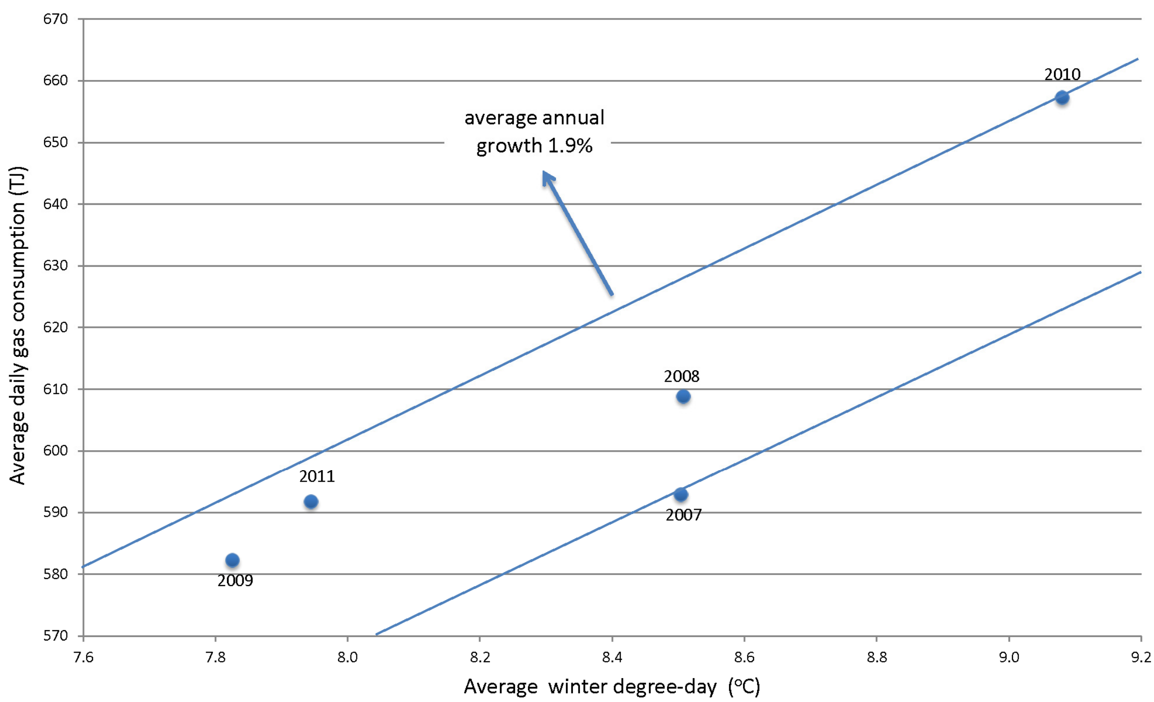
A comparison of the peak demand for the winter months of 2007 to 2011 using AEMO [67] data shows a linear relationship between the morning peak demand and minimum overnight temperature, with a high R-squared value for all years demonstrating a strong correlation. The dataset was limited to weekdays during winter in order to reduce weekend/weekday confounding and to try to draw out the heating trend. Referring to Table 5, which tabulates the five years of linear trend lines over the years 2007 to 2011, it is not obvious that any reduction in peak demand occurred between 2009 and 2010; indeed the trend shows an increase, probably due to the 2010 winter being cooler than 2009.

Using the same dataset and plotting the [*average daily gas consumption*] *versus* the [*daily "degree-day"*] permits the daily gas consumption to be normalized for temperature, exposing the annual growth rate in consumption. The "degree day" provides a measure of the difference between a standard indoor temperature and the outdoor temperature. The Victorian gas industry makes use of a more sophisticated formula for forecasting purposes (see [74,75]). In this case, a "base temperature" of 20 °C was used, however the choice of base temperature does not significantly alter the trend outcome. The "degree day" used BOM station 86071 temperature data, and is defined as:

$$\textit{base temperature} - [(\textit{maximum daily temperature} + \textit{minimum daily temperature})/2] \quad (3)$$

Referring to Figure 10, the annual growth between 2007 and 2010 appears unexceptional; however 2011 shows a slight decline and 2010 was noticeably cooler (higher degree-day) than the other four studied years. A reasonable conclusion to be drawn is that between 2009 and 2011 there was a net reduction in consumption from the growth trend, and that there may have been a decline from 2009 to 2010 except that the cooler winter of 2010 obscured the decline. The "degree day" method supports the conclusion that the HIP program led to a reduction in energy consumption equivalent to delaying consumption growth by two years at a calculated abatement cost of AUD 238/tonne $CO_2$-e, assuming no indirect or economy-wide rebound (see Table 6); however any reduction in daily peak demand is not evident using the linear regression peak demand analysis.

**Figure 10.** Average "degree-day" *versus* average daily gas consumption for winter week days 2007 to 2011 using "INT271" dataset.



The HIP program adds weight to the postulate that improving the efficiency of relatively inefficient housing will lead to a reduction in energy consumption, but may not lead to a commensurate reduction in peak demand. Of concern is that the actual abatement cost was significantly higher than the "below-cost" estimates that some authoritative modelling typically suggests (for example page 38 [3]).

**Table 6.** Greenhouse abatement cost for HIPS program in Victoria. Source: author's calculations.

| | |
|---|---|
| Assume annual natural gas reduction<br>150 days @ average 15 TJ/day<br>(Compare NIEIR estimate of 1.0 to 1.5 PJ [71]) | 2.3 PJ |
| Abatement per year @ 63.6 kg $CO_2$-e/GJ | 0.14 Mt $CO_2$-e |
| Assumed life of abatement–refer [76] | 10 years |
| Total abatement | 1.4 Mt $CO_2$-e |
| Victorian households participating in program | 279,344 |
| Assumed proportion of households using gas for heating | 75% |
| Cost per household | AUD 1,600 |
| Calculated abatement cost | AUD 238/tonne $CO_2$-e |

The problems associated with the HIPS program were unsurprising given the rapid and significant expansion of the industry, which drew in large numbers of opportunistic operators using minimally qualified labour. Following the sudden end of the program, industry sources indicated that some insulation suppliers were forced to dispose of large quantities of unused batts to land-fill.

In contrast, the widespread promotion and Victorian Government support for household water tanks has been much less controversial, and may provide lessons for the adoption of future energy efficiency programs. In the case of water tanks, work is required to be performed by qualified and licenced plumbers, along with a significant householder co-payment. This has avoided some of the problems inherent in programs such as the HIPS and Green Loans schemes, which have been subject to opportunistic targeting by operators, in which long-term reputation and consumer satisfaction are not primary business objectives.

## 7. Implications of a Widespread Conversion to Electric Heat Pumps

### *7.1. A Market Shift to Electric Heat Pumps*

In recent years, there has been a substantial shift towards heat pump systems to provide winter heating and summer cooling. Although only 4 per cent of Victorian households used heat pump heating as the main form of heating in 2005, 22 per cent of Victorian households had a heat pump cooler installed [41], a figure which has continued to increase since 2005. The cost difference of optioning heat pump heating, compared to a cooling only model, is usually relatively small, providing an incentive to purchase the heating option, even if it is not expected to be regularly used. Wall mounted split systems are sometimes favoured by builders and contractors, due to the ease with which they can be installed, particularly if the building or block layout makes it difficult to install ductwork or a ducted gas furnace. Additionally, with limited technical training and a "cash and carry" sales model, electrical bulk stores have a strong bias towards selling wall mounted split systems. Electrical bulk stores now dominate the residential air conditioning market, and it is expected that heat pump units will continue to increase their market share of the cooling market [77]. Further, some energy efficiency advocates promote air conditioners and heat pumps due to their relatively high COP, particularly when the most efficient models are chosen [7,78,79].

When the COP of heat pumps is taken into account, the running cost of high efficiency heat pump heating may compare favourably with natural gas in moderate winter climates, depending on the respective tariffs [32]. However in terms of greenhouse emissions, most of the efficiency gain is negated by the high greenhouse intensity of Victorian electricity generation.

One of the drawbacks of wall mounted split units is the reduction in the air distribution performance and increase in stratification, which are inherent characteristics of having a closely positioned supply and return air, and high positioned warm supply air. Depending on the supply grille type and position, ducted heat pump systems have improved distribution of heated air, combined with regular air changes due to the system fan drawing air back to a return air grille.

### *7.2. Heat Pump Operation in Cold Conditions*

Heat pumps operate with reduced performance at low outdoor temperatures, with the COP dropping 30 to 40 per cent at outdoor temperatures below 6 °C [77]. At low outdoor temperatures, ice builds up on the evaporator coil, necessitating the use of a defrost cycle to de-ice the coil. This is usually accomplished by reversing the refrigerant flow and running the equipment in cooling mode, thereby warming the evaporator. During this period, the indoor unit produces cool air, and the indoor fan unit will be operated at low speed to reduce occupant discomfort. This increases energy consumption, and reduces heating performance when it is most needed. Critically, the operation cycle time is significantly increased, with the equipment compressor running at a high duty cycle throughout the heating and defrost period. This has implications for the estimate of peak demand on very cold days, in which the predicted run-time of equipment based on outdoor temperature may be significantly understated.

Ground source heat pumps, in which the outdoor evaporator coil is warmed by the ground, overcome the need for a defrost cycle in cold climates, and generally provide a slightly higher COP. However, they are substantially more capital expensive due to the need to employ drilling or excavation equipment and install a piping system, costing typically double to triple the cost of an equivalent air-based system. There may be opportunities to develop a market for ground source systems, particularly for new "green" developments, however cost, space and other practical limitations will constrain their large-scale take-up in Melbourne.

### *7.3. Transfer of Gas Load to Electrical Load*

Peak electrical demand in Victoria is currently 2000 MWe below the summer peak [80] providing significant headroom for an increase in winter demand. This has permitted additional winter loads to "piggy back" onto the network upgrades required for summer loads while most attention to peak demand has focused on summer air conditioning. However, the current hourly gas peak is 83 TJ per hour or 23,000 $MW_{gas}$ averaged over the hour (page 1–14 [69], all gas use). Although residential use only makes up 34% of annual gas consumption [81], it is estimated that half of the winter peak demand is due to residential heating. Hot water heating typically compromises less than a quarter of the energy of space heating during the winter months. The extensive use of storage systems limits the contribution to peak demand, although the increased use of instant services would be expected to increase the morning peak load.

If all of the current gas heating load were transferred to electric heat pump, the resulting winter electrical peak would likely exceed the summer peak by a significant margin. However the actual peak is highly dependent on the specific heating equipment installed and complicated by operational differences between gas furnaces and heat pumps, and the impact of heat pump defrost cycling on cold days. It should be noted that inverter heat pumps will present only a part electrical load at moderate heating loads, but nonetheless will present full electrical load on the coldest mornings.

### *7. 4. Gas Networks and Peak Demand Smoothing with "Linepack"*

Unlike electricity, which requires a constant and dynamic operation of the network to maintain a constant balance between supply and demand, the Victorian gas network operates with a significant "linepack". As well as functioning as the transmission medium, the pipelines store gas under high pressure in large diameter pipelines, which also operate as a storage medium permitting the continued supply of gas for hours, up to several days, even with a stoppage of injection. The gas pipeline between Longford and Dandenong is 750 mm diameter, 173 km long and operates at up to 6750 kPa with injections of up to 1030 TJ per day [80]. The Victorian gas network also includes an LNG storage facility at Dandenong with a capacity of 12,000 tonne (659 TJ), permitting injections on high demand days, or in the event of restrained supply or transmission failure from Longford or Iona [80]. Further, the cost of upgrading the Victorian gas transmission and distribution network is much less expensive than upgrading the electricity network [63].

### *7.5. Peak Demand Reduction through Demand Management, Storage, and Smart Grids*

Smart grids refer to a range of technologies to monitor and manage the electricity network to improve the varying electricity demands of end-users, and improve the utilisation of non-dispatchable renewable sources [82]. At a household level, smart grid technology is considered a key tool in reducing network congestion in response to the increasing penetration of air conditioners [82]. For example, load-control devices have been successfully trialled on air conditioners to cycle compressors during periods of peak demand to moderate air-conditioning loads [83].

### *7.6. The Challenge of Maintaining Social Justice with Differential Energy Pricing*

The degree to which smart grid technology can be applied to household space heating is less obvious. The minimum temperature in Melbourne surrounds drops to near-freezing conditions on some winter mornings (for example, an eastern suburb, Scoresby, recorded an overnight minimum of below 1 °C on four mornings in 2010 and below 5 °C on 53 mornings in 2010). As such, heating has never been considered discretionary in Melbourne—in 2008, 99.8% of Victorian homes had at least one heater, but in 1994 for example, only 37% of households had a cooler [41]. As an essential service, the issue of households having access to sufficient space heating is sufficiently important to attract a range of government and community assistance [84,85]. Indeed, social justice and sustainability advocates highlighted the importance of low-income and disadvantaged households having access to affordable heating (and cooling) following the introduction of smart meters [86]. For example, the Victorian Council of Social Service [87] suggested that the "assumed enthusiasm for access to detailed information about electricity and differential pricing" is overstated, and that the majority of households are not concerned about "optimising their usage patterns", but rather, want access to affordable and reliable heating. Although extreme heat has been identified as more of a concern than extreme cold in Australia, the availability of adequate and affordable heating is a factor in reducing the risk of thermal illness in vulnerable people, such as the elderly or those with chronic illness [15].

### *7.7. Smart Grids and Electricity Storage*

Smart grids may permit the use of grid-based electricity storage to respond to demand peaks and provide a range of ancillary applications, such as wholesale market arbitrage, frequency regulation, wind integration support, photovoltaic time-shifting and other functions. With the exception of pumped hydro and compressed air storage, all grid-based storage technologies are currently uncompetitive relative to gas-fired generation for renewable integration or time-shifting applications (see Figure 5-3 in [88]), however future cost reductions may improve their competitiveness. For example, the prospect of a market shift towards electric vehicles (EVs) has been suggested as an enabler of intermittent renewable energy sources; however, given the high cost of EV batteries and their cycle-limited life, consumers would need an exceptional premium from network operators to justify limiting the life span of their batteries (and therefore possibly the resale value of the vehicle) with additional regular discharge and charge cycles [82].

The economic viability of grid-based storage for time-shifting applications is underpinned by a large wholesale price differential between the discharge and charge cycles, sufficient regular utilisation to recoup the capital investment, and the availability of a steady supply of reliable power during charging [89]. Melbourne's winter heating demand profile consists of two sharp daily peaks in demand, and the use of electrical storage would require a reliable daily supply of inexpensive power to recharge the storage. The only power sources that have the prospect of being both inexpensive and available on a predictable daily basis are baseload, thereby arbitraging between low-cost off-peak baseload and high-cost peak load. In the context of meeting winter heating demand, a more cost-effective storage process is to utilise the high heat capacity of water for energy storage, which is discussed further in section 9.

## 8. Sensible Regulation or the Institutionalisation of Unsustainable Habits?

### *8.1. House Energy Rating Schemes*

House Energy Rating Schemes (HERS) have been developed to measure the inherent thermal performance of the building shell in order to reduce energy consumption [90,91]. The energy rating tools are not intended to measure actual energy performance, but rather, measure the inherent thermal performance of the building shell with all other things being equal, and provide a means to rank the performance of one house compared to the other.

### *8.2. Criticisms of Rating Schemes*

Williamson [92] has been critical of the use of ratings tools and the concept of "generic needs", claiming that the assessment processes underpinning the building regulations do not correlate well with measured environmental performance, and fail to account for the "diversity of socio-cultural understandings, the inhabitants' expectations and their behaviours". Kordjamshidi [93] notes that simulated results, which are based as standardized conditions, can vary substantially from actual energy use due to variations in occupancy behaviour. Bannister [94] notes that "... there appears to be little correlation between the immediately recognisable components of good design and good performance", citing a raft of factors that impacted on the operational efficiency of office buildings.

Rating tools can also lead to unintended consequences. For example, a larger home generates a higher score than an equivalent smaller home when judged by the normalized index since geometrically, larger homes gain proportionally more interior space relative to exterior fabric area. But rating tools do not penalise larger homes even though it is obvious that they consume more energy, leading to the perverse outcome that rating tools favours homes that consume more energy, but do so "more efficiently".

Similarly, concrete slab construction achieves a relatively better rating than timber floors [95], subsequently leading to comparatively greater use of on-slab construction. This has encouraged a market shift from under-floor gas ducted heating to ceiling-based ducted heating and wall-mounted split systems, both of which exhibit greater levels of stratification, and provide less effective air distribution than under-floor ducted heating [32]. Further, energy rating schemes assume the standard use of heaters and coolers, even if none are installed, and cannot adequately assess "free-running" buildings, a point Soebarto [90] highlighted in a study that compared the actual performance with the predicted energy rating. Despite performing well in terms of comfort conditions, energy use and environmental impact, the home received a very low rating when examined with NatHERS. Indeed, many purpose-built, low-energy homes could not comply with efficiency standards as judged by rating schemes, because non-standard and novel low-energy features are not permitted within the software.

### *8.3. Legitimising Unsustainable Habits?*

Shove argues that we need to come to terms with the limits of policy intervention, since policy tools risk legitimising and fostering the "standardisation of unsustainable habits and expectations" [23]. In the long-run, policy interventions are likely to prove ineffective or counterproductive since a focus on technical energy efficiency denigrates the overall notion of sufficiency [96]. Indeed, the pursuit of technical efficiency as an environmental goal in itself, deludes us into believing that progress is being made, even while the broad indicators of environmental impact worsen [97].

## 9. Low Emission Power: A Way Forward or "Back to the Future"?

### *9.1. Energy Storage Using Hot Water*

Assuming that Victorians are going to continue demanding affordable and reliable winter heating, what are the options to provide this while reducing emissions with strong population growth? A glimpse into the past perhaps provides some clues. Domestic hot-water services and hydronic central heating have been available in Melbourne since the 1920s, with off-peak electricity rates available from the 1930s [98], and the installation rate of both electric and gas hot water services accelerated from the late 1940s in response to falling real prices and the convenience they afforded. From the mid-1960s, a storage space heating tariff was available at the same rate as the hot water tariff. Off-peak hot water, and to a lesser degree storage space heating, has traditionally provided an important load shifting role in Victoria, reducing peak daytime load, and increasing night time load to improve the utilisation of baseload generation [99]. But the high emission intensity of resistance element hot water has led to a regulatory phase-out of these heaters, with the encouragement of solar, electric heat pump, and gas [100], with storage space heating now a rarity.

In the event of a large-scale shift from gas heating, the availability of baseload generation provides an opportunity to encourage off-peak tariffs to power electric heat pump hot water systems, which could provide a valuable role in smoothing the daily space heating load and contribute to affordable heating. Hydronic heating through radiators or coils is already used, and water-to-air heat exchangers are readily available, which would permit hot water storage to function with forced-air heating with or without ducting. For example, 500 litres of hot water that is allowed to cool from 80 to 60 °C, will release 42 MJ of energy, representing 20 kW of power for 35 minutes. The use of hot water would also permit evacuated tube solar collectors to be incorporated into systems to supplement electric supply and to be integrated into the hot water system. Melbourne's winter climate has tended to favour heating systems with a short thermal time constant, especially forced-air systems, since the interspersion of moderate daytime temperatures with cold conditions favours heating systems that can be readily shut down to reduce energy use and prevent temperature overshoot during the day.

### *9.2. Baseload Electricity Generation*

Excluding gas, there are currently four "fit-for-service" low-emission baseload options available; coal with carbon capture and storage (CCS), nuclear fission, concentrated solar thermal (CSP) with gas backup, and possibly engineered geothermal [101]. All of these could potentially provide a large proportion of Victoria's electricity, but all face serious technical, economic, or social barriers to their introduction [102]. The inertia inherent in energy systems ensures that any potential energy source that will be contributing a majority share of Victoria's energy by mid-century would need to be already commercially available or close to rapid deployment [103]. Since electricity is an undifferentiated product, the sale of electrons from an innovative low-emission generator, even if it captures the public's imagination, has little scope to offset first-mover risks against potential rewards [104].

1. The first Australian commercial deployment of coal with CCS is projected to be at least 8 to 10 years away and demonstration will likely require government to take on some of the risks of

the project, particularly given the need to integrate development across multiple scientific and engineering disciplines. CCS will necessarily be significantly more expensive than unsequestered coal and will face substantial logistic and scaling challenges [102,105,106].

2. The State Electricity Commission of Victoria was weighing up the option of nuclear from the late 1960s, but the relatively cheaper cost of coal-fired generation and the ready availability of abundant lignite removed the incentive to develop alternative baseload sources [99,107,108]. According to the recent Australian draft energy white paper [105], there is no near-term prospect of Australia adopting nuclear since it currently "lacks the necessary social consensus", however in the absence of the successful deployment of low-emission baseload, the nuclear option may be revisited and could meet a large proportion of Australia's energy demand at a competitive cost assuming a moderate carbon price and a supportive regulatory environment [109].
3. There was strong interest in CSP in the 1980s and 90s, mostly in parabolic trough designs, but renewed interest in recent years has explored tower, dish and Fresnel designs. The primary strength of CSP is supplying peak and intermediate loads during summer in regions with strong sunshine and clear skies [110]. The fundamental challenge for CSP in winter is that solar supply and heating demand are inversely correlated, which is exacerbated by the thermal threshold characteristic of CSP, causing a sharp drop-off in electricity below a threshold daily insolation [111]. Trainer [112] notes that even high insolation regions in central Australia regularly experience sequences of several cloudy days in a row in winter during which little or no electricity would be generated without backup. In the context of meeting Melbourne's large winter heating load, it would make little sense to decommission gas furnaces in Melbourne and retrofit heat pumps powered by remote CSP plants, which themselves rely on large-scale natural gas during winter. CSP is significantly more costly than competing low-emission technologies, although future cost reductions are expected [101,113].
4. Research on engineered geothermal showed early promise in the USA from the 1970s [114], and has been regarded with optimism more recently in Australia [115]. However the technology has failed to proceed to early commercialisation in Australia and there remains uncertainty as to its long-term future. Reliability and costs are highly uncertain given the early stage of development [102,116].

### *9.3. Gas-Fired Generation*

In relation to gas-fired generation, it makes more sense to combust gas directly in household appliances, rather than retrofitting electric heat pumps driven by gas-fired generation; in theory, the net energy efficiency of the most efficient gas-fired baseload generation in combination with high efficiency residential heat pumps is higher than combusting gas in household furnaces. However the gas distribution network is far more effective at meeting the large winter load, and the primary use of gas in Australia has been in lower-efficiency open-cycle plants to meet infrequent peak loads, and more recently to provide firming for wind generation.

### *9.4. Wind*

There are many potential renewable options, of which wind is currently the most commercial; however wind lacks the key attribute of dispatchability, and its stochastic nature renders it a supplementary rather than a "firm" energy source (see page 75 [117]), providing an upper limit on grid penetration to around 20% [113]. For example, during the winter months of June, July and August 2010, the total Australian National Electricity Market (NEM) wind output exceeded 30% of rated capacity for around half of the time; however the output was below 10% for 26% of the time, and below 5% for 14% of the time [118]. The problem with wind generation in winter is that the passage of large high-pressure systems across the Australian continent leads to calm conditions across large regions for 2 to 3 days. For example, on 20 and 21 June 2010, the combined NEM wind output dropped below 6% of capacity for 33 hours continuous and remained below 3% for 12 hours continuous, co-incident with a minimum overnight temperature in Melbourne of 5.8 °C. Similar continent-wide synoptic events occurred in the same month from the 1st to 5th and 13th to 16th.

In the future, hydrogen storage could be combined with wind generation to "firm" wind output, and thereby substantially improve the capacity credit of wind, however key challenges to large-scale deployment would include cost, and the reliance on fossil fuelled energy to rapidly scale the infrastructure and the accompanying greenhouse emissions [119], and the limited capacity for wind energy to rapidly scale by "bootstrapping" its own energy [120].

### *9.5. Household Solar Air Heating*

All solar-based home heating options (for example; "Sun Lizard", "HRV") confront the same hurdle: they can provide supplementary heating when there is sufficient winter sunlight but cannot fulfil the primary role of providing heat when it is most needed; on cold winter mornings and evenings, and during daytime inclement weather [32].

### *9.6. Wood Heating*

Split wood is already used extensively in rural Victoria [37] and the potential exists for the expanded use of split wood or wood pellets for heating. Depending on a number of assumptions, wood can provide low emission heating [121], however it may also raise other issues, including impacts on biodiversity, wildlife, and land degradation [122]. Within the Melbourne urban environment, practical limitations including the resulting local air pollution, logistical challenges of large-scale solid fuel distribution and storage, high fuel and distribution costs, and lack of large-scale readily available supply constrain the potential for wood fuel when used as the primary form of heating [123].

## 10. Conclusions

The rebound effects of Melbourne's space heating efficiency gains have been significant, nearly always understated, and appear to be bound up with evolving notions of comfort, sufficiency and lifestyle. Policy prescriptions based around the "soft-energy path", which capture the public's imagination, can easily overlook the practicalities of the provision of affordable and reliable heating. In the context of capped emissions, energy efficiency could play a valuable role in maintaining consumer utility while reducing emissions; however the focus on technical efficiency as a greenhouse mitigation strategy *in itself* distracts from other efficacious greenhouse mitigation measures based on conventional energy supply, and avoids the more challenging social debates around population, sufficiency, and comfort.

**Conflict of Interest**

The author declares no conflict of interest.

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