Chapter 2
The State of the World

In the fourth assessment report of the UN Intergovernmental Panel for Climate Change (IPCC), the *robust finding* [defined as that which 'holds under a variety of approaches, methods, models and assumptions, and is expected to be relatively unaffected by uncertainties' (IPCC, 2007, AR4 SYR—Topic 6)] was that 'warming of the climate system is unequivocal,' and that 'most of the global average warming over the past 50 years is *very likely* due to anthropogenic Green House Gases (GHG) increases' (IPCC, 2007, AR4, 6.1). The IPCC also identified the building industry as the one with the most climate mitigation potential (Table 2.1). When Time Magazine (Kluger 2007) ran a special feature called *The Global Warming Survival Guide,* buildings accounted for the largest share of U.S. emissions, noting that:

> While the power and auto industries get the bulk of the blame for the planet's carbon crisis, the business of operating office buildings and homes is responsible for 38 % of U.S. CO2 emissions. In the case of offices, mid-20th century technology worked against us, as the development of low-temperature fluorescent lights and high-powered air conditioning made it possible to design sealed structures that you could drop into any climate. "It gave architects the power to design anything, then hand it over to engineers and say, 'Here, you heat and cool it,'" says Gail Brager of the Center for the Built Environment at the University of California, Berkeley.

Politicians on the other hand have had little will to commit to the recommended CO_2 abatement measures. With the 20-year long history of UN Climate Change Conferences (Table 2.2), it has become clear that an environmental imperative was not enough to demand a political response when the immediate economic costs were too high.

Since preindustrial times, the CO_2 emissions have increased by 'about 36 %, with the rate of increase being about 2 ppm per year and still increasing' (Bolin 2007, p. 215). The lack of political will is even more stark when considered against the availability of technologies and plans for CO2 mitigation. Pacala and Socolow (2004) explained the need to stabilise carbon emissions at present levels, which require substituting the business as usual (BAU) industries with existing sustainable technologies. Their multi-faceted approach is construed as an aggregate of

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Table 2.1 Economic mitigation potential in 2030 (IPCC 2007)

	Gt CO2-eq-year
Buildings	5.3–6.7
Agriculture	2.3–6.4
Industry	2.5–5.5
Energy supply	2.4–4.7
Forestry	1.3–4.2
Transport	1.6–2.5
Waste	0.4–1

wedges. Each wedge accounts for a reduction of 1 billion tons of carbon per year (Fig. 2.1 and Table 2.3). In 2004 when the paper was first published, it was anticipated seven wedges would be needed for stabilisation; and in 2011, it was increased to nine wedges, and would have resulted in ~0.5 °C higher stabilisation in temperature compared to 2004 (Socolow 2011). Further delays to act will only exacerbate an already monumental effort for transformation.

Table 2.2 History of climate change policy (Umashankar et al. 2009), mitigation outcomes (Lomborg 2010) and CO_2 ppm (NOAA 2012)

Year	Conference	Atmospheric CO2 concentration (ppm)	Mitigation outcomes
1992	Earth summit, Rio de Janeiro	356	to cut CO2 to 1990 levels by 2000
1995	'Conference of the parties' COP1, Berlin	361	
1996	COP2, Geneva	363	
1997	COP3, Kyoto	364	Kyoto Protocol: to cut CO2 to 5.2 % below 1990 levels by 2012
1998	COP4, Buenos aires	367	
1999	COP5, Bonn	368	
2000	COP6, The hague	370	
2001	COP6 (extraordinary conference), Bonn	371	
2001	COP7, Marrakesh	371	
2002	COP8, Delhi	373	
2003	COP9, Milan	376	
2004	COPIO, Buenos aires	377	
2005	COP11, Montreal	380	
2006	COP12, Nairobi	382	
2007	COP13, Bali	384	
2008	COP14, Poznan	386	
2009	COP15, Copenhagen	387	Copenhagen accord had no legally binding commitments
2010	COP16, Cancun	390	
2011	COP17, South Africa	392	

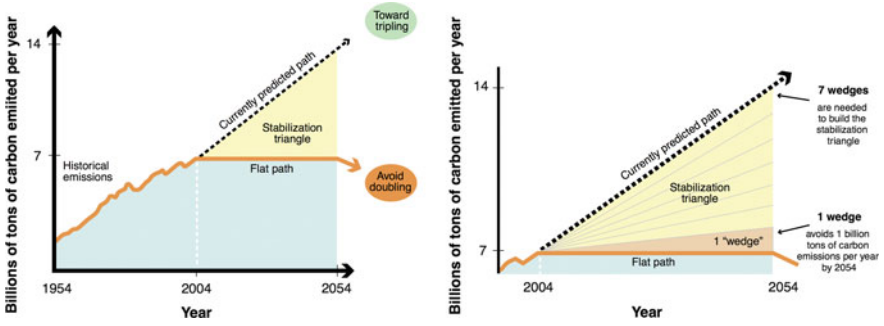

Fig. 2.1 Stabilisation wedges (Pacala and Socolow 2004)

By looking at the whole mosaic of stabilisation solutions we see that the energy problem is twofold: a lack of economically competitive renewable energy, and a lack of distribution capacity.

At its core, the global rise in living standards demand an increasing amount of energy to power modern conveniences. As long as renewables cost more than fossil-based energy, any measure to reduce carbon emission inevitably increases the affordability of a high standard of living. Developing economies are understandably resistant to any such commitment. However, even if renewables can be cost competitive it does not automatically ensure better living standards.

The problem of energy is not merely one of generation but of distribution as well. For example, the wholesale supply of nuclear electricity in the U.S. is 31 % of the meter price, with 69 % of the cost in transmission, distribution and management (Rosenfeld 1999). Rolling blackouts in developed economies illustrate both these problems combined: limited power generation capacity and inadequate transmission infrastructure.

In this regard, energy conservation solves both problems—it frees up capacity in both power generation and transmission. To be viable it also must be done in a way that does not compromise affluence. However it must be also noted that conservation has no media appeal, no star status, no poster boy. Thus Rosenfeld goes on to say:

> That makes it hard to convince most people that, for any given year in the foreseeable future, it will be cheaper and cleaner to improve efficiency by a few percent than to increase supply by the same amount. Give a congressman the choice of funding energy supply or energy efficiency, and he will go for supply almost every time (Rosenfeld 1999, p. 57).

2.1 Singapore as a Reference City

Singapore can be seen as the archetypal nation-city which transformed from third to first world status in a few decades. Without any natural resources for primary industries, Singapore's only recourse has been to rely on human resource.

Table 2.3 Examples of how to achieve a stabilisation wedge (Socolow and Pacala, in National Geographic Magazine, 2007)

Efficiency and conservation	Carbon capture and storage	Low-carbon fuels	Renewables and biostorage
Improve fuel economy of the two billion cars expected on the road by 2057 to 60 mpg from 30 mpg	Introduce systems to capture CO2 and store it underground at 800 large coal-fired plants or 1,600 natural-gas-fired plants	Replace 1,400 large coal-fired power plants with natural-gas-fired plants	Increase wind-generated power to 25 times current capacity
Reduce miles traveled annually per car from 10,000 to 5,000	Use capture systems at coal- derived hydrogen plants producing fuel for a billion cars	Displace coal by increasing production of nuclear power to three times today's capacity	Increase solar power to 700 times current capacity
Increase efficiency in heating, cooling, lighting, and appliances by 25 %	Use capture systems in coal- derived synthetic fuel plants producing 30 million barrels a day		Increase wind power to 50 times current capacity to make hydrogen for fuel-cell cars
Improve coal-fired power plant efficiency to 60 % from 40 %			Increase ethanol biofuel production to 50 times current capacity. About one-sixth of the world's cropland would be needed
			Stop all deforestation
			Expand conservation tillage to all cropland (normal plowing releases carbon by speeding decomposition of organic matter)

To capitalise on this resource, Singapore has always striven for a high education standard and a workforce that was industrious and productive. How did this happen in a hot and humid climate?

> Writing in the May 1929 inaugural issue of Heating, Piping & Air-Conditioning, Willis Carrier had been confident about air-conditioning's present and expressed buoyant optimism regarding its future. He imagined windowless office skyscrapers free of noise and dust and predicted air-conditioned comfort in the homes of average Americans as well as the wealthy. The air-conditioning industry could take credit, said Carrier, for the "present-day prosperity of the people of these United States." Its growth, he predicted, would be geometric (Ackerman 2002, p. 79).

This vision became reality in the knowledge-based economy of Singapore. The founding Prime Minister, Lee Kuan Yew, named the air-conditioner as the most significant innovation of the millennium, saying:

> The humble air conditioner has changed the lives of people in the tropical regions. Before air-con, mental concentration and with it the quality of work deteriorated as the day got hotter and more humid. After lunch, business in many tropical countries stopped until the cooler hours of the late afternoon. Historically, advanced civilizations have flourished in the cooler climates. Now lifestyles have become comparable to those in temperate zones and civilization in the tropical zones need no longer lag behind (Lee Kuan Yew, in Wall Street Journal, 1999).

Interestingly, Lee's style of governance created a climate that journalist Cherian (2000) described as politically stifling as an artificial climate, saying:

> So, think of Singapore instead as the Air-conditioned Nation—a society with a unique blend of comfort and central control, where people have mastered their environment, but at the cost of individual autonomy, and at the risk of unsustainability.

Over 70 % of the workforce is estimated to work in offices in Singapore (see Table 2.4 and over 80 % in the UK (CIBSE 1999).

For the purpose of this thesis the context for air-conditioning is confined to that for offices located in hot and humid climates.

2.1.1 Environmental Impact of Air-Conditioning

The environmental impacts of air-conditioners are two-fold: direct emissions via leakage of high global-warming potential (GWP) refrigerants, and indirect CO_2 emissions via the power needed to drive the air-conditioning and mechanical ventilation (ACMV) systems derived from fossil-fuel power stations.

2.1.2 Environmental Impact of Refrigerants

The refrigerants used in air-conditioning have tremendous global warming potential (GWP). Stated in terms of carbon dioxide's GWP, or CO_2-e, CFC

Table 2.4 Singapore resident employment in 2010 by occupation

Occupation	2010 employed (thousands)*	Office utilisation (lower)	Office utilisation (upper)
Legislators, senior officials and managers	335.2	335.2	335.2
Professionals	312.6	312.6	312.6
Technicians and associate professionals	373.4	373.4	373.4
Clerical workers	240.5	240.5	240.5
Service and sales workers	246.4	123.2	172.48
Production Craftsmen and related workers	86.5	8.65	17.3
Plant and machine operators and assemblers	154.2	15.42	30.84
Cleaners, labourers and related workers	145.5	14.55	29.1
Others	68.7	0	13.74
	1962.9	1423.52	1525.16
		72.52 %	77.70 %

"Office utilisation" are author's own estimates based on observation
Legislators, Senior Officials and Managers (100 %); Professionals (100 %); Technicians and Associate Professionals (100 %); Clerical Workers (100 %); Service & Sales Workers (50–70 %); Production Craftsmen and Related Workers (10–20 %); Plant and Machine Operators and Assemblers (10–20 %); Cleaners, Labourers and Related Workers (10–20 %); Others (0–20 %).
* Employment statistics from "Statistics Singapore—Yearbook of Statistics, 2011" (Singapore Department of Statistics 2011) (www.singstat.gov.sg/pubn/reference/yos11/statsT-labour.pdf)

(chloroflurocarbon) refrigerants have an extremely high GWP of 4,000–119,000 CO_2-e. Under the Montreal Protocol, ozone depleting CFC refrigerants have already been phased out, and the less active HCFC (hydrochlorofluorocarbons) will be phased out by 2030. However, even with refrigerants that have no ozone depleting potential (also referred to as Kyoto Protocol synthetic gases), the GWP ranges between 1300 (R134a) to 3900 (R507) (Australian Fluorocarbon Council 2001).

Globally, the various greenhouse gases responsible for radiative forcing in the atmosphere up to 2006 are (Australian Refrigeration Council 2011):

- CO_2: 61 %
- CH4: 22 %
- Montreal protocol gases (largely CFCs): 10 %
- N2O: 6 %
- Kyoto protocol synthetic gases (largely HFCs): <1 %

Refrigerants thus form a small but significant part of the global warming contribution. The successful phasing out of CFCs under the Montreal protocol bolsters a degree of confidence that the HCFCs will likely be well under control by the target dates. The remaining Kyoto protocol synthetic gases whilst insignificant

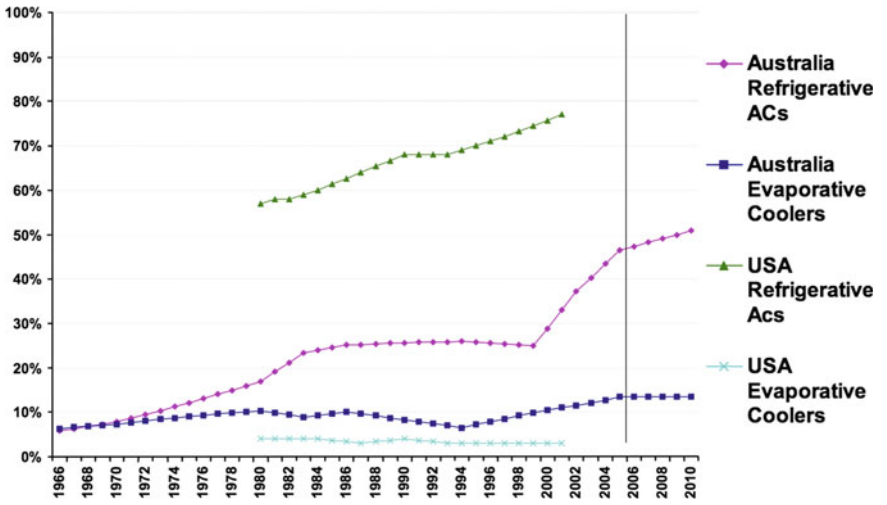

Fig. 2.2 Share of Australian households with air conditioning or evaporative cooling—historical and projected (Wilkenfeld 2006)

now will increasingly be an issue as these refrigerants replace those that have been phased out, and as the air-conditioning market continues to grow. Australia's growth in the decade 1995–2006 was by a factor of 2.5 times (see Fig. 2.2. Wilkenfeld 2006).

2.1.3 Environmental Impact of Air-Conditioning Power

Air-conditioning accounts for the largest share of building operational energy. In tropical cities like Singapore, it accounts for about 50 % of the system energy usage intensity in offices (Table 2.5). In the Australian commercial sector it typically accounts for 30–40 % of summer maximum energy demand (Wilkenfeld 2006).

Table 2.5 System energy usage intensity (SEUI, kWh/sqm/year) of offices in Singapore http://www.esu.com.sg

Percentile rating (%)	Class A 25th	Class B 50th	Class C 75th
Air-conditioning	82 (44 %)	132 (50 %)	144 (46 %)
Mechanical ventilation	23 (12 %)	36 (14 %)	51 (16 %)
Lighting	24 (13 %)	28 (11 %)	32 (10 %)
Lift and escalator	11 (6 %)	16 (6 %)	23 (7 %)
Others	47 (25 %)	53 (20 %)	61 (20 %)
Total (system) kWh/sqm/year	187	265	311

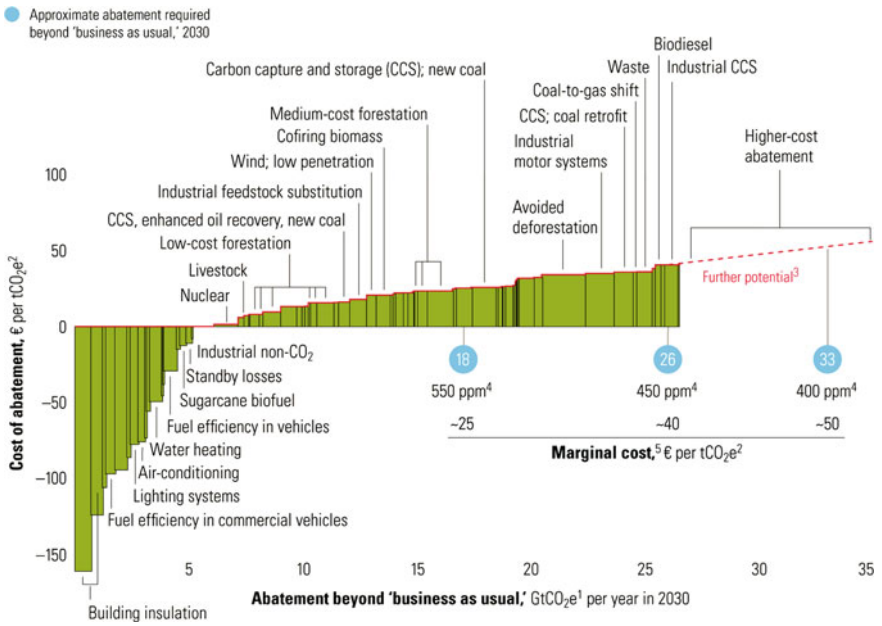

Fig. 2.3 McKinsey curve (McKinsey and associates 2007)

When the costs of abatement measures are compared to the tariffs on CO_2-e emissions, upgrading to more efficient air-conditioning becomes very attractive. As an abatement measure, more efficient air-conditioning gives one of the best returns for the capital outlay, coming behind building insulation, improved efficiency in commercial vehicles and more efficient lighting systems (Fig. 2.3).

2.2 The Role of Air-Conditioning in a Changed Climate

With global warming, the number of hot days associated with heat related injuries will be more frequent annually, together with more record highs (right end tail of Fig. 2.4). CSIRO projections of the number of days in excess of 35 °C (Table 2.6) show that heat waves are likely to be longer lasting. Nicholls et al. (2007) have discovered a trend in Melbourne's mortality rate anomaly which became substantially increased once mean temperatures exceeded 28 °C, and proposed a warning based on these criteria:

> If at any time during the forecast period the average of the predicted maximum temperature on one day and the predicted minimum temperature for the following morning exceeds 30 °C, a heat alert could be issued to the public and/or local authorities, ambulance services and other health and welfare organizations. The heat alert would indicate likely increases in mortality in the 24-h period following the high temperatures.

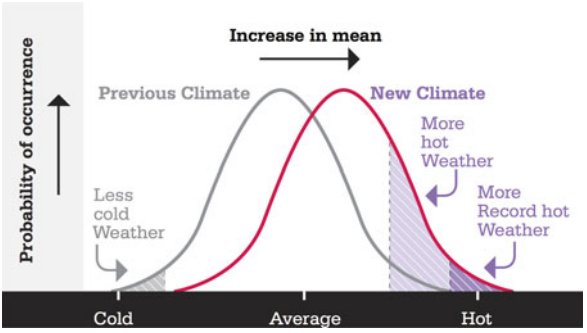

Fig. 2.4 Relationship between means and extremes, when extreme events are defined as some fixed threshold related to a significant impact (e.g., heatwave leading to excess deaths). (Australian Department of Climate Change and Energy Efficiency 2011)

Table 2.6 Projected number of days over 35 °C in Australian capital cities

	2008	2030	2070	2100
Melbourne	9	12	21	27
Sydney	3.3	4.4	9	14
Brisbane	0.9	1.7	8	21
Adelaide	17	22	34	44
Perth	27	35	56	72
Canberra	5	8	21	32
Darwin	9	36	221	312
Hobart	1.4	1.7	2.5	3.4

Hughes and McMichael 2011

Where a warmer climate will have an impact on physical and mental health, the most vulnerable, according to Lesley Hughes, co-author of Australia's Climate Commission Report, are 'the elderly, those with existing heart and kidney disease, children, people in remote communities and… any outdoor workers' (ABC News 2011).

Or in other words, those who are not typically in an air-conditioned environment.

As a matter of health, or even life and death, there will be an increasing demand for air-conditioning. The heatwave in France in 2006 had lower mortality levels than the previous one in 2003. A meteorologist commented this was particularly due to one aspect of the government's *National Heat Wave Plan:*

> It is worth mentioning here, that air conditioning can allow people to continue to work effectively in hot weather and undoubtedly lessens heat stress, thus protecting susceptible sections of the population throughout a heat wave (Tan 2008).

Air-conditioning will remain both a cause and arbiter of the climate change problem for the immediate future. The logical step then is to see how air- conditioning can deliver cooling with minimal impact to the environment.

2.3 A New Paradigm of Thermal Comfort

> … the main antagonist of rooted culture is the ubiquitous air-conditioner.
>
> Wherever they occur, the fixed window and the air-conditioner are mutually indicative of domination by universal technique (Kenneth Frampton, in Foster 1983, p. 27).

If the only problem with air-conditioning was the mindless adoption of the international style, we would have little to fear in terms of its environmental consequences. There are a select few who would take issue with air-conditioning *per se,* like Prins (1992) who saw air-conditioning both as an evil in itself and as a tool for capitalistic domination. These are threads of research in and of themselves, and are not the focus of this thesis.

Rather, this work is concerned with the *energy intensity* of the over reliance on air-conditioning. Air-conditioning, as we will see, contributes to workplace productivity in a way that cannot be casually dismissed. It is the excessiveness of air-conditioning and the over-reliance on it that becomes problematic. More importantly, the crux of the matter is the intensiveness of energy demanded by air-conditioning in a world that is now struggling to resource it. If air-conditioning could be supplied affordably and sustainably, it would hardly attract contempt, with too few ills to outweigh its benefits.

Thermal comfort studies have long been established and underpin mandatory building construction, operation and maintenance standards. However, today the standards for temperature and humidity control need to be interrogated in the context of energy limitations. In returning to first principles we enquire if the understanding of *thermal comfort* is adequately covered with the use of a sensation scale. Particular attention is given to explain the difference between the deterministic and adaptive thermal comfort models. Does comfort in a naturally ventilated office with fans have the same quality as comfort in an air-conditioned one? How can these differences be reconciled without disregarding the validity of decades of rigorous studies? I will postulate an explanation from disciplines that have traditionally been outside architectural science. The experimental validation of this theory is however beyond the scope of this thesis.

Any proposed solutions will be evaluated in terms of their engineering efficiency, because the primary aim is to achieve the *efficiency and conservation* wedge for building operational energy savings. At the same time, the approach cannot be purely academic but needs to be tempered by market realities, because after all, the uptake of an innovation is predicated on there being an improvement to the standard of living.

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