Passive Building Design and Integration with Intermittent Renewable Energy Sources

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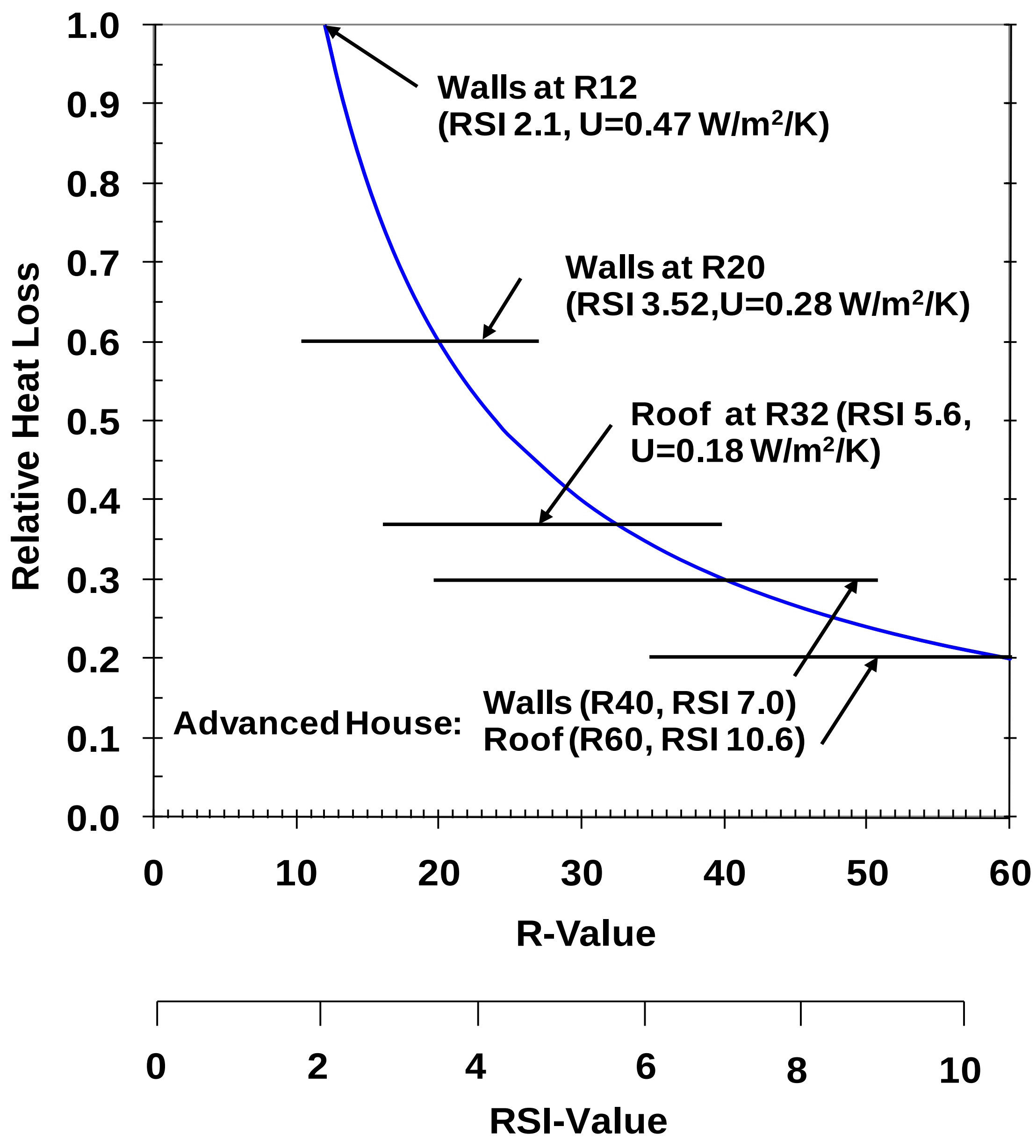
REDUCING HEATING ENERGY USE

- Reduce the heat load (the amount of heat that needs to be provided)
- Provide the required heat as efficiently as possible

Thermal Envelope

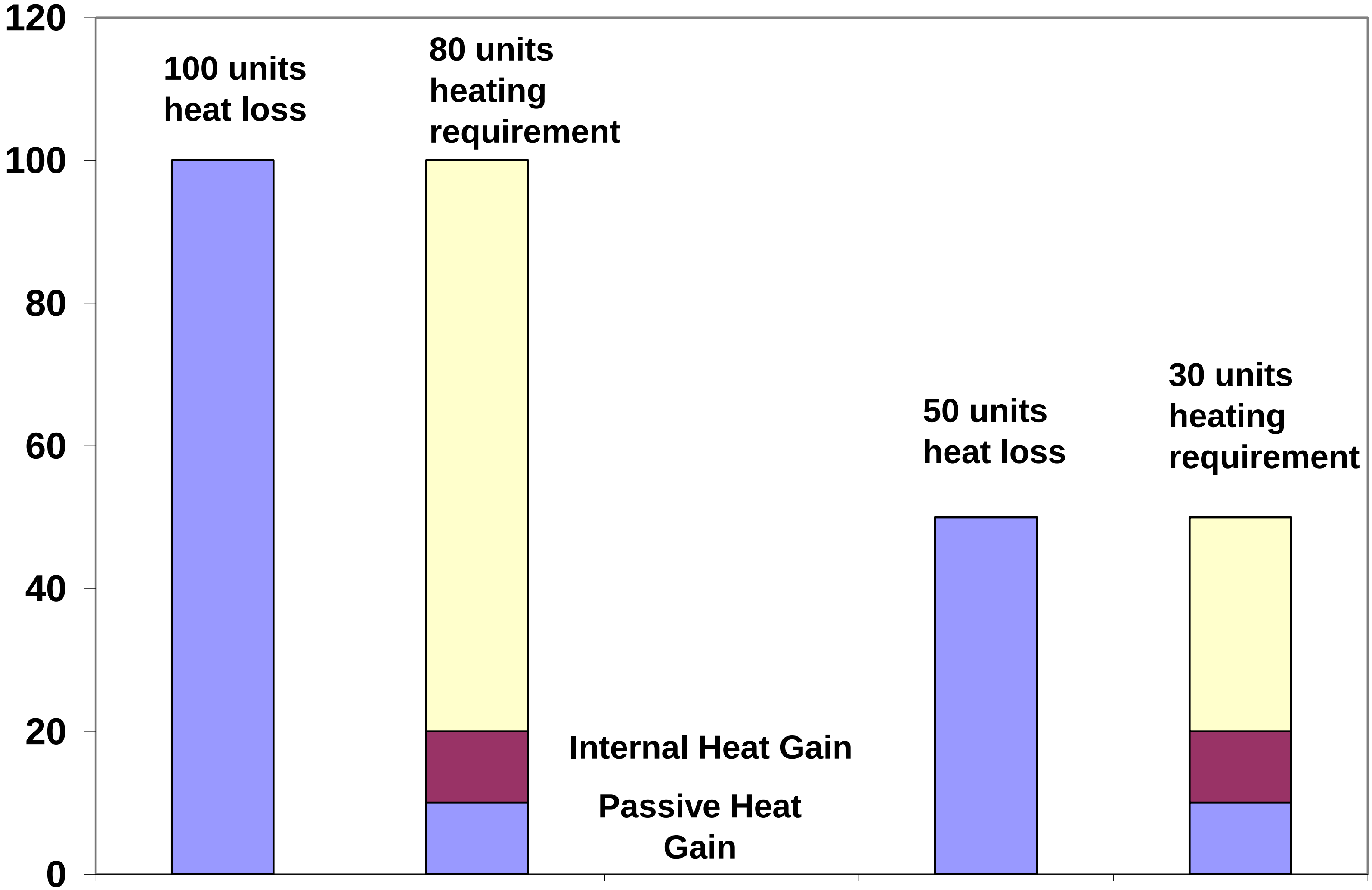
- Insulation
- Windows and doors
- Curtainwalls in commercial buildings
- Air leakage
- Double skin façades

Figure 4.9 Wall and Ceiling Heat Loss



The heating requirement is the residual (or difference) between heat loss, useful passive heat gain, and useful internal heat gain – so a given percentage reduction in heat loss has a disproportionately larger effect in reducing the heating requirement

Greater sensitivity of heating requirement than of heat loss to changes in the amount of insulation



Source: Danny Harvey

Windows: Benchmark

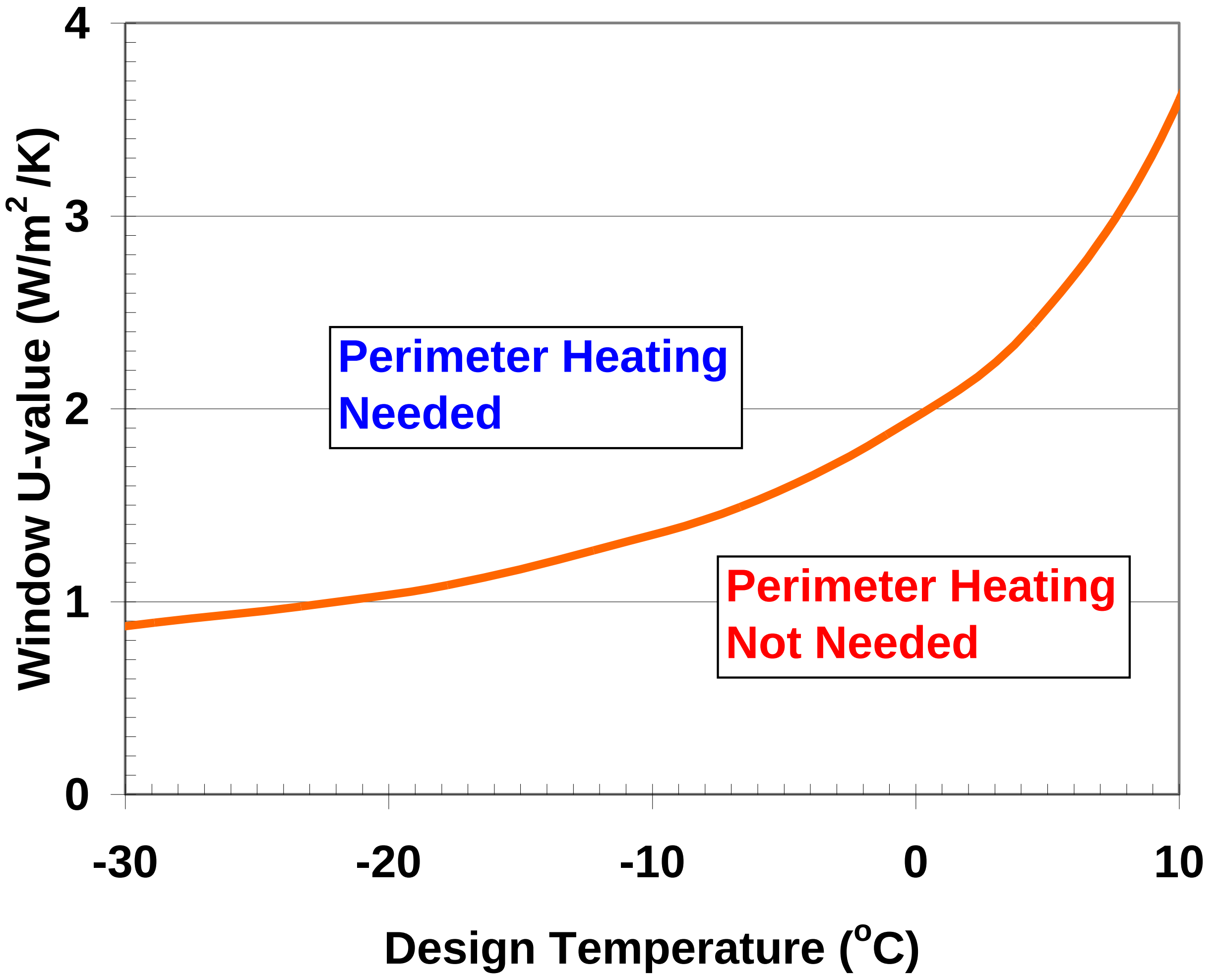
- A single-glazed, non-coated window has a U-value of about 5 $W/m^2/K$ – so the rate of heat loss is 200 W/m^2 when the outdoor temperature is -20ºC and the indoor temperature is +20ºC
- The best commercially-available high-performance window will have a centre-of-glazing U-value of 0.5 $W/m^2/K$ – so the heat loss will be a factor of 10 smaller!

The normal practice in building design is to place the heaters or warm-air vents below the window. This is because normally there is large heat loss from the window, so heating at the base of the window

- Keeps the window warm, thereby avoiding radiant asymmetry
- Prevents drafts
- Prevents condensation on the window

With high performance windows, the heat loss is so low that the heaters can be placed on the side of the room near the core of the building, thereby reducing costs (and reducing heat loss even further)

Figure 4.13 Required window U-value at which perimeter heating can be eliminated as a function of the coldest designed-for temperature



Passive Solar Heating

- Direct gain
- Solar collectors
- Air-flow windows

Not all solar gain is usable – some leads to overheating, requiring the windows to be opened

To maximize the useful solar gain, thermal mass (such as concrete or stone) is needed and should be exposed to the indoor air (so minimize interior finishings) (this is the new look anyway in many buildings now)

With thermal mass, absorbed solar energy goes into storing heat with minimal temperature rise (apart from being uncomfortable, high temperatures result in greater radiant and convective heat loss, and thus less heat available for later)

At night, the heat is slowly released when there is high thermal mass. This is adequate if the building is highly insulated with high-performance windows.

If there is too large a glazing fraction (which typically means > 60%), there will be more solar gain than can be used, and greater heat loss at night

Heat Pump, Operating Principles

- Heat pumps transfer of heat from *cold to warm* (against the macro temperature gradient)
- At each point in the system, heat flow is from warm to cold
- Heat pumps rely on the fact that a gas cools when it expands, and is heated when it is compressed, creating local temperature gradients contrary to the macro-gradient

Components of a heat pump

- Compressor
- Evaporator
- Condenser

Figure 4.23a Heat pump in heating mode

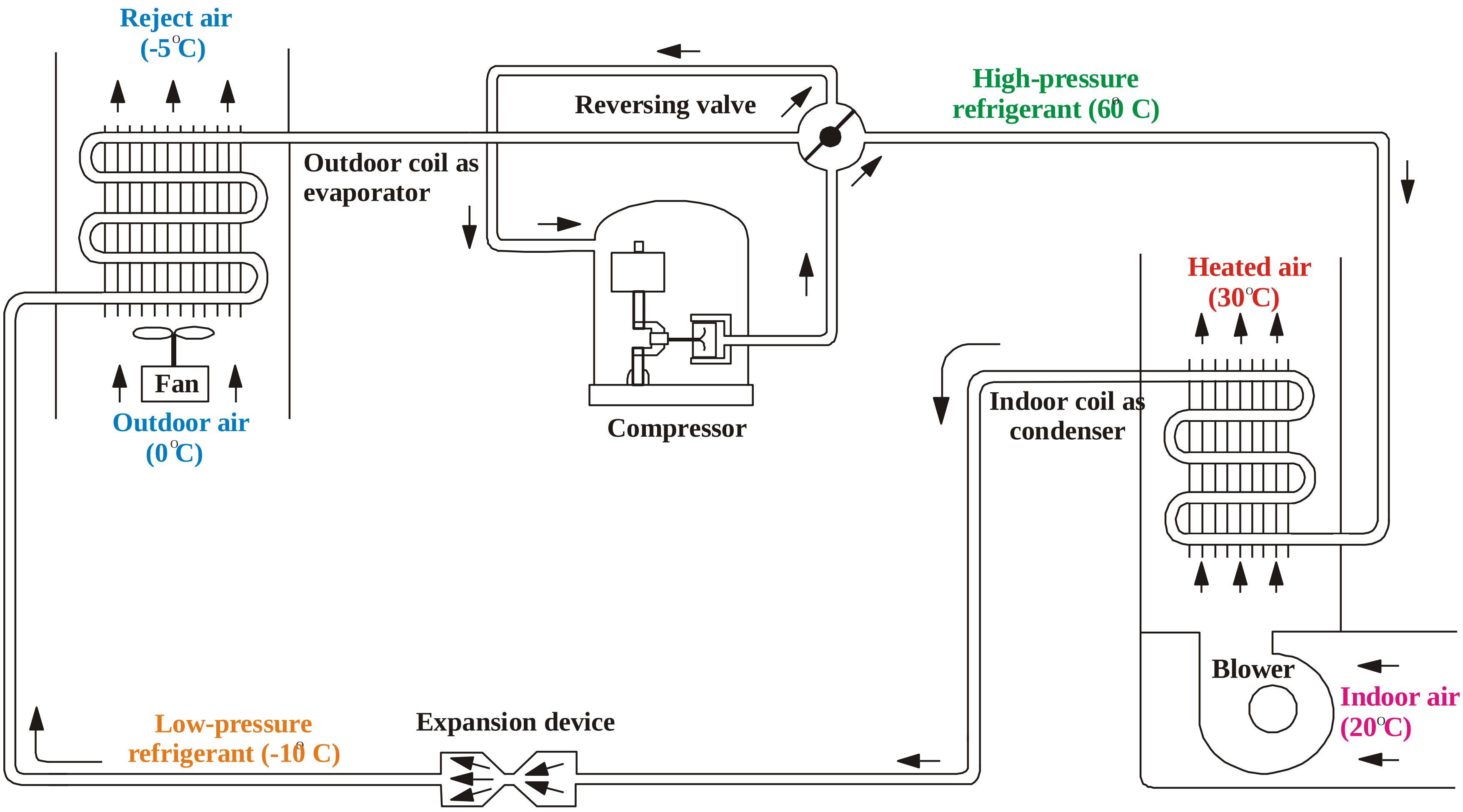
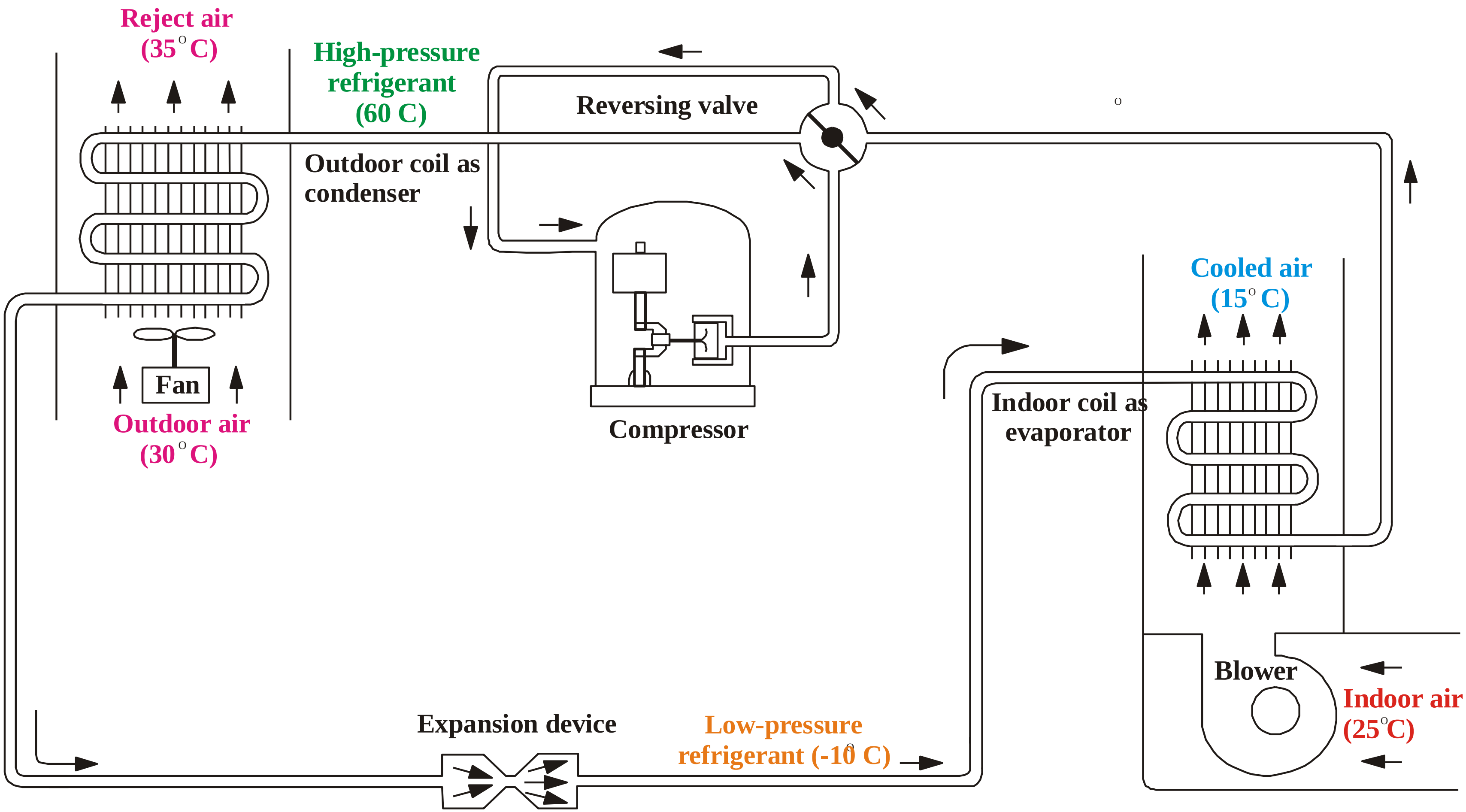


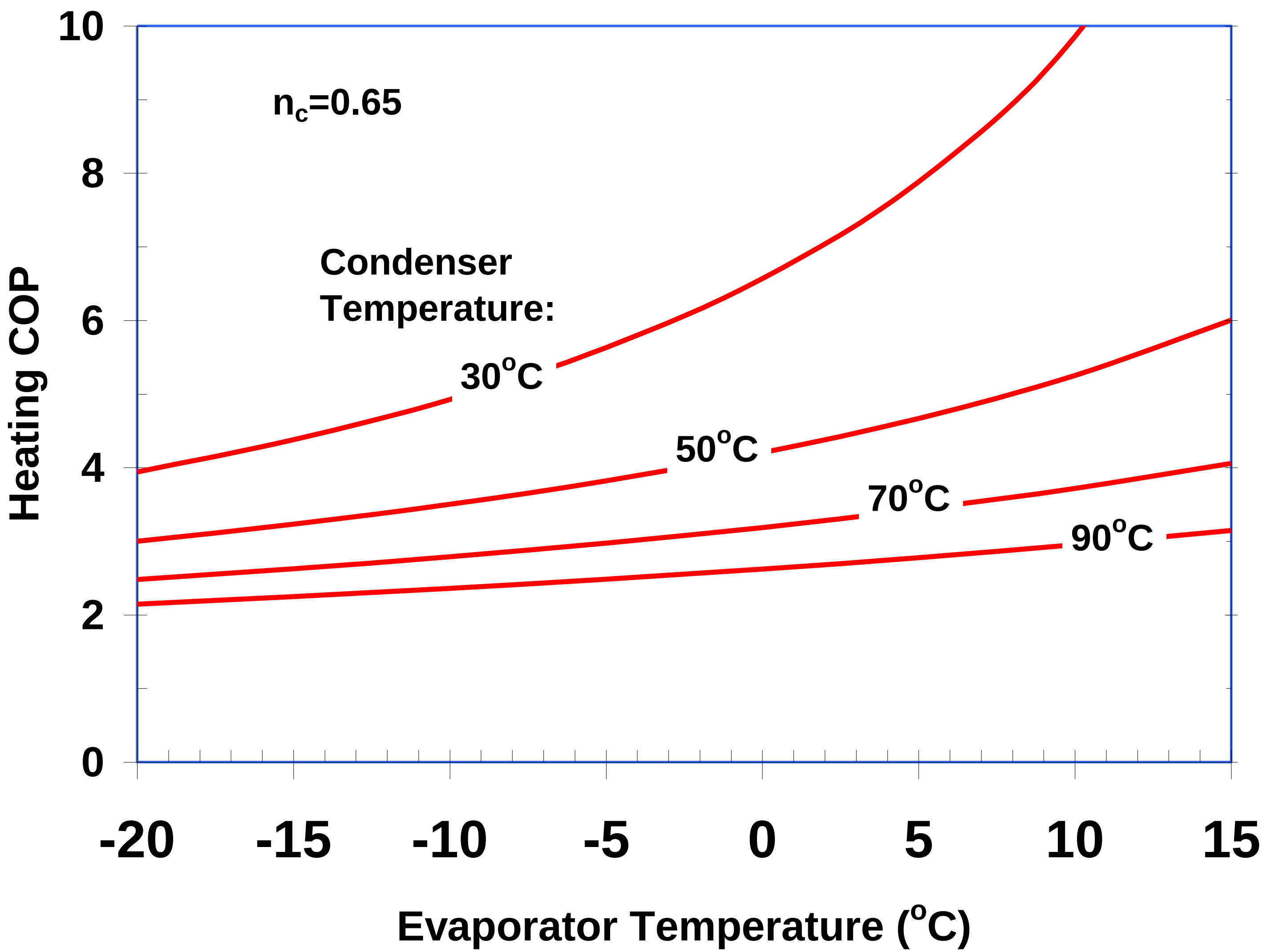
Figure 4.23b. Heat pump in cooling mode



The Efficiency of a Heat Pump depends not only on the heat pump itself, but also on the *entire system* to which it is connected.

- The ratio of heat delivered to energy input is called the ***coefficient of performance (COP)***
- In heating mode, the COP will be larger the warmer the source of heat and the cooler the temperature at which the heat is delivered (e.g, delivering heat at 30 C instead of at 90 C)
- In cooling mode, the COP will be larger the cooler the heat sink (such as the outside air or ground) and the warmer the temperature at which coldness is distributed (e.g, delivering coldness at 18 C rather than at 6 C)

Figure 4.24a: Heat Pump COP in heating mode



Large wall-mounted radiator in a daycare centre in Frankfurt – an inexpensive alternative to radiant floor heating

Source: Danny Harvey

Figure 4.24b: Heat Pump COP in Cooling Mode (or chiller COP)

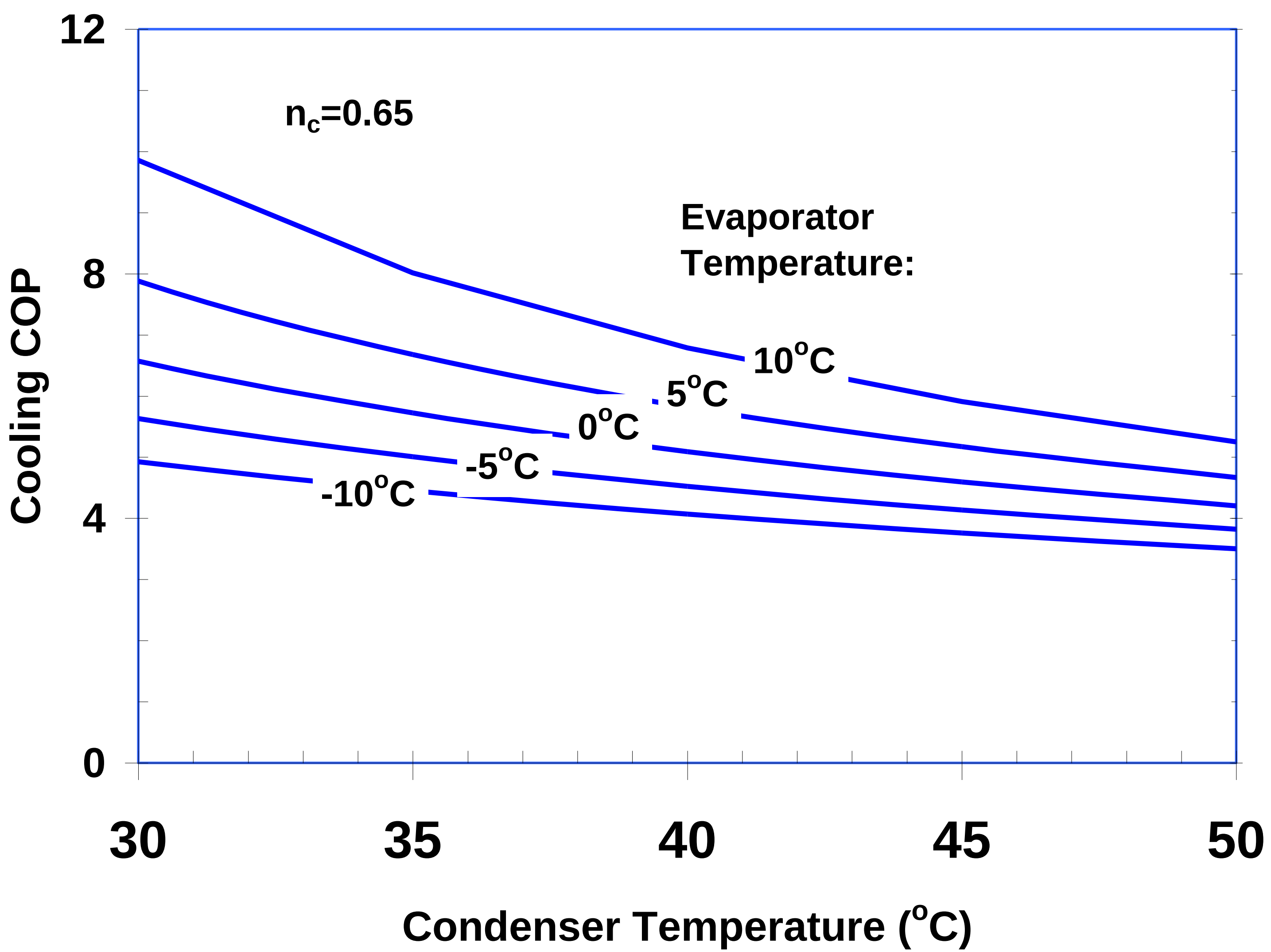


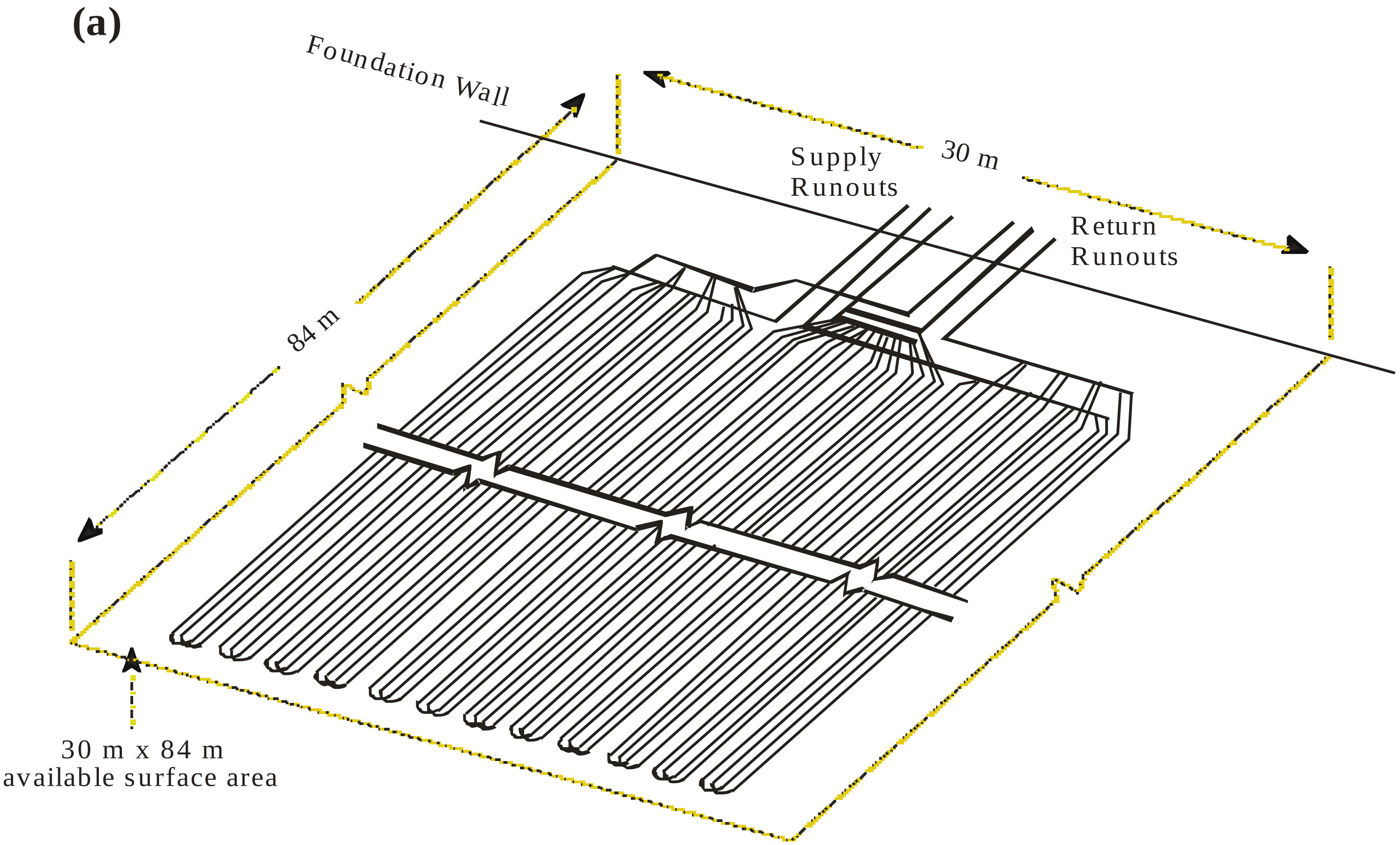
Figure 4.48 Chilled Ceiling cooling panels

Source: www.advancedbuildings.org

Sources of heat for a heat pump:

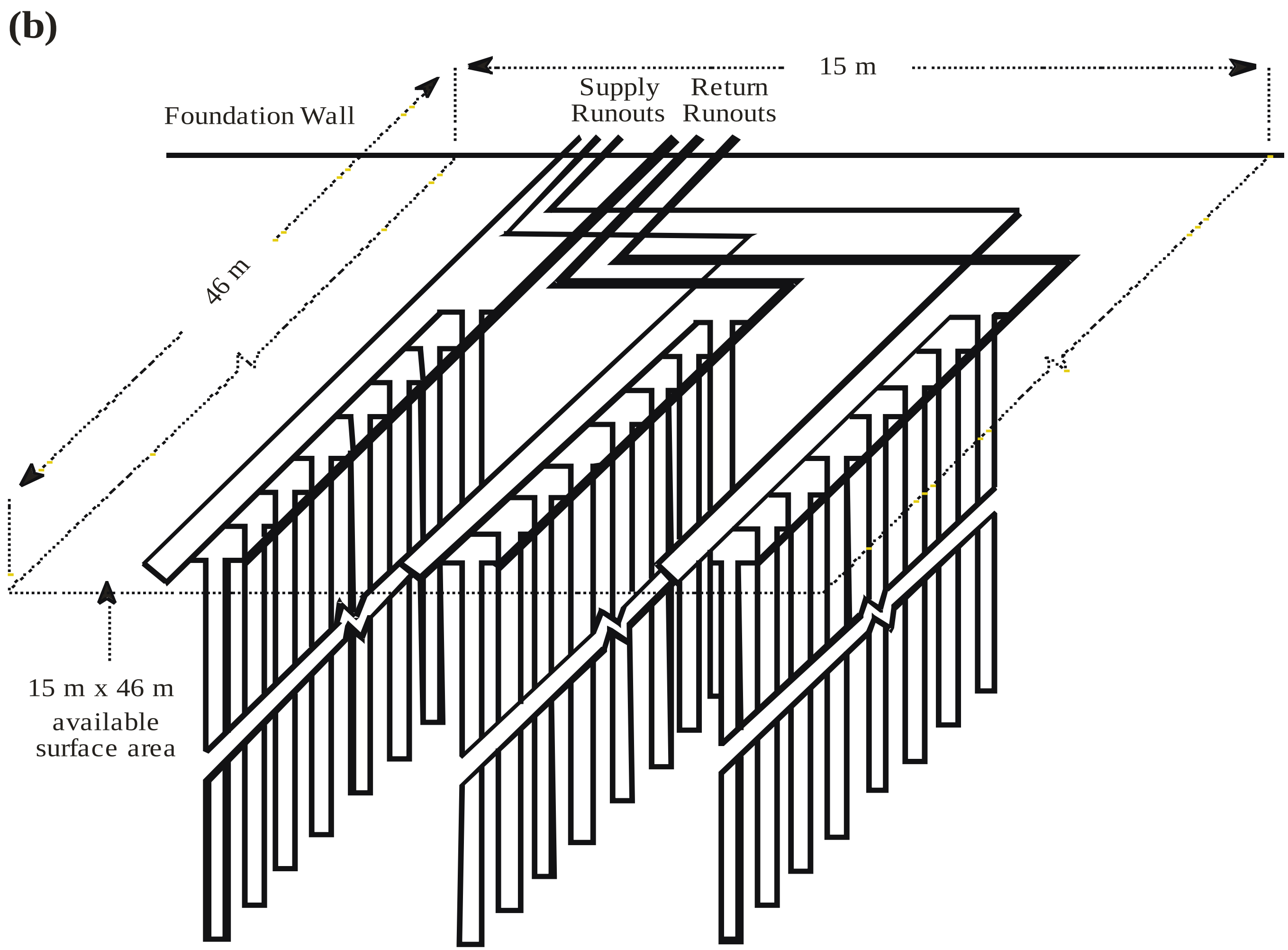
- The outside air (gives an Air-Source Heat Pump)
- The ground (gives a Ground-Source Heat Pump, now quite incorrectly called "geothermal heating" by vendors of this equipment)
- The exhaust air (gives an Exhaust-Air Heat Pump – now standard practice for new houses in Sweden) (extracts more heat from the outgoing exhaust air than a simple heat exchanger)

Figure 4.26a Ground Source Heat Pump, horizontal pipes



Source: Caneta Research Inc (1995, *Commercial/Institutional* Ground-Source *Heat Pump Engineering Manual*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta)

Figure 4.26b Ground Source Heat Pump, vertical pipes



Source: Caneta Research Inc (1995, *Commercial/Institutional Ground-Source Heat Pump Engineering Manual*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta)

The ground is a better source of heat than the air because, during the winter, the ground might be at 8-10ºC while the outside air is at -20ºC.

Conversely, during the summer the ground will be cooler than the air and so it is a good heat sink

A high-performance envelope saves fossil fuel energy in 3 ways

- By reducing the heating load (the amount of heat that needs to be provided)
- By increasing the efficiency of a furnace, boiler or (especially) of a heat pump in providing the required heat
- By providing flexibility as to when heat is provided (this flexibility is amplified if the building has a high thermal mass)

REDUCING COOLING ENERGY USE

- Reduce the amount of heat that a building receives, thereby reducing the cooling *load* (the amount of the heat that needs to be removed)
- Use *passive* and low-energy techniques to meet as much of the cooling load as possible
- Use *efficient equipment* and *systems* to meet the remaining cooling load

Reducing Cooling Loads

- Building orientation and clustering
- High-reflectivity building materials
- External insulation
- External shading devices
- Windows with low SHGC
- Thermal mass
- Vegetation (provides shading and evaporative cooling)
- Efficient equipment and lighting to reduce internal heat gains

Low-energy Cooling Techniques

- Natural (passive) ventilation
- Hybrid (passive-mechanical) ventilation
- Mechanical ventilation at night (combined with thermal mass and external insulation)
- Evaporative cooling
- Earth-pipe cooling

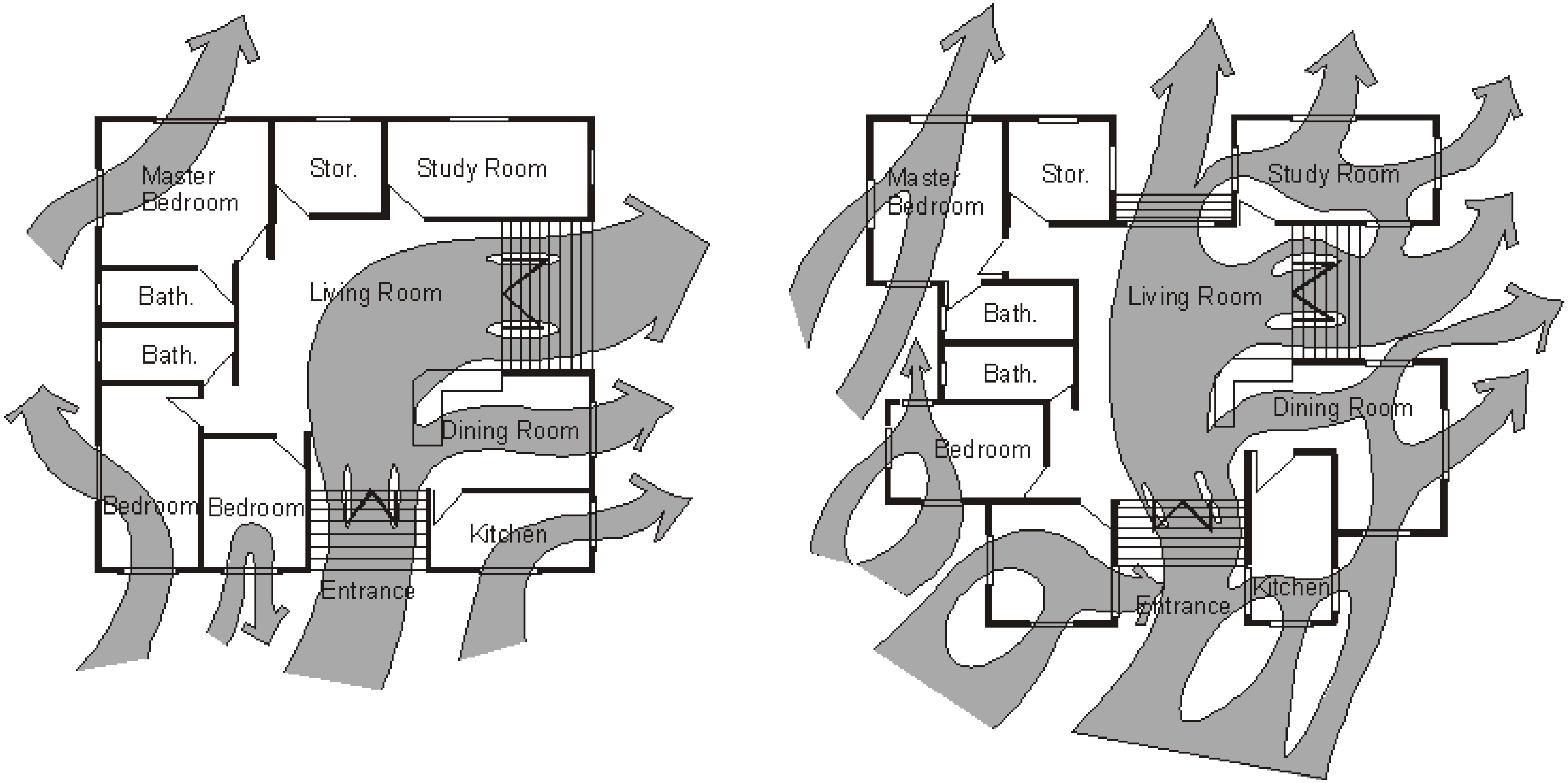
Natural driving forces for air flow:

- Wind forcing
- Temperature differences (which create pressure differences)

Wind forcing:

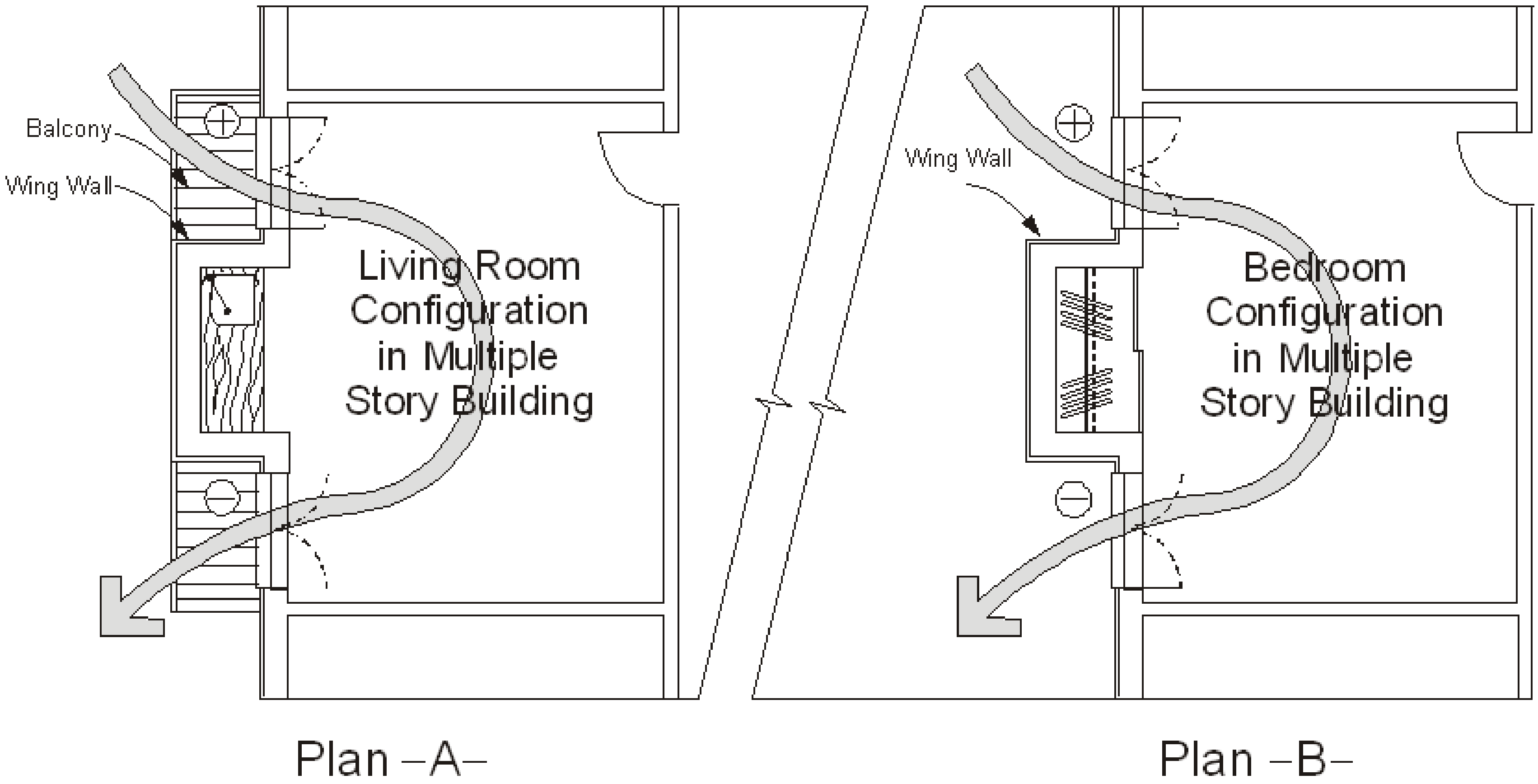
- Cross ventilation
- Wing walls
- Wind catchers
- Wind cowls

Cross-ventilation



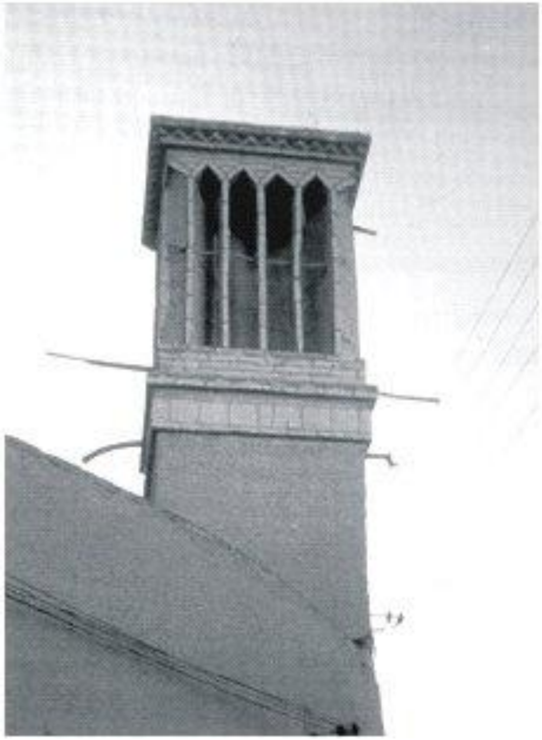
Source: Givoni (1998), *Passive and Low Energy Cooling of Buildings*, von Nostrand Reinhold, New York

Wing walls:



Source: Givoni (1998), *Passive and Low Energy Cooling of Buildings*, von Nostrand Reinhold, New York

Winds catchers in Iran and Doha

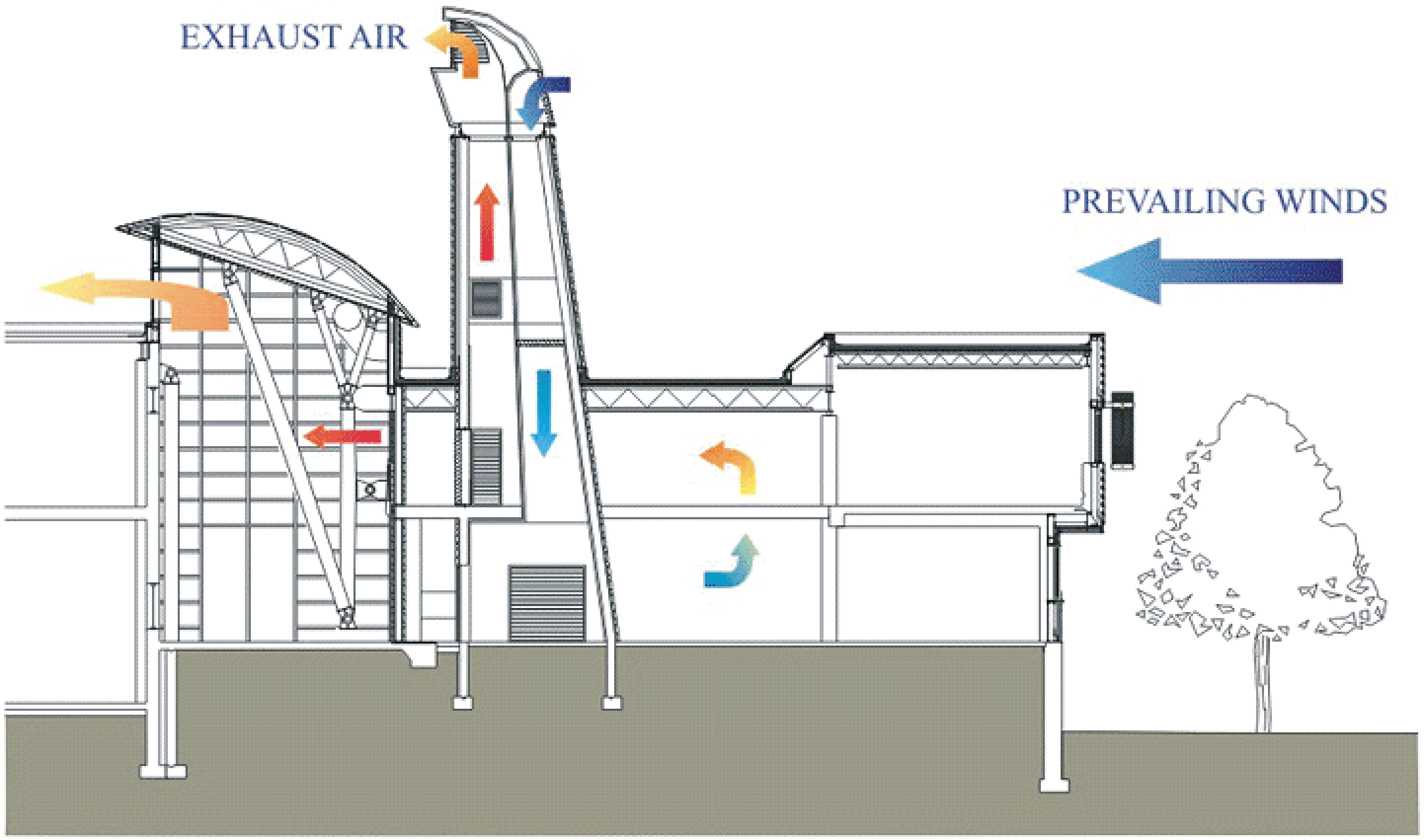


Source: Koch-Nielsen (2002), *Stay Cool: A Design Guide for the Built Environment in Hot Climates*, James and James, London

Wind catcher at Sir Sanfred Fleming College, Peterborough, Canada

Source: Loghman Azar, Line Architects, Toronto

Airflow at Sir Sanfred Fleming College, Peterborough, Canada



Source: Loghman Azar, Line Architects, Toronto

Wind cowl

Source: www.arup.com

Thermally-driven ventilation

- Atria
- Solar chimneys
- Cool towers

Figure 4.30 Solar chimneys on the Building Research Establishment (BRE) building in Garston, UK

Earth-pipe cooling

- Ventilation air is first drawn through underground pipes so as to be cooled by the ground
- COP (cooling over fan energy) of 7-50 obtained (depending on ground and air temperatures)
- Airflow can also be driven with solar chimneys

Figure 4.36: Jaer School, Norway – combining solar chimneys and earth-pipe cooling

Source: Schild and Blom (2002, *Pilot Study Report: Jaer School, Nesodden Municipality, Norway*, International Energy Agency, Energy Conservation in Buildings and Community Systems, Annex 35, hybvent.civil.auc.dk)

Atria and stair wells can also serve as solar chimneys, driving a natural ventilation if so-designed

EnergyBase building, Vienna

Source: Danny Harvey

Adjustable external shading

Source: Danny Harvey

Windows on south facade are slightly overhanging

Source: Ursula Schneider, Pos Architekten, Vienna

Exhaust air is overheated by passing through a sort of solarium, then passes through a heat exchanger to heat the incoming fresh air to a greater extent than would be possible with a conventional heat exchanger system. And unlike systems for passive solar preheating of ventilation air, we still get the benefit of heat recovery on the exhaust air at night

EXEMPLARY BUILDINGS FROM AROUND THE WORLD

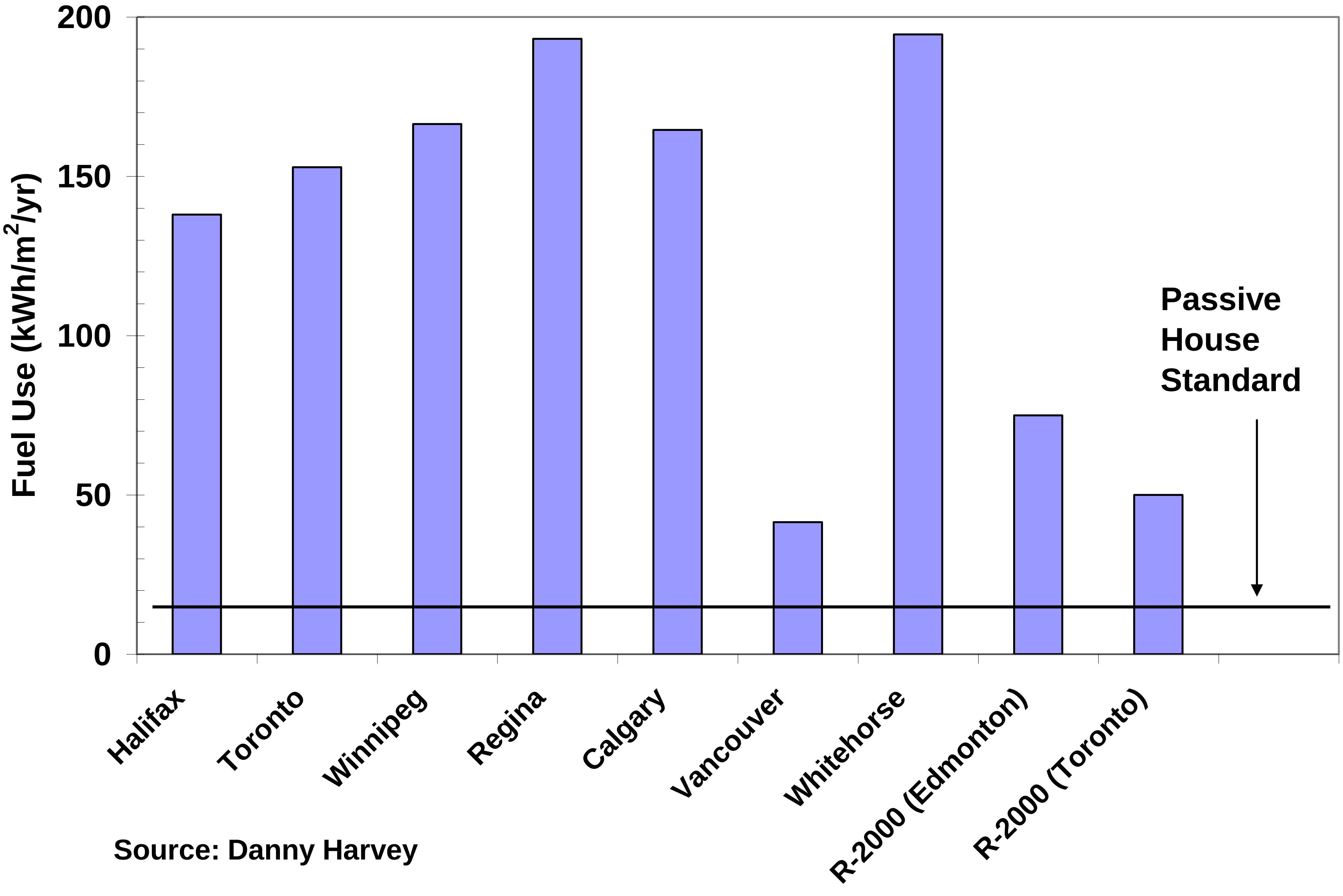
The German Passive Standard:

- A heating load of no more than 15 $kWh/m^2/yr$, irrespective of the climate, and
- A total on-site energy consumption of no more than 42 $kWh/m^2/yr$
- For cooling-dominated climates, the standard is a cooling load of no more than 15 $kWh/m^2/yr$

Current average residential heating energy use:

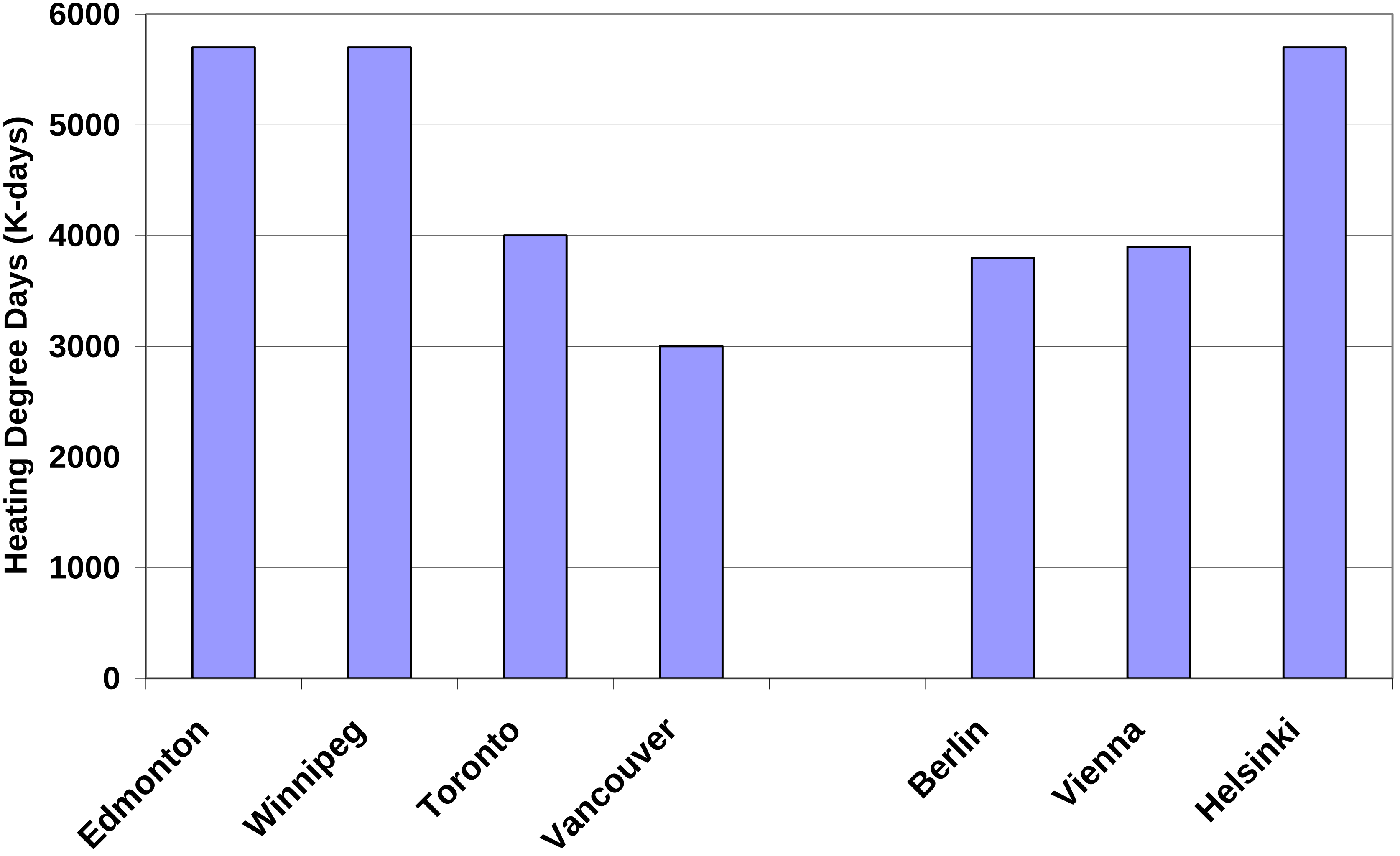
- 60-100 $kWh/m^2/yr$ for new residential buildings in Switzerland and Germany
- 220 $kWh/m^2/yr$ average of existing buildings in Germany
- 250-400 $kWh/m^2/yr$ for existing buildings in central and eastern Europe
- 150 $kWh/m^2/yr$ average of all existing (single-family and multi-unit) residential buildings in Canada

Estimated fuel energy use (largely for heating) in Canadian multi-unit residential buildings



Source: Danny Harvey

Climate Comparisons, Heating Season



Source: Danny Harvey

To achieve the Passive House standard on the heating side requires

- High levels of insulation (U-values of 0.10-0.15 $W/m^2/K$, R35-R60)
- High performance windows (usually TG, double low-e, argon-filled)
- Meticulous attention to avoidance of thermal bridges
- Meticulous attention to air-tightness
- Mechanical ventilation with heat recovery
- Attention to building form (achieving the standard is much easier in multi-unit than single family housing)

Thermally-separated balconies in Frankfurt

Source: Danny Harvey

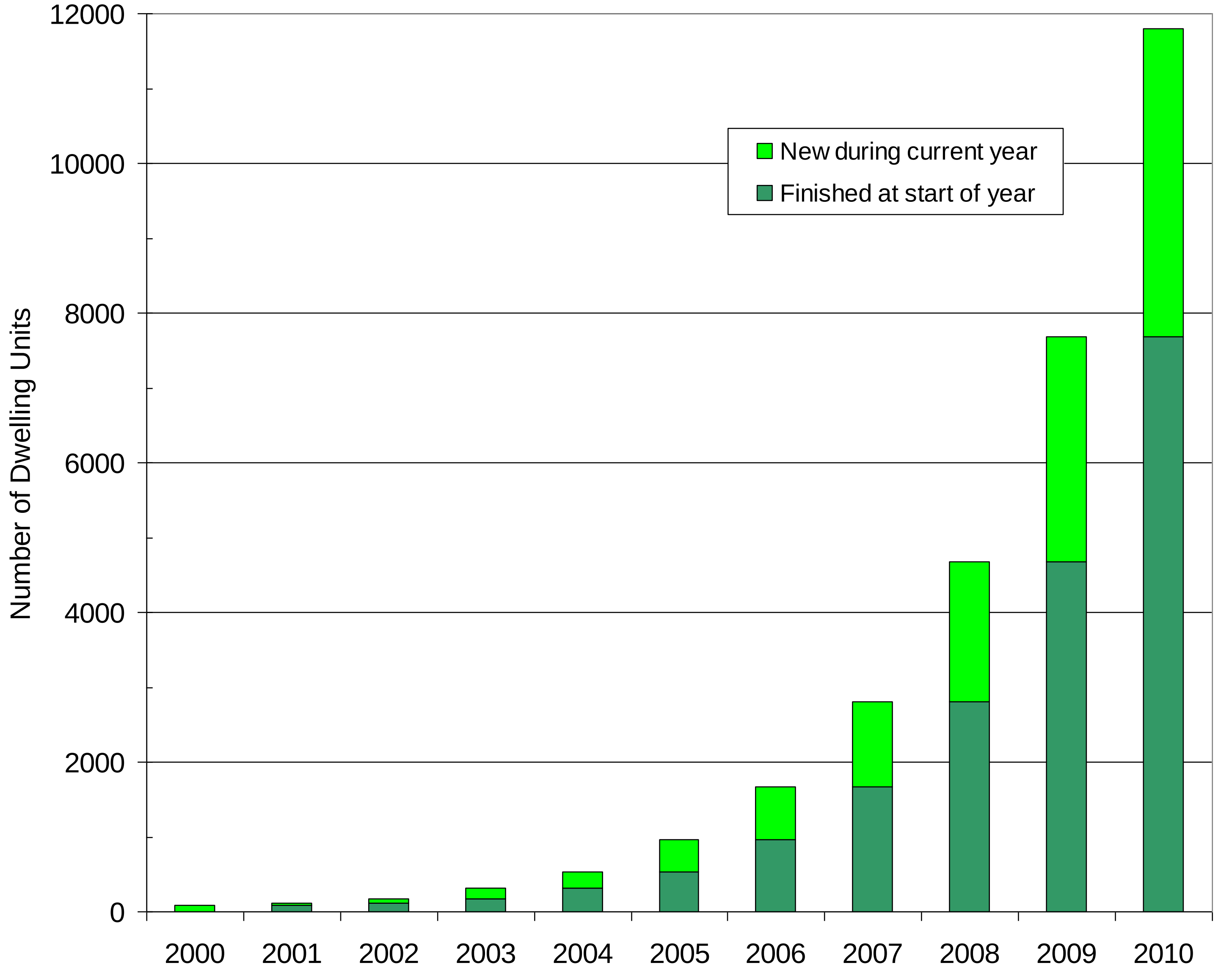
Occurrence of buildings meeting the Passive House Standard:

- Several thousand houses have now been built to and certified (based on measurements after construction) to have achieved the PH standard in Germany, Austria and many other countries in Europe
- The standard has also been successfully achieved in schools, daycare centres, nursing homes, gymnasia and a savings bank

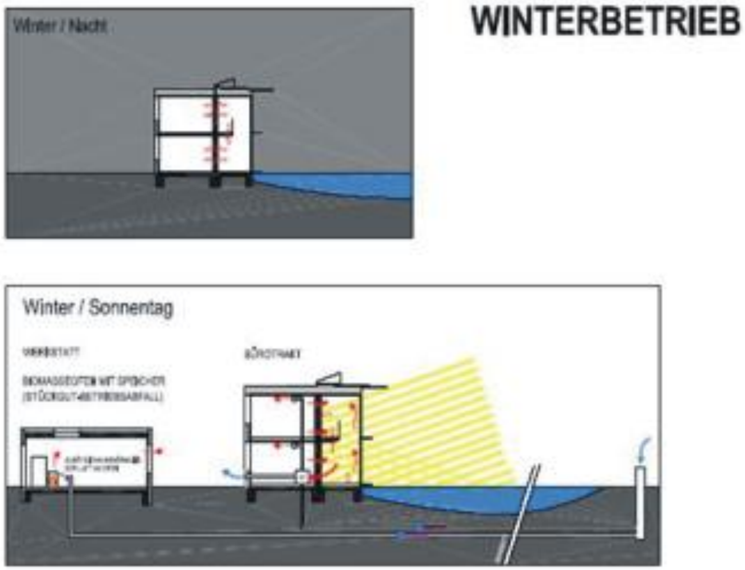
The PH standard is now the legally required building standard in many cities and towns in Germany and Austria

- City of Frankfurt: since 2007, all municipal buildings must meet the standard
- City of Wels, Austria: same thing since 2008
- Vorarlberg, Austria: Passive Standard is mandatory for all new social housing
- Freiberg, Germany: all municipal buildings must meet close to the PH standard
- City of Hanover: since 2005, all new daycare centres to meet the Passive House standard (resolution only – legal status not clear)

Explosive growth in the number of buildings meeting the Passive House standard in Austria



Biotop Office Building, Austria



High school example: Grandschule in Riedberg, Frankfurt

South facade

Source: Danny Harvey

Triple-glazing throughout, maximized passive solar heat gain

Source: Danny Harvey

Retractable external shading

Source: Danny Harvey

Passive ventilation and night-time cooling; mechanical system shut off from ~ early May to end of September

Source: Danny Harvey

Heating required during the winter for only a couple of hours Monday mornings, using two small biomass-pellet boilers

Source: Danny Harvey

Commercial Buildings:

The key to achieving savings in new buildings of 50-75% in overall energy use compared to recent conventional is in the *design process*.

To achieve ultra-low-energy office buildings requires

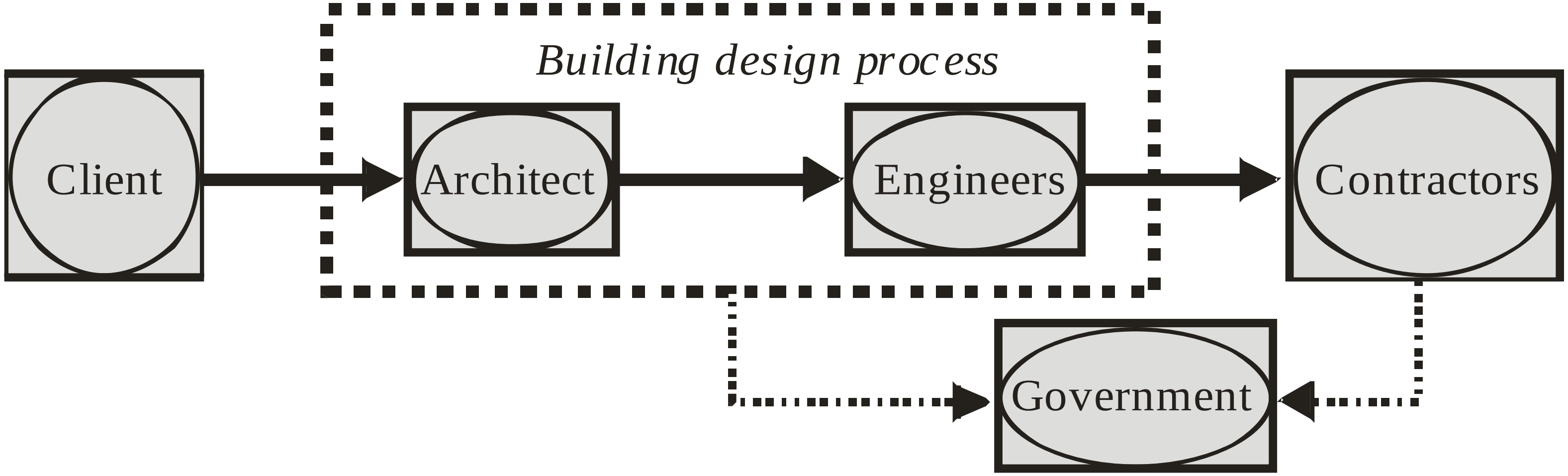
- Attention to building form, glazing fraction, thermal mass (all four facades will not be identical!)
- Attention to insulation levels and glazing properties
- Provision for passive ventilation (even on 50-story office towers), daylighting, heat recovery
- Almost mandatory use of demand-controlled displacement ventilation with radiant slab heating and cooling
- Lots of attention to control systems

In complex buildings, the usual largely linear design process needs to be replaced with the *Integrated Design Process* (IDP), in which

- The building is treated as a system
- Architects, engineers of various sorts, and specialists get together at the very beginning of the design process
- Multiple options for achieving deep energy savings are considered, then tested with building computer simulation specialists in order to find the optimal solution

Figure 4.79a Conventional design process when client will not occupy the building

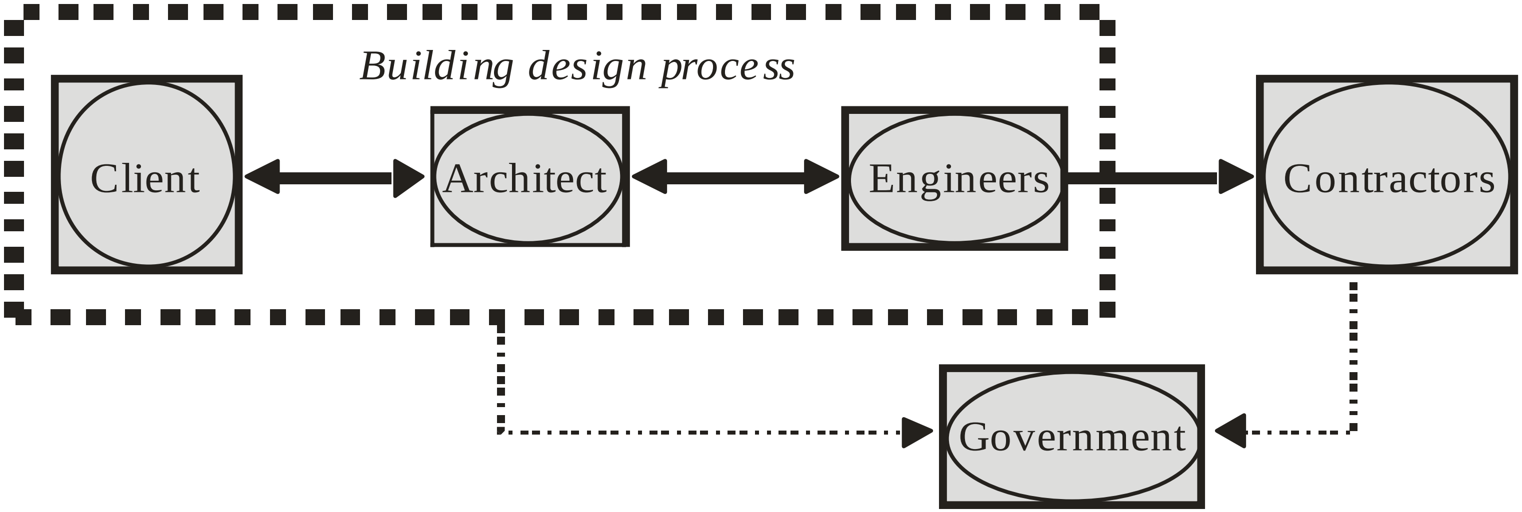
Level 1:



Source: Hien et al (2000, *Building and Environment* 35, 709-736, http://www.sciencedirect.com/science/journal/03601323)

Figure 4.79b Conventional design process when the client will occupy the building

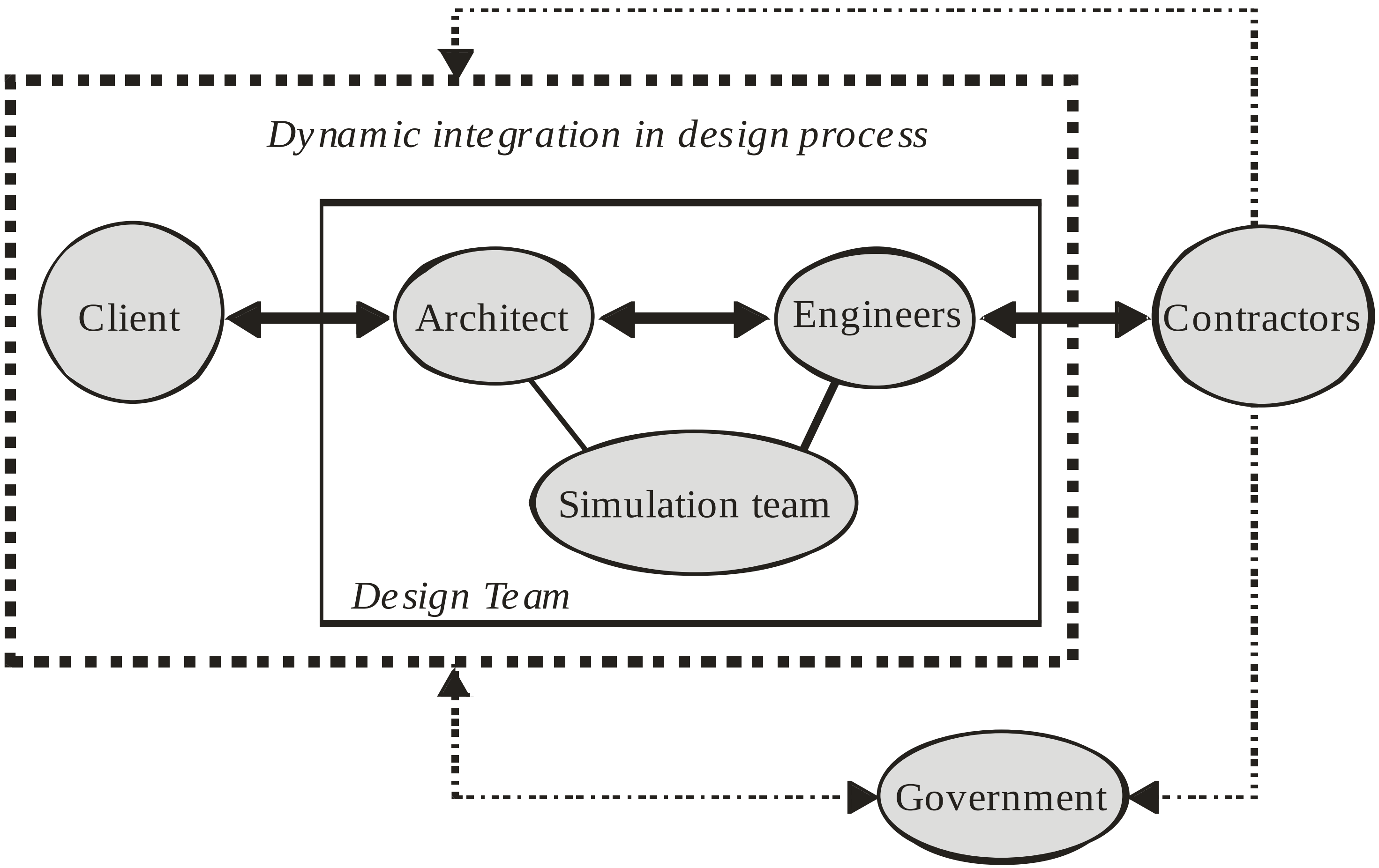
Level 2:



Source: Hien et al (2000, *Building and Environment* 35, 709-736, http://www.sciencedirect.com/science/journal/03601323)

Figure 4.79c Integrated Design Process

Level 3:



Source: Hien et al (2000, *Building and Environment* 35, 709-736, http://www.sciencedirect.com/science/journal/03601323)

Integrated Design Process: Principles

- Consider building orientation, form, shape, thermal mass and glazing fraction
- Specify a high-performance thermal envelope
- Maximize passive heating, cooling, ventilation and day-lighting
- Install efficient *systems* to meet remaining loads
- Ensure that individual energy-using *devices* are as efficient as possible and properly sized
- Ensure that systems and devices are properly commissioned

My Rating of architects & design teams:

- Can’t deliver 25% savings: totally incompetent, fire them all
- Can deliver 50% savings: competent and knowledgeable team
- Can deliver 75% or greater savings at little or no additional construction cost: truly outstanding

Retrofits of existing buildings

- Insulation
- Windows
- Air sealing
- Mechanical systems
- Lighting
- Solar measures

Renovations to the Passive House Standard (15 kWh/m^2/yr heating load)

- Dozens carried out in old (1950s, 1960s) multi-unit residential buildings in Europe, resulting in 80-90% reduction in heating energy use
- Two examples will be shown here:

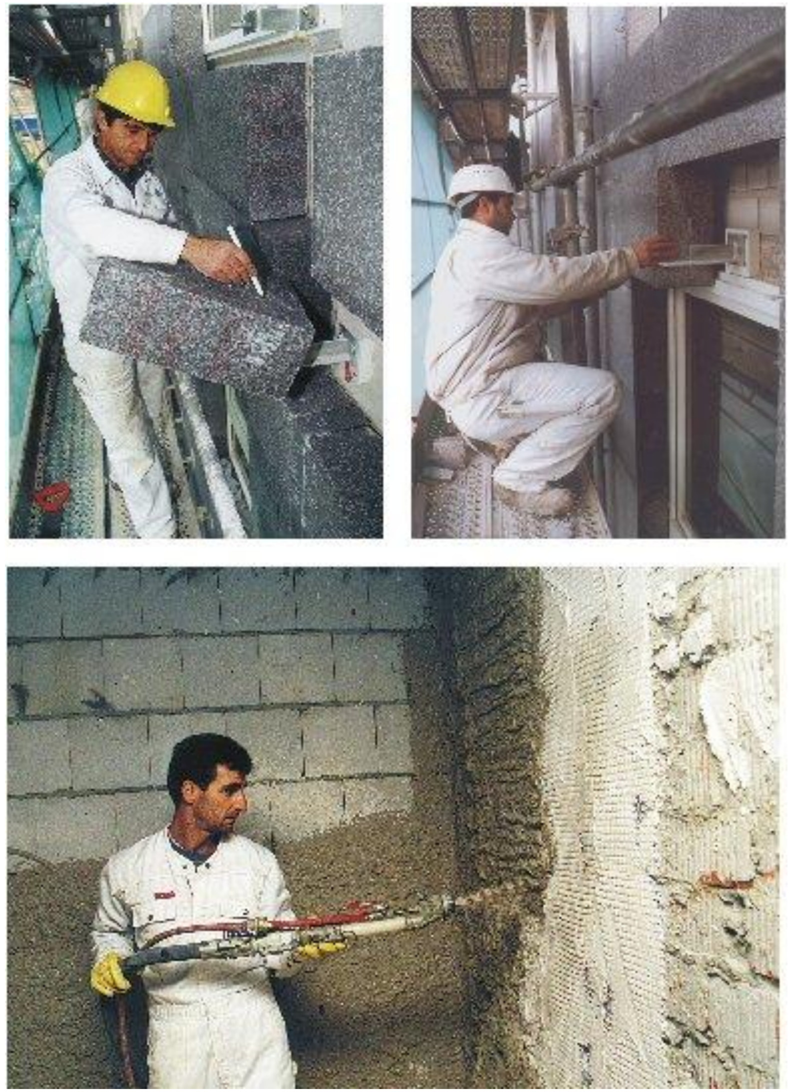
  -BASF buildings in Ludwigshafen, Germany

  - apartment block in Dunaújváros, Hungary

Figure 4.83 BASF retrofit, before and after

Source: Wolfgang Greifenhagen, BASF

Figure 4.84 BASF retrofit (a) installation of external insulation, (b) installation of plaster with micro-encapsulated phase change materials



Source: Wolfgang Greifenhagen, BASF

Figure 4.85 Renovation to the Passive House Standard in Dunaújváros, Hungary. Before:

Source: Andreas Hermelink, Centre for Environmental Systems Research, Kassel, Germany

After:

Source: Andreas Hermelink, Centre for Environmental Systems Research, Kassel, Germany

Net result:

- 90% reduction in heating energy use – this saves natural gas that can be used to generate electricity at 60% efficiency (or even higher effective efficiency in cogeneration), thereby serving as an alternative to new nuclear power plants
- Problems of summer overheating were greatly reduced
- A grungy, deteriorating building was turned into something attractive and with another 50 years at least of use

In Toronto and some other North American cities

- There are opportunities for similarly large reductions through retrofitted old 1960s and 1970s apartment towers
- Single-family houses will be harder and more expensive, but are doable
- But what will we do with all the glass condominiums and office towers being built now?

Table 4.34 Current and projected energy use (kWh/m^2/yr) after various upgrades of a typical pre-1970 high-rise apartment building in Toronto.

Measure	Natural Gas		Elec-tricity	Primary Energy	Cost ($/m^2)	Payback (years)	IRR (%/yr)
	Heating	DHW					
Current building	203	36	71	443			
Roof insulation	184	36	70	420	13	11.4	11.3
Cladding upgrade	167	36	69	398	44	18.1	3.4
Window upgrade	122	36	64	336	73	13.5	9.2
Balcony enclosure	122	36	68	345	121	21	4.3
All of the above	47	36	64	252	199	18.6	5.6
Boiler upgrade	118	36	70	347	23	5.5	23
HRV	136	36	68	362	17	7.8	25.8
Water conservation	203	25	70	430	5	3.4	35.1
Parkade lighting	203	36	70	440	0	4.4	28
All of the above	9.4	25	59	185	257	16.9	6.7
Above with 50% less tenant electricity	24.1	25	29	128			

DHW=domestic hot water, IRR=internal rate of return,
HRV=heat recovery ventilator.

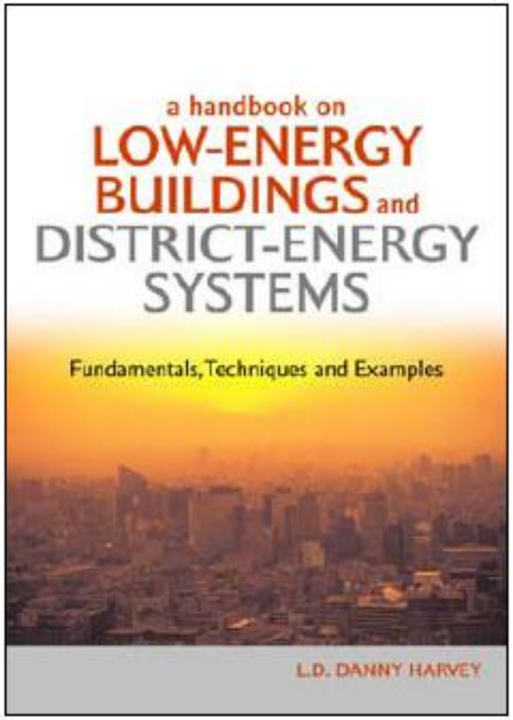
Getting a Factor-of-50 savings in heating energy requirements

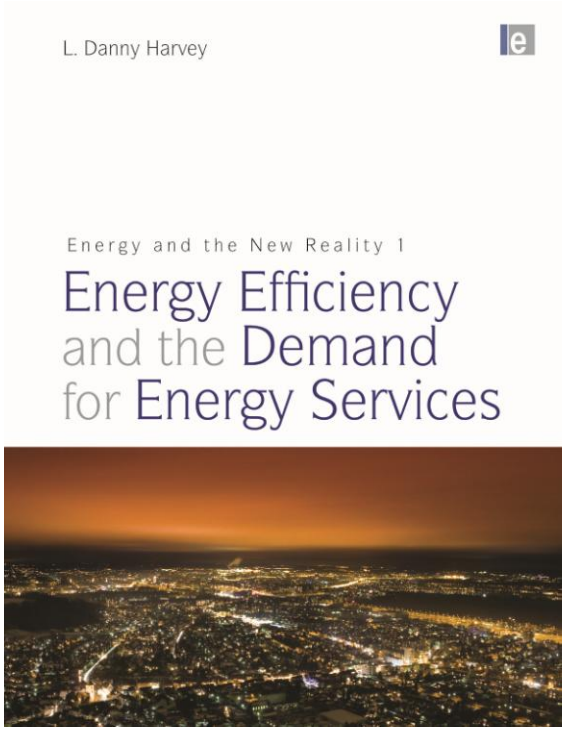
- In some cases, especially for 1970s apartment towers, we can retrofit them to reduce space heating requirements by 90% (a factor of 10 reduction)
- The low distribution temperatures required for heating would permit premium-quality ground-source heat pumps to operate with a seasonal COP of ~ 4 (equivalent to 400% efficiency)
- If these replace boilers at 80% efficiency, the improvement is a factor of 5
- Thus, the overall reduction in on-site heating energy requirement is a factor of 50!
- The rate of heat loss in such buildings would be so slow (thermal time constants of 5-7 days) that the heat pump could be run when the wind is blowing and turned off when it isn’t – thereby serving as a dispatchable electricity load that would permit larger use of intermittent renewable energy sources than otherwise

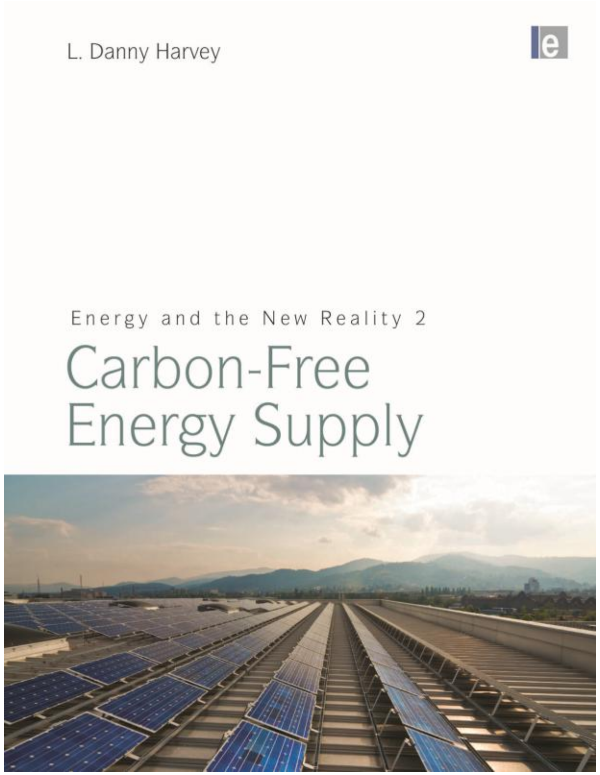
Some Final Thoughts on the Role of Buildings in Renewable Energy

- The rate of heat loss in buildings that meet the Passive House standard is so slow (thermal time constants of 5-7 days) that heat pumps used for heating and powered by wind electricity could be run when the wind is blowing and turned off when it isn't – thereby serving as a dispatchable electricity load that would permit larger use of intermittent renewable energy sources than otherwise.
- By building several widely-dispersed large wind farms in the regions of the best winds (which tend to be 500-2000 km from major demand centres), and relying on hydro-electric power as additional energy and especially using the reservoirs for energy storage, as well as flexible heat pumps for heating and cooling, and with a strong emphasis on efficient use of electricity, it is conceivable that renewable energy could completely displace fossil fuel and nuclear-generate electricity in Canada over the course of the next 30 years or so.

Further reading (books published by Earthscan):







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