Net climatic impact of solid foam insulation produced with halocarbon and non-halocarbon blowing agents

L.D. Danny Harvey*

Department of Geography, University of Toronto, 100 St. George Street, Toronto, Canada M5S 3G3

Abstract

The net climatic effect of increasing the amount of insulation in buildings through the use of halocarbon-blown foam insulation involves three factors: the greenhouse gas emissions associated with the energy used to make the insulation; the climatic impact of leakage of the halocarbon blowing agent from the insulation during its manufacture, use, and at the time of disposal; and the reduction in heating and/or cooling energy use and associated greenhouse gas emissions. Recent studies and assessments leave the impression that the use of halocarbon-blown foam insulation has a strong net positive impact on climate, with the reduction in heating-related emissions being 20–100 times greater than the CO_2-equivalent halocarbon emissions. This result applies only to the overall impact of rather modest levels of insulation applied to a pre-existing roof or wall with negligible thermal resistance. It is appropriate to consider the time required for heating-related emission savings to offset halocarbon and manufacturing emissions for the addition of successive *increments* of insulation—the *marginal* payback time. For typical blowing agent leakage rates and for insulation levels found in high-performance houses, marginal payback times can be in excess of 100 years using halocarbon blowing agents, but are only 10–50 years using non-halocarbon blowing agents. With a fixed thickness of insulation, the difference in heating energy savings using insulation with different blowing agents is generally only a few per cent, in spite of differences in thermal conductivity of up to 66%. The net savings in CO_2-equivalent emissions is larger using non-halocarbon blowing agents, with the relative benefit of using non-halocarbon blowing agents greater the greater the thermal resistance of the envelope element prior to adding foam insulation.
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1. Introduction

Building insulation can take the form of loose or spray-on cellulose fibres, fibreglass or mineral fibre batts, or solid or spray-on foam insulation. Solid foam insulation is widely used as external insulation in commercial buildings, as it can be fastened directly to poured concrete or block walls. It is also sometimes used as an external layer in wood-frame buildings having fibre insulation between the studs, as it can span the thermal bridges created by the studs. There are several kinds of solid-foam insulation materials: *expanded polystyrene* (EPS), *extruded polystyrene* (XPS), extruded *polyurethane* (PU), and extruded

polyisocyanurate (a PU derivative). EPS is produced from ethylene (a component of natural gas) and benzene (a derivative of petroleum). It begins as small liquid beads combined with a gaseous expanding agent and a fire retardant. The beads are heated and expand, then allowed to set for 24 h, during which time the expanding agent diffuses through the wall structure and, at some manufacturing facilities, is captured for reuse. The beads are then reheated with steam in a mould, causing the beads to fuse together. XPS begins as crystalline polystyrene, which is melted under pressure. PU and polyisocyanurate are made from polymeric methylene diisocyanate and polyohydroxyl, both of which are derived from petroleum. A substantial amount of energy, both as process energy (for example, for heating the ingredients) and as feedstock (petroleum and

*Tel.: +1 416 978 1588; fax: +1 415 946 3886.

E-mail address: harvey@geog.utoronto.ca.

natural gas), is required in order to manufacture foam insulation.

PU, EPS, and XPS can also be applied as spray-on foam insulation, which is particularly useful in retrofit applications, where often difficult-to-reach cavities need to be insulated. As with solid-foam insulation, some expanding agent is required.

Foam insulation has a cellular structure, created through the expansion of the expanding agent that is added before the ingredients are heated. The expanding agent used in foam insulation can be a halocarbon, pentane, water, or CO_2, depending on the type of insulation and its application. Halocarbons are compounds containing carbon and one or more halogen gases—chlorine, fluorine, and bromine. Those containing chlorine and fluorine are *chlorofluorocarbons* (CFCs), those containing hydrogen, chlorine and fluorine are *hydrochlorofluorocarbons* (HCFCs), and those containing hydrogen and fluorine are *hydrofluorocarbons* (HFCs). All three groups are greenhouse gases (GHGs), while those containing chlorine (the CFCs and HCFCs) lead to the depletion of stratospheric ozone as well. All uses of CFCs have been almost completely phased out, as required under various international agreements to protect stratospheric ozone. They have been temporarily replaced by the HCFCs in various applications, including foam insulation, and will in turn be replaced by HFC or non-halocarbon expanding agents in developed countries by 2010. Developing countries are allowed to increase their use of HCFCs up to 2015, after which production levels cannot increase, with a phaseout by 2040. Leakage of expanding agents can occur during the manufacture of the insulation, while the insulation is in use, at the time of demolition of the building, and—if building debris including insulation is placed in a landfill—after disposal of the used insulation.

The impact on climate of the emission of a given mass of gas depends on the effectiveness of the gas in trapping heat, on a molecule-by-molecule basis, and on the average lifespan of molecules of that gas in the atmosphere. As the amount of gas in the atmosphere decreases after a pulse emission, the heat trapping decreases. The integral (or summation) of this heat trapping over some arbitrary time horizon can be computed and compared with that for CO_2; the ratio of the two forms an index called the *global warming potential* (GWP). This is a rough but adequate measure of the relative contribution of equal emissions (in terms of mass) of gases to global warming (see Harvey [1] for a critique of the GWP index).

A tradeoff exists between the reductions in heating energy use and in CO_2 emissions on the one hand, and emissions of halocarbons on the other hand if an insulation with a halocarbon blowing agent is used. As well, the energy used to manufacture the insulation (referred to as the *embodied energy* of the insulation) needs to be compared with the savings in heating energy. The embodied energy will increase in proportion to the thickness of the insulation as more insulation is added,

but each successive increment of insulation will save less additional heating energy. Thus, at some point (depending on the climate and the magnitude of internal heat gains), it will not be worthwhile from a GHG emission point of view to increase the amount of insulation. The tradeoffs between halocarbon emissions, embodied energy, and heating energy savings are the subject of this paper.

2. Characteristics of different kinds of foam and non-foam insulation

In this section, the properties of insulation relevant to their net effectiveness in reducing GHG emissions are discussed.

2.1. Effectiveness in reducing heating and cooling loads

Heat loss from a building occurs through conductive heat transfer in roofs, walls, and ground or basement floors; through conductive, convective, and radiative heat exchange in windows; and through uncontrolled exchange of indoor and outdoor air through various leakage points in the building envelope. Conductive heat transfer through a building element varies inversely with the thermal resistance of that element, as represented by the RSI-value.[1] The RSI-value of a panel of insulation of given properties in turn varies directly with the thickness of insulation. Because heat loss varies with 1/RSI, there are diminishing returns to successive increases in the thickness of insulation. This is illustrated in Fig. 1, which shows the decrease in relative heat loss as the thermal resistance of the insulation increases from RSI 2 (a minimal level of insulation) to RSI 10 (corresponding to a *U*-value of $0.1 \, W/m^2/K$, as found in a many of the advanced houses surveyed by Hamada et al. [2] and Schnieders and Hermelink [3]). Increasing the wall or roof RSI-value from 2 to 10 would reduce the conductive heat loss through the wall or roof by a factor of 5.

If insulation is applied snugly between the studs and rafters (in the case of blown-in, spray-on, or batt insulation), or as a continuous layer sealed with caulking in the case of solid-foam insulation, then it is possible that insulation will also reduce heat loss due to exchange of indoor and outdoor air. This is a potentially significant additional benefit of insulation, as air exchange can constitute up to 40% of the total heat loss in leaky buildings. This benefit is most likely to accrue in the case of blown-in cellulose or spray-on foam insulation, where the insulation can easily fill the various small gaps and irregularities within the framing elements (studs and

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[1]Following usage in Canada, the term "RSI" will be used here to designate metric (système international, SI) resistance values. The resistance is referred to simply as the *R*-value in Europe (where only metric units are used), but in the USA and Canada, the term "*R*-value" refers to the resistance in non-metric units. The reciprocal of the *R*- or RSI-value gives the *U*-value in the same units.
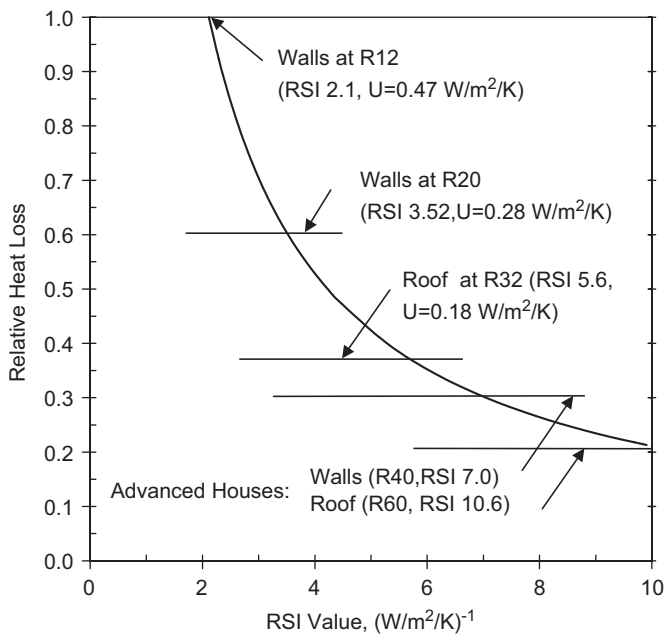
Fig. 1. Heat flow vs. thermal resistance for the range of resistances encountered in insulated walls and ceilings. Heat flow is relative to the heat flow at R12 insulation (RSI 2.1), which fits into $2'' \times 4''$ (38×89 mm) stud walls.

rafters), especially at corners and next to windows and doors.

Insulation, if applied externally and combined with night-time ventilation to remove heat from the wall thermal mass, can be very effective in reducing or even eliminating cooling loads (particularly in buildings with small internal heat gains). For average US climate conditions and cooling equipment efficiency, McBride [4] estimates that the savings in electricity used for cooling due to insulation is 20–30% of the savings in heating energy use. A similar ratio is found for other countries with hot summers and cold winters. For a 1-storey house in Cyprus, adding 5 cm of polystyrene insulation to the roof reduces the cooling load by 45% (and the heating load by 67%), while addition of 5 cm of polystyrene insulation to the walls reduces the remaining cooling load by about 10% (and the remaining heating load by 30%) [5]. The absolute savings in cooling energy use is about 60% of the savings in heating energy use. For a 1-storey building in Tehran, Safarzadeh and Bahadori [6] find that 10 cm of insulation on the walls and roof (U-value of $0.38 \, \text{W/m}^2/\text{K}$) reduces the cooling load by 14% (and the heating load by 55%), with the absolute savings in cooling energy use about 20% of the savings in heating energy use.

Insulation is particularly effective in reducing cooling loads in arid regions, where the amount of radiation reflected off of the ground onto walls can be almost as great as the amount of radiation directly striking the walls. This in turn causes the wall surface temperature to be substantially greater than the air temperature, so that the impact of insulation in reducing cooling loads is much greater than expected based on the difference between

indoor and outdoor air temperatures. Note that, if the savings in on-site electricity use due to reduced cooling loads is 1/3 the savings in heating energy use, and if the electricity is generated with an efficiency of 33%, then the savings in primary energy due to reduced cooling loads will be comparable to the savings in primary energy due to reduced heating loads.

2.2. Embodied energy

Table 1 summarizes various estimates of the embodied primary energy of different insulation materials on a mass basis. There is a remarkable disagreement among alternative estimates, with Lenzen and Treloar [9] giving an embodied energy for glass and mineral wool that is 4.5–6.5 times that of other estimates, while McBride [4] indicates an embodied energy for XPS that is 10–12 times less than three other estimates. However, there is no disputing the conclusion that the embodied energy of cellulose insulation (recycled newsprint) is close to zero.

Table 2 summarizes various estimates of the embodied primary energy on a volumetric basis for different insulation materials, along with thermal conductivity (k) values. The embodied energy on a volumetric basis increases directly with the insulation density, while the thermal conductivity decreases with increasing density. Thus, pushing a given insulation type to a lower thermal conductivity by increasing the density (in order to reduce the space requirements) increases the embodied energy for a given RSI increment (as well as increasing the cost). The polystyrene thermal conductivities given in Table 2 are for a pentane-blown commercial product called Neopar® (available in Europe in small quantities) that contains a low-e coating to minimize infrared radiative transfer within the insulation matrix. This reduces the thermal conductivity by 10–15% (see www.3lh.de). The resistance of a layer of thickness D is given by

$$\text{RSI} = k/D. \tag{1}$$

From this, the thickness of a slab with RSI 1.0 can be computed, and from that the embodied energy of an RSI = 1.0 slab can be computed using the volumetric embodied energy. These embodied energies are given in the last column of Table 2.

To compare the savings in CO_2 emissions resulting from additional insulation with the CO_2 emissions associated with manufacturing the insulation, the kinds of energy used to make the insulation, the kind of energy used for heating, and the sources of any electricity used for heating or manufacturing need to be considered. Table 3 gives the breakdown of primary energy inputs for the manufacture of polyisocyanurate insulation in Canada. About one-quarter of the primary energy input is coal, which has almost twice the CO_2 emission factor of natural gas (92 vs. 55 kg CO_2/GJ). Thus, if the heating energy that is saved is natural gas, the payback time for CO_2 emissions will be 17% longer than the energy payback time if we approx-

Table 1
Embodied primary energy (GJ/t or MJ/kg) of different insulation materials according to various published estimates

	Chen et al. [7]	Adalberth [8]	Lenzen and Treloar [9]	Petersdorff et al. [10]	McBride [4]
Cellulose	3.3			0.9	
Fibreglass	30.3				22.2[a]
Polyester	53.7				
Glass wool	14.0		93.1		
Mineral wool		19.2	93.1	18	
Polystyrene	105	106.7		127	10.3[b]
Polyurethane				137	
Urea formaldehyde	78.2				

[a]Energy use at the manufacturing facility is 40% electricity, 60% natural gas. The amount of primary energy used to generate electricity is estimated here assuming the powerplant × transmission efficiency to be 0.33.
[b]Energy use is entirely electricity, converted to primary energy assuming a powerplant × transmission efficiency of 0.33. Computation of MJ/kg requires the foam density, assumed here to be 30 kg/m^3.

Table 2
Embodied primary energy for a 1-m^2 insulation panel with an RSI value of 1, computed from embodied energy per unit volume and thermal conductivity

Type of insulation	Density (kg/m^3)	Embodied energy		Conductivity (W/m/K)	Embodied energy (MJ/m^2/RSI)
		(MJ/kg)	(MJ/m^3)		
Cellulose	40–70	0.9	36–61	0.045	1.6–2.8
Fibreboard	190–240	11.2–11.8	2124–2826	0.053–0.045	113–127
Polystyrene	15–30	127	1900–3780	0.032–0.030	61–113
Polyurethane	30–35	137	4104–4788	0.035–0.020	144–96
Mineral wool	20–140	18	360–2520	0.045–0.035	16–88
Mineral wool					40
Fibreglass					16.5
Fibreglass	35[a]	22.2	777	0.04	31.1

Embodied energies (as MJ/m^3), densities, and thermal conductivities are from Petersdorff et al. [10] and are used to compute other entries, except for polystyrene thermal conductivities (which are from BASF) and embodied energies in the last two rows (which are from Norris, [11]).
[a]Assumed here.

Table 3
Energy and feedstocks used to produce a 1 kg of polyisocyanurate insulation in Canada

Input	Used as feedstock		Used as energy (MJ)	Total embodied energy (MJ)
	Mass (g)	Energy equivalent (MJ)		
Oil	482	20.2	4.0	24.2
Natural gas	203	10.1	19.3	29.4
Coal			9.3	9.3
Other			3.4	3.4
Total	685	30.3	35.9	66.2

Feedstocks have been converted to energy equivalents using 1 gm oil = 42 kJ and 1 gm natural gas = 50 kJ.
Source: Franklin Associates [12].

imate the embodied primary energy as 75% natural gas, 25% coal. For fibreglass and XPS insulation manufactured in the US, McBride [4] indicates that 40% and 100%, respectively, of the energy inputs are as electricity. If the electricity is generated from coal with a generation ×

transmission efficiency of 0.33, and the heating energy that is saved is natural gas, then the payback times for CO_2 emissions will be 45% and 67% longer than the energy payback times.

If the focus of interest is the depletion of non-renewable energy supplies, rather than emissions of GHGs, then the use of natural gas and oil as a feedstock (in addition to their use as an energy source in the production process) should be taken into account. As seen from Table 3 for polyisocyanurate manufactured in Canada, consideration of feedstocks roughly doubles the computed embodied energy of the insulation. Given the similarities among different kinds of foam insulation, a roughly comparable factor should be applicable to other types of foam insulation.

2.3. Halocarbon emissions and thermal conductivity of foam insulation

Table 4 lists the CFC, HCFC, HFC, and non-halocarbon expanding agents that had been used, are used, or could be used in various kinds of foam insulation except EPS (which uses pentane). Also given is the GWP of the

Table 4
Blowing agents used for polyisocyanurate, polyurethane, and extruded polystyrene insulation, and the global warming potential (GWP) of the blowing agent relative to CO_2 over a 100-year lifespan given

Type of insulation	Original blowing agent	HCFC blowing agent	HFC blowing agent	Non-halocarbon blowing agents
Polyisocyanurate	CFC-11	HCFC-141b		Pentane, cyclopentane
	GWP = 4680	GWP = 713	—	
Polyurethane (PU)	CFC-11	HCFC-141b	HFC-245fa	Pentane, CO_2, CO_2/H_2O (for spray foams)
	GWP = 4680	GWP = 713	GWP = 1020	
			HFC-365mfc	Various isomers of pentane (GWP = 7)
			HFC-227ea	
			GWP = 950–1100	
Extruded polystyrene (XPS)	CFC-12	HCFC-142b	HFC-134a	Pentane (GWP = 7), CO_2 (GWP = 1)
	GWP = 10720	GWP = 2270	GWP = 1410	
		HCFC-22	HFC-152a	Cyclopentane/isopentane blends
		GWP = 1780	GWP = 122	

Source: Ashford et al. [13].

halocarbon expanding agents. The following additional information is taken from Ashford et al. [13] except where indicated otherwise:

- Polyisocyanurate is made with normal pentane and cyclopentane/isopentane blends in North America and Europe.
- PU is made using HCFC-141b in developing countries, while in developed countries the use of HCFC-141b is limited to smaller contractors using spray foam. For solid PU in building applications in developed countries, pentane has rapidly gained widespread use. The use of pentane (or other hydrocarbons) in polyisocyanurate and PU requires significant re-engineering of production sites and worker training to prevent explosions, thereby entailing costs that can be prohibitive for small- and medium-sized enterprises in both developed and developing countries. Supercritical CO_2 has been used for some PU spray foam applications in Japan. A water/CO_2 mixture has been used in Europe, with a 10–20% market share by 2000 [14].
- XPS is made using HCFC-142b and HCFC-22 in developing countries, and these HCFCs continue to be used for XPS in North America. However, in Europe (where HCFCs are being phased out early), CO_2 is used alone in XPS or as a co-blowing agent with hydrocarbons. The use of CO_2 is technically challenging and requires a substantial new investment for many product lines.
- For spray foams, the choices are HFCs, hydrocarbons, or CO_2. Hydrocarbon blowing agents raise safety concerns (the risk of fire), but the hazards can be eliminated during the manufacture of solid foam but not yet with spray foam. CO_2-blown spay foams suffer from low density and high thermal conductivity compared to HFC foams. The building style in many countries lends itself to the use of spray foams in retrofit applications, such as upgrading flat roofs in Spain. Spray foams are the least expensive (about half that of XPS or EPS when

accounting for labour costs), so more insulation can be done for a given budget.

HFCs are expensive and so are used only where they are perceived to be absolutely necessary. The first HFCs to be available for foam insulation were HFC-134a and HFC-152a, which were used in XPS, either alone or co-blown with pentane. HFC-152a leaves the foam quickly, while HFC-134a is long-lived in foam. Systems with it can match the thermal conductivity of HCFC-142b. HFC-227ea, HFC-245fa, and HFC-365mfc are more recent products, which can be used in PU. The GWPs of HCFCs used in insulation range from about 700 to 2300, while GWPs of HFCs used in insulation range from about 120 to 1400.

The blowing agent can leak into the atmosphere during the production of foam insulation, during its use, and at the time of disposal. There is a rough consensus in the literature concerning the rates of emission of blowing agents from foam insulation, as summarized in Table 5. Leakage rates during manufacture appear to be substantially greater for XPS (about 25%) than for PU solid foam (5–12.5%) or for PU spray (5–15%). Leakage rates during use are also highest for XPS (0.75–4.0%/year) and lowest for PU solid foam (0.2–0.5%/year), with the estimated leakage rate of PU spray (1.2–1.5%) overlapping the lower part of the estimate range for XPS. PU solid foam can be manufactured without facings, or with tri-laminate facings (aluminium foil/kraft-paper/aluminium foil, each 7 μm thick) on both sides [14]. Leakage rates will be lower in the latter case.

A portion of the blowing agent remaining at the end of the life of the insulation will be emitted to the atmosphere, depending on the method of disposal. If the building is demolished and the insulation placed in a landfill, then essentially all of the remaining blowing agent will reach the atmosphere (bacterial degradation is thought to be negligible). If the insulation can be separated from the building debris and incinerated, essentially the entire

Table 5
Comparison of assumptions concerning rates of emission of blowing agents used in foam insulation

Type of insulation	Emission up to point of disposal			Reference
	Manufacture or application (%)	Use[a] (%/year)	Total (%)	
XPS	25	4.0	90	Harnisch et al. ([15], Table 9)
XPS	25	0.75	49	Ashford et al. ([16], Chapter 7)
PU using HFC-134a	10	0.5	30	Ashford et al.([16], Chapter 7)[b]
	12.5	0.5	32	
PU using HFC-277ea, 245fa, 365mfc	5	0.5	26	Ashford et al. ([16], Chapter 7)[b]
	12	0.5	32	
PU Roof panels	8	0.2	17	Harnisch et al. ([15], Table 23)
PU panels	0	0.2	10	Krähling and Krömer ([14], Table 3)
Generic PU Panels in 2010	5	0.5	26	Harnisch et al. ([15], Table 9)
PU Spray	15	1.5	60	Ashford et al. ([16], Chapter 7)
PU Spray	5 (1st year diffusion)	1.2	49	Krähling and Krömer ([14], Table 3); Krähling et al. ([17], Table 7)

Total emissions have been computed assuming a 50-year lifespan.

[a]Assumed to be a linear rate of emission as a fraction of the initial loading by some sources, but assumed here to apply to the annual decrease in the amount remaining at the start of any given year.

[b]First row is for continuous panels, second row for discontinuous panels.

blowing agent is destroyed. However, unless buildings are constructed with the intention of eventually separating and recycling the insulation, doing so will be very difficult. As well, some of the blowing agent remaining at the time of demolition will be released to the atmosphere during the demolition process (Harnisch et al. [15] assume a release of 20%). Foam insulation can also be recycled, either by recovering the raw materials (by, for example, glycolysis) if the chemical composition of the foam is known, or can be shredded and used in the production of pressed boards if it is not damp [17].

Foam insulation made with halocarbon expanding agents tends to have much lower thermal conductivity than foam insulation using non-halocarbon expanding agents, or than most non-foam insulation. This is due to the lower molecular conductivity of the heavy-molecular-weight halocarbon blowing agent. However, as the blowing agent leaks over time and is replaced by air, the thermal resistance of halocarbon-blown insulation will decrease. The rate of decrease in the halocarbon loading, and hence the rate of increase in thermal conductivity, depends on the type of blowing agent used and the thickness of the insulation panel (thicker panels experience a smaller relative loss). In spite of leakage, halocarbon-blown foam insulation provides greater long-term resistance to heat loss than non-halocarbon-blown insulation for a given thickness. This is illustrated in Table 6, which compares the thermal conductivity of a 5-cm thick layer of XPS insulation at the time of manufacture and after 10, 20, and 50 years for different blowing agents, as modelled by Vo and Paquet [21]. Also given are the thermal conductivities averaged over a 50-year life. The long-term thermal conductivity of 50-mm thick XPS panels is about 13% less using HFC-134a than using CO_2. Table 7 gives long-term

thermal conductivities for spray and solid PU insulation using different blowing agents as given by Krähling and Krömer [14]. For a given blowing agent, the thermal conductivity is about 30% less for solid foam than for spray foam.

As noted above, the rate of leakage of the blowing agent from foam insulation depends on the thickness of the insulation panel. Table 8 gives the initial blowing agent loading and the loading after 50 years for XPS panels of various thicknesses, as computed by Vo and Paquet (2004). Also given are the average annual rate of loss of blowing agent over 50 years and the initial and final thermal conductivities (results have been adjusted to give an initial conductivity of 0.027 W/m/K). Annual rates of loss range from 3.8%/year in 25-mm boards to 0.74%/year in 100-mm boards. This spans the range of annual losses given in Table 5 for XPS.

3. Assessing the tradeoff between embodied energy and reduced heating energy use

In this section we examine the tradeoff between increasing embodied energy and decreasing heating energy use due to decreasing conductive heat loss as the thickness of insulation is increased. As noted in Section 2.1, increasing insulation may provide additional heating energy savings through reduced envelope air leakage, as well as savings in cooling energy. These are not considered here, but could as much as double the benefit of increasing insulation thickness.

The time required for the energy savings of an energy-efficiency (or renewable energy) feature to offset the embodied energy of the feature is referred to as the payback time. Payback times for insulation can be

Table 6
Thermal conductivity (mW/m/K) of a 50-mm-thick XPS panel, with a density of 32 kg/m³, for various blowing agents at various times since manufacture

Blowing agent	Time (years)					
	0	5	10	20	50	Average
CFC-12	22	27.9	28.0	28.3	29.0	28.1
HCFC-142b	22	28.8	29.0	29.4	30.0	29.1
HFC-134a	22	28.8	29.0	29.4	32.3	29.1
HFC-152a	24	31.2	32.9	33.9	34.0	30.0
HCFC-22	24	33.2	33.9	34.0	34.0	33.3
CO_2	24	33.8	33.9	34.0	34.0	33.3

Source: Vo and Paquet (2004, Fig. 11).

Table 7
Long-term thermal conductivity of spray and solid PU foam insulation blown with different blowing agents

	Blowing agent	Conductivity (mW/m/K)
Sprays	HCFC-141b	29
	HFC-365mfc	30
	Water/CO_2	35
Solid	HCFC-141b	21
	HFC-365mfc	22
	HC-n-pentane	24

Source: Krähling and Krömer [14].

Table 8
Initial blowing agent load (per cent by mass) and after 50 years for XPS insulation panels of various thicknesses when blown with HCFC-142b.

Thickness (mm)	BA loading (%)		Rate of loss (%/year)	Conductivity (mW/m/K)	
	Initial	After 50 years		Initial	After 50 years
25	8.0	1.2	3.8	27	31.0
50	8.0	3.8	1.5	27	28.9
75	8.0	5.0	0.94	27	28.2
100	8.0	5.8	0.75	27	27.8

Also given are the average exponential rate of loss and the initial and final thermal conductivities.
Source: Vo and Paquet (2004), Fig. 16 for residual BA loadings, with initial and 50-year conductivities inferred from these loadings and their Fig. 12.

computed based on the savings in heating energy and the embodied energy in the full thickness of insulation—referred to here as the *overall payback time*—or based on the additional savings in heating energy and the additional embodied energy when an extra increment of insulation is added. In analogy to economic cost/benefit analysis, the latter will be called the *marginal payback time.* Because the absolute reduction in heat loss with successive increments of insulation decreases as more insulation is added (as seen from Fig. 1), the marginal payback time is longer for a given increment of insulation the greater the pre-existing insulation level. At any level of insulation, the overall payback time is less than the marginal payback time. The overall payback time is a useful indicator of the value of a given amount of insulation, while the marginal payback time is useful in deciding when (on a lifecycle energy basis) to stop adding more insulation: the amount of insulation should not be increased beyond the point where the

marginal payback time equals the expected lifespan of the insulation.

Fig. 2 gives overall and marginal payback times based on the primary energy needed to manufacture (but not transport or install) various kinds of insulation for a climate with 4000 heating degree-days (HDDs) and a heating-system efficiency (η) of 0.9. A climate with 4000 HDD pertains to regions with moderately cold winters, such as Toronto or Zurich (heating and cooling degree-day data for a sample of 77 world cities are given in Harvey [18]). The savings in heating energy is computed as

$$\text{Savings } (J) = \text{HDD} \times 24 \times 3600 \times \Delta U/\eta, \qquad (2)$$

where ΔU is the difference in U-values with and without foam insulation (or with and without a given increment of foam insulation) (U-value $= 1/RSI$-value). Fig. 2a gives overall payback times relative to an uninsulated brick or masonry wall with an RSI-value of 0.5. Even for the most
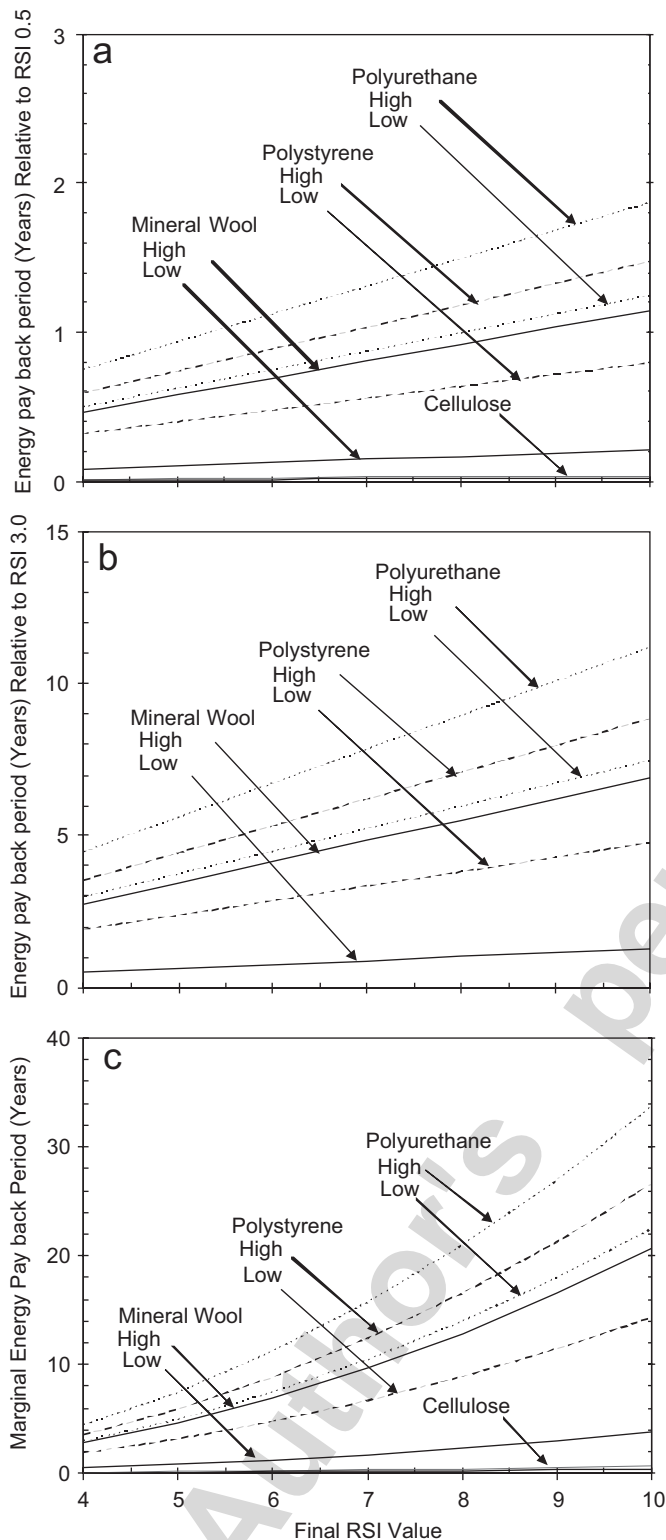
Fig. 2. Variation in the overall energy payback time as the total RSI is increased from (a) 0.18, (b) 0.50, or (c) 3.0 to values as large as 10.0, and (d) variation in the marginal energy payback time when the RSI-value is increase by 1.0 to the indicated final value. Energy payback times are for a climate with 4000 HDD and a heating system efficiency of 0.9, and are based on the embodied energies given in Table 2.

energy-intensive insulation, the overall payback time is less than 2 years for an RSI of up to 10. An alternative base case is a wood-frame structure with internal insulation giving an effective RSI-value (including thermal bridges) of 3.0. Fig. 2b gives the overall payback times when external insulation is added sufficient to bring the total RSI to values ranging from 4.0 to 10.0. The overall payback time for the added external insulation when sufficient external insulation is added to bring the total RSI to 6.7 (about the most that has been done for walls) is 3–6 years for polystyrene and 5–8 years for PU, depending on the efficiency of the manufacturing process. Fig. 2c gives marginal payback times, based on the last RSI increment of 1.0 added. When the RSI is increased from 9 to 10, the payback time for this increment is as large as 34 years, but inasmuch as this is less than the expected lifetime of the insulation, increasing the RSI to as high as 10 using the most energy-intensive foam insulation is justified on a lifecycle energy basis with a 4000 HDD climate. However, RSI-values as large as 10 have been used only in roofs which, if flat could be insulated to this level using a continuous bed of cellulose insulation, which is much less energy intensive.

4. Assessing the tradeoff between halocarbon emissions and reduced heating energy use

The climatic tradeoff involved in halocarbon emissions and reduced heating energy use will be assessed here in three ways. For the first two are based on the overall and marginal payback times computed for embodied energy, with the fractional rate of leakage and long-term thermal conductivity of the insulation assumed to be independent of the thickness of insulation. In the third method, the fractional rate of leakage is assumed to be smaller the thicker the insulation, and as this leads to a larger average blowing agent loading over the lifetime of the insulation, the average thermal conductivity is smaller the thicker the insulation. One can expect these assumptions to reduce the increase in marginal payback time as the thickness of insulation increases.

4.1. Results as the thickness of insulation is increased with fixed rates of leakage

4.1.1. Results for polyurethane foam

For PU foam cases with a fixed rate of leakage of the blowing agent, we assume an emission of 8% during the manufacture of solid foam insulation, emission of 0.2%/year or 0.5%/year of the blowing agent remaining at the start of each year over a 50-year lifespan, and complete destruction or recovery of the blowing agent remaining after the 50-year lifespan. These emission assumptions result in 16.8% and 28.4% of the original blowing agent being emitted to the atmosphere over a period of 50 years for the 0.2%/year and 0.5%/year cases, respectively. As a

Table 9
Input and computed intermediate parameters used to compute the time required for savings in heating energy CO_2 emissions to completely offset the GHG emissions associated with the manufacture of polyurethane solid foam insulation and associated with the leakage of three different blowing agents into the atmosphere

Parameter	Blowing agent (BA)		
	HCFC-141b	HFC-365mfc	n-pentane
GWP	713	782	7
Kilogram of BA used per kg of foam	0.100	0.123	0.050
BA density (kg/m³ foam)	3.200	3.936	1.600
Insulation conductivity (W/m/K)	0.021	0.022	0.024
Area of RSI-1 panel (m²) produced from 1 m³ of foam	47.619	45.455	41.667
Foam mass (kg/m²/RSI)	0.672	0.704	0.768
BA mass (kg/m²/RSI)	0.067	0.087	0.038
Foam-embodied energy (MJ/m²/RSI)	92.06	96.45	105.22
CO_2 from manufacture (kg/m²/RSI)	5.92	6.21	6.77
CO_{2eq} of BA emission (kg/m²/RSI) for 0.2%/year leakage over 50 years, 0% thereafter	8.03	11.35	0.05
CO_{2eq} of BA emission (kg/m²/RSI) for 0.5%/year leakage over 50 years, 0% thereafter	13.61	19.23	0.08
CO_{2eq} of BA emission (kg/m²/RSI) for 100% emission	47.91	67.71	0.27

In all cases, the foam density is assumed to be 32.5 kg/m² and the embodied energy 137 MJ/kg. Foam density and embodied energy are taken from Table 3, while foam conductivities and blowing agent GWP and loading are taken from Harnisch et al. [15], emission during manufacture is 8% of the initial loading, emission at disposal is 0% or 100% of the remaining blowing agent, and emission during use is either 0.2%/year or 0.5%/year over a period of 50 years.
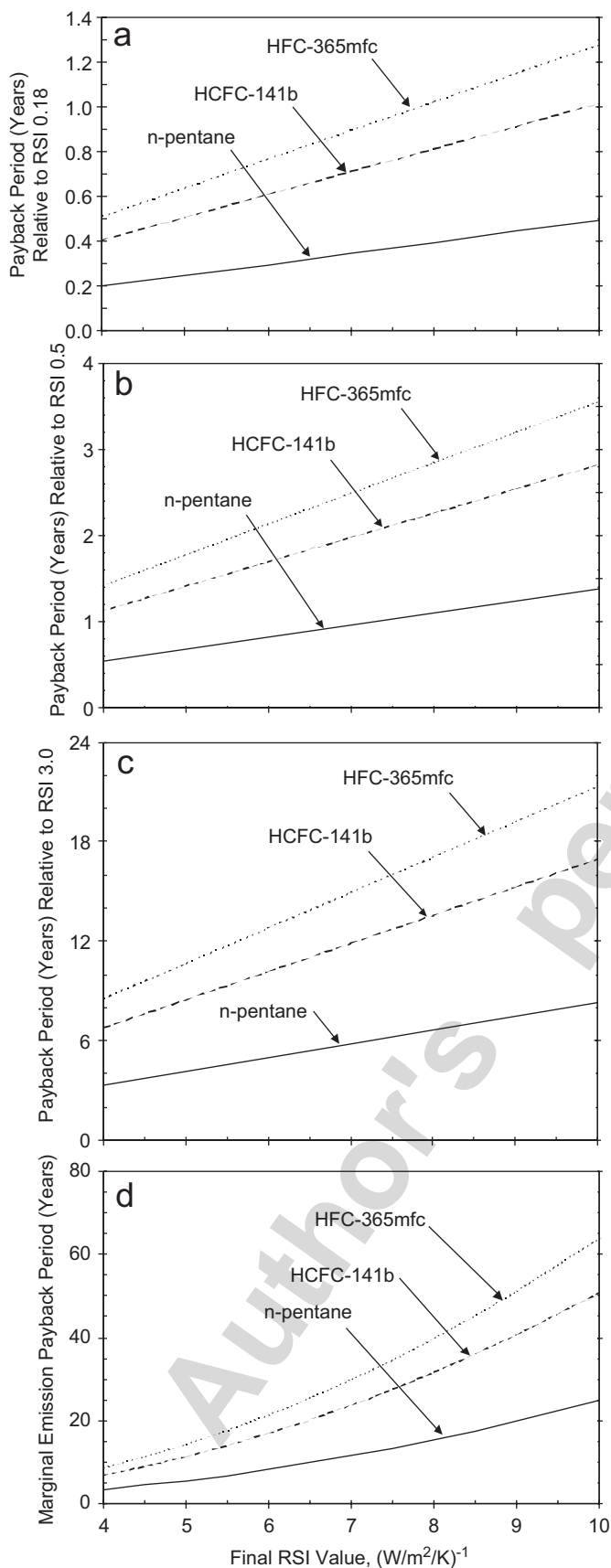
third case, 100% of the remaining blowing agent at the end of life is assumed to be emitted to the atmosphere.

Table 9 gives the GWP, amount of blowing agent used, and the foam thermal conductivity for solid PU foam manufactured using HCFC-141b, HFC-365mfc, or n-pentane as blowing agents. From these parameters, and given a foam density of 32.5 kg/m³, the embodied energy and mass of blowing agent used in 1 m² of foam with an RSI-value of 1.0 can be computed, and are given in Table 9. Assuming the energy used to manufacture the foam to be one-quarter coal and three-quarters natural gas, with emission factors of 92 and 55 kg CO_2/GJ, respectively, the CO_2 emission associated with the manufacture of the insulation is as given in the fourth last row of Table 9. Given the initial BA loadings, GWP, and total leakage, the CO_2 equivalents of the BA leakage can be computed and are given in the last two rows of Table 9 for 0.2%/year leakage rate, 0.5%/year leakage rate, and complete end-of-life emission cases.

Figs. 3–5 give the number of years required for the savings in heating energy CO_2 emission (resulting from the application of the PU foam insulation) to completely offset the equivalent CO_2 emissions associated with the manufacture of the insulation and with leakage of the blowing agent for the 0.2%/year, 0.5%/year, and complete-emission cases, respectively. Heating energy savings are computed using Eq. (2), assuming 4000 HDD and a heating efficiency of 0.9, then converted to CO_2 emissions assuming the energy used for heating to be natural gas. Results are given for foam insulation sufficient to give a total RSI ranging from 4.0 to 10.0, beginning with an initial RSI-value of either 0.18 (Figs. 3–5a, corresponding to 2-cm Douglas Fir sheathing), 0.5 (Figs. 3–5b, corresponding to a brick wall) or 3.0 (Figs. 3–5c, corresponding

to pre-existing fibreglass insulation batts between 38 mm × 89 mm studs). Also given are marginal payback times, based on RSI increments of 1.0 up to a final RSI-value of 10.0 (Figs. 3–5d).

As seen from Figs. 3–5, payback times are largest using HFC-365mfc, with the payback being about 75% as large using HCFC-141b and 20–25% as large using n-pentane. For 0.2%/year leakage using HFC-365mfc, the overall payback time is about 1.3 years when PU is used to increase the total RSI from 0.18 to 10 (Fig. 3a), about 3.6 years when PU is used to increase the total RSI from 0.5 to 10 (Fig. 3b), and about 20 years when PU is used to increase the total RSI from 3.0 to 10 (Fig. 3c). For a final RSI-value of 6.5, the marginal payback time is about 25 years, while for a final RSI-value of 10.0 (obtained in the roofs of some low-energy houses), the marginal payback time is about 65 years using HFC-365mfc, 50 years HCFC-141b, and 25 years using n-pentane (Fig. 3d). If the leakage rate during use is 0.5%/year rather than 0.2%/year (Fig. 4), the payback times are increased by about 40% (so, for example, marginal payback times for HFC-365mfc are about 35 years at RSI 6.5 and about 90 years at RSI 10). However, for PU blown with n-pentane, the marginal payback at an RSI-value of 10.0 is only 25 years, and average paybacks (based on the total thickness of foam insulation) are 8 years and 1.4 years if the starting RSI-values are 3.0 and 0.5, respectively. These payback times are largely independent of the assumed leakage rate, because they are dominated by the embodied energy of the insulation. Finally, if 100% emission of the blowing agent remaining at the end of life occurs, payback times for HCFC-141b and HFC-365mfc are about 3 times longer than for the 0.5%/year case.

Fig. 3. Variation in the overall payback time for equivalent CO_2 emissions as the total RSI is increased (a) from 0.18, (b) from 0.5, or (c) from 3.0 to values as large as 10.0, and (d) variation in the marginal emission payback time when the RSI-value is increased by 1.0 to the indicated final value. Emission payback times are for polyurethane insulation using either HCFC-141b, HFC-365mfc, or *n*-pentane as blowing agents, for a climate with 4000 HDD, for a heating system efficiency of 0.9, 8% leakage at the time of manufacture, 0.2%/year leakage during use, and no release of the blowing agent remaining at the time of disposal (after 50 years of use).

If the payback time for the addition of an increment of insulation is greater than the expected lifetime of the insulation, then the increase in the amount of insulation is *counterproductive* from a climatic point of view – over the lifetime of the insulation increment, the savings in heating-related CO_2 emissions is less than the CO_2-equivalent of the halocarbon emissions. Based on these results, it is seen that the net climatic benefit of halocarbon-blown foam insulation can be quite small, and that when used to build the total RSI-value up to the levels of wall insulation used in low-energy houses (RSI 6.5), halocarbon-blown foam insulation is counterproductive from a climatic point of view if, as is normally the case at present, there is complete loss of the remaining blowing agent at the end of a 50-year insulation life.

An alternative way to view the impact of varying amounts of insulation and of different blowing agents is to plot the variation in net emission reduction vs. RSI, where the net emission reduction is the savings in annual heating-related emissions minus the CO_2 (or CO_2-equivalent) emissions associated with the embodied energy and blowing agent averaged over the lifetime of the insulation. This is shown in Fig. 6 for a leakage rate of 0.2%/year. For halocarbon blowing agents, net saving peaks at some intermediate RSI-value and then declines; the maximum net saving occurs at the RSI-value where the marginal payback time is equal to the lifespan of the insulation. For *n*-pentane, the net saving increases with increasing RSI-value over the range (2–10) considered here.

4.1.2. Results for extruded polystyrene

The leakage rate from XPS insulation (0.75–4.0%/year according to Table 5) is substantially larger than from PU solid-foam insulation (0.2–0.5%/year), the GWPs of the halocarbon blowing agents are about twice as large (1800–2300 vs. 1000–1100), and the thermal conductivity is about 30% greater (so less heating energy is saved for a given thickness of insulation). As a result, the payback times for XPS are substantially greater than for PU solid-foam insulation. Payback times are given in Figs. 7 and 8 for leakage rates of 0.75%/year and 4.0%/year, respectively, with complete recovery of the remaining blowing agent at the end of life, and additional assumptions and intermediate results as given in Table 10. About 90% of the initial blowing agent has been emitted after 50 years in the 4%/year case, so the results for this case are almost the same as if complete emission of the remaining blowing agent had been assumed. In building from RSI 0.18 to RSI 10,
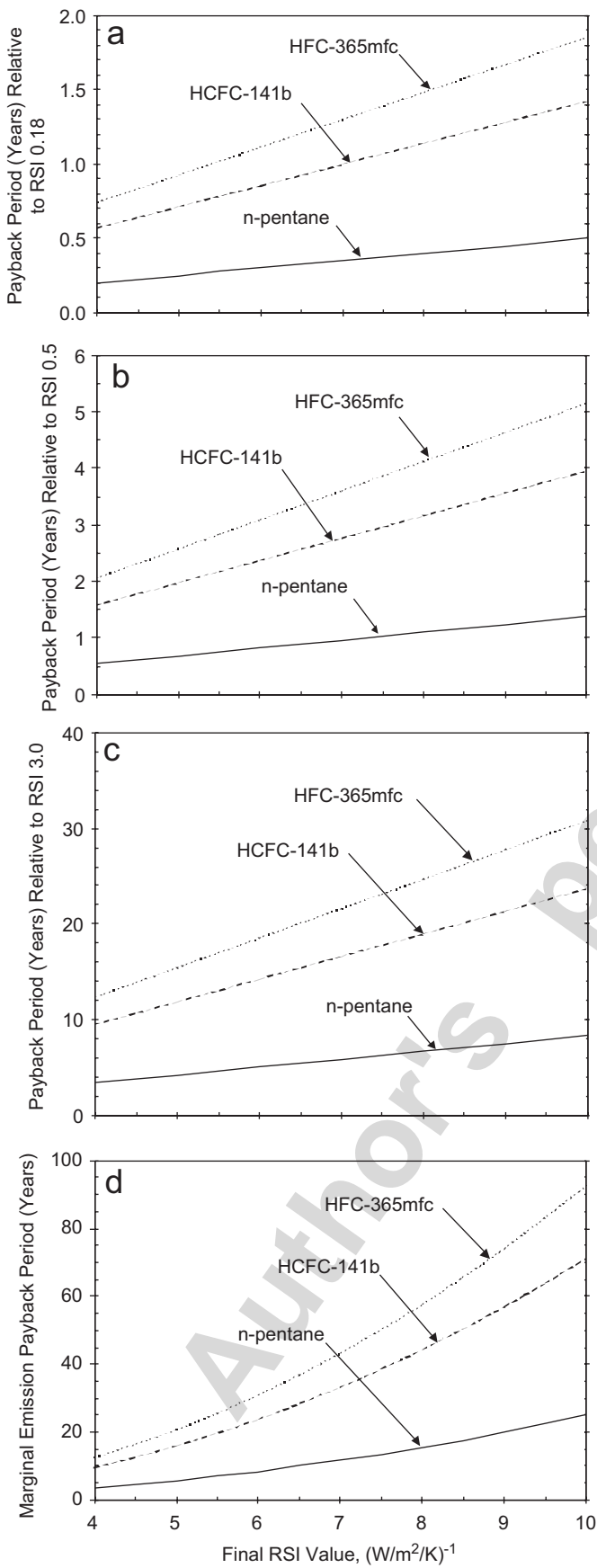
Fig. 4. Same as Fig. 3, but for 0.5%/year leakage of the blowing agent during use.
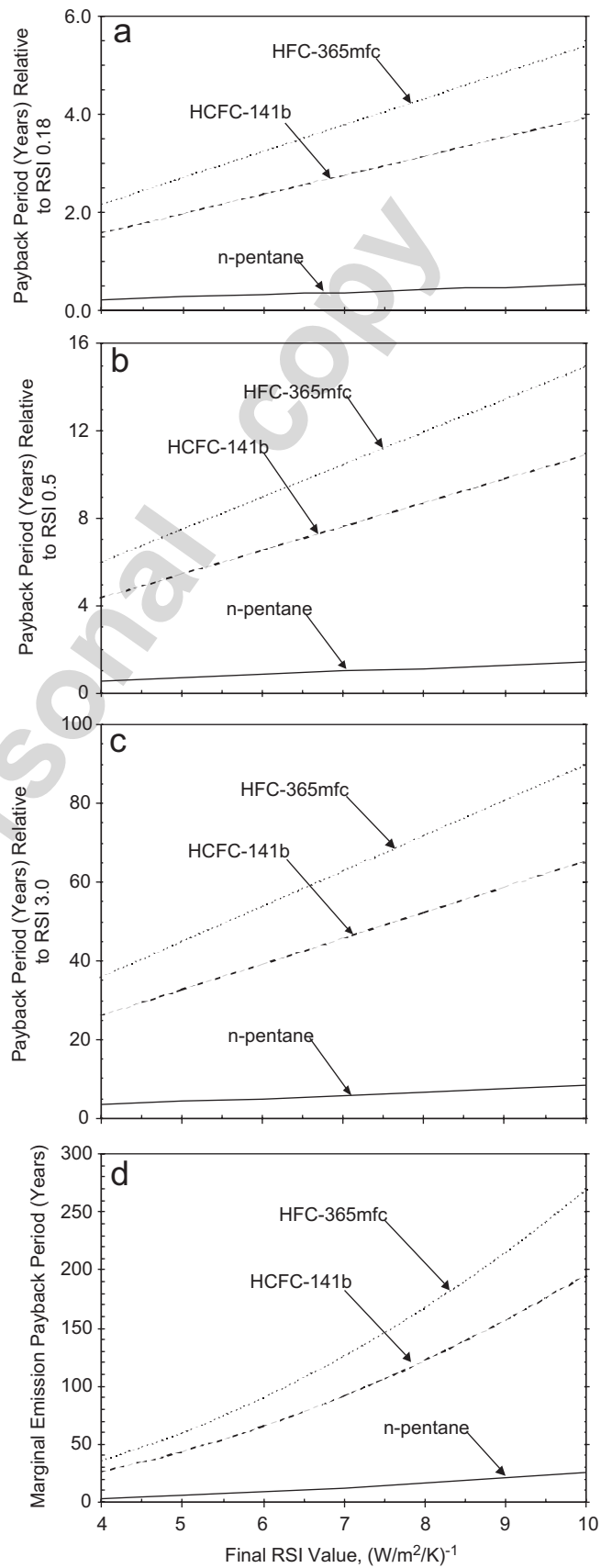
Fig. 5. Same as Fig. 4, except for complete release of the blowing agent at the end of use.
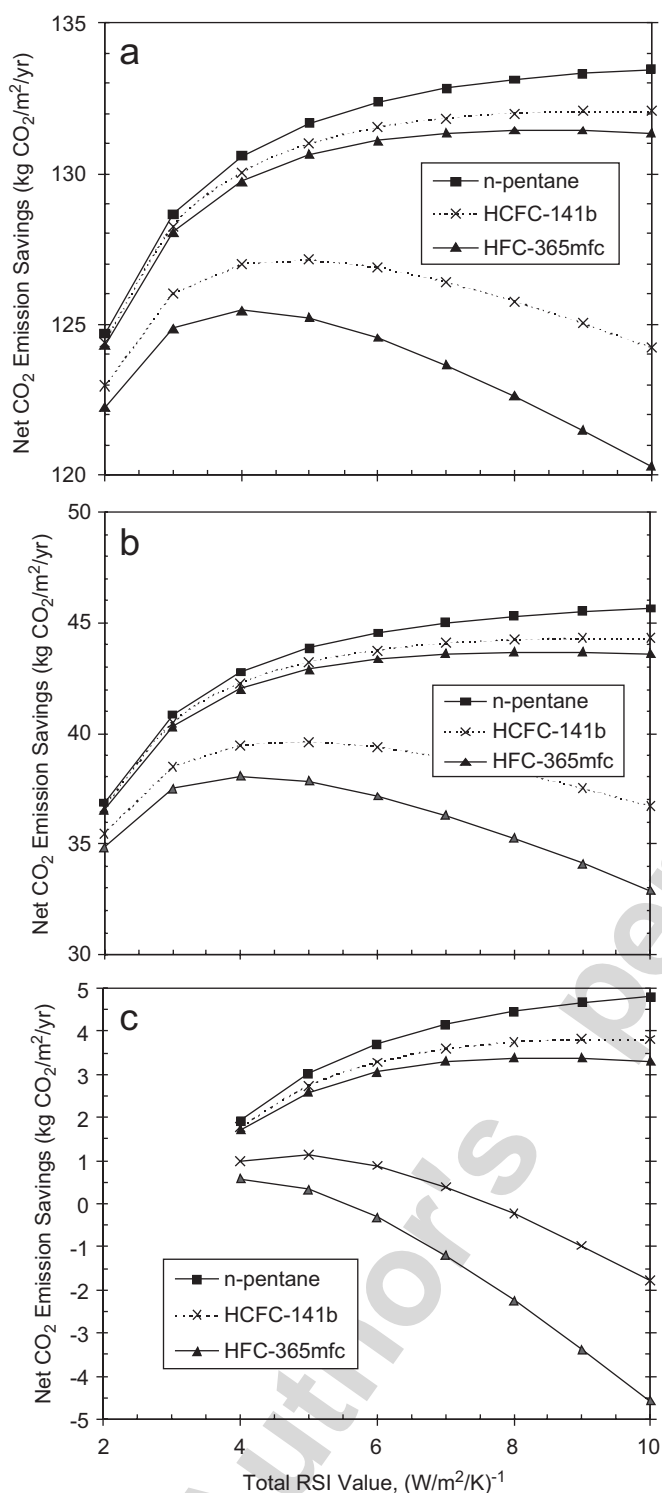
Fig. 6. Net annual CO_2-equivalent emission savings for PU foam with 0.2%/year leakage, starting from (a) RSI = 0.18, (b) RSI = 0.5, and (c) RSI = 3.0. Net emission savings are the savings in heating-related emissions (assuming a natural gas furnace at 90% efficiency and a climate with 4000 HDD) minus the total embodied-energy and blowing agent emissions averaged over an assumed insulation lifespan of 50 years. The upper curves for HCFC-141b and HFC-365mfc assume no release of the remaining blowing agent after 50 years of use, while the lower curves assume complete release.

the overall payback times are 3–5 years using HFC-134a and 5–8 years using HCFC-142b (depending on the leakage rate). However, the marginal payback times at RSI 10.0 are 150–260 years for HFC-134a and 230–410 years for HCFC-142b! At a more modest RSI of 6.5, marginal payback times are still 60–100 years for HFC-134a and 90–160 years for HCFC-142b. For CO_2-blown XPS, the marginal payback time at RSI 10 is about 20 years, most of which is related to manufacturing emissions.

4.1.3. Results for spray-on polyurethane foam

Spray-on foam insulation has the advantages that it can be applied in difficult-to-reach situations, can fill irregular voids, and can form an effective seal against air flow, thereby reducing heat losses due to exchange of inside and outside air as well as reducing conductive heat loss. Fig. 9 gives overall and marginal payback times for spray-on PU insulation using HFC-365mfc, HCFC-141b, and water/CO_2 as blowing agents, in all cases assuming 5% leakage during application, 1.2%/year leakage during use, and complete recovery of the remaining blowing agent at the end of 50 years. Fig. 10 gives payback times assuming complete emission of the remaining blowing agent. Additional assumptions and intermediate results are given in Table 11.[2] Assuming complete end-of-life recovery, the marginal payback time is 50–70 years at RSI = 6.5 and 130–170 years at RSI 10 using the halocarbon blowing agents, but is only 20 years at RSI 6.5 and 47 years at RSI 10 using a water/CO_2 mixture as the blowing agent. The halocarbon payback times are almost doubled if complete emission of the blowing agent that remains at the end of the insulation life occurs.

4.2. PU marginal payback time when leakage rate depends on thickness

The above results are based on a leakage rate that is independent of the thickness of the foam insulation. In reality, the fractional leakage will decrease the thicker the insulation, and this decrease will offset to some extent the declining marginal benefit of greater thicknesses of insulation. This in turn will cause the marginal payback time to increase more slowly as the thickness of insulation increases.

Based on the data presented in Table 8, it will be assumed here that the rate of leakage during use is given by

$$R = 0.005(4/H), \tag{3}$$

where H is the thickness of insulation in cm. This produces the rates of leakage shown in Fig. 11a, which range from 1.2%/year for a total RSI of 1.0 to 0.1%/year for a total RSI of 10 if the uninsulated case has RSI = 0.18. At a given RSI-value, the rate of leakage is smaller the more of

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[2]The H_2O/CO_2 loading when used as blowing agent is not known, nor are the proportion of H_2O and CO_2, so a CO_2 loading about half that when used as a blowing agent in PU is assumed.
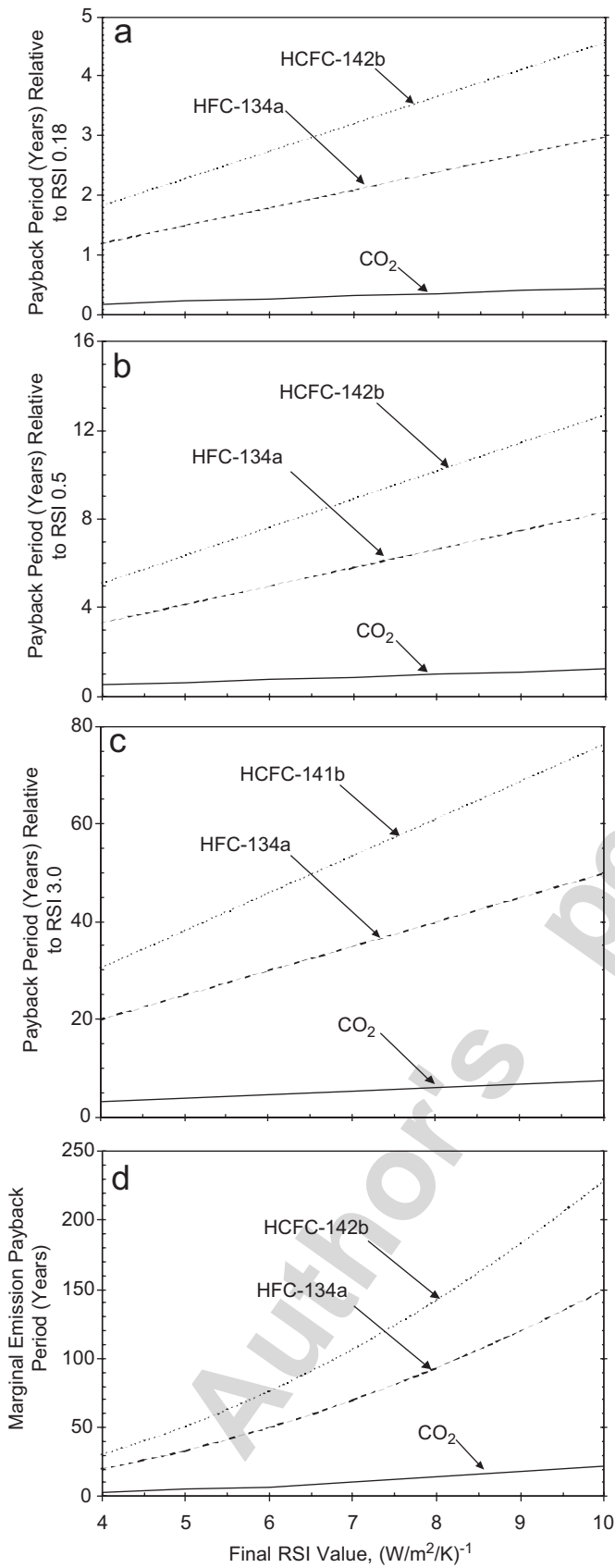
Fig. 7. Same as Fig. 3, but for XPS foam insulation with 0.75%/year leakage of the blowing agent during use and other assumptions as given in the main text.
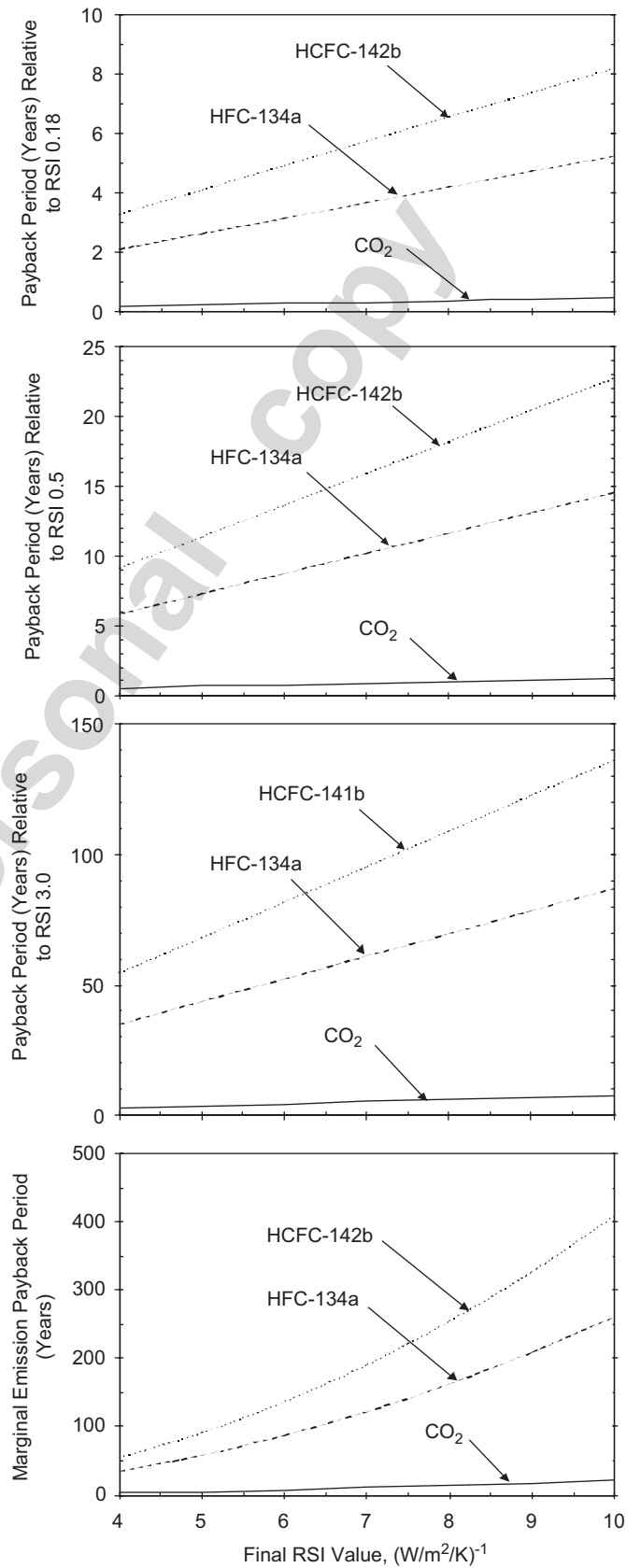
Fig. 8. Same as Fig. 3, but for XPS foam insulation with 4.0%/year leakage of the blowing agent during use and other assumptions as given in the main text.

Table 10
Same as Table 9, except for XPS solid foam insulation

Parameter	Blowing agent (BA)		
	HCFC-142b	HFC-134a	CO_2
GWP	2270	1410	1
Kilogram of BA used per kg of foam	0.08	0.08	0.08
BA density (kg/m³ foam)	1.80	1.80	1.80
Insulation conductivity (W/m/K)	0.029	0.029	0.033
Area of RSI-1 panel (m²) produced from 1 m³ of foam	34.48	34.48	30.30
Foam mass (kg/m²/RSI)	0.653	0.653	0.743
BA mass (kg/m²/RSI)	0.052	0.052	0.059
Foam-embodied energy (MJ/m²/RSI)	82.87	82.87	94.30
CO_2 from manufacture (kg/m²/RSI)	5.33	5.33	6.07
CO_{2eq} of BA emission (kg/m²/RSI) for 0.75%/year leakage over 50 years	69.70	43.29	0.03
CO_{2eq} of BA emission (kg/m²/RSI) for 4.0%/year leakage over 50 years	109.26	67.87	0.05

In all cases, the foam density is assumed to be 22.5 kg/m² and the embodied energy 127 MJ/kg (based on Table 2). GWPs are from Table 4, foam conductivities are average values from Table 6, and the blowing agent fraction is from Table 8 (for HCFC-142b and assumed to apply to other blowing agents). Emissions during manufacture and use are assumed to be 25% of the initial loading and either 0.75 or 4.0%/year, respectively, based on Table 5, and no emission of the remaining blowing agent is assumed.

the total RSI that is attributable to the solid foam component of the wall assembly, as this implies a greater thickness of solid foam insulation. The relationship show in Fig. 11 assumes that a greater RSI is obtained by using thicker foam panels, rather than by combining 2 or more panels in layers. Fig. 11b shows the total leakage fraction over a 50-year lifespan, including emissions during manufacture but assuming no end-of-life emissions. As increasing amounts of PU insulation are used, sufficient to increase the total initial RSI from 1.0 to 10.0 starting from an uninsulated sheathing with RSI = 0.18, the total emission decreases from 48% to 12%. Thus, as the thickness of insulation increases by a factor of 12 (from 1.7 to 20.6 cm), the total halocarbon emission increases by only a factor of 4. If solid foam insulation is applied to pre-existing insulation, the emission fraction at any given total RSI-value is larger the greater the starting RSI-value, as this corresponds to a thinner slab of foam insulation. Thus, for a total RSI of 4.0, the emission fraction is 43% for a pre-existing RSI of 3.0 and 19% for a pre-existing RSI of 0.18. These results should be regarded purely as an illustration of how important to overall emission the dependence of leakage rate on insulation thickness could be, as the specific numbers depend on the assumed relationship between foam thickness and annual leakage, as well as on the assumed emissions during manufacture and disposal.

The average thermal conductivity of the insulation is given here by

$$K = K_o + 0.050\Delta BA_f, \qquad (4)$$

where K_o is the initial conductivity (at full BA loading), and ΔBA_f is the decrease in the blowing agent loading expressed as a fraction of the foam mass. For $K_o = 0.0220$ W/m/K, K at the end of 50 years ranges from 0.0249 W/m/K for a 2-cm layer to 0.0227 for a 22-cm layer.

However, the smaller K for a thicker slab has very little effect on the marginal heating energy savings compared to the variation in 1/RSI.

Fig. 12 compares the resulting marginal payback times for PU insulation blown with either HFC-142b or HFC-365mfc. Shown are cases with a leakage rate fixed at 0.5%/year and thermal conductivity of 0.021 W/m/K (HFC-142b) or 0.022 W/m/K (HFC-365mfc), for a leakage rate given by Eq. (3) but fixed conductivity, and for a leakage rate given by Eq. (3) with conductivity given by Eq. (4). Accounting for the decrease in leakage rate with increasing insulation thickness reduces the marginal payback times by about 50%. This is consistent with BA agent accounting for about 70% of the total greenhouse heating (including embodied energy) at RSI = 10, and a reduction in this contribution by about 70% with thickness-dependent leakage rates. Allowing for the increase in thermal conductivity as BA leaks has a negligible effect on the marginal payback times.

4.3. Comparisons with a fixed thickness of insulation

In the preceding discussion we have compared payback times and net emission savings as the RSI-value is increased for different kinds of insulation and with different blowing agents. Insulation with a larger thermal conductivity needs to be thicker in order to provide the same RSI-value. However, in some situations (particularly involving renovations), the total thickness available for insulation is fixed. In this case, use of insulation with a larger thermal conductivity results in a smaller RSI-value. However, if the lower thermal conductivity is due to the use of a non-halocarbon blowing agent, then CO_2-equivalent emissions associated with leakage of the blowing agent are greatly reduced or eliminated altogether. This tradeoff is assessed here.
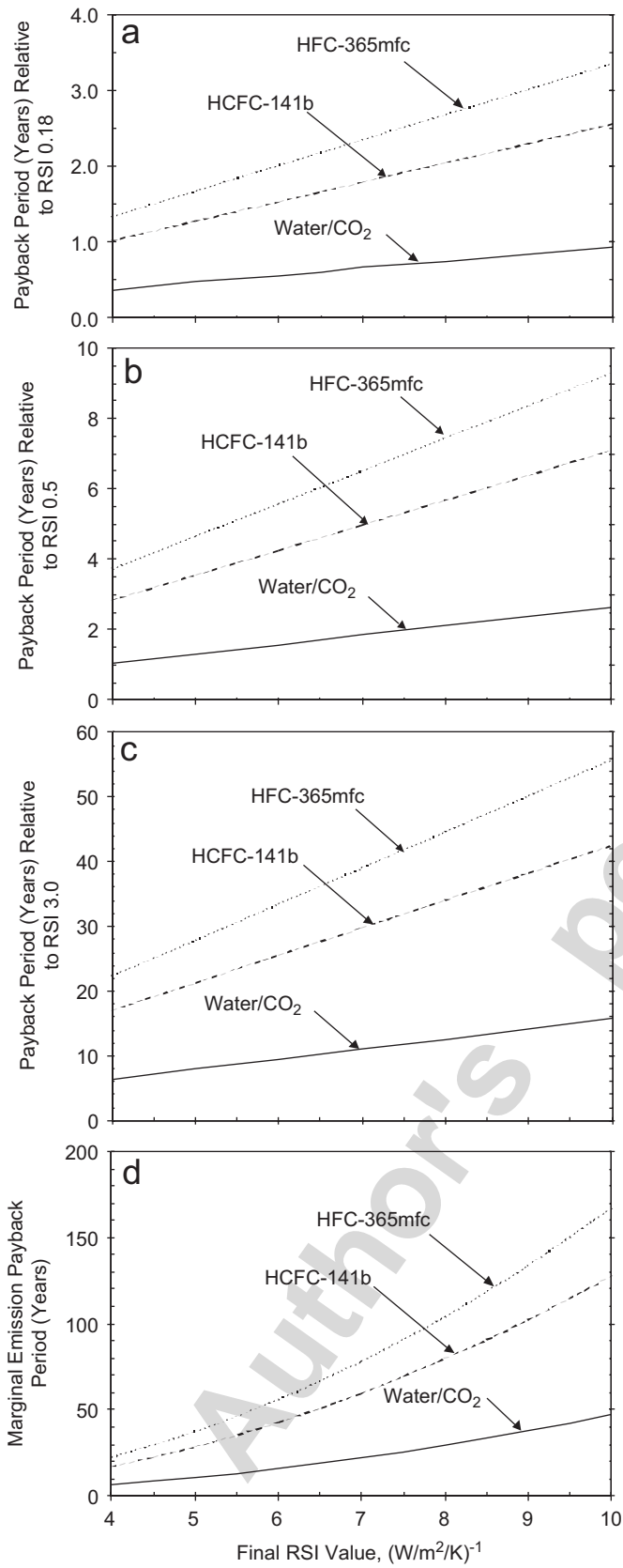
Fig. 9. Same as Fig. 3, but for spray-on polyurethane insulation with 1.2%/year leakage of the blowing agent during use, 100% capture of the remaining blowing agent at the end of 50 years of use, and other assumptions as given in the main text.
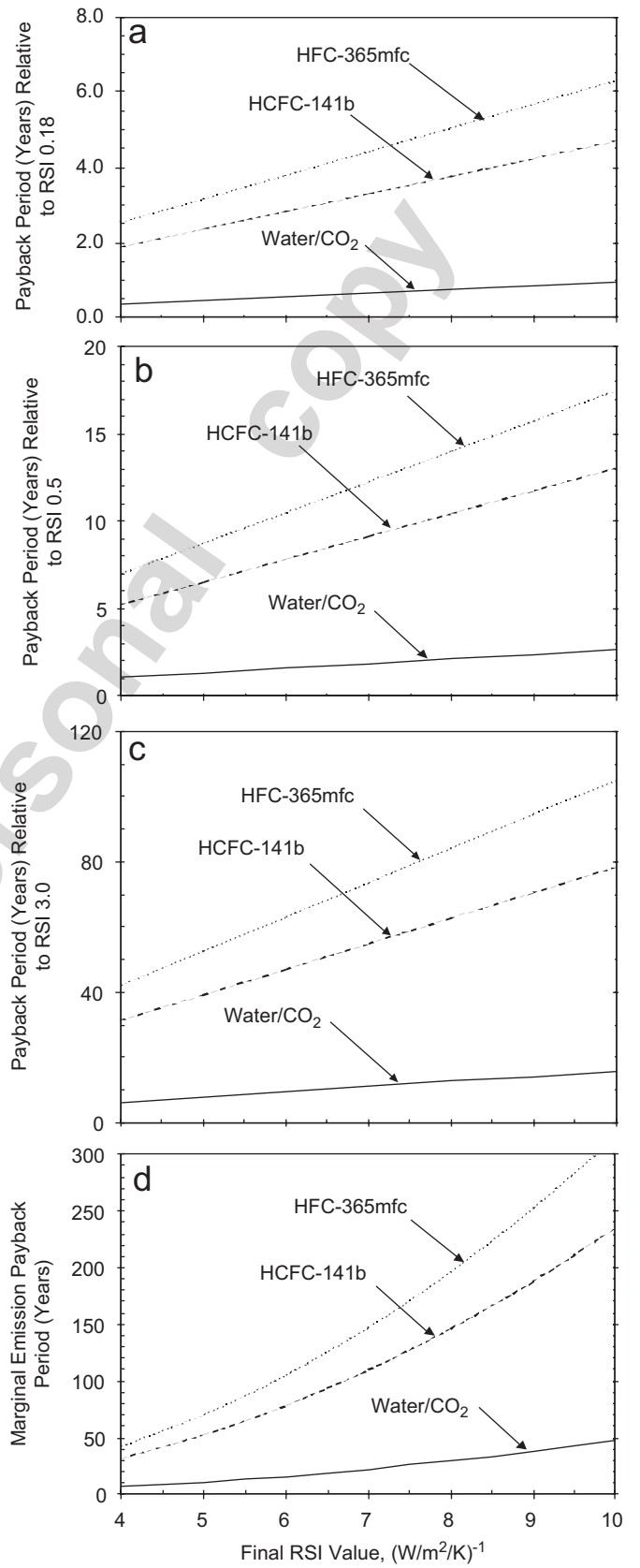
Fig. 10. Same as Fig. 9, but assuming complete release of the remaining blowing agent after 50 years of use.

Table 11
Same as Table 9, except for PU spray-on solid foam

Parameter	Blowing agent (BA)		
	HCFC-141b	HFC-365mfc	H2O/CO$_2$
GWP	713	782	1
Foam density (kg/m^3)	34	34	42
BA density (kg/m^3 foam)	3.06	3.57	1.0
Insulation conductivity (W/m/K)	0.026	0.028	0.035
Area of RSI-1 panel (m^2) produced from 1 m^3 of foam	38.46	35.71	28.57
Foam mass (kg/m^2/RSI)	0.884	0.952	1.470
BA mass (kg/m^2/RSI)	0.080	0.100	0.035
Foam-embodied energy (MJ/m^2/RSI)	121.11	130.42	201.39
CO$_2$ from manufacture (kg/m^2/RSI)	7.79	8.39	12.96
CO$_{2eq}$ of BA emission (kg/m^2/RSI), 0% emission at end of use.	27.26	37.56	0.02
CO$_{2eq}$ of BA emission (kg/m^2/RSI), 100% emission at end of use.	56.73	78.17	0.04

In all cases, the foam-embodied energy is 137 MJ/kg. Foam and blowing agent density and foam thermal conductivities and are taken from Krähling et al. [17], Tables 5 and 17), while GWPs are taken from Table 6. Emission during manufacture is assumed to be 5% of the initial loading, emission during use is 1.2%/year over a period of 50 years, and emission at disposal is 0% or 100% of the remaining blowing agent.
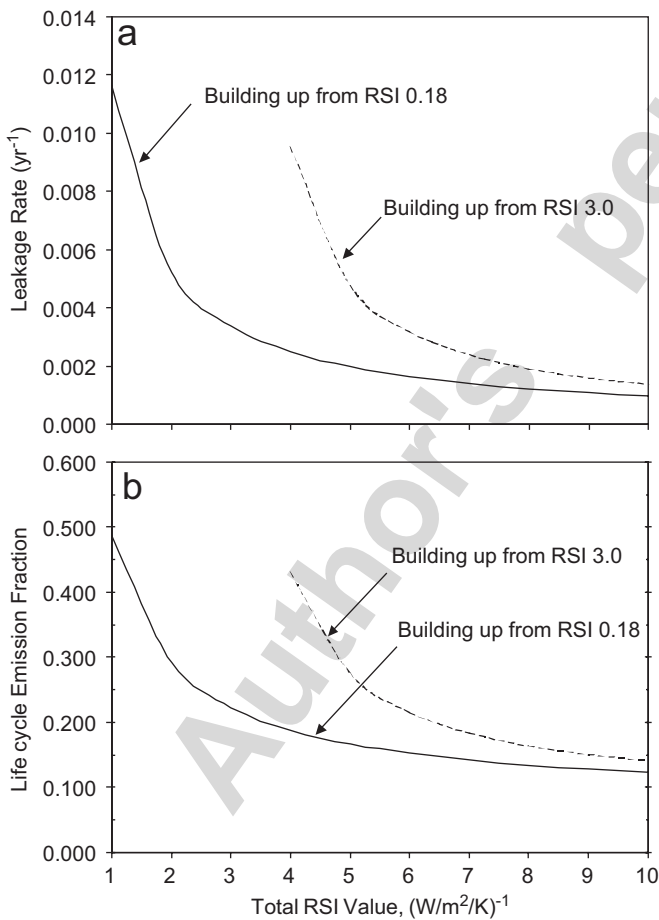

Fig. 11. (a) Variation with RSI in the rate of leakage of blowing agent assumed for the variable-leakage-rate case, and (b) total cumulative emission fraction over 50 years (including emissions during manufacture and disposal of the insulation).
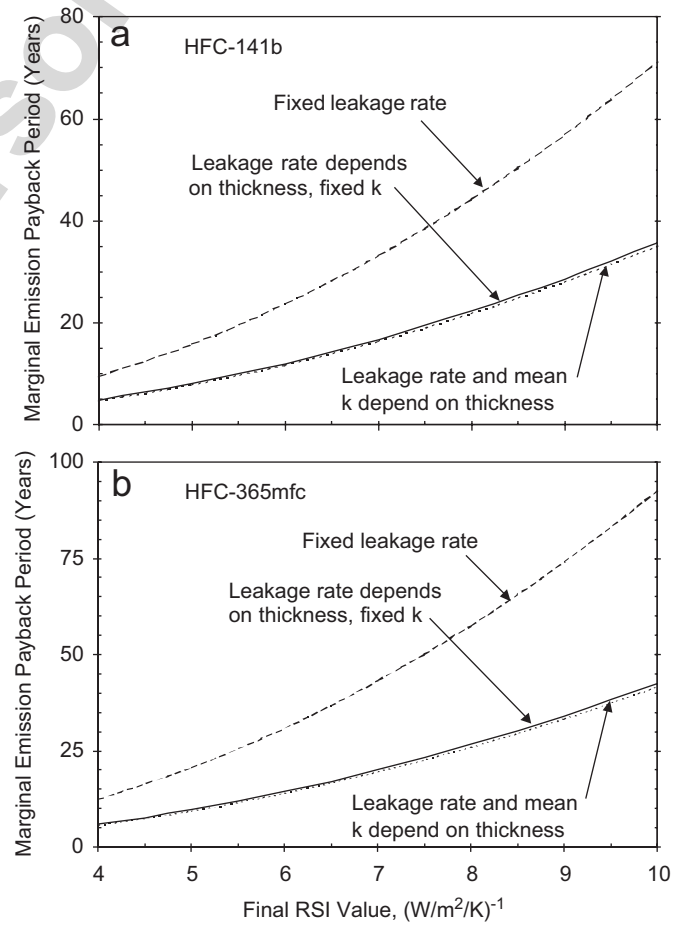

Fig. 12. Marginal payback times for PU insulation blown with (a) HFC-141b and (b) HFC-365mfc, for the case where leakage rate varies with insulation thickness and assuming a natural gas furnace at 90% efficiency and a climate with 4000 HDD. Emissions at the time of manufacture and at the end of life are assumed to be 8% and 0%, respectively, while emissions during use are given by Eq. (3).

Table 12
RSI values for different kinds of insulation with different blowing agents and with prescribed thicknesses of 5, 10, or 15 cm, and, for 5-cm and 15-cm insulation layers, the percent reduction in heating energy use compared to solid PU foam with HCFC-141b for different starting RSI values

	Solid PU foam			Solid XPS foam			Spray-on PU foam		
	HCFC-141b	HFC-365mfc	Pen-tane	HCFC-142b	HFC-134a	CO_2	HCFC-141b	HFC-365mfc	Water/CO_2
k	21	22	24	29	29	33	29	30	35
Insulation RSI values for the indicated thickness of insulation									
5 cm	2.381	2.273	2.083	1.718	1.718	1.502	1.724	1.667	1.429
10 cm	4.762	4.545	4.167	3.436	3.436	3.003	3.448	3.333	2.857
15 cm	7.143	6.818	6.250	5.155	5.155	4.505	5.172	5.000	4.286
Percent reduction in heating energy savings for the indicated initial RSI value and a 5-cm layer									
$RSI_o = 0.18$		0.3	1.0	2.6	2.6	4.0	2.6	2.9	4.5
$RSI_o = 0.50$		0.8	2.4	6.3	6.3	9.2	6.2	6.9	10.4
$RSI_o = 3.00$		2.6	7.4	17.7	17.7	24.6	17.5	19.3	27.1
Percent reduction in heating energy savings for the indicated initial RSI value and a 15-cm layer									
$RSI_o = 0.18$		0.1	0.3	0.9	0.9	1.4	0.9	1.0	1.6
$RSI_o = 0.50$		0.3	0.9	2.4	2.4	3.6	2.4	2.7	4.2
$RSI_o = 3.00$		1.4	4.1	10.1	10.1	14.5	10.1	11.3	16.5

Table 12 gives the thermal conductivity and RSI-value for nine insulation/blowing agent combinations and for thicknesses of 5, 10, and 15 cm. The reduction in heating energy use due to the addition of insulation is proportional to $(1/RSI_o - 1/(RSI_o + RSI_i))$, where RSI_o is the RSI-value prior to the addition of insulation and RSI_i is the insulation RSI-value. Although RSI_i is 67% greater for HCFC-141b PU compared to water/CO_2-blown spray-on PU (this being the largest difference), the heating-energy savings is reduced by only 4.5% using a 5-cm thick layer of the latter rather than of the former if the initial RSI-value is 0.18. For initial RSI-values of 0.5 and 3.0, the heating-energy savings are reduced by 10.4% and 27.1%, respectively. For a 15-cm insulation layer, the savings in heating energy is only 1.6%, 4.2%, or 16.5% smaller using the water/CO_2-blown insulation for RSI_o-values of 0.18, 0.5, and 3.0, respectively. The small effect of alternative insulation and blowing agents on heating energy savings is because the $1/(RSI_o + RSI_i)$ term in the $(1/RSI_o - 1/(RSI_o + RSI_i))$ difference is substantially smaller than the $1/RSI_o$ term, irrespective of RSI_i within the range considered here, so the difference is close to $1/RSI_o$ itself and thus little affected by differences in RSI_i. Thus, the use of insulation with a larger thermal conductivity has a disproportionately small impact on the savings in heating energy.
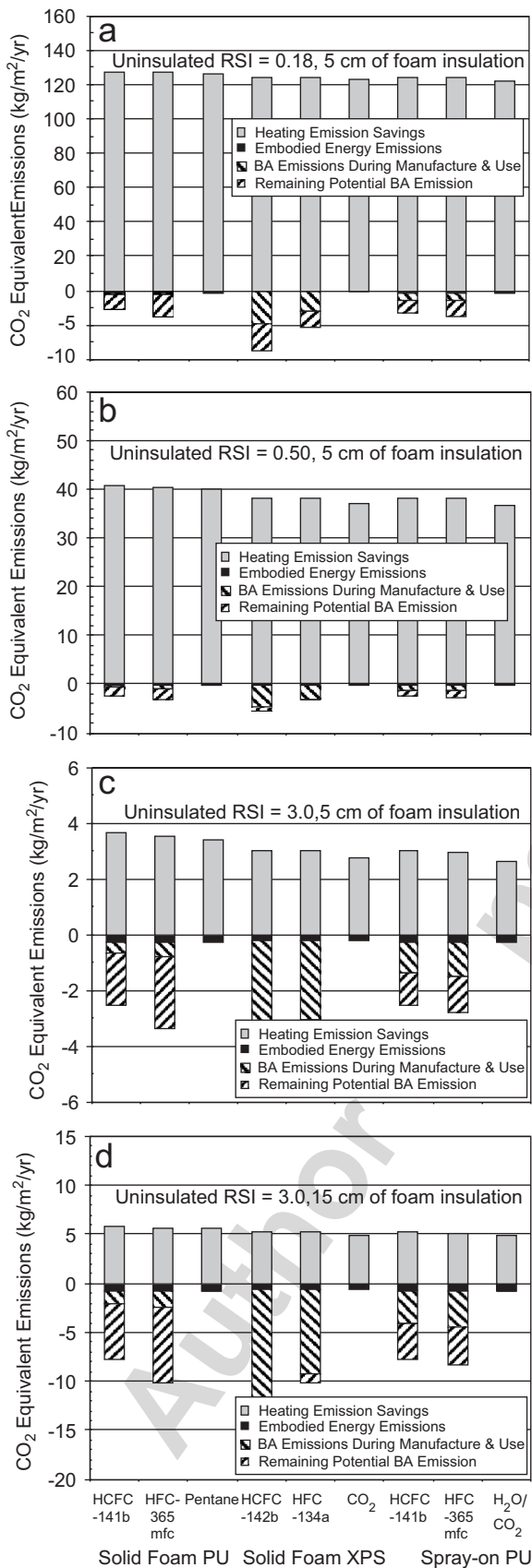
As well, the following generalizations apply:

• the greater the uninsulated RSI, the more important the thermal conductivity is to the fractional energy savings resulting from the additional insulation; and
• the thicker the layer of insulation that is added, the less important the differences in thermal conductivity.

On the other hand, the CO_2-equivalent emissions from leakage of the blowing agent are strongly influenced by the choice of blowing agent and the type of insulation. This is illustrated in Fig. 13, which shows the tradeoff between differences in heating-energy savings and in embodied energy and blowing-agent emissions. Results are given for 5 cm of foam insulation added to RSI 0.18, 0.5, and 3.0, as well as for 15 cm of foam insulation added to RSI 3.0. If one starts from RSI = 0.18, the heating energy savings are so large, and the relative differences in the savings so small, that the choice of insulation is not important (even if 15 cm is added). However, if one starts from RSI = 3.0, then the blowing agent emissions are large or larger than the heating-energy emission savings, and the choice of insulation type is very important. In some halocarbon cases, the use of additional insulation (beyond RSI 3.0) is counterproductive from a climate point of view. This negative balance could be reversed if savings in cooling energy use are included, or (in the case of spray-on foam), if savings in air exchange are included. Even in the absence of such additional savings, there are significant net benefits if non-halocarbon blown insulation is used in applications where there is already substantial thermal resistance.

5. Comparison with previously published work

This paper has presented results showing the time required for savings in heating-related energy due to foam insulation to offset the emissions associated with the manufacture of the insulation and with leakage of the blowing agent from the foam. Comparisons have been presented for a given RSI-value (but different thicknesses of insulation) across different insulation types, and for different kinds of insulation of the same thickness (but different RSI-values). In this section, the results obtained here are compared with other assessments.

5.1. Comparisons with fixed RSI, differing thickness

The insulation lifespan divided by the time required to pay back manufacturing and blowing-agent emissions (direct emissions) is equal to the ratio of heating-energy emission savings (indirect emissions) to direct emissions. Little ([19], Table 9-4) reports, for 10 cm of HFC-365mfc-blown insulation (about RSI 4.8) with lifetime emissions of 75% of the blowing agent, a ratio of indirect to direct emissions of about 21–23 for the average US climate, based on heating-energy savings only. The payback time and hence the emission ratio depends strongly on the pre-existing RSI-value, which is not given in Little [19]. However, for an uninsulated RSI of 0.18 (total RSI of 5.0), the payback time for 75% emission computed here is 2.1 years, implying an indirect:direct emission ratio of about 24. For the average US climate (having about 3000 HDD instead of 4000 HDD), the ratio would be about 18. This is 15–20% less than the value given by Little [19].

Ashford et al. [13], (Table 7C) report an indirect:direct ratio of 14–21 for 10 cm of foam insulation without recovery of HFC at the time of disposal (i.e., for an eventual 100% emission of the blowing agent) and 92–140 with full recovery of the halocarbon remaining at the time of disposal. It is possible, within the framework of this paper and with appropriate assumptions, to obtain an indirect:direct emission ratio on the order of 90 for 10 cm of 365mfc foam insulation, as given in Ashford et al [13]. Fig. 14 gives the payback times for 365mfc foam assuming 8% leakage at the time of manufacture, 0.2%/year leakage during 50 years of use, and complete destruction of the remaining halocarbon at the end of 50 years. Results are given as a function of the total RSI-value, assuming the uninsulated RSI-value to be 0.18 (this corresponds to the thermal resistance of a 2-cm slab of Douglas Fir plywood). For the assumed climate of 4000 HDD, the indirect:direct ratio is 90 at a total RSI of 4.72, which corresponds to 10 cm of 365mfc foam insulation. Thus, the exceedingly long marginal payback times (25–65 years at RSI of 6.5–10 and 0.2%/year leakage, or 105–270 years with 100% lifecycle emission) presented here (in Figs. 3–5) are consistent with the results given in Ashford et al. [13]. The results given in Ashford et al. [13] pertain to a specific case (negligible RSI in the absence of insulation) and are not applicable to the installation of very high (RSI 6-10) levels of insulation.

5.2. Comparisons with fixed insulation thickness, differing RSI

Krähling and Krömer [14] compared the total CO_2-equivalent emissions (due to heating energy use and

Fig. 13. Comparison of savings in heating energy and CO_2-equivalent emissions related to the insulation-embodied energy and to leakage of the blowing agent. Results are given for a 5-cm foam layer added to an initial RSI of (a) 0.18, (b) 0.50, and (c) 3.0, as well as for (d) a 15-cm foam layer added to RSI 3.0.
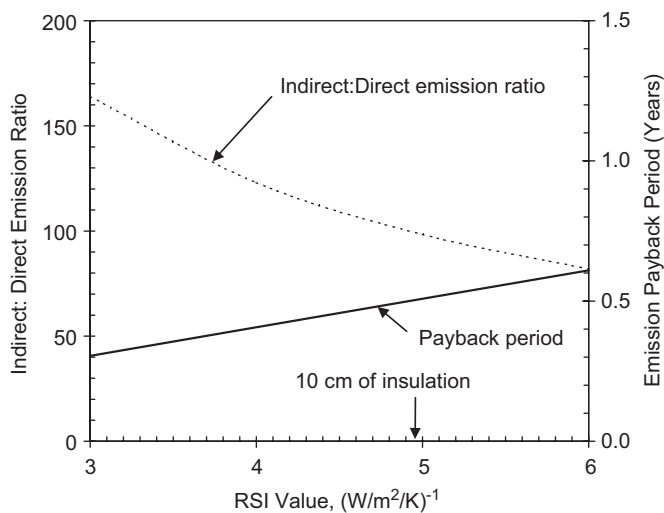
Fig. 14. Ratio of indirect emission savings (due to reduced heating-energy use) to direct emissions (due to leakage of blowing agent) for PU insulation with 0.2%/year leakage and complete destruction of the blowing agent remaining of 50 years, assuming an initial RSI of 0.18.

leakage of the blowing agent) using HFC-365mfc and n-pentane in a fixed thickness of foam insulation. They find that the total emissions are a few per cent smaller using 365mfc compared to n-pentane if the thickness of the insulation is 5 cm, and a few per cent larger using 365mfc if the insulation thickness is 10 cm (see their Fig. 2). In both cases, the total CO_2-equivalent emission is overwhelmingly due to heating-related emissions rather than halocarbon emissions. However, the relevant quantity—and the one computed here—is the *savings* in heating-related emissions due to the use of a given amount of foam insulation compared to the halocarbon-related emissions. According to the results presented here, the net emission savings is smaller (sometimes substantially smaller or even negative, depending on the uninsulated RSI-value) using 365mfc instead of n-pentane. This is contrary to the results of Krähling and Krömer [14], and appears to be due to their assumption of a very small overall leakage (about 10%, as indicated in Table 5).

Harnisch et al. [15] also examined the impact of using alternative blowing agents in a given thickness of insulation (namely, 10.5 cm). Unlike Krähling and Krömer [14], they find that, for 10.5 cm of PU roof insulation with 50 years of use, the average lifecycle CO_2—equivalent emission per square metre of roof area is substantially higher using HFC-365mfc than using pentane as a blowing agent—5.78 kg/year vs. 3.55 kg/year. This is in qualitative agreement with the results obtained here. The only major input difference between the two is the assumed rate of leakage (see Table 5). They, like Krähling and Krömer [14], compute heating energy use rather then heating energy savings, and add this to the direct emissions to get total emissions.

Murakami et al. [20] assessed the net impact on CO_2-equivalent GHG emissions of upgrading the Japanese 1992

insulation standard for residential buildings to the 1999 insulation standard. They find that the 1999 standard results in a decrease in lifecycle emissions of about 60% if hydrocarbon-blown insulation is used, but an increase in lifecycle emissions by 14% using HCFC-141b and by 42% using HFC-245fa. This is consistent with the conclusion reached here that use of halocarbon-blown insulation can be counterproductive from a climatic point of view when incremental additions to insulation are considered.

6. Summary

The net climatic effect of building insulation depends on three factors:

- the GHG emissions associated with provision of the energy used to manufacture the insulation;
- leakage into the atmosphere of any expanding agents that have a greenhouse effect (that is, which absorb in the infrared part of the electromagnetic spectrum); and
- the reduction in GHG emissions due to a reduction in the amount of energy used for heating and/or cooling.

In this paper, the benefit of foam insulation in terms of heating energy savings due to reduced conductive heat loss only is considered. All the results and tradeoffs presented here are for a moderately cold climate with 4000 HDD. Not considered here are possible additional benefits due to reduced exchange of inside and outside air due to a less leaky building envelope, or reduced cooling energy use. In some circumstances, the savings in primary energy use due to reduced cooling loads can be comparable to the savings due to reduced heating loads.

In deciding how much halocarbon-blown insulation it is worth using, it is appropriate to consider the time required for heating-related emission savings to offset manufacturing and halocarbon emissions for the addition of successive *increments* of insulation. This is referred to here as the *marginal* payback time, and needs to be considered if solid foam insulation is used to top off the pre-existing insulation in building up to the very high insulation levels (RSI 6-10) used in high-performance houses in cold climates. It is worth adding insulation, from a climate point of view, up to the point where the marginal payback time equals the expected lifespan of the insulation (usually assumed to be 50 years).

The key parameters affecting the climatic impact of foam insulation produced with different blowing agents are initial blowing agent loadings and the rates of leakage. Differences in thermal conductivity are of minor importance. The analysis presented here considered a range of leakage rates, but usually had to rely on only one source for the blowing agent loading for different insulation/blowing agent combinations.

A key conclusion of the analysis presented here is that the marginal payback time for foam insulation using halocarbon blowing agents is exceeding long. For PU foam

insulation using HFC-365mfc as the blowing agent, the marginal payback time at RSI = 6.5 is 25 years assuming 0.2%/year leakage and complete recovery of the remaining blowing agent after 50 years, 37 years assuming 0.5%/year leakage and complete recovery after 50 years, and 105 years with eventual emission of all of the blowing agent. At RSI = 10.0, the corresponding marginal payback times are 64, 93, and 270 years. The marginal payback times are reduced by about 50% if one accounts for the fractional rate of leakage being smaller the thicker the insulation in the manner assumed here. Pentane-blown foam insulation has a marginal payback time of 25 years at RSI 10, and an average payback time (based on the total thickness of insulation) of 8 years when building up from RSI 3.0 to RSI 10.0 and only 1.4 years when building up from RSI 0.5 to RSI 10.0. Thus, pentane-blown insulation is better from a climate point of view than HFC-365mfc-blown PU insulation. For XPS insulation, use of CO_2 as a blowing agent is strongly preferable to the use of HCFC-142b or HFC-134a, and for spray-on PU insulation, use of an $H2O/CO_2$ mixture is preferable HCFC-141b or HFC-365mfc from a climatic point of view.

When the heating energy savings obtained using different blowing agents in a fixed thickness of insulation are compared, it is found that there is very little difference (up to 4.5–27% for a 5-cm thick layer, depending on the uninsulated RSI-value), in spite of the relatively large differences (up to 67%) in thermal conductivity. The small additional savings in heating energy emissions using halocarbon blowing agents is swamped by the larger impact of leakage of the blowing agent. Thus, non-halocarbon blowing agents are again better from a climate point of view.

The time required to pay back the embodied energy of foam insulation is about 25 years for the increment from RSI 9 to RSI 10 (the payback time based on the total thickness of insulation is only 8 years if the initial RSI is 3.0). Inasmuch as the marginal payback time is less than the expected insulation lifespan of 50 years, building up to RSI 10 is justified in terms of energy use. However, cellulose and other natural materials have a negligible embodied energy and a negligible marginal payback times, while fibreglass or rock wool have a significantly lower embodied energy than foam insulations [18], and so would be preferred whenever this is possible.

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