Building Shell and Thermal Insulation

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** The building shell and thermal insulation have a significant effect on heating and cooling loads. Incorporating high levels of thermal insulation and increasing air tightness in buildings can reduce energy demand in both cold and warm climates. In almost all OECD countries, Building Codes require new buildings to include some level of thermal insulation; in general, colder climates have stricter requirements although the standards vary significantly between countries and regions. Older building stock typically has lower levels of insulation, as Building Codes have become stricter over time and many properties are specified to meet the minimum standards in force at the time of construction. Many developing countries also have Building Codes; however, ensuring compliance has been a problem in the past. The most popular building thermal insulation materials include expanded polystyrene, extruded polystyrene, polyisocyanurates, polyurethane, mineral wool, cellulose (recycled newspapers) and fibreglass. The traditional market leader in the US is fibreglass and in Europe it is mineral wool. Both types are used primarily in the residential market. Demand for foamed plastic insulation (used mainly in non-residential market) is increasing due to the higher performance levels required by stricter Building Codes. Penetration of double-glazed windows is high in most European countries, and triple-glazed units are common in Scandinavian countries. Heat losses due to air infiltration may be reduced by using air tight construction and sheltering exposed walls. Some Building Codes have provisions for air tightness, but this is less common than for thermal insulation. Improvements to air tightness can be achieved by a variety of means including caulking, weatherstripping, use of certain insulation materials and installing impermeable barriers.

■ **PERFORMANCE AND COSTS –** In general it is far more cost-effective to integrate insulation and air tightness into new buildings than to retrofit an existing building. Improvements to the building shell can reduce heating requirements by a factor of two to four compared to standard practice at an additional cost of the order of a few percent of the total cost of residential buildings. There is little to no incremental cost in commercial buildings when downsizing of heating and cooling systems is accounted for. Using materials with higher thermal conductivity (resulting in higher k-values and poorer performance as an insulation material) means that a greater thickness is required to achieve the same performance. Mineral wool and natural fibre insulation materials typically have a range of thermal conductivities measured in k-values from 0.03 to 0.04 W/mK. Mineral wool costs around €4.40-7.80 per square metre (€/m^2) and cellulose costs around 10 €/m^2. For 50 mm thick flax, sheep's wool, hemp or cotton the cost is around 5.50 €/m^2 and for 100 mm thickness the cost is approximately doubled. Foam boards typically have a higher thermal performance compared to natural fibres, and have k-values of 0.025-0.035 W/mK. Foil-faced versions have improved values of 0.02-0.0235 W/mK. A 50 mm thick expanded polystyrene board costs around 3.14 €/m^2. Foamed-in-place insulation is more expensive compared to traditional forms of insulation, but is much more effective, with k-values of 0.023-0.028 W/mK. Use of foamed-in-place insulation can reduce other construction costs such as labour (as it requires less time to install) and improve air tightness measures (as it conforms to surfaces to create an airtight seal). Prices for window replacement in residential buildings vary from around 140 €/m^2 to 430 €/m^2 depending on the thermal performance (with better-performing windows costing substantially more). If installed as part of a general renovation or in a new building, the same performance windows would cost from 60€/m^2 to 130€/m^2. In domestic properties, use of products to improve air tightness can reduce air leakage rates by a factor of five to ten compared to standard practice in regions such as North America, Europe and Asia. Some types of thermal insulation can provide high levels of air tightness, such as spray-applied cellulose and foamed-in-place polymers. Other techniques include the use of caulking and weatherstripping. The addition of caulking strips to reduce air ventilation is expected to cost between 3 €/m^2 and 10 €/m^2 of living area.

■ **POTENTIAL AND BARRIERS –** Improvements in building shell and thermal insulation are largely driven by Building Codes, which regulate the design and construction of new buildings. For new buildings, the IEA envisages that Building Codes in cold climates will reach standards that reduce energy demand to between 15 and 30 kWh/m^2/year of useful energy for heating and cooling by 2020 or 2030. Achieving these standards for new buildings is expected to increase construction costs by between 2 % and 7 %. These costs are expected to decline over time as high-performance building shell materials achieve mass market penetration. In developing countries, new construction accounts for a large share of buildings, so energy efficiency measures for new-builds offer a major energy saving opportunity. In OECD countries, retrofitting existing stock is important, as many of the buildings in existence today will still be in use in 2050. Despite its cost-effectiveness, there are many barriers to energy efficiency in buildings, including access to finance, insufficient information, split incentives, users' lifestyle choices and multiple decision makers. In developing countries, access to finance is the most important barrier.

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Process and Technology Status

In most countries, the building sector accounts for at least 40% of primary energy use and the absolute figure is increasing due to higher construction rates, particularly in China, India and South Mediterranean countries [1]. The residential sector uses significantly more energy than commercial buildings (around 70% of total building sector energy consumption) [10]. Currently, around 39% of CO_2 emissions from the global residential sector are due to space heating and cooling needs, and around 35% of the service sector's [10]. In order to keep the average global temperature rise below the 2°C limit agreed at the United Nations climate negotiations, average building energy consumption per person will need to be cut by 60% by 2050 compared to 2005 levels [2].

The building shell (also known as the envelope) includes components that separate the internal spaces from the external environment, such as walls, roofing and windows. The building shell has a major effect on heating and cooling loads, especially in envelope-dominated structures, i.e. those with a large proportion of total energy demands used for space heating and cooling (such as residential properties) [9]. In contrast, internal-load dominated buildings (typically commercial and industrial buildings) use more energy for internal needs such as lighting, appliances, computing etc. The building envelope has a much greater impact on energy use in envelope-dominated structures; therefore this brief focuses mainly on solutions for these types of building (i.e. domestic properties) although commercial buildings are also covered where relevant.

Heat transfer occurs by *transmission* through the building fabric and by *ventilation* of air. The main ways to improve the building shell are to **increase thermal insulation** and to **decrease air infiltration**. This can significantly slow down the loss of heat from buildings in cold climates, thereby reducing the energy needed for space heating. High levels of thermal insulation and increased airtightness work equally well in protecting buildings from overheating in warm climates provided there is adequate **solar shading**.

■ **Building Fabric -** Thermal insulation works by resisting heat flows by conduction, convection and/or radiation. Conduction refers to the direct flow of thermal energy through materials that are in physical contact. Convection occurs when fluids (including air) become less dense on heating, setting up convection currents that physically transfer hot material. Radiation refers to energy propagation as an electromagnetic wave. The most important heat transfers occur through roofs (30% to 35%), walls (25% to 30%), windows (15%) and ventilation (25%) [13]. Most insulating materials work by trapping air within cells to suppress its movement, so that convective heat flows are reduced [9]. Some materials are filled with a low conductivity gas that replaces air within the cells and improves its thermal properties. Closed cell structures (small cells) also reduce radiation effects because the temperature difference across them is small. However, conduction usually increases as the cell size decreases because the density of the material increased [9]. Reflective insulation uses larger air spaces faced with foil on one or both sides to reduce heat transfer by radiation. Reflective insulation is most effective at reducing downward heat flow, so it is typically located between roof rafters and floor joists, although sometimes also between wall studs [6]. Advanced materials such as vacuum insulated panels create an evacuated space within the insulation, which reduces conduction and convection. If combined with reflective insulation, all three modes of heat transfer are significantly reduced.

Many recently constructed buildings in the US, Europe and Asia adopt the same form and designs [17]. In almost all OECD countries, new buildings must incorporate some level of thermal insulation in order to comply with Building Codes. Generally, cold climates tend to have stricter requirements, although the standards vary significantly between countries and regions. However, older building stock typically has lower levels of insulation, or none at all unless it has been retrofitted, because buildings are often constructed to meet the minimum standards in force at the time Many developing countries also have building codes that require thermal insulation; however, ensuring compliance has been a problem in the past [16]. The performance of buildings in developing countries is of growing importance, particularly as construction is projected to outpace growth in developed countries. China owned the largest stock of residential buildings in 2008, followed by the US and then Europe (in terms of floorspace) [1]. Energy consumption for heating and cooling in urban Chinese buildings is 2-3 times higher per unit of floorspace compared to buildings in comparable climates in developed countries, primarily due to the poor insulation performance of the buildings [4]. In rural areas, which account for 60% of China's building stock, the performance is a further 2-3 times worse compared to urban buildings in China [4].

The most popular thermal insulation materials include expanded polystyrene, extruded polystyrene, polyisocyanurates, polyurethane, mineral wool, cellulose (recycled newspapers) and fibreglass. Sales of these materials in North America totalled at $5.74 billion in 2010. The traditional market leader in the US is fibreglass, which is used primarily in the residential market [6]. Demand for foamed plastic insulation in the US (used mainly in the non-residential market) has reached the same level as for fibreglass in recent years, due to increased construction in the commercial sector and demand for higher performance insulation products needed to comply with Building Codes [5]. Rigid urethane makes up the largest segment of the foamed plastic insulation market, at about 70% by weight, followed by polystyrene at 27% [5]. In Europe, mineral wool is the most popular insulation material, but fibreglass and foamed plastics are also common.

Thermal insulation can come in many different forms. Flexible fibres can be formed into **blankets (**including mats, batts and rolls), which are used in roof insulation, stud walls and under suspended timber floors. Blanket insulation is one of the most common types, and is available in a wide variety of sizes [21]. Mineral fibres

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include rock wool and fibreglass. Rock wool is based on natural minerals and recycled post-production waste materials that are melted and spun into fibres [6]. Fibreglass is made from sand, limestone and soda ash with a high proportion of recycled glass and other minerals [6]. Natural fibres (e.g. cellulose, cotton, wool) are treated to ensure they are resistant to fire and pests before they are suitable for use in construction. Fibres can be **sprayed in place** after mixing with adhesive foam to make them resistant to settling. Fibre insulation is also available as **loose fill** material, which is ideal for obstructed or awkwardly shaped areas but can settle over time. The most common types of loose fill insulation include cellulose, fibreglass and mineral (rock) wool [6]. Small particles of foam and other materials are also available as loose fill (or "pour-in") products. **Foam boards** are made from polymers, which are foamed with a low-conductivity gas. These can be used in almost any part of a building. Common types of polymer include polyurethane, polyisocyranurate, phenolic foam and expanded or extruded polystyrene [6]. Insulating Concrete Forms consist of interconnected foam boards that create forms for concrete to be poured into – the insulation then becomes part of the structure. Alternatively, foam boards can be manufactured as **Structured Insulated Panels** (SIPs), which are prefabricated insulated structural elements for use in building walls, ceilings, floors and roofs. **Foamed-in-place** polymers are suitable for cavity wall insulation. They are pressure-sprayed into place where they expand and harden, ensuring a thorough seal. Very high-performance insulation materials are available, including aerogels and vacuum insulated panels, although they are unlikely achieve significant market penetration due to their comparatively high costs.

Insulation can also be characterised by where it is placed in a building. **External insulation** methods involve attaching insulation material to the external face of a wall. Coating the insulation with a final layer is common in central Europe, whereas placing a cladding with an air gap over the material is common in Northern Europe [19]. Insulation can be installed between **cavity walls**. It can be used in new builds and can also be retrofitted by blowing or pouring insulation material into the gap between walls. Cavity wall construction is common in the Netherlands, UK, Ireland and parts of Greece [19]. **Interior insulation** is attached to the inner surface of exterior walls. It is common in some European countries (France, Ireland, Greece) but is generally not used in cold climates because of the living space reduction [19]. For practical purposes it is common to use insulation on the inside, between wall cavities or as part of the structure itself (e.g. cellular concrete) [8]. **Roof insulation** can be added between and beneath rafters or applied to the external surface and covered in a waterproof layer. In buildings with a cellar, insulation can be added under the cellar ceiling or underneath the ground floor (with no cellar).

■ **Windows** – Windows are an important source of heat transfer because of their relatively poor energy performance. In residential buildings most rooms have at least one window [22]. In Europe, glazing makes up around 20-30% of the exterior wall space [19] while in North America windows make up 10-25% [8]. However, commercial buildings often have far higher proportions of glazing. Windows are composed of two basic sections: the glass used for the main body of the window, and the frame used to mount the glass and secure the structure into the building envelope. Single, double or triple-glazed units are available. Usually thermal spacers built as part of the frame separate the panes of glass. In Europe the penetration of double-glazing is high in all countries, and triple glazing is common in Scandinavian countries [22]. Older existing window frames are most commonly made of wood, particularly in residential buildings [22]. In new buildings insulated aluminium and PVC frames are common [22].

■ **Improving air tightness -** Air infiltration can significantly contribute to heat losses from a building. Vulnerable sites include window and door frames, floor joists, and any holes put through the structure. Heat losses due to ventilation may be reduced by using airtight construction and sheltering exposed walls to reduce infiltration. Most of the materials used in a house for structural purposes and finished surfaces also act as air barriers, including drywall, sheathing and decking. The most common air barrier material in the US residential market is **house wrap**, which is wrapped around the exterior of a house during construction [6]. Wraps usually consist of fibrous spun polyolefin plastic, and may also have other materials woven or bonded to them to help resist tearing [6]. New buildings can be constructed using airtight methods. Both the **Airtight Drywall Approach** (ADA) and **Simple Caulk and Seal** (SCS) create an effective airtight wall by sealing the drywall to the building structure. To create a continuous air barrier, the exterior sheathing and interior wall finish are sealed to the framing [6]. The main difference between the two methods is SCS seals gaps after the exterior sheathing and drywall have been installed whereas with ADA, sealing is carried out during the entire construction process [6]. Caulking and weatherstripping are two simple approaches to improve airtightness in existing buildings. **Caulking** can seal cracks or gaps in a variety of placed including around windows and doors. Silicone, butyl rubber, oil-based and resin-based caulking is suitable for most building materials including wood, stone, metal and brick. Polyurethane expandable spray foam is good for larger cracks as it can expand to fit. **Weatherstripping** around doors and windows can be achieved using vinyl, felt, reinforced foam and other materials [6]. High levels of airtightness have been associated with poor indoor air quality; therefore ventilation systems should be introduced. Heat recovery ventilation systems exchange heat from warm extracted air to fresh incoming air, which reduces heat losses.

■ **Solar shading and reflectance -** In hot climates where cooling loads dominate, solar shading and reflectance can reduce overheating. The principles of design to reduce cooling load are well known, and include (in addition to increasing thermal insulation) [9]:

- Building orientation to reduce east/west-facing walls
- Clustering buildings to provide shading
- Using high reflectivity materials

- Providing fixed or adjustable shading
- Using selective glazing and smaller areas of glazing
- Using heavier materials to improve thermal mass

In some countries Building Codes regulate orientation, for example, Australia, China, India, Japan and South Korea. South Korea and Japan recommend that houses should face South [24]. Building Codes in the US and Canada, do not regulate orientation [24].

Reflective roof coatings can reduce surface temperatures. They include elastomeric, polyurethane and acrylic paints; rubber, plastic, PVC and metal tiles.

Window overhangs are popular in warm climates, and Building Codes in Australia, China and India have provisions for shading such as requirements for installation of shading devices to reduce indoor energy consumption [24]. The US also has provisions for shading in commercial buildings [24].

Residential buildings in Asia tend to have heavier construction than houses in Australia, Canada and the US [24]. Heavy materials have high thermal inertia and tend to keep temperatures more constant.

PERFORMANCE AND COSTS

In general it is far more cost-effective to integrate insulation and airtightness into new buildings than to retrofit an existing building. Improvements to the building shell can reduce heating requirements by a factor of two to four compared to standard practice. This would incur an additional cost of the order of a few percent of the total cost of residential buildings, and at little to no incremental cost in commercial buildings (when downsizing of heating and cooling systems is accounted for) [9]. Advanced houses exist in cold climates worldwide, such as Scandinavia and Canada that need around 10% of the heating energy of houses built to the standards of local building codes [17].

■ **Building fabric -** In warm climates (including many developing countries) a small amount of additional insulation can reduce heating requirements by a factor of two or more, as well as reducing summer indoor temperatures and summer cooling energy use [9]. There are several metrics commonly used to assess the performance of building insulation including:

- **k-value (W/mK)**: A measure of how easily heat flows through a material, which is independent of material thickness. The lower the number, the better the thermal performance.
- **R-value (m^2K/W)**: A measure of thermal resistance, i.e. how much heat loss is reduced through a given thickness of material. The higher the number, the better the thermal performance.
- **U-value (W/m^2K)**: A measure of how much heat is lost through a given thickness of material, which includes conduction, convection and radiation. It is found by taking the reciprocal of the R-value and adding convection and radiation heat losses. Effective insulation has a low U-value to limit wintertime heat losses and reduce summer overheating.

Using materials with poorer thermal conductivity (lower k-values and therefore better thermal insulation performance) means that a lower thickness is required to achieve the same thermal insulation performance. For example, to achieve a U-value of 0.25 W/m^2K would require around 155 mm of glass wool (k-value 0.036 W/mK) or 295 mm of strawboard (k-value 0.081 W/mK) [20]. In cases where space is at a premium (e.g when retrofitting existing buildings) the highest performing materials may be needed to reduce the thickness required.

Mineral fibre and **natural fibre insulation** materials typically have a range of thermal conductivities from 0.03 to 0.04 W/mK (requiring 135-170 mm thickness to achieve a U-value of 0.25 W/m^2K) [20]. **Fibreglass** is one of the most popular insulation materials and costs around 5-9 € per m^2 [6]. Mineral wool costs around 4.40-7.80 €/m^2 and cellulose 10.06 €/m^2. For 50 mm thickness of flax, sheep's wool, hemp or cotton the cost is around 5.50 €/m^2 and for 100 mm thickness the cost is approximately doubled [3]. If fibres are in the form of **loose fill** product, they can become less effective over time due to settling, especially when placed in attics. Cellulose settles more than rock wool or fibreglass (20 % compared to 2-4 %), but this can be offset by installing additional material [21]. Good quality installation would avoid voids, gaps and insufficient density ("fluffing") in order to obtain the expected thermal performance.

Foam boards typically have a higher thermal performance compared to natural fibres with k-values of 0.025-0.035 W/mK (requiring 95-130 mm thickness to achieve a U-value of 0.25 W/m^2K) [20]. A 50 mm thick expanded polystyrene board costs around 3.14 €/m^2 [3]. Over time, the thermal performance of foamed insulation can drop as some of the low-conductivity gas escapes. Plastic or foil facings can be attached to reduce this effect. Foil facings can act as a radiant barrier and as well as preserving the thermal properties for 10 years or more [6]. Foil-faced foam boards have an improved k-value of 0.02-0.0235 W/mK (requiring 75-85mm thickness to achieve a U-value of 0.25 W/m^2K) [20]. Polyisocyanurate and Polyurethane Foam Boards typically have k-values that are 30-40 % lower compared to other common foams. [6].

Polymers can also be used to make **Structural Insulated Panels** (SIPs) [6]. SIPs are made in a factory and shipped to construction sites where they can be assembled quickly, saving time and labour costs. They provide superior and uniform insulation compared to traditional construction methods (e.g. timber frame), typically offering energy savings of 12-14 % [21]. Compressed straw SIPs are also available and are considered to be more environmentally friendly because they are made from recycled straw; however, they provide less effective insulation and are considerably heavier compared to polymer SIPs [6].

Foamed-in-place insulation has k-values ranging from 0.023 to 0.028 W/mK (requiring 80-100 mm thickness to achieve a U-value of 0.25 W/m^2K) [20]. Foamed-in-place insulation usually costs more than traditional insulation rolls, but is cheaper and more effective compared to foam boards as it can conform to all surfaces [6]. Since foamed-in-place materials provide an airtight barrier, they may reduce other costs related to applying caulking and vapour barriers [6]. When used in new homes, foamed-in-place insulation reduces construction time, which may save costs for labour [6].

The highest performance commercially-available materials are **aerogels** and **vacuum insulated panels**. Aerogels are derived from a gel in which the liquid component has been extracted through supercritical drying. They have k-values of 0.013-0.014 W/mK (requiring 50-55 mm thickness to achieve a U-value of 0.25W/m^{2}K) [20]. Vacuum insulated panels have an open porous core material that is evacuated in order to reduce heat transfer. Vacuum insulated panels have k-values of 0.008 W/mK, requiring just 30mm to achieve a U-value of 0.25 W/m^{2}K [20]. These advanced insulation materials are significantly more expensive compared to conventional types due to the complexity of the manufacturing process.

The total cost of insulation varies greatly depending on the choice of material, labour cost and installation method. In most cases, skilled labour is required to ensure proper installation. The installed price of **roof insulation** in Europe is 16-45 €/m^2 [19] and in the US estimated costs are 10-27 €/m^2 [21]. **Cavity wall insulation** thickness is limited by the width of the existing cavity (generally 50 mm to 150 mm) [19]. The investment costs per square metre are considerably lower compared to external insulation because it is less labour intensive [19]. For practical reasons (e.g. reduction of living area) the thickness of interior insulation is generally limited to a maximum of approximately 100 mm [19]. In Europe, installed cost for cavity insulation range from 17 €/m^2 to 40 €/m^2, assuming a typical mix of materials common in Europe [19]. In Europe, installed cost for **interior insulation** are estimated at 23-32 €/m^2 [19]. In existing buildings, a potential drawback of increased insulation is reduction in useable living area – for this reason it is not traditionally considered feasible in cold climates because the required thickness of material is greater compared to warmer climates. For example, the European Passive House standard aims to reduce heating and cooling needs to almost zero. Insulation thickness of 500 mm is often used to achieve U-values as low as 0.05 W/m^{2}K [13]. In Europe, installed cost for retrofitted **external insulation** are around 70 €/m^2 to 150 €/m^2 [19]. Installation costs for external insulation may be reduced by combining the work with other maintenance of the facade, in which case the installed costs fall to around 30 €/m^2 to 80 €/m^2 [19]. In the US, the installed cost for all types of wall insulation is around 15-17 €/m^2 [21]. The installed price of **ground floor insulation** in Europe is 18-44 €/m^2 [19] and in the US it is around 11-26 €/m^2 [21].

In heating-dominated climates, windows can account for over a quarter of a home's total winter heat losses [8]. The performance of **windows** can be improved by using different types of glazing (glass or plastic), increasing the number of layers of glazing, increasing the size of the air space between layers, applying low-emissivity coatings on one or more glazing surfaces, and using very low-conductivity framing materials such as extruded fibreglass or PVC [13]. The most energy-efficient glass is low emissivity (Low-E) glass. This often has a coating of metal oxide, which lets in light but reduces heat losses. Multiple layers of small areas of glass will typically perform better than larger windows with fewer layers [13]. Very efficient windows use gases such as argon, xenon or krypton in the cavity between glazing sheets. Triple glazing with 52mm overall depth, low-E coating and argon fill windows with heat losses of only 0.75 W/m^{2}K are commercially available [22]. This represents a 30% to 35% improvement on coated double-glazed windows [13]. Prices for window replacement in residential buildings vary from around 140 €/m^2 to 430 €/m^2 depending on the U-value (with better-performing windows costing substantially more) [19]. If installed as part of a general renovation or in a new building, the same performance windows would cost from 60€/m^2 to 130€/m^2. For office buildings, replacement of windows is around 300 €/m^2 to 400 €/m^2, again depending on the U-value [19]. Generally the higher the performance of the window, the more expensive it is, with triple glazed units costing around 20-40 % more than double-glazes units [22]. In most buildings, windows will have a shorter service life (around 8-20 years depending on the type) compared to the building as a whole [22]. It is therefore likely the windows will need replacing several times over the life of the building.

For typical construction, the embodied energy required to manufacture building materials is equivalent to only a few years of operating energy [9]. Thus, over the lifetime of the building, operating energy is usually significantly more important than embodied energy (around 84% for all energy use including heating, ventilation, cooling, hot water and electricity) [1]. For traditional buildings in developing countries, the embodied energy can be quite a large proportion of total life cycle energy, but this is only because operating energy demands are very low [9]. Therefore in most circumstances, choosing building envelope materials that minimize operating energy use also minimizes total lifecycle energy use – even in the case of high embodied energy products such as triple glazed argon-filled windows [9].

The **payback time** indicates the average time it takes investors to get back the initial money they invested, for example through reduced energy costs. Payback to the end user depends on the installed cost and also on the potential savings. The savings are highly dependent on climatic conditions, and also on energy prices; therefore the pay back varies widely. Without financial incentives it is unlikely that thermal retrofitting and new efficient buildings will be taken up in developing countries, because of relatively low energy prices. Energy efficiency measures may not be profitable for the end user in regions with heavily subsidized energy prices. Subsidized energy in the Middle East and North Africa means the pay back is often longer than 10 years and can be as high as 30 years [1]. As a guide, an upper limit for an acceptable period of payback is 5-7 years, even though the economic lifetime of a building is typically around 30 years [1]. In Europe, the payback period of cavity wall insulation is around 2 years; internal wall insulation is 15-23 years; external wall insulation is 27-37 years and floor insulation is around 2 years [3]. Table 4 shows the expected payback time in years for various insulation measures. Payback times are generally higher for retrofitting insulation in cold climates due to the relatively high standard of existing insulation [19].

■ **Improving air tightness -** In cold climates, air infiltration can account for up to half of total building heat loss [17]. Air-sealing retrofits alone can save 15–20% of annual heating and air conditioning energy use in US houses [9]. A common metric is to measure Air Changes per Hour (ach) within a given volume (such as the building). The leakage flow rate is usually measured at a reference pressure of 50 Pa. Some Building Codes have provisions for air tightness (e.g. Australia and Canada), but this is less common than for thermal insulation [24].

In typical buildings where no attention is paid to airtightness, airtightness ranges from 3 ach to 6 ach or more. Air tightness requirements for low-energy building standards such as Passivhaus require less than 0.6 ach. In domestic properties, use of a continuous impermeable barrier and other measures such as weather stripping can reduce air leakage rates by a factor of five to ten compared to standard practice in regions such as North America, Europe and cold-climate regions of Asia [17]. Some types of insulation can also provide high levels of air tightness. For example, spray-applied cellulose insulation is effective for sealing walls in existing homes, and foamed-in-place polymers can conform to surfaces to form a seal when used to insulate buildings (as well as being suitable for spot applications) [8]. The addition of caulking strips to reduce air ventilation through windows is expected to cost between 3 €/m^2 and 10 €/m^2 living area, and would need replacing every 5 to 10 years [19].

■ **Solar shading and reflectance -** In cooling-dominated climates, the solar energy that is transmitted through windows can account for up to one third of a house's cooling load [8].The solar heat gain coefficient is a measure of how much heat from the external environment is transferred through a window into the interior of a building. Depending on the regional climate a building may benefit from the heating effects, or it may be beneficial to prevent this. Coatings on the glazing that reflect or absorb solar radiation while allowing transmission of visible sunlight can reduce solar heat gains (and thus cooling loads) by up to 75% [13]. Shutters can also improve energy efficiency [11].

Reflective roof coatings can reduce energy usage by 25% [12]. They cost from around 6 €/m^2 for acrylic paints to over 25 €/m^2 for PVC single-ply membranes [12]. Bright white paints are the most effective, with a solar reflectance of 85 % [12]. Roof coatings tend to lose their reflectance over time due to dust and dew, therefore regular cleaning and maintenance is required.

POTENTIAL AND BARRIERS

According to IEA projections, early improvements in the thermal envelope of buildings and other building shell improvements could account for 22% of the total savings of 5.8 Gt CO_2 available to the buildings sector in 2050 [13]. The slow stock turnover of most buildings, particularly residential buildings in OECD countries is a significant barrier to more ambitious targets to reduce emissions [13].

Improvements in building shell and thermal insulation are largely driven by building codes, which regulate the design and construction of new buildings. Improvement of a building's energy performance at the planning stage is important because buildings are typically expected to last for decades and some options to improve efficiency are only available at the construction stage. The number of households worldwide is projected to increase by 67% between 2005 and 2050 [13]. This is due to population growth and the trend toward fewer people per household. China is adding around 2 billion square meters of floor area each year (60% residential and 40% industrial), making it the fastest growing building market in the world [4].

In the US there are no Federal building codes – standards are set at the State level. Standards vary widely and some states have no mandatory codes at all [14]. The most common standards (adopted by 40 States) are based on the International Energy Conservation Code (IECC) for residential buildings and the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Energy standards for commercial properties. However, in 2009 all 50 states applied for funding from the State Energy Program contingent on adopting the most stringent codes at the time (IECC 2009 and ASHRAE 90.1-2007), and on the State's providing a plan to achieve at least a 90-percent compliance within 8 years [14]. The IECC is typically updated every three years. The most recent version in 2012 increased requirements for wall insulation and increased floor/ basement wall insulation requirements for the coldest regions. The new codes require new and renovated homes and commercial buildings to use 30% less energy than those built to the previous set of standards [5].

In Europe, the Energy Performance in Buildings Directive governs energy efficiency of new buildings. Each Member State sets the level of energy efficiency requirements, but these levels have to be revised at least every 5 years and updated, based on technological development. The European Directive on Energy Performance sets standards for major refurbishments or renovations of large buildings with more than 1,000 m². All residences must be net zero energy buildings by 2021; and commercial buildings must be net zero energy by 2019 [5].

Energy efficiency for buildings in Japan is set by two different standards; Criteria for Clients on the Rationalization of Energy Use for Buildings for non-residential buildings, and Design and Construction Guidelines on the Rationalization of Energy Use for Homes for residential buildings. Houses that comply with the latest building energy standard consume 40% less energy than houses without insulation, and offices that meet the latest standard use 75% less energy than those that do not [16].

Until 2007 there were no energy efficiency requirements for new buildings in India, but a new regulation for large commercial buildings was adopted June 2007. Requirements include many options based on the US ASHRAE code and the building code in California [16].

China is divided into five main climatic zones: severe cold, cold, mild, hot summer and cold winter, and hot summer and warm winter [18]. The first building codes were introduced in 1986 and since then many revisions have been made, although buildings are generally less efficient than those in other parts of the world [18]. In the past, compliance was a large problem but there have been improvements in recent years [16].

For new buildings, the IEA envisages that building codes in cold climates will reach standards that reduce energy demand to between 15 and 30 kWh/m^2/year of useful energy for heating and cooling by 2020 or 2030, which is equivalent to the European Passive House standard when normalized for climate [13]. Achieving these standards for new buildings increases construction costs by between 2% and 7%, although costs are expected to fall when high-performance materials achieve mass market deployment [5]. Building codes may also serve as the efficiency target for refurbishment of existing stock. Several voluntary initiatives set targets beyond minimum standards required for building code compliance. For example, the Energy Star label in the US, the Comprehensive Assessment System for Building Environmental Efficiency in Japan, the Passivhaus and energy certification ratings in Europe and 1-5 star ratings in Australia [16]. Revenue from sales of insulation materials in North America are expected to grow at an average annual rate of 2.1% until 2016 [5]. Demand for foamed plastic insulation is expected to increase at a faster rate as compliance with stricter building regulations requires higher-performance materials. The use f foamed plastic insulation materials in North America is projected to grow at 5.3% annually to $4.4bn in 2014 [5]. In developing countries, new construction accounts for a large share of buildings, so energy efficiency measures for new-builds offer a major energy saving opportunity. Improvement of building energy efficiency at the design stage is relatively simple and cost-effective, whereas retrofit measures are often much more costly [16]. Since construction rates in OECD countries are relatively low, retrofitting offers a large potential for energy savings. Refurbishing existing building stock is also more difficult because major renovations are likely to happen every 30-40 years [16].

Despite its cost-effectiveness, there are many barriers to energy efficiency in buildings. For new buildings, energy efficiency is just one concern of many, and may conflict with other desires such as room size and aesthetics [16]. Split incentives are common, for example, the designers and construction companies do not typically gain from the low operating costs of efficient buildings. Insufficient awareness among consumers could mean they are not aware of the long-term gains of energy efficiency, or may not be able to influence the construction process [16]. Some measures require special equipment or expertise that may not be available in all markets, and builders may be unwilling to invest in training [16]. Even the introduction of building codes may not be sufficient to improve energy efficiency to the highest levels, as they stipulate minimum standards and builders rarely go beyond these requirements [16]. Other barriers to more energy efficient buildings include hidden costs that may prevent investment and financial costs related to research, appraisal, installation and disruption. In developing countries, the main barrier to increased energy efficiency in buildings is access to finance [17].

Table 1 – Performance of window types [22]

Glazing Type	Typical U-values (W/m^{2}K)	Typical solar heat gain coefficient
Single clear glass	5.3	0.86
Double glazing with 12mm air gap	2.8	0.76
Double glazing with 20mm air gap and low-E coating	1.7	0.72
Double glazing with 20mm gap and low-E coating and argon fill	1.5	0.71
Triple glazing with 28mm overall depth	1.1	0.68

Table 2 - Typical thermal performance of existing building elements (W/m^{2}K) [4]

Region	Roof U-value (W/m^{2}K)	Wall U-value (W/m^{2}K)	Window U-value (W/m^{2}K)
Beijing	0.6-0.45	0.3-0.6	2.8-2.5
Shanghai	0.8-1.0	1.0-1.5	3.2-4.7
S. Sweden	0.12	0.17	2.0
Germany	0.2	0.2-0.3	1.5
USA	0.19	0.32-0.45	2.04
EU	0.3	0.25	1.3

Table 3 – Characterisation of common building thermal insulation materials [6], [3]

Form	Material	Density (Kg/m^3)	Thermal Conductivity (W/m-K)	Typical applications
Blankets (batts or rolls)	Fibreglass	12-56	0.04-0.033	Frame wall or ceiling, partitions, prefabricated houses, irregularly shaped surfaces, ducts, and pipes.
	Rockwool	40-200	0.037	Frame wall or ceiling, partitions, prefabricated houses, irregular surfaces, ducts, pipes. Settling is expected.
	Natural fibres (wool, hemp, cotton)		0.037-0.039	Frame wall or ceiling, partitions. Settling is expected.
Loose-fill, blown-in or pour-in	Fiberglass, open cell structure	10-48	0.038-0.030	Cavities and around obstructions. Added adhesive provides more resistance to air infiltration.
	Rockwool -open cell structure		0.040	Cavities
	Cellulose (ground-up waste paper)	24-36	0.054-0.046	Blown into small cavities
	Perlite (natural glassy volcanic rock)	32-176	0.06-0.04	Fill or mixed with Portland cement for walls, roofs, and floors, plastering.
	Vermiculite	64-130	0.068-0.063	Poured into ceilings, cavity walls, cores of hollow blocks.
Rigid board	Fibregass, open cell structure	24–112	0.035–0.032	Cavity walls, roofs, and prefabricated structures.
	Expanded Polystyrene (closed cell foam)	16-35	0.038-0.037	Walls, roofs, and floors. Must be covered inside for fire and against outside weather.
	Extruded Polystyrene (closed cell foam)	26-45	0.032-0.30	Walls, roofs, floors, perimeter, basements, and foundations. Must be covered inside for fire and against outside weather.
	Polyurethane/Polyisocyanurate (closed cell foam)	40-55	0.023	Walls and roofs. Must be covered inside for fire and against outside weather.
	Perlite (nat. glassy volcanic rock)	32-176	0.06-0.04	Blocks (industrial / commercial insulation), light weight insulating concrete
	Vermiculite (nat. mineral)	64-130	0.068-0.063	Not in houses (due to heavy weight).
Foamed-in-Place	Polyurethane/Polyisocyanurate (closed cell foam)	40-55	0.023	Roofs, cavities, irregular and rough surfaces (experienced help needed). Hard to control quality and thickness on site. Needs time to dry to avoid moisture problems
Reflective Systems	Aluminized thin sheets (reflective foil, separated by airspaces)		Reduces only radiant heat transfer	Ceilings, walls, and floors. Most effective in reducing downward heat flow (i.e., summer heat gain in cooling dominated climates, usually installed directly under the roof).
	Ceramic coatings -acrylic paint filled with ceramic micro spheres - brush, roller or spray	1.25	Radiation control	Metal roofs, built-up roofing, walls, storage systems. Ducts and pipes

Table 4 – Typical cost of retrofitting residential and commercial thermal insulation (Europe) [19]

Element	Insulation properties	Units	Cold climate e.g. Copenhagen	Mild climate e.g. Stuttgart	Warm climate e.g. Madrid
Wall insulation	U-value before retrofit	W/m^{2}K	0.50	1.50	2.60
	U-value after retrofit	W/m^{2}K	0.17	0.38	0.48
External Insulation	Total investment for independent installation	€/m^2	152	92	70
	Payback for independent installation	Years	50	18	13
	Additional investment as part of general renovation	€/m^2	77	42	32
	Payback for coupled installation	Years	25	8	6
Cavity Insulation	Total investment for independent installation	€/m^2	41	21	17
	Payback for independent installation	Years	14	4	3
Interior insulation	Total investment for independent installation	€/m^2	n/a	32	23
	Payback for independent installation	Years	-	6	4
Pitched roof	U-value before retrofit	W/m^{2}K	0.50	1.50	3.60
	U-value after retrofit	W/m^{2}K	0.13	0.23	0.43
	Total investment for independent installation	€/m^2	46	25	16
	Payback for independent installation	Years	14	4	2
Ground floor	U-value before retrofit	W/m^{2}K	0.50	1.20	3.40
	U-value after retrofit	W/m^{2}K	0.17	0.41	0.48
	Total investment for independent installation	€/m^2	44	22	18
	Payback for independent installation	Years	27	12	7
Windows	U-value before retrofit	W/m^{2}K	3.0	3.5	4.2
	U-value after retrofit	W/m^{2}K	1.33	1.68	2.71
	Total investment for independent installation	€/m^2	433	316	142
	Payback for independent installation	Years	29	38	37
	Additional investment as part of general renovation	€/m^2	133	116	60
	Payback for coupled installation	Years	16	14	8

Notes: The basis for the cost calculations for insulation measures is a heat transmission coefficient (λ-value) of 0.04 W/mK for the insulation layer; an average price has been assumed representing a typical mix of insulation materials used in retrofit projects in Europe; values are normalised to one square metre of wall; total investment costs include material, labour, taxes and profit; Additional investment costs refer to cases where the insulation is included in general renovation measures. Payback periods for measures in the cold zone are high due to the relatively high standard of existing insulation in houses. Energy prices are assumed based on 2002 tariffs with annual rate of increase of 1.5%. Gas: 4.03c/kWh, electricity 8.84c/kWh, district heating 5.00c/kWh.

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Table 5 - Comparison of Building Codes (as of 2009) [24]

Climate zone	Country	Roof U-value (W/m^2K)	Wall U-value (W/m^2K)	Suspended floor U-value (W/m^2K)	Window U-value (W/m^2K)
Hot	Australia (Darwin)	0.31	0.56	0.67	n/a
	China (Hainan)	0.9	1.5	1.5	3.0-6.5
	India (New Delhi)	0.26-0.41	0.41	n/a	2.0
	USA (Miami)	0.36-0.37	0.64-3.30	1.83-1.99	6.8
Warm	Australia (Perth)	0.31	0.56	n/a	n/a
	China (Shanghai	0.7	1.0	1.0	4.7-2.5
	India (Shillong)	0.26-0.41	0.35	n/a	3.3
	Japan (Toyko)	0.76-1.52	1.33-1.00	n/a	2.5-1.0
	Korea (Inchon)	0.29	0.47	0.35-0.41	3.0-3.4
	USA (Atlanta)	0.27-0.37	0.48-0.7	0.3-0.61	2.61-3.24
Cool	Australia (Thredbo)	0.23	0.56	0.4	n/a
	Canada (Vancouver)	0.23-0.47	0.45-0.81	0.22-0.47	1.3-3.4
	China (Lanzhou)	0.45-0.55	0.50-0.6	0.5-0.6	3.5-2.0
	India (Mukteswar)	0.26-0.41	0.35-0.40	n/a	3.3
	Japan (Sapporo)	0.76-1.52	0.76-0.38	n/a	0.75-1.5
	USA (Chicago)	0.36-0.37	0.48-0.70	0.3-0.5	2.61-3.24
Very cold	Canada (Calgary)	0.23-0.47	0.33-0.55	0.22-0.47	1.4-2.8
	China (Harbin)	0.3-0.35	0.4-0.45	0.4-0.45	1.7-3.0
	India (Leh)	0.26-0.41	0.35-0.40	n/a	3.3
	USA (Duluth)	0.36-0.37	0.32-0.51	0.3-0.5	2.61-3.24

Notes: Climate zones are based on International Climate Zone Definitions of IECC 2006. The hot zone corresponds to Zone 1 in IECC 2006, the warm zone corresponds to Zone 3, the cool zone to Zone 5 and the very cold zone to Zone 7.

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