Technology Roadmap

Energy efficient building envelopes

International
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The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of carbon dioxide (CO_2) will more than double by 2050, and increased fossil energy demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to sharply reduce greenhouse gas (GHG) emissions. Every major country and sector of the economy must be involved. The task is urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing of the need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is leading the development of a series of roadmaps for some of the most important technologies. By identifying the steps needed to accelerate the implementation of radical technology changes, these roadmaps will enable governments, industry and financial partners to make the right choices. This will in turn help societies make the right decisions.

Buildings represent the largest energy-consuming sector in the economy, with over one-third of all energy and half of global electricity consumed there. As a result, they are also responsible for approximately one-third of global carbon emissions. With improvements in economic development and living standards expected to increase as the planet's population grows by 2.5 billion by 2050, energy use in the buildings sector is also set to rise sharply, placing additional pressure on the energy system.

In most regions of the world, heating and cooling loads represent the largest building-sector energy end-use. The building envelope – the boundary between the conditioned interior of the building and the outdoors – can be significantly improved to reduce the energy needed to heat and cool buildings. Actually, with innovative technologies such as advanced facades, highly insulating windows, high levels of insulation, well-sealed structures, and cool roofs in hot climates, the need for interior conditioning can be avoided in many parts of the world, including some of the fastest-growing regions in hot climates.

Furthermore, while research and development (R&D) will offer improved performance and greater economic viability, there are many products and technologies that are cost-effective and ready for deployment today. Much more can be done to aggressively pursue systems level policies such as effective building codes and deep renovation programs that utilise building envelope advancements. *Transition to Sustainable Buildings* detailed how to achieve deep energy and emissions reduction in the buildings sector through a combination of best available technologies and intelligent public policy. This roadmap, together with the *Policy Pathway: Modernising Building Energy Codes*, lays out the key actions required to transform how buildings are constructed – which is essential, since they will remain in service for generations to come. It also articulates the actions to pursue the energy efficient refurbishment of the existing building stock, since the majority will still be in service beyond 2050.

This publication is produced under my authority as Executive Director of the IEA.

Maria van der Hoeven
Executive Director
International Energy Agency

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Key findings and actions

- The building envelope – the parts of a building that form the primary thermal barrier between interior and exterior – plays a key role in determining levels of comfort, natural lighting and ventilations, and how much energy is required to heat and cool a building.
- The construction of new buildings offers the best opportunity to deploy passive heating and cooling designs, which make use of energy-efficient building materials to minimise energy required for heating and cooling. Energy consumption for cooling is expected to increase sharply by 2050 – by almost 150% globally, and by 300% to 600% in developing countries. In hot climates, low-cost solutions such as reflective roofs and walls, exterior shades, and low-emissivity window coatings and films can curtail energy consumption for cooling. In cold climates, passive heating contributions can be increased by optimising building design and using advanced window and glazing systems.
- Transforming typical building renovation to make way for deep reductions in energy consumption – known as deep renovation – should be a high priority.[1] Once established, building renovation will need to be doubled from its current rate of 1% per year to 2% per year, especially among continental northern hemisphere countries, where approximately 75% to 90% of current building stock will still be standing in 2050. As well as enabling permanent ongoing reductions in energy costs, deep renovation can reduce the capital cost of heating, ventilation and air-conditioning (HVAC) equipment.
- Building envelope improvements can improve occupant comfort and the quality of life to millions of citizens, while offering significant non-energy benefits such as reduced health care costs and reduced mortality of "at risk" populations.
- Air sealing – restricting the passage of air through the building envelope – is a key way of increasing energy efficiency during new construction and deep renovation. It is vital to validate the results of air sealing by carrying out standardised tests of its effectiveness. Air sealing alone can reduce the need for heating by 20% to 30%. Tightly sealed structures with proper ventilation control can ensure the indoor climate is healthy. Energy audits, such as the energy performance certificates that are mandatory in the European Union, should include regular, validated testing of air leakage (e.g. at least every 10 years).
- New office buildings should be fitted with integrated facade systems that optimise daylight while minimising energy requirements for heating, cooling, artificial lighting and peak electricity use. Exterior shading, proper orientation and dynamic solar control should become standard features globally in new buildings and can also be applied to existing buildings; in new buildings, window-to-wall ratios can also be optimised. Pilot projects have demonstrated that such systems can enable energy savings of up to 60% for lighting, 20% for cooling and 26% for peak electricity.
- It is vital to increase global collaboration on developing more affordable zero-energy buildings, especially in cold climates. Market development is needed to help move niche products into the mainstream, including in developing markets, through economies of scale and more cost-efficient production processes. This will also encourage consumers to value the benefits of zero-energy buildings.
- R&D on the following technologies will lead to greater returns on investment:
  - highly insulated windows
  - advanced, high-performance, "thin" insulation
  - less labour-intensive air sealing, and lower-cost validation testing
  - lower-cost automated dynamic shading and glazings
  - more durable and lower-cost reflective roof materials and reflective coatings.
- To provide policy makers with the information they need, key energy efficiency indicators and benchmarks should be established for the energy consumption of multiple building types, and the market share of advanced building envelope technologies and products should be tracked.

1. Deep renovation is considered here to mean refurbishment that reduces energy consumption by 75% and limits energy consumption for heating, cooling, ventilation, hot water and lighting to 60 kWh/m^2/yr (GBPN, 2013). Several organisations, including EuroAce, are calling for a tripling of the current rate of renovation.

Key actions in the next ten years

To enable advanced building envelopes to be used in a wider range of climates and regions, all interested parties must make greater effort to support mechanisms that favour R&D and deployment of energy-efficient building materials.

- Policy makers must take responsibility for establishing goals for the energy efficiency of building envelopes, when new buildings are constructed and during deep renovation. Progress should be tracked, reported and integrated with national energy policy plans.

- National and local government authorities should urgently establish and enforce stringent energy codes for new buildings that identify affordable technological solutions, particularly in urban areas of developing countries with tropical or arid climates. Such codes, whenever possible, should be performance-based with minimum technical/prescriptive criteria for components. They should also be adapted to local conditions and market barriers. To facilitate compliance, it is essential to develop and harmonise testing, ratings and certification of building materials, and to improve the knowledge base.

- It is vital to accelerate deployment of proven technologies such as insulation, air sealing, low-emissivity (low-e) windows, exterior shading or other attachments, through innovative financing mechanisms such as utility programmes, revolving funds and energy-performance contracts. Support is needed for market development of efficient building materials and systems. Particularly inefficient materials such as single, clear, glazed windows, which continue to be installed in many countries, should be avoided, and existing materials replaced with a minimum of double-glazed, low-e windows, or upgraded with window attachments.

- Building energy codes should require that roof/attic insulation that meets the latest standards – including proper air and duct sealing if applicable – is installed when roofs are replaced. This can be done quickly and typically offers a major opportunity for whole-building energy savings, reaching 10% to 15% in cold climates.[2] To improve the sophistication of the construction industry, it is vital to develop the knowledge and skills of installers, designers and inspectors.

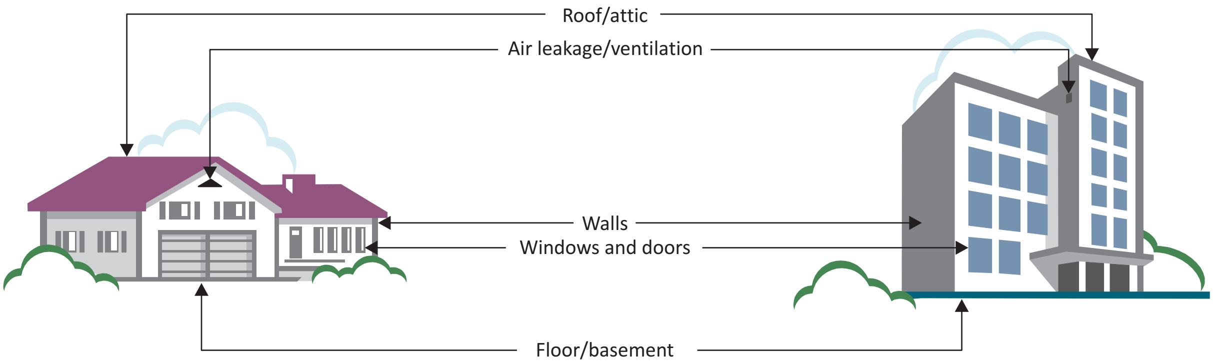
- The economic, comfort and health benefits of low energy buildings need to be better communicated to the public and financial communities. Governments should implement public information campaigns and programmes to accelerate adoption rates.

2. Savings vary significantly according to building configurations and climate, and do not apply to high-rise buildings, whose roofs make up a small portion of the entire building envelope.

Introduction

The building envelope – also known as the building shell, fabric or enclosure – is the boundary between the conditioned interior of a building and the outdoors. The energy performance of building envelope components, including external walls, floors, roofs, ceilings, windows and doors, is critical in determining how much energy is required for heating and cooling (Figure 1). Energy loss through the building envelope is highly variable and depends on numerous factors, such as building age and type, climate, construction technique, orientation, geographical location and occupant behaviour.

Figure 1: Building envelope components



Note: unless otherwise stated, all material in figures and tables derives from IEA data and analysis.

KEY POINT: all elements of the building envelope affect energy use.

The building envelope's impact on energy consumption should not be underestimated: globally, space heating and cooling account for over one-third of all energy consumed in buildings, rising to as much as 50% in cold climates and over 60% in the residential sub-sector in cold climate countries.[3] Overall, buildings are responsible for more than one-third of global energy consumption.

The envelope's design and construction also affects the comfort and productivity of occupants. Common problems in many countries include leaky windows with cold interior surfaces causing draughts, glare from inappropriately oriented or un-shaded windows, and excessive heat gain from east- or west-facing windows. Leaky and uninsulated walls and roofs lead to high energy bills and uncomfortable conditions when heating or cooling equipment is unable to maintain desired temperatures.

When buildings are constructed or renovated, a whole-building perspective is preferred, which involves considering all parts of the building and the construction process to reveal opportunities to improve energy efficiency. Numerous whole-building perspectives and policy mechanisms exist, such as building performance certificates (IEA, 2010a) and whole-building labelling programmes, but they are beyond the scope of this roadmap.[4]

While whole-building approaches are ideal, every day building envelope components are upgraded or replaced using technologies that are less efficient than the best options available. These advanced options, which are the primary focus of this roadmap, are needed not only to support whole-building approaches but also to improve the energy efficiency of individual components:

- high levels of insulation in walls, roofs and floors, to reduce heat losses in cold climates, optimised through life-cycle cost (LCC) assessment
- high-performance windows, with low thermal transmittance for the entire assembly (including frames and edge seals) and climate-appropriate solar heat gain coefficients (SHGC)

3. Energy statistics in this roadmap come from the IEA energy balances, IEA Energy Efficiency Indicators Database, and the IEA Buildings Model unless otherwise stated (IEA, 2013a).

4. For more information, see *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013a) and *Modernising Building Energy Codes to Secure our Global Energy Future* (IEA-UNDP, 2013).

- highly reflective surfaces in hot climates, including both white and "cool-coloured" roofs and walls, with glare minimised
- properly sealed structures to ensure low air infiltration rates, with controlled ventilation for fresh air
- minimisation of thermal bridges (components that easily conduct heat), such as high thermal conductive fasteners and structural members, while managing moisture concerns within integrated building components and materials.

Analysis of building envelopes is complicated by the extreme global diversity of building materials, climates, and standards and practices of building design and construction. There are vast differences in construction practices between traditional dwellings in developing countries and houses constructed in OECD member countries. As populations grow, housing demand also increases, and rapid increases in wealth usually drive greater increases in floor area per capita and in many cases higher land usage. It is vital to ensure new buildings use the most efficient technologies, as retrofits can be difficult and cost-prohibitive.

The suitability of energy-efficient technologies depends on the type of economy, climate and whether the materials are being used for new buildings or retrofits (see Table 1). Thus, policies need to be devised and implemented at the city, regional and country levels.

Table 1: Building envelope technologies according to economy, climate and construction type

Type of economy	Climate	Technology: New construction	Technology: Retrofit
		Insulation, air sealing and double-glazed low-e windows for all buildings*	
Developed	Hot climate	• Architectural shading • Very low-SHGC windows (or dynamic shades/windows) • Reflective walls/roofs • Advanced roofs (integrated design/BIPV) • Optimised natural/mechanical ventilation.	• Exterior window shading and dynamic glass/shading • Reflective roofing materials and coatings • Reflective wall coatings • Window film with lower SHGC • New low-SHGC windows.
Developed	Cold climate	• Highly insulated windows • Passive heating gain (architectural feature /dynamic glass/shades) • Passivhaus-equivalent performance based on LCC limitations.	• Highly insulated windows • Low-e storm or interior panels • Insulated shades and other insulating attachments (low-e films) • Exterior insulating wall systems • Interior high-performance insulation.
Developing	Hot climate	• Exterior shading and architectural features • Low-SHGC windows • Reflective roofs and wall coatings • Optimised natural/mechanical ventilation.	• Exterior shading • Reflective coatings (roof and wall) • Low-cost window films • Natural ventilation.
Developing	Cold climate	• Highly insulated windows (possibly double-glazed with low-e storm panel) • Passive heating gain (architectural feature) • Optimised low-cost insulation and air sealing.	• Low-e storm or interior panels • Insulated shades and other insulating attachments (low-e films) • Exterior insulating wall systems • Cavity insulation, lower-cost (e.g. expanded polystyrene) interior insulation.

Notes: BIPV = building-integrated photovoltaic. Passivhaus, an advanced residential building programme that calls for very high levels of building envelope performance, has gained significant momentum in Europe and is active globally (see www.passiv.de/en/index.php).

* The IEA recommends a minimum performance for all new windows globally to meet the performance of double glaze low-e with low-conductive frames and climate-optimised SHGC. Air sealing is needed for any building that will have heating and cooling provided. Insulation is needed for all applications, renovation is more challenging but possible, especially for roofs in all climates.

Rationale for energy-efficient building envelopes

In most of the world, the energy performance of building envelopes has been significantly neglected. While there has been substantial success in improving the energy efficiency of new appliances, lighting and heating and cooling equipment, many buildings are still being constructed that are leaky, have no insulation or exterior shade control, and have single-glazed clear glass windows and solar-absorbing roofs in hot climates. Given that heating and cooling account for over a third of global energy consumption in the buildings sector, optimising building envelope design should be a key part of any long-term energy reduction strategy.

The quality and energy efficiency of building envelopes are the most important factors that affect the energy consumed by heating and cooling equipment. Since investments in both envelope and mechanical equipment are attempting to save the same portion of end-use energy consumption, investment in either is likely to result in diminishing returns for the other.

There are two predominant perspectives on the relative importance of the building envelope and heating and cooling equipment. The passive design approach supports high levels of energy efficiency in building envelope components, with any remaining need for heating or cooling met by basic, efficient mechanical equipment. The smart technology approach promotes high energy efficiency in mechanical equipment because it is routinely replaced and installing it is easier than retrofitting old, inefficient building envelopes. Either approach can be appropriate. The balance between advanced envelopes and advanced equipment needs to be established at the regional or local level while considering product availability, cost, climatic conditions and energy prices. Whenever possible, however, it is usually better to invest in the most energy-efficient building envelope that is justified, because it will be in place for many years and in most cases advanced envelopes provide greater comfort. Improved comfort can foster behaviour that leads to additional energy savings, such as not raising thermostat set points.

Roadmap approach and scope

The primary purpose of this roadmap is to describe efficient building envelope technologies and the actions required to support greater investment in them. The roadmap focuses on the need to improve building component performance metrics and market diffusion, and highlights areas that with improved design and R&D could result in big gains in the future.

IEA analysis of building envelopes included a call for data and information from many regions around the world. In addition, the IEA hosted and participated in five events focused specifically on establishing roadmaps for building envelopes (see Box 1).

There are many building envelope technologies and applications, so this roadmap focuses only on the most important. Its primary focus is on reducing energy requirements for heating and cooling; other issues, such as city planning, environmental sustainability, embodied energy, maintenance and durability, historical preservation and building simulation, are not covered in any detail. Furthermore, while occupant behaviour such as adjusting thermostat set points is an important factor in saving energy, the roadmap does not explore this issue in any depth.

Box 1: Roadmap workshops to build collaboration and seek improved data

The IEA worked in collaboration with a number of organisations to participate and co-sponsor events:

- IEA Building Envelope Technologies and Policies Workshop, Paris, 17 and 18 November 2011
- United States Department of Energy (US DOE), Building Envelope R&D Program Stakeholder Engagement Workshop, San Antonio, Texas, 26 June 2012
- US DOE, Window Technology R&D Program Stakeholder Engagement Workshop, Minneapolis, Minnesota, 28 June 2012
- IEA – Tsinghua University, China Building Envelope Workshop, Beijing, 24 August 2012
- IEA – Russian Energy Agency, Russia Building Envelope Workshop, Moscow, 28 November 2012.

Building envelopes today

While proponents of energy efficiency rank energy conservation as the top priority when considering building envelope design, the primary purpose of the building envelope is to protect occupants and provide basic shelter. The building envelope performs many different functions, offering security, fire protection, privacy, comfort and shelter from weather, as well as benefits such as aesthetics, ventilation and views to the outdoors. The key challenge is to optimise the design of the overall building and the building envelope to meet the needs of the occupants while reducing energy consumption.

Maximising the benefits of sunlight to reduce heating and lighting needs is a core element of integrated designs. Similarly, energy needs for cooling can be reduced by minimising heat gains in summer using thermal mass, efficient glazing, insulation, shading, reflective surfaces and natural ventilation. Automated exterior shading offers dynamic solar control in new and existing buildings. Recent innovation in dynamic window technology could enable greater passive heating in winter and shading in summer, once the technology is mature and becomes economically viable.

Many of these design elements can be implemented at modest additional cost when constructing a new building. Advanced near-zero-energy buildings are being constructed in many regions around the world, and several European Union (EU) countries have adopted policies to mandate zero-energy buildings by the end of the decade (IEA, 2013a). Many advanced building design concepts are already cost-effective if LCCs are taken into account, especially in locations where the climate is severe or energy prices are higher than average. As well as lowering energy costs, advanced building envelope design can reduce the capital costs of heating and cooling systems, as the need for heating and cooling can be reduced by up to 60% (Winbuild, 2012).[5]

5. Generally many advanced building renovation programmes are calling for heating and cooling improvements of 75% to 80%. Approximately half of these expected savings (40%) are from envelope and the remainder are from mechanical equipment. These values are for all buildings and vary significantly based on many factors as described throughout the roadmap.

History of building envelopes and passive approach

In many parts of the world, buildings have long been constructed using local materials to maximise comfort given the local climate. Thus, highly reflective roofs and walls were typical many centuries ago in hot climates, while thick thatched roofs offered insulating properties in cold climates. The use of natural ventilation was also very common. Structures with high thermal mass have been common for a very long time and are still typical in many regions, but their use has diminished in some regions to reduce cost. Modernisation has resulted in higher densities in urban areas, the need for faster construction techniques, and more affordable approaches that in many cases result in less efficient structures than old techniques.

A primary goal when designing advanced buildings is to eliminate the need for heating or cooling equipment. This may not be possible in severe cold or hot climates, but should still be a key design aim. Cooling loads can be reduced with the help of building energy simulation design software that optimises natural daylight by specifying building orientation, narrower building profiles, and features that enable shading and natural ventilation. This approach has been pursued by many advanced building designers and promoted by high-performance building programmes. Key elements of it have been implemented in the French building code. The IEA *Modernising Building Energy Codes to Secure Our Global Energy Future* is calling for this approach to be pursued in future building codes (IEA-UNDP, 2013).

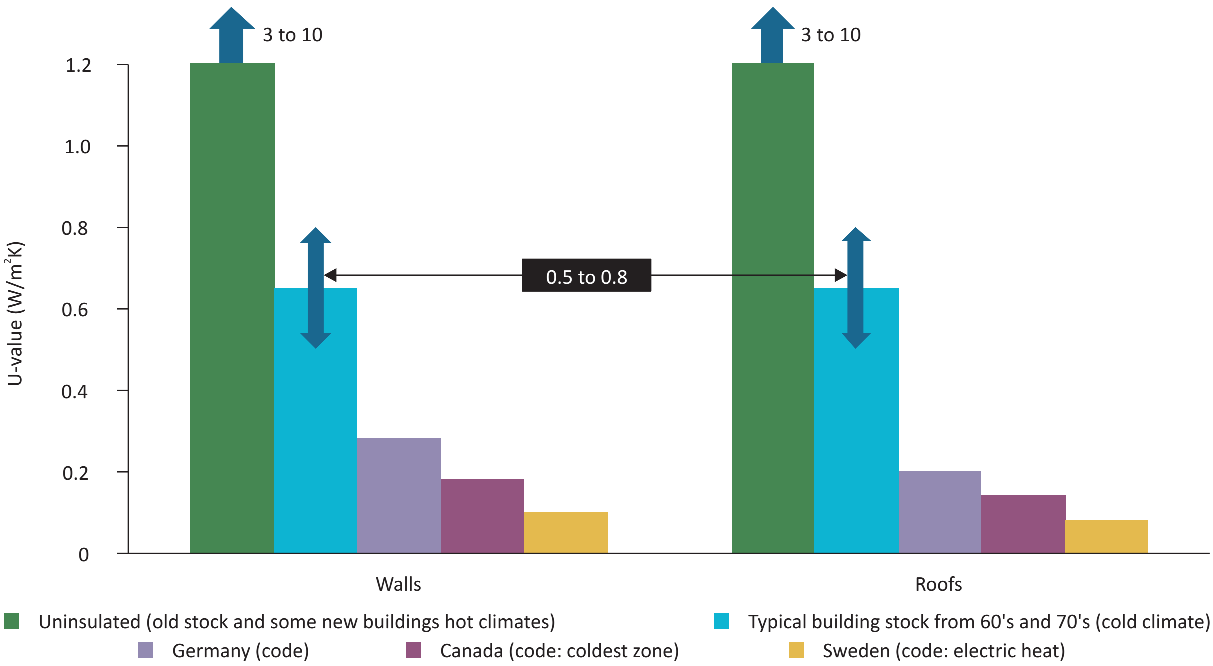
While such systems-level approaches are preferred, they predominantly apply to new construction. (Furthermore, at many construction sites it may not be possible to implement them, because of land restrictions, zoning laws or other constraints that cannot be overcome even with the help of proactive planning and zoning officials.) Given that a significant effort is needed to upgrade existing buildings, it is vital to focus on technologies for individual building envelope components, which are the principal subject of this roadmap.

Insulation

Most heat is lost from buildings through walls, roofs and floors, which represent the largest external area of most residential and services sub-sector buildings. Proper insulation reduces heat loss in cold weather, keeps out excess heat in hot weather, and helps maintain a comfortable indoor environment without incurring maintenance costs. The type and amount of insulation needed varies considerably according to building type. Many service-sector buildings have higher internal thermal loads, for example, because of a higher density of people, more electrical equipment and more artificial light, so they may need less insulation than a residential building. There are many types of insulating material, and certain types are better suited to different applications (see Annex A).

Most new buildings in cold climates are being constructed with insulation. In most parts of the world, however – except for a few regions, such as Northern Europe – the level of insulation is not as high as economically justified (see Figure 2). Furthermore, many existing buildings have little or no insulation. In hot regions, especially in less developed countries, many new buildings are being constructed without any insulation, thus substantially increasing cooling loads. Policy makers need to make significant efforts to ensure the building industry uses more insulation.

Figure 2: Insulation levels vary greatly, from old buildings to buildings meeting stringent current codes



Source: adapted from IEA (2013a), *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*, OECD/IEA, Paris.

KEY POINT: levels of insulation vary widely for the existing stock of buildings, as well as for new construction.

The majority of the world's wall construction involves a "stick built" framing structure (wood or metal studs) or a high thermal mass structure (stone, masonry or concrete).[6] Framing structures allow for cavities to be filled with insulation, but the structural members remain as thermal bridges, with significantly higher heat transfer properties. High thermal mass structures were often built without any insulation but conserve some energy because of their thermal mass. Older framed structures often do not have insulation in cavities. Insulation strategies need to take into account these different characteristics, which can make integrated solutions very complex if they involve a variety of insulation materials. A new approach to construction that has been growing in popularity includes structural insulated panels (SIPs).

Modern insulated walls, roofs and floors can lead to moisture damage because there is less energy loss to evaporate moisture. Furthermore, thermal bridges, improper design and assembly can result in condensation within structures, so building envelopes need to be designed to avoid this problem. Solutions may include a vapour retarder, depending on the climate, and moisture assessment software, which is used in advanced building envelopes in Europe and North America (WUFI, 2013).

Air sealing

Normal air movement in and out of buildings – infiltration and exfiltration – is known as air leakage and is usually measured using air changes per hour (ACH). ACH is equal to the fraction of the volume of air in a structure that is exchanged with the outside at a specified pressure difference in one hour (e.g. ACH of five would be a flow rate that equals five times the volume of the building leaking in one hour). Natural weather conditions, such as wind and temperature differences, can increase air leakage. Air-distributed heating and cooling systems can also increase air leakage if they create pressure differences between the inside and outside of a building.

6. The term "stick built" is common in North America, where structural framing made of wood or steel is used. Another common term is "structural member", which provides the primary support of the building. In high thermal mass structures, the entire wall provides the structural support.

To measure ACH, the structure is pressurised and air leakage rates are collected over a range of pressures. The overwhelming majority of buildings in the world have not been air-sealed. Air sealing has been carried out most in Northern Europe, followed by Canada and the United States. Even in the European Union, however, many mandatory energy performance certificates do not require validated air leakage measurements.

Buildings should be sealed as tightly as possible, but if there is no ventilation, air quality can deteriorate and combustion gases can accumulate, leading to safety concerns. Thus, air leakage rates are often specified with consideration of mechanical ventilation for fresh air. Combustion air powered by sealed fossil fuel heating equipment is the preferred option (e.g. condensing gas boilers with dedicated intake air), but many existing structures using conventional combustion have been successfully sealed; guidelines call for "dedicated combustion air" to be provided (Lstiburek, 2013).

Uncontrolled air infiltration involves air passing through old, dirty walls and cracks that may contain decaying rodents, mould and insects. Air sealing with controlled ventilation improves indoor air quality rather than degrading it.[7] Most advanced building programmes in the world focus on very low leakage rates, although specified requirements still vary considerably (see Table 2).

7. Extensive research has been carried out on this subject (see the IEA Technology Network project at www.aivc.org).

Table 2: Air leakage rates for European Union, United States and advanced housing programmes

	Northern European Union without ventilation (code)	*Northern European Union with ventilation (code)*	*United States, residential (code)*	*Passivhaus residential guideline*	*Typical for very tight new houses with ventilation*	*Old leaky houses*
Performance metrics, air leakage at 50 Pa	2.5 ACH to 3.0 ACH	1.0 ACH to 0.6 ACH	≤ 3.0 ACH cold climate; ≤ 5.0 ACH hot climate	≤ 0.6 ACH	Approximately 0.2 ACH	10 ACH to 20 ACH

Source: IEA (2013a), *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*, OECD/IEA, Paris.

Potential energy savings also vary significantly. Simulations on a large number of building types in widely varying climates have shown that reducing air leakage can save 5% to 40% of heating and cooling energy. With reasonably tight structures in cold climates, typical energy savings are 20% to 30% (Zhivov et al., 2012). Air sealing is needed in all buildings, regardless of climate, except those without mechanical equipment that are fully conditioned with natural ventilation.

While all "joints" (interfaces and building envelope penetrations) contribute to air leakage, windows require particular attention, especially during installation or replacement. Using correct window installation techniques, including flashing, sealants and insulation (e.g. low pressure expandable foam), can significantly reduce air leakage and thermal bridges. Several requirements for proper installation exist in more mature markets, such as ASTM E 2112 in the United States. Windows that can be opened and closed – operable windows – are also susceptible to air leakage around sashes. New windows tend to have lower leakage rates, which are or should be specified in window performance criteria. Air leakage from older windows can be reduced by using sealants, gaskets and additional window panels (interior or exterior). New exterior low-e storm panels added to old homes have been shown to reduce whole house infiltration by 5.7% to 8.6% (Drumheller et al., 2007).

Windows

Windows have several functions, including giving access to the building, providing outlook, letting in daylight and offering safety egress.[8] In most cases, windows should let in as much light as possible, but heat gain needs to be minimised in summer and maximised in winter. Appropriate choices of sizing, orientation and glazing are essential to balance the flows of heat and natural light.

Heat flow (or energy balance) depends on the season, building type and operation of the building. If the building is heated and the outdoor temperature is cold, the window should retain heat (low U-values, see Annex A for more details), minimise losses and let in as much solar radiation as possible (high SHGC or g-value). On the other hand, if the temperature inside the building is too high and cooling is needed, the windows should keep out heat from the sun (low-SHGC or g-value) and if possible enable heat to be shed from the building.

In specifying window performance for a specific region, it is necessary to consider both heating and cooling loads to maximise performance and achieve the lowest total annual energy impact, or best energy balance. In some climates, a positive energy balance – or energy gain – can be achieved using advanced static glazings combined with well-insulated window systems and architectural shading optimised for seasonal impacts (e.g. a triple-glazed window system with two layers of low-e glass, high

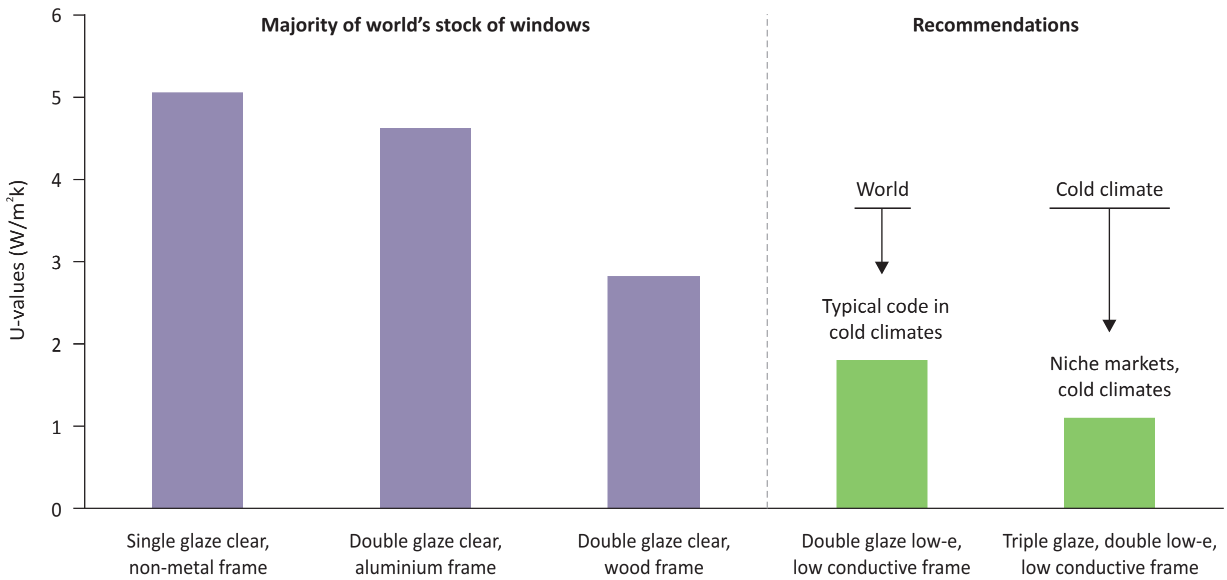
8. This section discusses windows in detail, but the majority of inefficient doors are glass doors that can be considered as a type of window for energy efficiency. Also, many countries combine windows and doors as a common "fenestration" product category.

solar heat gain, low-conductive frame, exterior shading, in a moderate European climate) (Cazes, 2011). Well-insulated window systems are especially important for cold climates but are also needed in hot climates. The solar or optical characteristics of glass, which determine how much of the sun's energy is transmitted into the building or rejected, need to be seasonally optimised for the climate.

Most cold-climate OECD member countries are making a significant effort to promote high-performance windows, but triple-glazed windows, which have been available for many decades, have not achieved full market share in any country. Triple glazing with clear glass was more prevalent in Northern European countries but then diminished because manufacturers were able to achieve comparable performance using modern, double-glazed, low-e coated windows. This trend is changing, however, with the promotion of the Passivhaus programme and recent more stringent building codes. Austria, Germany and Switzerland have the highest market share for triple glazing usually with two low-e surfaces, at 54% of total window sales. New construction and the residential sector have the highest market penetration. Overall, the majority of windows sold in the European Union are still double-glazed (Interconnection, 2013).

Unfortunately, windows are still being sold in many regions of the world that are only single-glazed, with clear glass and poorly insulated frames. These have U-values of approximately 4.5 watts per square metre per Kelvin (W/m^{2}K) to 5.6 W/m^{2}K. The majority of OECD member countries in cold climates have moved to double-glazed windows with low-e coatings, low-conductive frames, and inert gas for the residential sub-sector, with U-values of approximately 1.8 W/m^{2}K. Highly insulated windows such as the ones discussed above for the European Union, have U-values around 1.1 W/m^{2}K (see Figure 3).

Figure 3: Most common types of windows in service and being sold today



Note: U-values presented in this roadmap represent whole-window performance unless noted in accordance with International Organization for Standardization (ISO) 15099, thus an ISO 10077 standard of 1.0 W/m^{2}K is roughly equal to 1.1 W/m^{2}K per ISO 15099.

KEY POINT: the majority of the world's installed windows can be significantly improved and more work is needed to ensure that new sales meet more stringent performance criteria.

Higher-performance windows with lower U-values and warmer interior surfaces in winter reduce occupant discomfort near windows. Solar control still needs to be improved, however, because occupants often complain of too much solar heat and glare, especially in service-sector buildings. Advanced solar control glazings that are tuned to reject as much heat as possible (e.g. that reflect near-infrared light),[9] while transmitting high levels of visible light, perform significantly better than clear or tinted glass. Combining these advanced solar control glazings (static SHGC) and exterior architectural shading offers an improved solution that is being deployed in many markets and needs to be promoted in areas that use clear glass. However, automated exterior shading provides the best viable technology today to improve occupant comfort and save energy by modulating the solar energy that is hitting the glass. Such systems are still expensive from an energy efficiency perspective for many parts of the world, but they provide many non-energy benefits.

New dynamic glazings that are now being commercialised offer the potential to modulate solar heat (variable SHGC) through the glazing while maintaining a full view to the outdoors, such as electrochromic glazing, which changes opacity in response to voltage and thus allows control over the amount of light and heat passing through (see Figure 4). Pilot projects have demonstrated lighting savings up to 60%, cooling load reduction up to 20%, and peak electricity reduction up to 26% (Sbar, 2008). More R&D and economies of scale are needed to improve dynamic solar control so that it can become cost-effective for mainstream markets (see Annex A).

9. These coatings are often called "spectrally selective" and generically called "low-e" coatings. This topic can be complex, see Annex A and the Glossary for more information.

Figure 4: Large-scale demonstration of electrochromic glazing at Chabot College, California

Source: Sage (Sage Electrochromics) (2013), "Portfolio - Chabot College, Hayward, California" http://sageglass.com/portfolio/chabot-college/.

KEY POINT: dynamic windows are on the cusp of market viability and will fundamentally change how people design buildings to optimise solar control while increasing passive heating.

Reflective surfaces

In hot climates, it is best to reject as much heat as possible from the roof surface and to prevent heat building up in the attic or conditioned space. "Cool roofs", which can be simply white in colour, reflect visible and near-infrared light very well. Cool roofs' ability to reflect gradually diminishes because of soiling and weathering, so to ensure accurate energy-saving measurements, ratings specified in policy programmes take age into account.[10] Recently, the concept of a cool roof has included detailed rating requirements that provide performance criteria for solar reflectance (SR) and thermal emittance after a roof sample has been aged (undergoing weathering tests in a variety of climates) for a specified period, such as three years.[11]

10. Aging refers to a combination of "soiling", which includes particulates and microbiological growth, and "weathering", which includes natural degradation by exposure to factors such as ultra violet light and thermal cycling.

11. Solar reflectance measures the fraction of sunlight that is reflected, and thermal emittance is the efficiency with which a surface emits radiation. Higher thermal emittance allows the roof surface to reject any heat that is absorbed if it is hotter than the surrounding environment (see Cool Roof Rating Council, www.coolroofs.org).

Reflective roof benefits are highly dependent upon climate, existence of insulation and the types of roofs installed (see Table 3). The United States has been leading the world on reflective surfaces, which have been incorporated into mandatory building codes in many locations with hot climates (Akbari et al., 2012). Currently, research on this topic and some market deployment work is under way in Brazil, China, India, Japan, southern Europe and other regions.

Table 3: Performance characteristics and energy-savings potential for reflective roofs

	SR of a dark roof	SR of a white roof	SR of a cool-coloured roof	Roof energy-savings potential (with high level of insulation)	Roof energy-saving potential (with low level of insulation)
Roof performance characteristics	SR 5 (black) to SR 20 (grey)	SR 60 (soiled) to SR 80 (clean)	SR 25 (darker colour) to SR 50 (lighter colour)	13%	25%

Note: high insulation refers to a U value of 0.29 W/m^2K, and low level of insulation has a U value of 0.51 W/m^2K or higher.

Source: CRRC (Cool Roof Rating Council) (2013), "Rated Products Database", www.coolroofs.org/index.html. Konopacki, S., L. Gartland, H. Akbari and I. Rainer (1998), "Demonstration of Energy Savings of Cool Roofs", *Technical Report*, LBNL (Lawrence Berkeley National Laboratory), http://escholarship.org/uc/item/4p14n8hw. Parker, D., J. Sonne and J. Sherwin (1997), "Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall", Florida Solar Energy Center, Cocoa, Florida, www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-964-97.pdf, October.

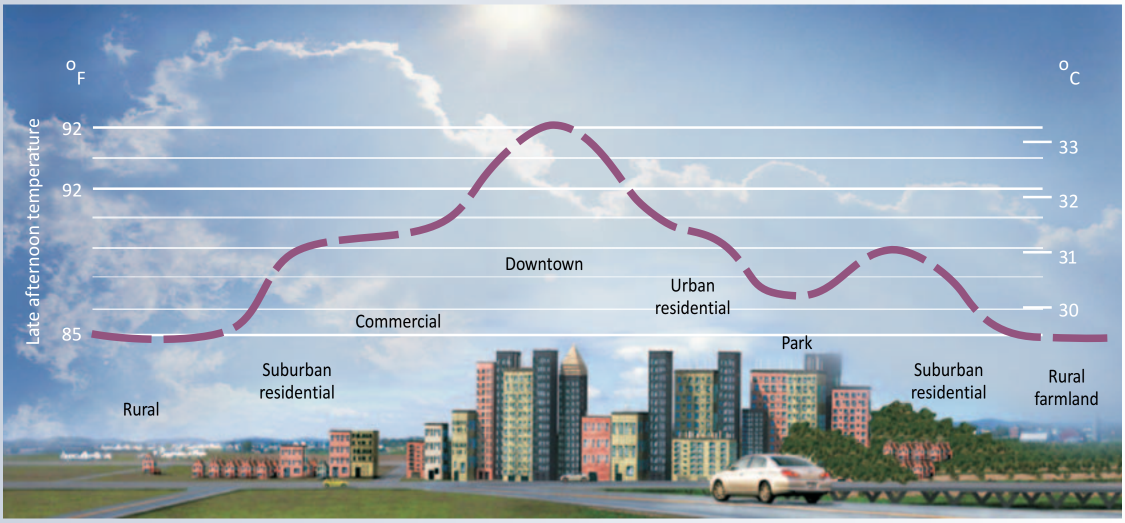
In addition to offering typical energy savings, passive strategies such as reflective roofs can reduce interior temperatures in hot climates, thus avoiding the need for air conditioning (Sahoo et al., 2013). Similarly, reflective walls can offer energy savings from 4% up to 13% for walls (Desjarlais, 2009).

While some practitioners believe that roof insulation can be eliminated in hot climates, this is not the case because heat gain from high ambient temperatures needs to be avoided. In-depth analysis based on local conditions can determine a balance between insulation levels and types of cool roofs that results in substantial energy savings at the lowest possible cost. The benefits of cool roofs go well beyond the energy efficiency of buildings, however. These multiple benefits are driving the interest in reflective surfaces, especially in the United States (see Box 2). Japan has also been actively researching urban heat islands (city centres with much higher temperatures than surrounding areas) (Miyazaki, 2009).

Box 2: Cool roofs and reflective urban surfaces can cool the planet

Reflective surfaces can improve building energy efficiency, reduce urban heat island effects and cool the planet. Cool roofs have long been a proven way of reducing the need for cooling. Reflective urban landscapes including cool pavements could reduce urban temperatures by 2°C to 4°C (see Figure 5). In recent years, several studies have been conducted on the global cooling potential of reflective surfaces, including cool roofs and more reflective roadways and parking lots. These studies concluded that rejected heat from the planet could have the cooling effect of approximately 1.5 years of global man-made carbon emissions, or around 44 gigatonnes of carbon dioxide (Gt CO_2) (GCCA, 2013). However, this is a onetime total effect of converting urban landscapes to more reflective surfaces.

Figure 5: Urban heat islands increase energy consumption and pollution



Source: LBNL (Lawrence Berkeley National Laboratory) (2013), Heat Island Group, http://heatisland.lbl.gov/.

KEY POINT: pursuing a reflective surfaces programme, where appropriate, can reduce building energy consumption, urban pollution and global temperature rise.

Recently, progress has been made towards achieving this carbon savings potential. Researchers in India and the United States conducted a study that attempted to validate the upward radiation flow from cool roofs using satellite- and land-based measurement techniques. A key consideration is the impact on atmospheric pollutants that absorb solar energy in both the downward and upward directions. Clouds also affect radiation flows. The key finding is that the ability to reject radiation (heat) from the earth from reflective surfaces has now been validated through measured data and is no longer just a theory (Salamanca et al., 2012).

Market assessment of energy-efficient building materials

To achieve the large energy savings that efficient building envelopes can offer, full market saturation (deployment) of high-priority, energy-efficient building materials is essential. Data on current market share are difficult or expensive to obtain in developed countries and are often not available in emerging markets, so the IEA has used assessment and inputs from experts worldwide to estimate three levels of market saturation: mature market (greater than 50%), established market (approximately 5% to 50%), and initial market presence (available but less than 5%) (see Table 4). Policy makers should collect better data and track the progress of energy-efficient building envelope materials and technologies, in order to promote high-performance buildings as part of comprehensive building technology programmes.

Table 4: An assessment of market saturation for high-priority building envelope components

Market maturity/ saturation	ASEAN	Brazil	China	European Union	India	Japan/ Korea	Mexico	Middle East	Australia/ New Zealand	Russia	South Africa	United States/ Canada
Double-glazed low-e glass	●	▲	▲	★	▲	●	●	▲	●	●	●	★
Window films	▲	▲	▲	●	▲	●	▲	▲	●	▲	▲	●
Window attachments (e.g. shutters, shades, storm panel)	●	▲	●	★	▲	●	▲	●	●	▲	●	●
Highly insulating windows (e.g. triple-glazed)		▲	▲	●		▲		▲	▲	▲	▲	▲
Typical insulation	★	●	★	★	●	★	●	★	★	★	●	★
Exterior insulation	●	▲	●	★	●	●	▲	●		▲	▲	★
Advanced insulation (e.g. aerogel, VIPs)				▲		▲				▲	▲	▲
Air sealing	●	▲	▲	★	▲	●		▲	▲	▲		●
Cool roofs	▲	▲	▲	●	▲	▲	▲	▲	▲			★
BIPV/ advanced roofs	▲	▲		▲	▲	▲			▲	▲	▲	▲

★ Mature market ● Established market ▲ Initial market

Notes: ASEAN = Association of Southeast Asian Nations. Blank cells indicate that there is currently not any market presence or it is so low that it is not known to domestic experts. Some technologies may not be recommended for all climates, such as cool roofs in Russia or highly insulated windows in hot climates. Typical insulation refers to widely available products such as fibreglass and various foams with thermal conductivities higher than 0.02 watts per meter Kelvin (W/mK). VIP = vacuum-insulated panel. See Annex A and Glossary for more detailed descriptions.

The IEA market assessment shows clearly that Canada, the European Union and the United States have made the most progress in deploying energy-efficient building envelopes. Japan also has made some progress. From a technology perspective, the deployment of typical insulation has been successful with full maturity in most regions, followed by low-e glass with some established markets. However, much more work is needed globally to promote market saturation for advanced building materials.

Vision for deploying more efficient building envelopes

The vision for this roadmap is based on the 2°C Scenario (2DS) described in *Energy Technology Perspectives 2012 (ETP 2012)* (IEA, 2012a), in which energy-related CO_2 emissions are halved by 2050, helping to limit the global average temperature rise to no more than 2°C (see Box 3). To achieve this ambitious goal, all sectors need to act; in the building sector, unprecedented deployment and market uptake is needed of advanced and more energy-efficient building envelopes, and other low-carbon and energy-efficient building technologies. This roadmap outlines the key technologies and actions required to achieve significant heating and cooling energy savings through the development and widespread deployment of advanced building envelopes.

Box 3: The 2DS

The 2DS describes how energy technologies across all sectors could be transformed by 2050 to achieve the global goal of reducing annual CO_2 emission levels to half of those in 2009 (IEA, 2012a). The model used for this analysis is a bottom-up TIMES model that identifies least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The ETP model is a global 29-region model that permits the analysis of fuel and technology choices throughout the energy system. The model's detailed representation of technology options includes about 100 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. In addition, the ETP model is supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors (see *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* for a detailed discussion on the building's demand model) (IEA, 2013a).

ETP 2012 considers other scenarios. The *ETP 2012* 6°C Scenario (6DS) assumes that no major new policies to reduce greenhouse gas emissions will be introduced in the coming decades. The 6DS is considered to be the baseline scenario in the Technology Roadmap series. Achieving the 2DS will be difficult; some of its assumed rates of change (e.g. annual change in sales of new building technologies) are unprecedented but realistic. To achieve such a scenario, strong policies will be needed from governments around the world.

Most of the technologies needed to make building envelopes more energy-efficient are commercially available, but are not widely deployed because of high upfront costs and non-economic barriers such as split incentives and lack of information (see the Policy and Implementation section for a more detailed analysis of barriers and policies necessary to overcome these barriers). The potential for energy efficiency improvements in buildings remains largely untapped (IEA, 2012b).

Rapid economic growth, rising populations and increased urbanisation in many non-OECD countries will transform the global buildings stock. In OECD member countries, by contrast, the building sector is expected to change less, as 75% to 90% of the current building stock will still be standing in 2050. In both cases, however, there is an urgent need to make building envelopes more energy-efficient, as 20% to 60% of all energy used in buildings is affected by the design and construction of the building envelope. Globally the number of households is expected to rise nearly 70% by 2050, from 1.9 billion in 2010 to 3.2 billion in 2050, and total floor area to increase 70% from 206 billion square metres (m^2) in 2010 to 357 billion m^2 in 2050 (see Table 5).

Table 5: Key drivers for the buildings sector

Region \ Drivers	Population (million)		Per-capita income (USD/capita)		Number of households (million)		Total residential floor area (billion m²)		Total services floor area (billion m²)	
	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050
World	7 006	9 448	10 608	28 262	1 886	3 159	168	294	38	63
OECD	1 230	1 399	33 312	64 974	474	608	58.8	81.5	20.9	30.5
Non-OECD Europe and Eurasia	332	313	11 746	41 635	121	148	8.5	13.6	1.0	1.5
Asia	3 741	4 589	5 186	26 791	906	1 520	75.2	132.2	13.3	25.3
Latin America	477	607	9 460	24 251	124	249	8.9	18.9	0.7	1.0
Africa	1 022	2 192	2 966	6 149	184	489	13.4	37.2	0.7	1.7
Middle East	204	348	12 215	34 255	76	145	3.6	9.9	1.0	2.4

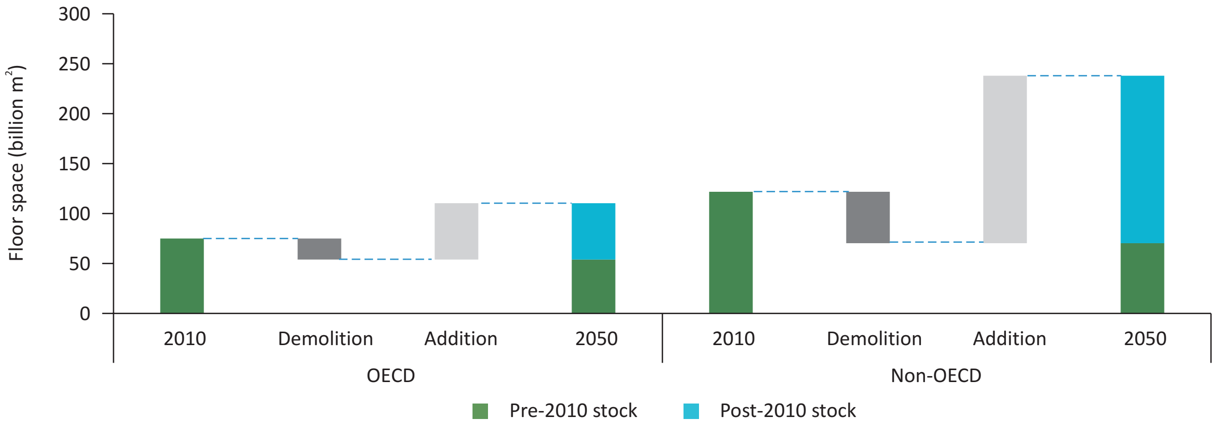
Notes: Per-capita income is based on 2010 USD at purchasing power parity. Number of households and average house size for most non-OECD countries are estimated based on available information on income per capita, people per house and new constructions, as well as information on building stock from national statistical agencies.

Source: IEA (2013a), *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*, OECD/IEA, Paris.

Evolution of global buildings stock and energy demand

Given the differing vintage of the building stock and its expected development (see Figure 6), non-OECD countries face huge growth in expected construction. OECD member countries have a large stock of residential buildings, most built before 1970, that is not growing quickly and will be retired slowly. Currently, the rate of refurbishment of residential buildings in which there is an opportunity to significantly improve envelope efficiency is estimated to be low, at 1% per year (BPIE, 2011). Urgent policy action is required to increase this rate, because energy efficiency refurbishments are potentially expensive and are likely to make economic sense only during major refurbishments, which occur every 30 or more years. It is very common for building life spans to reach 50 years to 100 years or more.

Figure 6: Evolution of building stock between 2010 and 2050



KEY POINT: more than 50% of the current global building stock will still be standing in 2050; in OECD member countries, that figure is closer to 75% or higher.

In developing countries, by contrast, some buildings tend to have shorter life spans, of 25 years to 35 years, and the rate of growth of the overall building stock is rapid. Consequently, policies should first focus on improving the energy performance of new buildings, especially with respect to their heating and cooling loads. Building codes that reduce heating and cooling loads, through better design and better building envelope performance, need to be implemented rapidly to avoid the continued construction of buildings with high energy consumption that will be standing for decades to come.

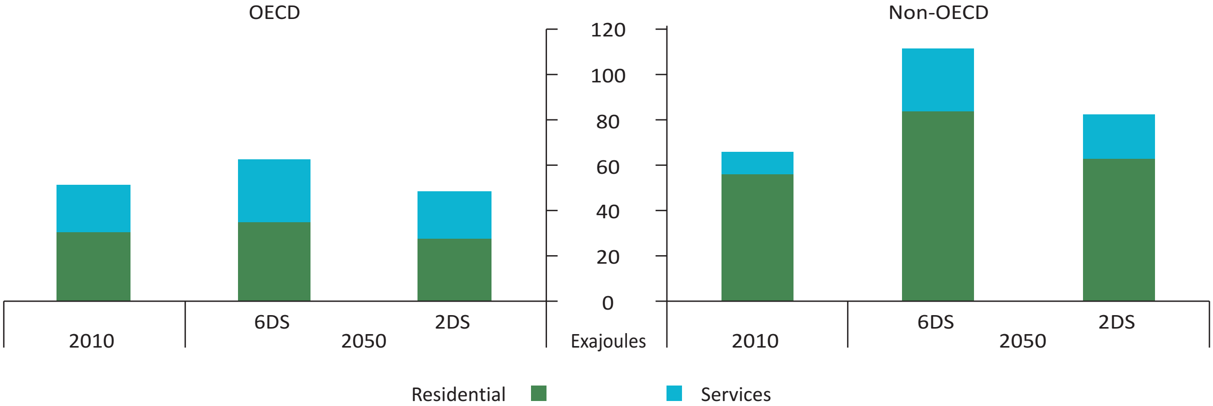
The basis for the scenarios in this roadmap is that the entire building stock would be refurbished within 65 years, with deep renovation between 35 years and 45 years after a building is constructed. While retrofit rates are the same in both the 6DS and the 2DS,[12] the 2DS assumes that efficiency will be the main component of the retrofit. If no action is taken to improve energy efficiency in the buildings sector, energy demand is expected to rise by 50% by 2050, when the global population is expected to have grown by 2.5 billion people. This increase would be driven by rapid growth in the number of households, the floor area of residential and services buildings, ownership rates for existing electricity-consuming devices and demand for new products.

Energy consumption in the buildings sector is no longer dominated by OECD member countries, whose share of total energy consumption fell from 57% in 1971 to 44% in 2010. However, OECD member countries still account for the largest consumption of modern commercial fuels, with much of the energy consumed in non-OECD countries still derived from traditional biomass. When combustible renewables (e.g. biomass) and waste are excluded, OECD regions accounted for around 60% of total energy consumption in buildings in 2010.

In 2010, 70% of energy consumption in the world's buildings came from the residential sector and 30% from service buildings (see Figure 7). These proportions are expected to stay the same until 2050. Residential heating represents the largest share of consumption so it should be a key focus of efforts to save energy. Cooling loads will also increase rapidly in hotter developing countries (by 300% to over 600%), but will still only be responsible for a small share of energy consumption compared with the heating loads in cold climates.

12. These modeling assumptions were established for the IEA *ETP 2012* and have been maintained for consistency with this and recent building publications. Future analysis may consider many more options, including the higher renovation rates suggested by many EU proponents of deep renovation.

Figure 7: Buildings in OECD and non-OECD countries, end-use energy by sector, in 6DS and 2DS



Note: in this roadmap energy and emission savings potential from enhanced daylighting are mentioned, but savings were not included in any modelling results. They are included in the IEA lighting savings estimates found in other IEA publications.

KEY POINT: buildings in non-OECD countries are expected to have large energy increases that could be significantly curtailed within the 2DS.

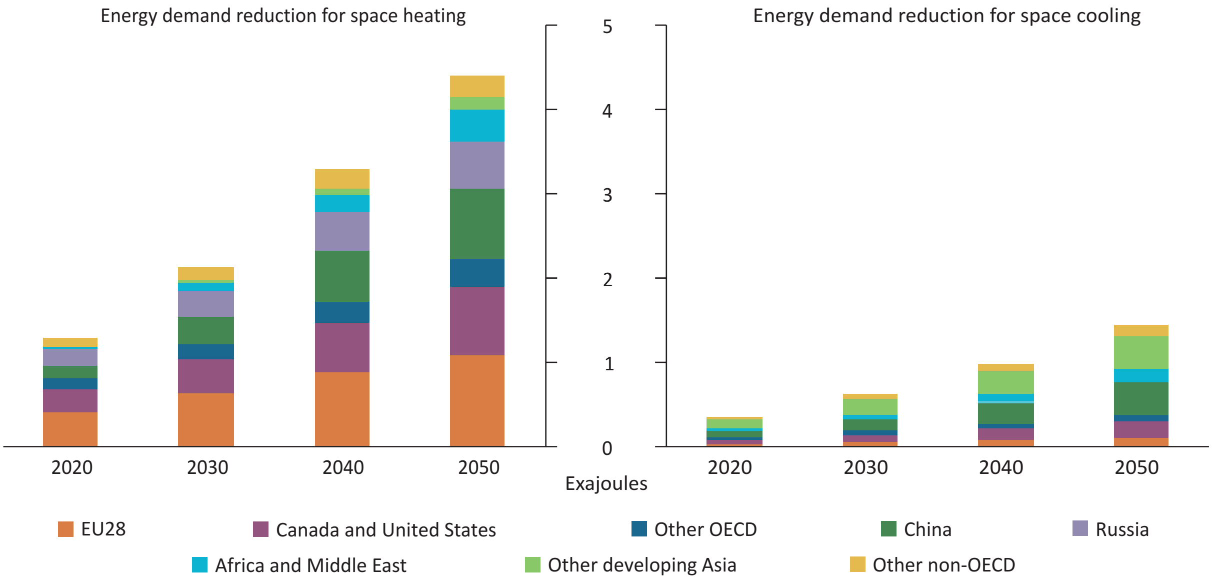
Energy demand and emission reduction potentials

The total heating and cooling energy savings in 2DS, compared with the 6DS, add up to 14.5 exajoules (EJ), with approximately 40% directly attributable to improvements in building envelopes. These improvements will also contribute to a reduction in heating and cooling capacity, as they will allow a downsizing of mechanical equipment.

Over the forecast period of the 2DS scenario, deep renovation will allow heating and cooling load reductions of 50% to 65%. The heating load of new residential buildings in OECD member countries will fall to 25 kilowatt-hours per square metre (kWh/m^2) by 2050 in the 2DS, an improvement of over 40% from today's level. In the services sub-sector, the heating load of new buildings will fall 30% to 25 kWh/m^2 by 2050.

Overall, savings from envelope improvements in the 2DS will amount to 5.8 EJ – 4.3 EJ in residential buildings and 1.5 EJ in services buildings – equivalent to almost 20% of the overall savings in the buildings sector (see Figure 8). Building envelope improvements will play a major role in reducing the consumption of energy for heating in China, the European Union, Russia, Canada and the United States and elsewhere. They will also offer a key way of restraining growth in space-cooling energy consumption in developing countries.

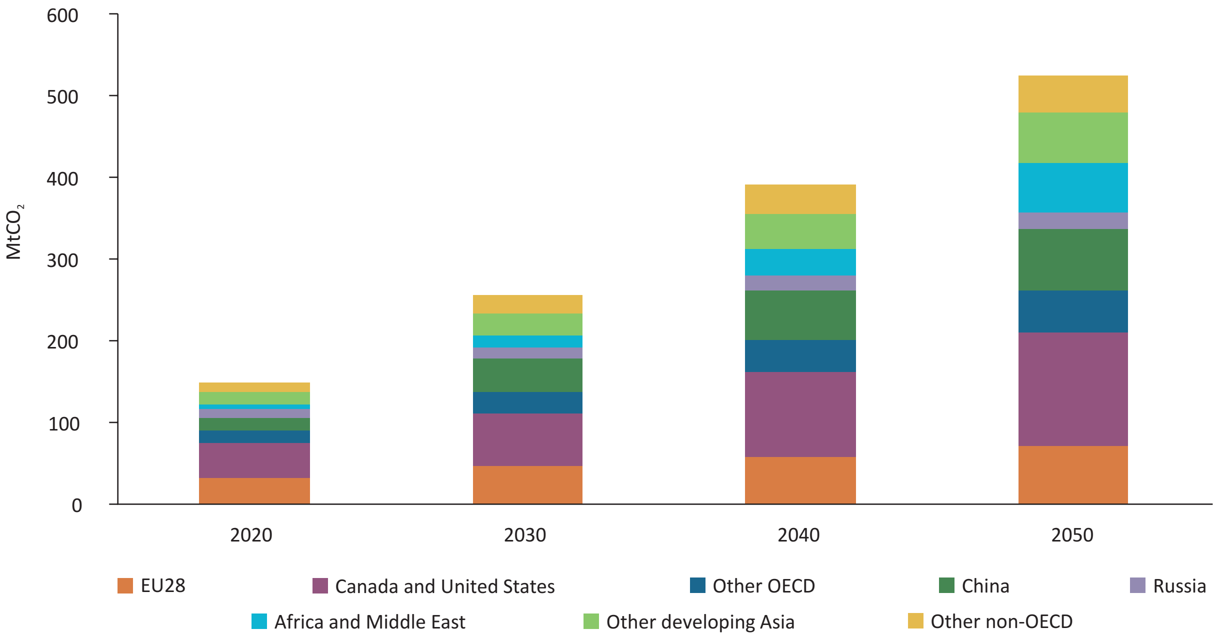
Figure 8: Energy reductions from improvement in building envelopes between the 6DS and 2DS



KEY POINT: building-envelope energy savings under the 2DS are significant, with heating savings around four times higher than cooling savings.

In the 2DS, reductions in direct CO_2 emissions from energy-efficient building envelopes are 525 Mt CO_2 in 2050, including 287 Mt CO_2 from the European Union, China, Canada and the United States (see Figure 9). The United States has the greatest potential to reduce emissions because its buildings use more energy, with a large floor area per capita. China also has large potential for savings due to large growth in construction of new buildings in which improved envelopes can be implemented, but floor area per capita will still be lower than in more developed regions, so potential reductions are not proportional to expected growth in floor area. Aggressive deep renovation of existing buildings, especially in OECD member countries, will also help reduce emissions.

Figure 9: Direct emissions savings from improvement in building envelopes between the 6DS and 2DS, in Mt CO_2



Note: these savings exclude indirect emissions for electricity that are greatest for electricity end-uses (e.g. does not reflect air-conditioning electricity generation benefits).

KEY POINT: direct emissions reductions for building envelope are greatest in large countries and regions with high residential heating loads.

Cost reduction and performance goals

For energy-efficient building envelopes to become standard practice, more work is needed to reduce costs and increase performance so that more cost-effective applications are available to builders and designers. Today, especially in more mature markets, most advanced building envelope alternatives are cost-effective over a long-term investment period but require greater initial capital financing. Reducing "first cost" and increasing annual savings that result in a greater overall improved return on investment will enable greater market uptake of advanced building envelope designs.

Establishing specific cost and performance criteria for the entire world is almost impossible because factors such as climate, occupant behaviour, construction practice and availability of resources vary widely. Key improvement metrics and goals can be established, however, that provide benchmarks for policy makers (see Table 6). For most regions, these criteria will be seen as aggressive, but for several advanced programmes in cold climates where energy prices are high, they may be seen as not stringent enough. Based on local conditions, more stringent criteria can easily be pursued. The core focus of these criteria is to move the world's stock of existing buildings and new construction to much higher levels of performance by 2050.

Table 6: Cost and performance goals for building envelope technologies, 2020-30

Technology	*Market perspectives*	*Performance goals*	*Cost targets*
Typical insulation (widely available, thermal conductivity of > 0.02 W/mK)	Highly competitive market with uniform performance metrics in all regions for existing stock and new construction.	Average U-value walls and roof, cold climate ≤ 0.15 W/m²K; hot climate ≤ 0.35 W/m²K.	LCC neutral or lower at moderate energy prices.
Advanced insulation (e.g. aerogel, VIPs)	Used for very high-performance buildings in cold climates and space-constrained applications.	Thermal conductivity of ≤ 0.015 W/mk.	Material cost less 50%, installed cost competitive with typical insulation.
Air sealing	Widely applied to over 95% of world structures with heating and cooling loads.	Retrofit ≤ 3.0 ACH or 50% reduction; New ≤ 0.5 ACH with mechanical ventilation.	Validation testing reduced by 30% to 60%; 50% lower ACH in existing buildings reduced from USD 24/m² to ≤ USD 10/m².
Reflective surfaces	Applied to new roofing materials and after-market coatings for hot climates and dense urban areas.	Long-lasting SR of ≥ 0.75 for white surfaces, and SR ≥ 0.40 for coloured surfaces.	Additional installed price premiums ≤ USD 10/m².
Windows (double low-e galzing, low-conductive frames)	Minimum for global market.	Whole-window performance, U-value ≤ 1.8 W/m²K.	Price premiums from single-glazed (≤ USD 40/m²), from double clear (≤ USD 5/m²).
Highly insulating windows (e.g. triple-glazed, low-e, and low-conductive frames)	Needed for cold climates for all buildings, and mixed climates for residential.	U-value ≤ 1.1 W/m²K.	Price premiums from double low-e (≤ USD 40/m²).
Energy-plus windows in cold climates (highly insulating and dynamic solar)	Dynamic solar control for most service buildings that have glass to optimise daylight; and highly insulating and dynamic solar control for mixed and cold climates residential.	Whole-window performance, highly insulating U-value ≤ 0.6 W/m²K and variable SHGC 0.08-0.65.	Highly insulating dynamic SHGC price premium from double low-e (≤ USD 120/m²).
Window attachments* (automatic solar control, e.g. exterior solar shades and blinds)	Priority for existing windows but also for alternative option to dynamic glass.	Ability to reduce solar heat gain almost to zero, but preferred options would have daylight features (e.g. SHGC 0.05 to 0.5) to prevent increased lighting energy.	USD 70/m² (not including control systems that can be expensive if not used for other building systems).
Window attachments (highly insulating, e.g. cellular shades, low-e films)	Predominately retrofit market but also applicable to new zero-energy buildings.	Installed with existing windows, total performance, U-values ≤ 1.1 W/m²K.	USD 40/m².

Notes: VIP = vacuum-insulated panel. This table is based on IEA analysis, with data taken predominantly from envelope roadmap workshop presentations. Targets have not been vetted by all regions and will vary considerably. These targets are provided as a reference or starting points so regions and countries can develop implementation plans tailored to local markets, climates and conditions.

* For more information, see Annex A and www.efficientwindowcoverings.org.

Additional investment costs and financing needs

The transition towards more energy-efficient building envelopes will require rapid deployment of a large range of advanced building envelope technologies. Many of these technologies are significantly more expensive and will require higher upfront investment costs. In the 2DS, an estimated USD 3.7 trillion of additional envelope investments will be needed between 2015 and 2050, to retrofit existing buildings and to construct more energy-efficient envelopes in new buildings.

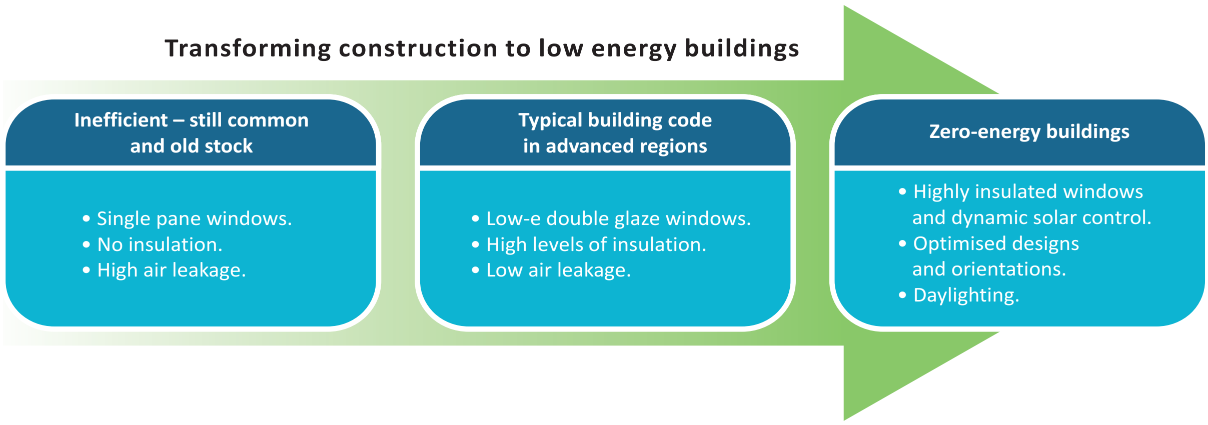
In OECD member countries, the largest share of additional investment will need to be made before 2030 as the existing building stock requires significant retrofitting. Investment in more energy-efficient building envelopes accounts for 35% of the USD 10.8 trillion needed in additional investment for the world to achieve significant energy and emissions reduction in the buildings sector from 2015 through 2050. Although these costs are substantial, they will be offset by significant fuel savings for heating and cooling. In the 2DS, energy saved annually from the transition to more energy-efficient building envelopes will reach an estimated 5.8 EJ in 2050, valued at approximately USD 125 billion (IEA, 2013a).

Technology development: Actions and milestones

The overall goal of this roadmap is to show how policy makers and the building industry can promote and adopt advanced practices that result in widespread construction of low-energy or zero-energy buildings. The transition to efficient building envelopes can be understood in terms of three distinct stages of technological evolution (see Figure 10). The first would be a very basic building with a poorly performing building envelope, single-glazed clear windows, no insulation and high rates of air leakage. The second would be a typical code-compliant building being constructed today in Canada, Northern European or the northern United States,[13] that has double-glazed, low-e windows and high levels of insulation, and is sealed fairly well. The third stage is represented by buildings of the future with greater passive design, highly insulated windows and passive heating contributions, along with advanced facades that harvest natural daylight while reducing cooling loads. Such buildings will probably incorporate solar thermal systems.

13. This type of construction is occurring in many regions of the world, but mostly represents a limited market given the global scale of building construction.

Figure 10: Progression of building envelopes from old stock to future technology



KEY POINT: the world needs to shift from very old buildings to modern buildings, and then to low-energy or zero-energy buildings.

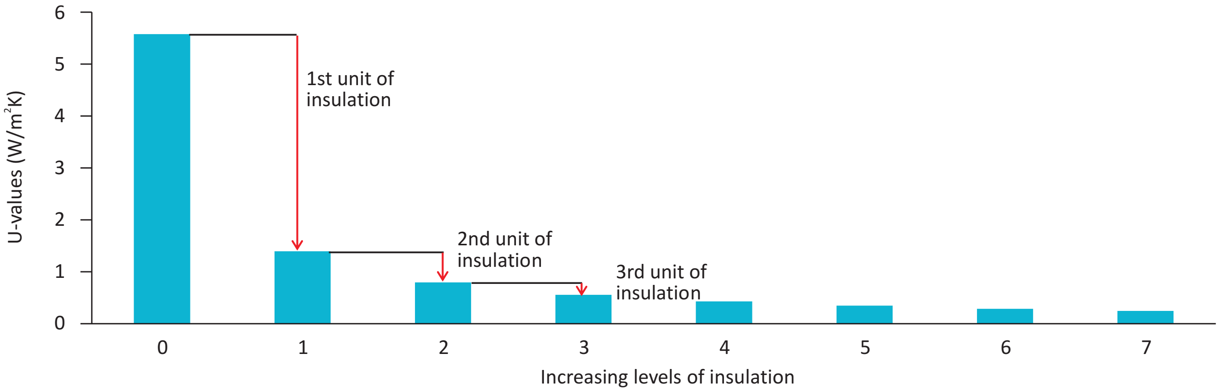
Zero-energy buildings, which today only represent a niche market in some countries, should become typical around the world. To achieve this, product and market development is needed to increase the availability of affordable advanced building materials. New technology needs to be developed, supported by performance metrics, and advanced building components need to be adapted so that they are viable in new markets.

Many building-material manufacturers spend less of their revenue on research than other sectors of the economy, because of the commodity-based nature of building materials and products, the long cycle to change to new technology, and relatively low profit margins. Therefore, governments should sponsor R&D that will reduce the risk of investing in cutting-edge technologies. Government R&D priorities should be determined in consultation with private sector industry leaders; an industry perspective can increase the chances that government-sponsored R&D innovations will ultimately make their way into commercial products.

Insulation

Existing buildings in cold climates with little or no insulation offer the greatest potential for saving energy by installing insulation. There is also significant potential for saving energy in developing countries, where insulation is often not installed. Adding to existing insulation has a much smaller effect on energy savings than installing insulation initially (see Figure 11) (IEA, 2013a).

Figure 11: Representation of diminishing returns of extra insulation



Source: IEA (2013a), *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*, OECD/IEA, Paris.

KEY POINT: it is critical that all buildings be insulated to optimal levels using LCC assessment. If not, future upgrades may be prohibitively expensive.

The Passivhaus programme has spread around the world since it was initiated in Germany in 1990. It has very stringent envelope requirements to ensure that the building is comfortable regardless of the climate. These buildings require very little energy for cooling and heating because they have extremely high levels of insulation and very low infiltration. The Passivhaus specifications established in 1990 (less than 15 kWh/m^2 for heating, cooling and ventilation per year) are still equivalent to the best performance being achieved today (PHI, 2013). The Passivhaus programme has driven the spread of zero-energy buildings, but some researchers believe that the additional material resources required to achieve such high levels of insulation are unsustainable for the entire building stock in cold regions (Rovers, 2013). Other studies have found such high levels of insulation to be economically cost-effective in several EU countries (BPIE, 2013).

It is a fundamental principle to insulate to the greatest level that is justified, based on LCCs, when constructing a building or when retrofitting an existing building without any insulation. The marginal cost of installing additional insulation is generally low. If a minimal amount of insulation is installed, it may have an immediate efficiency improvement, but large savings will not be realised and future retrofits are unlikely to be cost-effective (IEA, 2013a). Higher levels of insulation can be justified during new construction or deep renovation by considering full-system impacts that allow for downsizing of mechanical equipment in accordance with LCC assessment. The IEA is providing recommendations for minimal levels of insulation based on climate (see Table 6), but decisions on specific applications are best made at the local and regional level, while taking into account a variety of factors, including fire and safety standards, material and labour costs. A detailed discussion of optimal insulation is provided in the Policy and Implementation section and in Annex B.

The insulation market is highly mature and global material suppliers are actively increasing sales in developing markets. While the majority of suppliers are responsible and provide accurate information about product performance, including building application advantages and disadvantages, there are some instances of overly assertive companies marketing materials that may not be in the best interest of consumers. Therefore, it is best for independent bodies or government agencies to provide unbiased information about product energy performance, appropriate applications, and to ensure that appropriate product material certifications are available. Building-material thermal energy performance is specified by performance metrics such as U-values, R-values and thermal conductivity (λ) (see Annex A).

Performance research to foster material development

To enable one type of insulation to be compared with another, it is vital to have accurate test protocols, ratings and performance declarations for the energy performance of different materials. The performance of insulation types may vary according to types of applications, climates and the aging of materials. For example, when loose-fill fibreglass insulation is applied to thick depths in attics in very cold climates, a thermal siphon effect will occur and performance will be reduced. Some time ago, this phenomenon was documented and the resultant test and rating adjusted to reflect the true performance of the product in that application. Similarly, newly formed foam insulations usually have reduced performance after several years due to air diffusing into cell structures that reduce blowing agent concentrations. New test protocols have been developed that provide an aged rating that will reflect the true life of the product's performance. For example, one protocol has a mechanism to accelerate aged test ratings by measuring thin samples and then extrapolating data. This approach is intended to spur innovation by reducing the burden on manufacturers to test materials, while still ensuring an accurate test metric.

Three core activities related to performance research are needed to promote high-performance buildings globally:

- Promulgation of accurate and not overly burdensome (scalable, affordable and repeatable) test mechanisms globally so that designers, builders and building code officials can ensure that appropriate insulation materials are being specified and installed in buildings.
- Harmonisation of any major differences between test mechanisms in different regions of the world to foster commerce and to reduce barriers to higher efficient envelope adoption.
- Collaboration on core technical analysis, performance research and proposed test protocols before initiating standard organisation activities, such as the ISO and ASTM International standards.

There is currently strong interest in establishing improved performance metrics and ratings for high-performance insulation. Core technologies that are of interest include vacuum-insulated panels and aerogels. The IEA Implementing Agreement on Energy in Buildings and Communities recently initiated a new annex that is expected to address the need for improved performance metrics, along with additional analysis of benefits and applications where high-performance insulation can contribute to more efficient building systems. The annex is called Long-term Performance of Super-Insulation in Building Components and Systems, and results of this project are expected to be used to improve existing insulation standards (EBC, 2013).

R&D

Advanced insulation materials are beginning to enter the market in various niche applications. Cost is a primary barrier to greater application and in some cases there are also concerns about long-term performance. There also is a lack of knowledge about innovative applications, and detailed design guidelines are limited. Greater effort is needed to highlight applications that are viable in market terms, such as locations in buildings with space limitations that will usually require a combination of high thermal performance insulation with lower material cost. Also, a systems perspective can allow for high-performance insulations to reduce labour costs, especially for building renovations (e.g. interior wall insulation in historic buildings), so cost-effectiveness does not have to be limited just to the material cost of a system. High-performance

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Establish performance metrics in developing markets.	2014-25	All.
Harmonisation of established test protocols.	2014-20	All.
Development of new test procedures for advanced products such as vacuum-insulated panels, aerogels and phase change material.	2014-20	All.

Note: "all" refers to trade associations, manufacturers, researchers, non-government organisations, academia, governments and other interested parties.

insulation should offer the greatest value in applications with space constraints and in the existing building stock.

Another concern, raised at the Russia Roadmap Workshop, is that advanced foam insulation can be difficult to install at lower ambient temperatures. At lower temperatures, the adhesion of spray foams may be reduced and annual construction timeframes can be short in severely cold climates. Temporary shelters can be built to maintain warmer temperatures in the construction area, but developing lower-temperature formulations that would improve adhesion and air sealing capability would be highly beneficial to cold climate applications, which are among the most important for advanced insulation.

There also has been interest in developing a new class of foam insulation, generally referred to as nano cell foams, with cell structures that may be 100 times smaller than current formulations and include new radiation-absorbing materials. If successful, they could improve insulating performance by around 25%, reduce material usage by over 60% (most of the structure is air), and be manufactured at the same or lower cost. R&D projects have been funded in the European Union and the United States, but possible market introduction is still uncertain (US DOE, 2012).[14]

14. Several presentations such as DOW Corporation and Industrial Science and Technology Network, Inc.

This roadmap recommends the following actions:	*Milestone timeline*	*Stakeholder*
Develop advanced foam insulations with high performance, lower cost, less petroleum fuel stocks, and greater applications and adhesion in cold climates.	2015-25	Manufacturers and researchers.
Develop advanced aerogel insulation that has high performance, lower cost, and offers greater benefits for space constraint applications.	2015-25	Manufacturers and researchers.
Develop high-performing vacuum panels with long life and lower cost that can be used in building systems to achieve very high system performance, such as embedded in EIFS systems.	2015-25	Manufacturers, builders, researchers.
Develop low-cost phase change material as separate material, integrated with varying types of insulating materials.	2015-25	Manufacturers, builders.
Develop advanced wall, roof, and foundation* systems in collaboration with whole building programmes.	2015-25	Manufacturers, builders, researchers.

Note: EIFS = exterior insulation finishing systems.

* See Annex A for more information regarding foundation and floor systems.

Air sealing

For the vast majority of buildings that require heating or cooling, tight air sealing with mechanical ventilation will result in large energy savings. While air-sealing methods during new construction are widely available, validation testing can still be expensive, especially in large buildings, so more work is needed to reduce its cost. Many approaches may be appropriate: validation testing could be conducted on every building, or could be implemented with a workmanship performance certification programme that requires verification and sampling criteria. Some cost-effective validated process is essential, however.

The most common way of measuring air leakage, a blower door test (see Figure 12), usually at 50 Pa (pressure difference across building envelope), is widely used on residential and small service-sector buildings. This test can be expensive, however, especially in developing economies, and requires sophisticated analysis. Large service-sector buildings can be tested using larger equipment and more sophisticated methods, in accordance with standards such as ISO 9972. Air-leakage requirements can be confusing because they can also be specified in a leakage rate per square metre of building surface area, or at higher pressures such as 75 Pa, especially for large buildings. This can make it difficult to compare one programme requirement with another.

Retrofitting with air sealing can be much more complex. Many building interfaces ("joints") that need to be sealed are not readily accessible, so improved techniques are needed to enable tighter air sealing during renovation. Furthermore, in many cases air sealing is highly labour-intensive. Some air-sealing solutions have been proposed that will be less time-consuming, easier and more effective. One example is an aerosol approach that has been commercialised for duct work. R&D is under way to apply it to building envelopes, but more research is needed to commercialise this possibly solution (WCEC, 2013).

Fresh air ventilation is vital to maintain air quality, but allowing high rates of air leakage does not satisfy ventilation requirements because air leakage is uncontrolled and often will not be delivered to the areas where it is required. Economisers are sometimes used, which condition incoming ventilation air with available energy from exhaust air to conserve energy. Many advanced concepts for reducing air ventilation energy consumption in new buildings include innovative designs such as large open areas that act as a ventilation chimney, or double-cavity wall systems to preheat incoming air. Such solutions can optimise whole-building design.

Figure 12: Blower door tests are the most common method to measure air leakage

Source: ORNL (Oak Ridge National Labotory) (2013), Building Technologies Research and Integration Center, www.ornl.gov/sci/ees/etsd/btric/.

KEY POINT: verifying air leakage is vital but can be expensive and a burden for builders, especially in less mature markets.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Establish improved methods of air-sealing test validation in all buildings. Implement air sealing validation as part of retrofit and audit programmes for a specified period of times such as 10 years during building energy performance certification.*	2014-20	Builders, researchers, air sealing companies and standard organisations.
Develop improved techniques to seal existing buildings that will result in more cost-effective solutions.	2014-25	Researchers, builders, air sealing companies, and government.

* Air leakage can change over time due to materials aging, weather events, and a variety of other building system operations. A specified period of time for air leakage validation certification would reduce test burden for any subsequent building energy performance certification performed prior to expiration of the air leakage certification.

Windows

The energy efficiency of windows is highly dependent upon the design of the whole window, including whether it is fixed or can open and close to allow natural ventilation ("operable" windows). Window elements include framing materials, glazings, coatings, spacers between panes of glass and low thermal conductivity inert gases[15] to reduce heat transfer within cavities, thermal breaks and operating hardware.

The complex technical characteristics of windows are simplified for policy makers and consumers through the use of window rating programmes, which specify methods of deriving U-values and SHGC for the entire window. In many regions of the world it is still common for windows to be specified by glass characteristics rather than for the entire window system. Since the U-value of the glass is better than that of the frame, this leads to an overestimation of window performance. It is therefore important to specify whole-window performance to ensure the true energy characteristics are considered. Standard mechanisms are also used to test other factors, such as air leakage and visible light transmission, and are important for whole-building energy performance.

A core technology used in higher-performing windows is a low-e coating, which can be applied to glass and to thin films such as polyester. These films can be suspended between panes of glass to create multiple convection cavities, or as an after-market product that can be applied directly to the glass. When low-e coatings are widely available as a commodity technology in a mature market, they can cost as little as USD 2.50/m^2 to manufacture and offer energy savings that can pay back their cost in only a couple of years.

Technological solutions more advanced than double-glazed, low-e windows can be less cost-effective because additional energy savings are lower. Triple-glazed, low-e, low-conductive frame windows are cost-effective in cold regions with high energy costs. Price premium goals above typical code-compliant windows (double-glazed, low-e) for highly insulating windows in regions with moderate energy costs are USD 20/m^2 to USD 60/m^2, but price premiums for currently available products are often much higher. It is vital to describe the full performance benefits of window systems to establish a starting point for cost targets for specific countries and regions.

Performance research to foster material development

Window performance metrics are used by design simulation software to optimise the contribution of new windows to whole-building energy efficiency during renovation or new construction. It is crucial to establish performance metrics in all regions of the world to ensure that each economy adopts the window products that are most efficient in its climates and energy markets. Establishing performance metrics for a variety of window improvement or retrofit products is also critical to enable informed consumer choice, and because it will not be cost-effective to replace many existing windows unless a major building renovation occurs. If window replacement is not possible, low-e storm or interior panels, insulated shades and exterior shading offer significant energy benefits.

Window energy performance is complex but the hard work of many global experts has made it possible for policies to specify performance if a rating programme has been established. Historically, thermal transmittance or U-value ratings were tested in a sophisticated test chamber called a "hot box", which functions as a calorimeter and requires full-scale prototypes to be built and tested. Today, window performance is simulated with sophisticated computer tools in accordance with ISO standards. These tools take into account heat transfer of framing materials and spacer materials, geometry, inert gas fills, shading materials, and glazing characteristics (see Box 4). The United States LBNL has established an international glazing database. It requires measurements in accordance with specifications and spectrophotometers that characterise optical properties, including surface emissivities. These properties are also used by simulation programmes to calculate whole-window (frame, spacer and glass) U-values and SHGC. The database currently includes glazing systems from four continents, and the data are peer-reviewed. This database goes beyond glass and includes window films that have been applied to standard glass samples prior to testing.

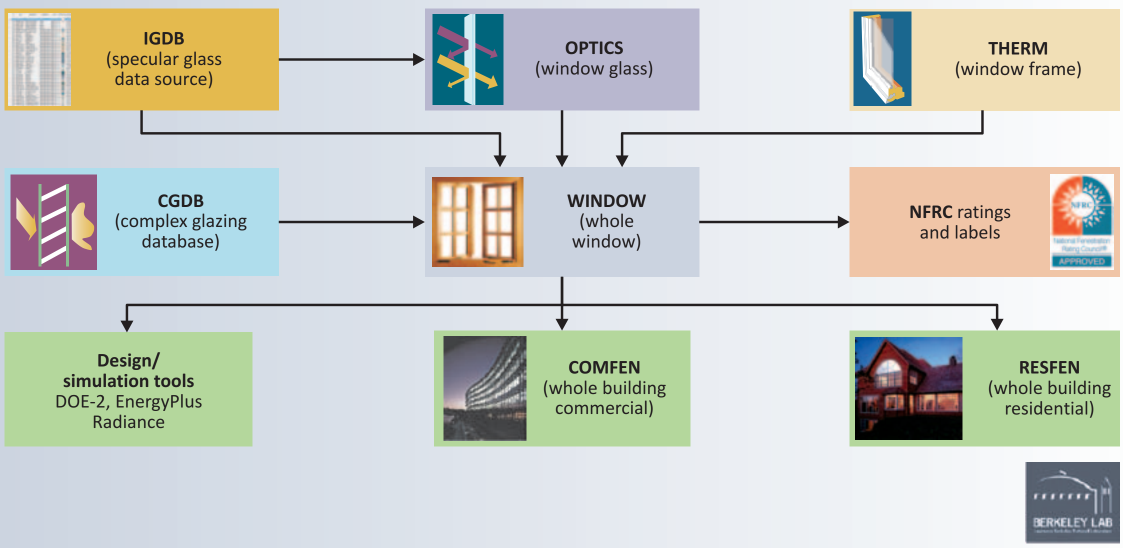
15. Argon gas is commonly used and is affordable. Krypton gas performs better but is expensive and generally not cost-effective in locations with moderate energy prices. Research is under way to reduce its extraction cost. Different inert gases have different minimum glass glaze gap width for optimal reduction of convection (Selkowitz, 2012).

Box 4: Window rating programmes are crucial for promoting high-performance products

The LBNL maintains a suite of software tools that have been supported by the United States Department of Energy and are free in the public domain (see http://windows.lbl.gov/software/ and Figure 13). These tools provide detailed window U-value and SHGC ratings and also include whole-building (residential and service sector) simulation tools that predict energy performance and savings from upgrading windows to more sophisticated designs. These tools have been developed in accordance with the ISO 15099 standard. An older simulation standard for window systems is ISO 10077. Generally, higher-performing window systems result in a more stringent rating if ISO 15099 is followed. However, for less sophisticated windows such as clear glass, that is not always the case. Thus, there is controversy among scientists, researchers, and manufacturers on ISO standards for window performance (van Dijk, 2003) (Curcija, 2005).

To solve this problem of multiple ISO standards, a new effort to harmonise them was initiated in September 2012 but was tabled in September 2013 (ISO, 2013). The use of multiple standards unnecessarily delays more countries from adopting window testing and rating programmes. Today, Europe has an ISO 10077 programme. Australia, Canada, India, South Africa and the United States have ISO 15099 programmes. China and Japan have programmes that use both ISO standards (Parker G. et al., 2011) (LaFrance, 2011) (Sawachi, 2013).

Figure 13: LBNL suite of software tools to design and rate windows, along with building impacts



Note: ISO 15099 Compliant, http://windows.lbl.gov/software.

Source: LBNL Windows Group; Selkowitz, S. (2012) "LBNL Windows and Daylighting RDD&D DOE MYPP Overview and Enabling Tools for Window Design and Selection," presented at US DOE Window Technology R&D Stakeholder Engagement Workshop, Minneapolis, Minnesota, 28 June.

KEY POINT: windows are difficult to test, but free ISO 15099-compliant software tools can be used to design and rate them for performance metrics such as U-value and SHGC.

The key rationale for window ratings is so decision makers can mandate their use in the form of window labels or performance certificates. The United States has had residential window labels for over 20 years and is beginning to issue window energy performance certificates for the services sector. Several countries have recently made significant progress on window labels including Australia, China and South Africa. In the European Union, many countries have rating systems in place, including France, Portugal and the United Kingdom. A comprehensive study to assess how such a programme could be established throughout the European Union is being undertaken by the European Commission (Ecodesign, 2013).

Multiple label designs exist in the European Union that usually take into account the energy balance for windows in the heating and cooling seasons. This provides an excellent way to show the full energy impact and potential for advanced windows (Cazes, 2011). Since windows can enable buildings to gain energy (more solar heat gained than energy lost in cold climates annually), future labels in the European Union should be scaled to allow for windows that will reach these high levels of performance. Historically, EU appliance and equipment labels were not always scaled with future technology in mind and rescaling of labels has subsequently been controversial (ECEEE, 2013).

The European Union has done significant work on window attachment performance standards. A variety of products including roller shades, awnings, and exterior or interior blinds, using different materials, fabrics and configurations, can be tested and compared in accordance with EN 14500 for solar properties. The results of this standard can be used in whole-building simulation software programs to estimate energy savings. Further work is needed to show thermal transmission or U-value benefits from insulated shades that are attached tightly to existing window systems, or from other attachments that offer improved thermal performance. It is important to consider that the benefits of such window attachments can only be realised if the attachments are properly installed and used. Therefore, performance metrics are also important to ensure that benefits are not exaggerated.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Harmonisation of ISO 15099 and ISO 10077 standards.	2014-18	Manufacturers, researchers.
Develop and promulgate harmonised test protocols for window attachments including insulated blinds, solar shades, insulated shutters, awnings, and products that can reduce energy consumption of windows.	2014-20	All.
Promulgation of test ratings and infrastructure to emerging markets.	2014-25	All.
Window labelling and/or performance certificate establishment and promotion.	2014-20	All.
Long-term energy performance metrics (U-value, SHGC, and air leakage aged values due to thermal cycling) of window systems.	2014-20	Manufacturers, researchers.

Note: "all" refers to manufacturers, researchers, non-governmental organisations, academia, governments and other interested parties.

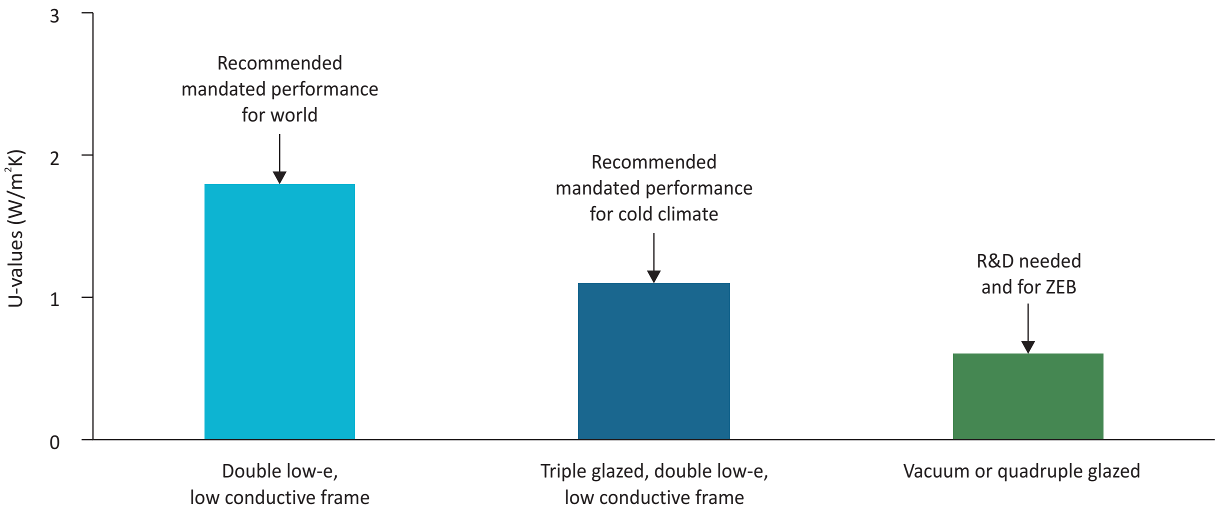
R&D

Most existing windows, as well as many new windows – mostly in hot climates or in developing countries – perform very poorly. They have low thermal resistance and are highly sensitive to solar radiation. Advanced windows, by contrast, offer great potential for passive heating; in some moderate climates, highly insulating windows designed with optimised architectural building features can outperform well-insulated walls. However, to make this possible in colder climates and on existing buildings, more R&D is needed.

There has been significant interest in developing highly insulating windows with greater passive heating benefits. This could be achieved by combining higher fixed solar heat gain on equator-facing orientations and very low U-values, and large overhangs that allow for winter heat gain while avoiding unnecessary heat gain in summer. A more sophisticated approach that would also be applicable to the existing building stock is the incorporation of dynamic solar control. A mature market exists for exterior dynamic shade control that offers significant benefits for all buildings, regardless of their design, including the large stock of existing buildings.

The cost-effectiveness of highly insulating windows depends significantly on heating requirements, so lower U-values can be justified where climates are colder and energy prices are higher. For most cold regions, this would indicate a performance of 1.1 W/m²K or lower. However, if the goal is to achieve zero-energy buildings or "energy-plus" windows (windows that harvest more passive heating than energy losses annually), then a low U-value (0.6 W/m²K or lower) needs to be coupled with a higher SHGC to provide the best energy balance (Arasteh et al., 2006) (Cazes, 2011). The IEA calls for all regions of the world to strive for a minimum window performance of 1.8 W/m²K, with lower levels in cold climates (see Figure 14) (IEA, 2013a).

Figure 14: Typical window U-values performance and IEA recommendations



Note: ZEB = zero-energy building, performance in accordance with ISO 15099.

KEY POINT: low-e, double-glazed window performance levels are recommended for worldwide application, and advanced windows for cold climates.

While windows can be made highly insulating by using multiple panes or glazings, additional layers of glazing beyond two tend to reduce solar heating and make it more difficult to increase passive heating. Multiple-glazed products also tend to be thicker and heavier, which can pose an additional obstacle to installation and adoption. Thus, the greatest technical opportunity for the future is likely to be a vacuum glazing with only two layers of glass. However, there remain many technological barriers to such a solution and many industry representatives believe a more traditional approach to highly insulating windows is more viable. A vacuum glazing combined with highly insulating frames whose edges have minimal thermal bridges, as well as dynamic solar control, can offer the best thermal performance with a wide range of solar control for all climatic conditions. Such a product can also optimise daylighting and minimise cooling in a variety of building applications.

Such advanced window designs could be cost-effective once they reach market maturity with expected price premiums of USD 50/m² to USD 120/m² (see Table 6). However, such maturity will take time and significant market conditioning. Builders and policy makers need to look beyond the specific energy-saving benefits of the window and consider system efficiencies. For example, if much higher-performing windows significantly reduce the costs of HVAC or thermal distribution systems, then these benefits need to be factored in. While a systems perspective is often considered by advanced builders and researchers, it has yet to be implemented on a wide scale or incorporated in building codes.

To achieve market viability for very high-performance window systems, with U-values below 0.6 W/m²K, significant additional R&D will be needed. While several independent efforts are under way globally, international collaboration can accelerate the effort. The potential market for high-performance windows is enormous in cold climates, including northern North America, Northern Europe, Russia, northern China, Japan and Korea. There are additional smaller markets in cold Southern Hemisphere climates, as well as in mixed or moderate climates that can benefit from high-performance windows.

Dynamic solar control with exterior shading is cost-effective from an energy efficiency perspective in regions with higher energy costs and when a systems approach is considered. For example, many designers have chosen to eliminate air-conditioning systems in moderate climates and have installed exterior automated shading. In hot regions with lower energy prices where air conditioning cannot be eliminated, installation based solely on energy efficiency can be harder to justify. Comfort, aesthetics and other preferences tend to be the main reasons for installation. More R&D is needed to reduce total system costs, (e.g. by enabling lower-cost motors, sensors and controls, and increasing ease of installation) and to better quantify benefits so that installation can be increasingly driven by energy efficiency in all global markets.

Additional R&D and manufacturing economies of scale are under way for dynamic glazings that will lead to much lower costs. Dynamic solar control options that are more viable in the market will be essential to encourage a robust market for zero-energy buildings. The next generation of energy-plus window systems can become market viable with more R&D and product integration. It will be vital to integrate dynamic solar control using shading or glazings with advanced-highly insulating windows such as vacuum glazings (see Table 7).

Table 7: BAT for windows and classification based on market readiness and R&D

Key technical attribute	*BAT (market viable)*	*BAT (pre-market viable)*	*Future technology/R&D*
Low U-value	Triple-glazed, dual low-e coating, advanced frames.	Quadruple-glazed, exotic inert gases, aerogel-filled frames.	Vacuum-insulated glass; market-viable, multiple-glazed cavity system (U-value 0.6 or lower).
Variable SHGC	Automated shade control; exterior shading; architectural features.	Dynamic solar control (glazing and shading – still with high price premiums).	Dynamic glazing (SHGC 0.08-0.65).

Note: BAT = best available technology.

Advanced frames and edges

Window edges usually conduct heat, so better edge design can significantly improve energy efficiency, particularly in conventional windows. Edge spacers, used in insulated glass with multiple layers of glazing, are often aluminium with a desiccant and commonly have dual seals, to increase structural performance and reduce moisture permeability. Edge and seal assemblies are critical to high quality glazings; if they are not implemented correctly, this can hinder adoption of insulated glass. Advances include the use of lower conductivity materials such as very thin metals and polymers. For vacuum-insulated glass, edge interfaces offer significant R&D challenges as they likely include advanced metal-to-glass bonding.

Low-conductive frame materials, such as vinyl with improved cavity configurations, can perform significantly better than traditional materials such aluminium. For applications with high structural requirements, such as in the services sub-sector or high-rise, multi-family buildings, low-conductive materials are usually not strong enough. High-performance window framing systems have recently been developed, however. The aluminium framing incorporates state-of-the-art thermal breaks, low-e interior frame coatings and advanced insulation within the frame cavity. When the frame is combined with a triple-glazed, double low-e glass package, it achieves a U-value of 1.1 W/m^{2}K, which is impressive for a window with a high structural rating (Kawneer, 2012). Existing buildings throughout the world have many aluminium window frames without any thermal break, and mostly single- or double-glazed clear glass. These inefficient frames are still being installed in many countries, especially in developing markets.

More effort is needed globally to research, develop, deploy and expand the market for high-performance window technology in all building applications.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Develop more affordable highly insulating windows for cold climates, with U-values ≤ 1.1 W/m^{2}K.	2014-20	Manufacturers, researchers and governments.
Develop advanced highly insulating windows for zero-energy buildings in cold climates with U-values ≤ 0.6 W/m^{2}K.	2014-25	Manufacturers, researchers and governments.
Develop energy-plus windows, with U-values ≤ 0.6 W/m^{2}K and solar heat gain > 0.50 SHGC, or with dynamic solar control.	2014-25	Manufacturers, researchers and governments.
Promote low-conductive frames and double-glazed, low-e glass globally as the minimum energy performance standard for windows (≤ 1.8 W/m^{2}K).	2014-25	All.
Develop more affordable options for retrofitting existing windows, lower-cost low-e window film, low-cost low-e storm or interior panels, highly insulating window frame caps, lower-cost insulated shades, lower-cost automated external shading, etc.	2014-25	All.

Note: U-values in accordance with ISO 15099.

Reflective technology

Reflective roofs, walls, pavements and roadways can bounce solar energy back into space, minimising the heat gained by buildings, cities and the atmosphere. This can improve energy efficiency and comfort in dwellings without cooling equipment. Many countries are aware of the urban heat island effect and have looked at an array of approaches to reduce heat build-up in cities, including natural convection and orienting buildings according to prevailing wind patterns. However, the most direct way to reduce the heat gained from the sun is to reflect it. While the United States has had an active research programme in this area for several decades, other regions are beginning to focus on roof reflectivity. The Cool Roofs and Pavements Working Group, formed as a sub-group of the Global Superior Energy Performance Partnership (GSEP) at the second Clean Energy Ministerial in 2011, is addressing this issue, and several countries have participated and shown interest, including

Brazil, China, India, Japan, Mexico and the United States (GSEP, 2013). The group is focusing on product performance metrics and promoting more affordable products with improved reflectivity that resists aging.

Performance research to foster material development

The Cool Roof Rating Council in the United States and the EU Cool Roof Council promote cool roofs while offering rating protocols that show aged performance after samples have been exposed to environmental conditions. The aging mechanisms include ultraviolet (UV) light degradation, thermal cycling, biological growth and particulate accumulation. The samples are generally exposed for three years to simulate real world performance since it is expected that the majority of degradation occurs within three years, after which further reflectivity reduction is much slower.

While some building codes and organisations that offer incentives for cool roofs allow for provisional ratings prior to the completion of three-year aged tests, the overall requirement for aged ratings is seen as a barrier to the introduction of innovative products with superior reflectivity over a long period. In essence, manufacturers are attempting to develop materials that have self-cleaning properties.

The LBNL is collaborating with the Oak Ridge National Laboratory (ORNL) and other partners to develop an accelerated rating simulation test that can predict aged performance in a much shorter timeframe. This would allow for provisional test ratings to be representative of improved performance that is consistent with innovative materials, rather than old-standardised material categories. There is interest in developing such a test protocol to use globally in standardised ratings (see Box 5).

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Establish cool roof aged test ratings to promote introduction of innovative, long-lasting, highly reflective materials.	2014-18	Researchers, manufacturers, and standard organisations.
Establish cool roof building code criteria in appropriate hot climates and in dense urban moderate climates.	2014-25	Building code and government officials, and researchers.
Pursue urban heat island mitigation programmes in appropriate cities, such as in hot locations, or with high densities or poor air quality.	2014-25	City planners, building code officials, and researchers.
Demonstrate benefits of cool roofs and urban heat island mitigation to prevent the need for air conditioners in emerging economies in hot climates.	2014-25	Researchers and governments.

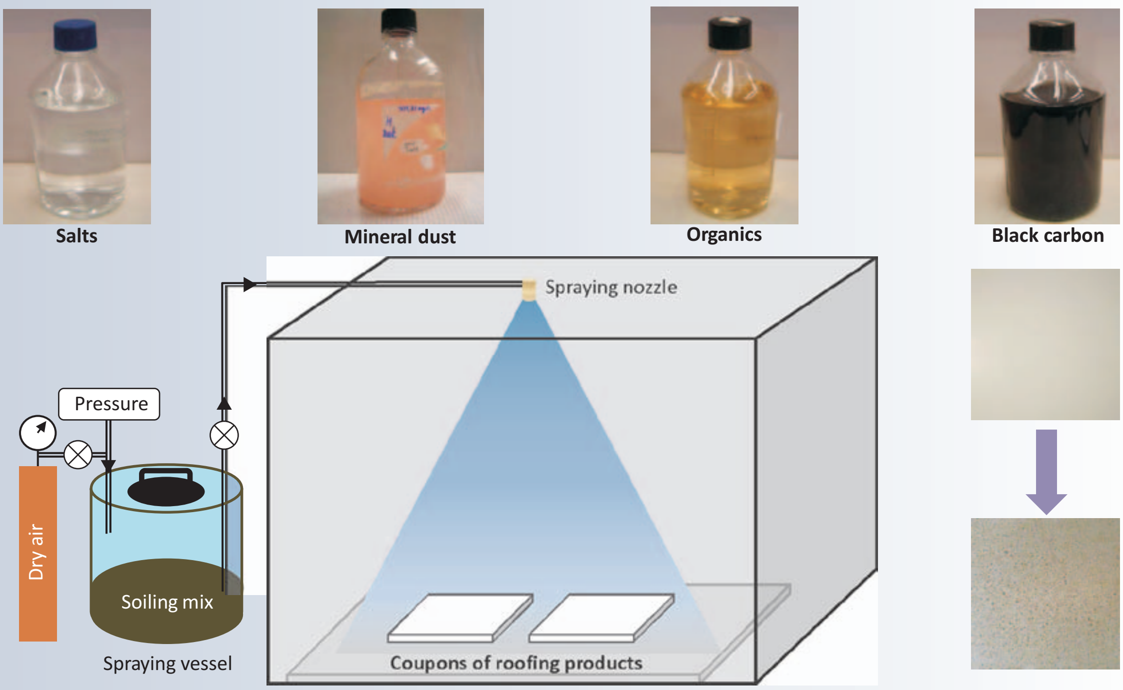
Box 5: Developing accelerated aged rating for cool roofs

The concept of accelerated aged rating was first presented at the International Workshop on Advances in Cool Roof Research, in July 2011, with participation of roofing companies, academia, government and international delegations (http://coolroofs2011.lbl.gov/). Participants agreed to pursue ASTM and ISO standards and to build a network of international partners. Preliminary findings were presented at ASTM Committee D08 in San Diego, United States, in June 2012, and a task group, named D08.20.45 Test Method for Accelerated Aging of Solar Reflectance of Roofing Materials, was initiated.

ISO efforts were initiated in September 2012 in La Rochelle, France, at the annual meeting of TC163 (Thermal Performance and Energy Use in the Built Environment). The effort includes collaboration with the EU 7th Framework programme Cool Coverings, led by a Spanish manufacturer, and researchers in Brazil (University of São Paulo) and Italy (Politecnico de Milano). Researchers in China and India are expected to join the collaboration soon (GSEP, 2013).

The initial simulation test apparatus includes a variety of soiling compounds and environmental treatment processes, exposing samples to heat and humidity. The goal is to achieve aged test ratings in less than six months, and possibly in only a few weeks (see Figure 15).

Figure 15: Simulation test apparatus to predict accelerated aged cool roof ratings



Source: LBNL Heat Island Group, Sleiman, M., T. Kirchstetter, H. Destaillats, R. Levinson, P. Berdahl and H. Akbari (2013), "Mixture and method for simulating soiling and weathering of surfaces", *Patent Application Publication: US 20130287966 A1*, October.

KEY POINT: adopting accelerated aged ratings globally will expedite market introduction of innovative products while reducing barriers to adoption.

R&D

There is a need for lower-cost, durable, reflective roof technology for emerging markets in hot climates. Very low quality coatings have been used in some climates for a long time but they are less effective and require annual applications. Developing affordable, long-lasting cool roofing solutions will enable greater market saturation of reflective technology and lead to continued energy savings. In very humid locations or areas with high levels of atmospheric particulates from burning fossil fuel and biomass, aged performance is critical because roof reflectivity can degrade very quickly.

This roadmap recommends the following actions:	*Milestone timeline*	*Stakeholder*
Development of affordable, long-lasting roof coatings for the existing roofing market.	2014-20	Researchers, manufacturers and governments.
Development of improved roofing materials that offer longer-lasting reflectivity at more affordable prices.	2014-25	Researchers, manufacturers, and governments.

Advanced roofing systems

There are two predominant roof geometries: pitched (sloped) roofs and flat or low-sloped roofs.[16] Most pitched roofs have an attic space that allows for buffering of the thermal impacts of roofs. In some countries this space is used to install mechanical equipment; this can be a problem where the mechanical equipment is in unconditioned space that can be extremely hot in summer and cold in winter.[17] Sloped roofs with cathedral ceilings (pitched roofs without attics that are open to the living space) are probably the biggest challenge for insulation, because the primary location for insulation is within the depth of the structural members, although higher-performance foam insulation (interior side) and above-deck insulation boards are viable solutions to improve performance. Pitched roofs are most common in locations with significant snow loads. Flat roofs are predominant on large services buildings and many urban buildings.

Radiant barriers (with low-emissivity surfaces) on the underside of roof decks can help in both hot and cold climates, although they are generally more cost-effective in hot climates for cooling benefits. It is important that they not be installed on the floor of an attic where they will accumulate dust and no longer be effective.

16. Technical practitioners use the term low-sloped because even flat roofs have a very small pitch to shed water.

17. This is predominately an issue for residential buildings in the United States, but similar applications exist for plenums – air spaces – under flat roofs in the service sector globally.

Integrated advanced roofing designs[18] have been developed by researchers at ORNL using above-deck ventilation, insulation and radiant barriers that demonstrated a reduction of over 87% in peak heat flow through the roof surface, compared with conventional dark asphalt shingles fastened directly to the roof deck. Expected energy usage is estimated 50% less than typical practice (Desjarlais et al., 2010). ORNL has expressed interest in combining the features of a semi-conditioned attic – insulated on the roof plane and air-sealed on the floor – with the above-deck features to develop total optimal performance.

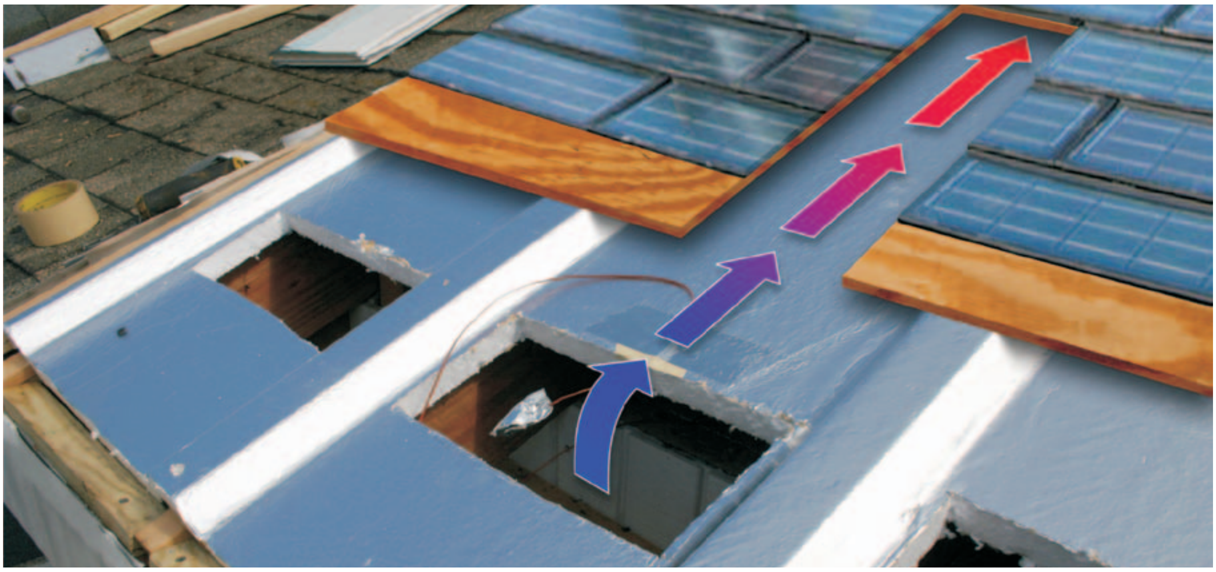
Roof integration with PV

With the promotion of buildings that consume little or no energy, roofs are becoming a typical location for the installation of photovoltaic (PV) cells. Conventional PV panels are installed on rack mount systems and can help improve the thermal performance of the roof by offering shading, while also producing electricity. Most are installed well above the roof surface, with natural ventilation below the solar panel to provide heat rejection of the absorbed energy and maintain PV efficiency. The challenge is to ensure that roof penetrations do not cause water leaks. It is also vital to ensure that 30-year PV systems are not installed on older roofs that may have fewer years of useful life remaining. Guidelines for appropriate and sustainable building practices should be promoted.

18. See technical features shown in Figure 16 along with BIPV.

The installation of PV panels can be complex and adds significantly to the cost of solar energy systems. There has been significant interest and funding to develop BIPV systems. These systems use thin films that cost much less but generally are also less efficient. The PV cell is encapsulated within a protective, flexible layer that serves as the roofing surface. The intent is to install these systems over the majority of the roof area, using a much easier installation technique, to derive a more cost-effective PV system. However, there are two possible negative impacts of this approach: first, the PV cell will not reject its heat as well and may have lower output due to higher cell temperatures; second, if the roof is not well-insulated, the absorbed energy will flow into the building and increase cooling loads. The latter issue can be fairly easily mitigated with proper insulation levels, and research efforts are under way to keep BIPV systems cooler while operating. The proposed approach by ORNL may offer superior roof performance while improving BIPV performance on both new and retrofit applications (see Figure 16).

Figure 16: Integration of PV with advanced roofing systems for optimal performance



Source: figure courtesy of ORNL in LaFrance, M., (2012), "Overview of DOE Envelope R&D", presented at US DOE Building Envelope R&D Program Stakeholder Engagement Workshop, San Antonio, Texas, 26 June.

KEY POINT: BIPV systems may offer greater economic benefit when total installed costs are considered but need to be integrated with advanced roofing techniques.

Research is needed to develop advanced roofing systems that offer the greatest energy efficiency while enabling PV installation. BIPV may offer a better market opportunity where entire roof surfaces are covered and this approach may also be more appealing aesthetically. PV can also be installed on façades, but PV output is reduced on vertical surfaces. PV can be installed on angled façade surfaces, such as on top of fixed awnings that also provide superior window shading.

Integrating solar thermal collectors

There is significant interest in using large areas of façades and roofs as part of integrated solar collectors.[19] Collectors on building surfaces may harvest less energy than traditional solar

19. The IEA Technology Roadmap *Solar Heating and Cooling* provides the core technical elements of solar collector technology (IEA, 2012c).

collectors per unit area, but since the systems serve dual purposes of a building material (cladding and roofing) and a collector, they may offer superior economics. These systems are generally only applicable to new construction and major refurbishment but could become a market-viable alternative option for advanced building envelopes that incorporate solar thermal energy. These systems would also incorporate advanced insulation and air sealing so that they also provide high levels of building energy efficiency. For example, the above proposed design for advanced roofing and BIPV could also harvest solar thermal energy.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Optimised roof performance with features such as above-deck ventilation, radiant barriers, insulation and phase change material.	2014-20	Researchers, roof material manufacturers, and government.
Improved BIPV installation that avoids increased roof energy impact while reducing BIPV operating temperatures.	2014-25	Researchers, PV and roof material manufacturers.
Establish PV guidelines for roof applications to ensure full-life performance of PV.	2014-18	Researchers, manufacturers, trade associations, and building code officials.
Integrated building envelope solar thermal collectors that provide improved economics during new construction or major building refurbishment.	2014-25	Researchers, material manufacturers, and government.

Envelope performance research assessment

In consultation with many experts representing six continents, the IEA conducted an assessment of research on building envelope performance, which covered infrastructure (methodologies and mechanisms) for testing, rating and labelling energy-efficient building materials (see Table 8). For each country or region, infrastructure was classed as "mature" (usually mandatory), "established" (usually voluntary) or "initiating" the process. While it is difficult to fully assess the current situation, these metrics are intended to highlight areas that need improvement. (The above recommendations for new and improved performance metrics go beyond the current assessment and are needed in every region.)

Table 8: Building envelope material test, rating and labelling assessment

Level of test and labelling infrastructure	*ASEAN*	*Brazil*	*China*	*European Union*	*India*	*Japan/ Korea*	*Mexico*	*Middle East*	*Australia/ New Zealand*	*Russia*	*South Africa*	*United States/ Canada*
Window test protocols	●	▲	●	★	▲	●	●	▲	●	★	●	★
Window labels	●	▲	▲	▲	▲	●		▲	●	▲		●
Window attachment test protocols	●			★		▲		●	▲	▲	▲	▲
Window attachment labels	▲			●		▲		●		▲		▲
Insulation test protocols and certificates	●	▲	●	★	●	●	●	●	★	★	●	★
Air sealing validation testing	●			★	▲	●		●	▲	▲		●
Cool roofs aged ratings and certificates	▲	▲	▲	▲	▲	▲	▲				▲	★
Moisture evaluation of envelopes			▲	★	▲	●		▲	▲			★

★ Mature ● Established ▲ Initiating

Notes: a country or region where test mechanisms are in place and the overwhelming majority of products are being shipped with a performance label or certificate will get the highest mark. A country or region where the test mechanism may be in place but labels or certificates are seldom found on products and inquiries are needed to obtain performance criteria would be assessed as established. A region or country actively working on a programme that is not yet fully functioning would be assessed as “initiating”. Where spaces have been left blank, the process has not been initiated.

Policy and implementation: Actions and milestones

Market barriers preventing the adoption of energy-efficient buildings or building materials can be real or perceived. As well as simple failures such as a lack of knowledge about alternative options, they can include concerns about the performance, expected energy savings, reliability and service life of a new product. Some new construction materials and approaches (e.g. SIPs) oblige builders to completely change the way a building is erected. Barriers in emerging markets can include import tariffs, a lack of product performance metrics and a lack of installation procedures. In many countries there are also institutional barriers such as lack of government oversight or interest, lack of appropriate market signals to promote efficiency, and lack of basic infrastructure.

It is critical to understand local market barriers so that appropriate policies can be formulated, particularly when implementing a policy that may have been highly effective elsewhere (see Table 9). A typical, widely used policy can fail if it does not address specific market conditions, or regional construction practices and preferences. For a comprehensive discussion of building-related policies, please see the recent IEA publication *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013a).

Table 9: Technology maturity phase, market barriers and policies for buildings

	R&D		***Voluntary demonstrations, deployment, diffusion***			***Mandatory***
Technical maturity	Basic and applied research.	Field evaluation.	Initial market introduction.	Limited sales.	Mature market.	Standards and building codes.
Barriers	Lack of private-sector investment.	Safety codes, consumer expectations, and integration concerns.	High cost, lack of information, reliability, higher risk.	Reluctance by policy decision makers, high cost, etc.	Entry into mainstream marketing programmes, split incentives.	Political will of governing body, sufficient data set to convince.
Policies	Competitive R&D sponsors, collaborative research, technology procurement.	Field studies of prototype, model homes, responsibility for any human health impacts.	Award of excellence, detailed case studies, extended warranties, loan guarantees.	Tax credits, utility incentives, financing, volume purchases.	Distinction labels, modest incentives, financing, education.	Minimum efficiency standards and practices.

To deploy energy-efficient building envelopes widely, several institutional and market barriers need to be overcome. The following core elements should serve as good starting points for policy makers in regions where construction practices do not typically include energy-efficiency strategies.

- **Improve governance**: In many countries, energy efficiency policy is managed by the Ministry of Energy and involves responsibilities such as energy supply, transportation and minimum efficiency standards for building equipment. Often, a separate Ministry of Construction is responsible for building materials, urban development, safety of construction workers, structural safety, fire safety and occupant health. Sometimes energy efficiency falls within the charter of these organisations but due to higher priorities, it may not receive the attention it deserves. It is vital to ensure that a government agency has a clear responsibility for promoting energy-efficient building envelopes so that proactive, mandatory building codes will be possible. For more information, please refer to *Energy Efficiency Governance – Handbook*, (IEA, 2010b).

- **Foster appropriate energy prices:** The cost-effectiveness of advanced building envelope materials and technologies depends directly on energy prices, so establishing an appropriate policy on energy prices is a key way of motivating the private sector to pursue more efficient construction practices. Many regions of the world that will be seeing unprecedented construction growth in the coming decades still have large energy subsidies in place. These pose a major barrier to energy-efficient construction practices, because they lengthen the time needed to recuperate the costs of improved solutions.
- **Build infrastructure and human capacity:** There is a large array of technical requirements to enable the installation of more efficient building envelopes. These include proper test performance metrics and associated testing equipment so that third-party test ratings, certificates and labels can be established. Skilled labour is essential to conduct tests, assess alternative building solutions, promote efficient building policy, install new materials, conduct inspections and ensure compliance. It is also vital to make available general education materials such as guidelines adapted for the specific markets; energy calculators based on local climate, energy prices and occupant behaviour; and an overall improved knowledge base of more efficient options. Effective policy will articulate the benefits beyond energy efficiency such as job creation, increased domestic wealth, energy security, lower carbon emissions and less pollution.
- **Make materials available at commodity-based prices:** While demonstration buildings can be built with materials imported from distant places, for energy-efficient buildings to become viable the materials need to be manufactured much closer to the construction region, since shipping costs for large, heavy materials can be prohibitively high.

  Advanced materials such as low-e glass can be manufactured in large quantities at very cost-effective market price premiums below USD 5/m^2. When such products are specially ordered or imported, however, the price can double or even quadruple. To ensure that factories are built that can produce commodity materials on a large scale, governments need to give clear signals about their interest in promoting efficient building envelopes, and often other support such as market-based or higher energy prices (higher tariffs). Policy makers need to have an open dialogue with the building material industry about key elements that will help drive investment. Manufacturing building materials domestically, or at least regionally, creates jobs not only in local manufacturing but also for global investors involved in specialised tooling and unique raw materials.

- **Provide voluntary programmes to stimulate the market**: A primary voluntary measure can be the establishment of performance goals or guidelines for the energy consumption of buildings. To encourage the construction and renovation of efficient building envelopes, voluntary programmes can help stimulate the construction industry. Voluntary programmes for whole-building labelling, such as the US Green Building Council's Leadership in Energy and Environmental Design programme (LEED) or the UK Building Research Establishment's Environmental Assessment Method (BREEAM),[20] are intended to get owners to seek environmental recognition. Financial incentives can not only encourage builders to use innovative techniques and energy-efficient materials but also prompt suppliers to invest in manufacturing so that they can make more products available at more competitive prices. Voluntary measures also include development of the large array of education materials and training for multiple audiences.

- **Implement mandatory building codes:** To minimise energy consumption in new buildings and buildings undergoing major renovation, mandatory building codes have been very effective in several regions of the world. While full compliance by all builders continues to be a concern in almost every country, the progression to much more stringent criteria over the last several decades has resulted in much higher-performing building envelopes. Thus, while full compliance is a critical goal, the overall progression to more efficient buildings is the key expected outcome and should be evaluated over time. More details about building codes can be found in the IEA Policy Pathway *Modernising Building Energy Codes to Secure our Global Energy Future* (IEA-UNDP, 2013), and in *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013a).

Each region or country needs to assess how these core policy elements can be best combined to promote efficient building envelopes and ultimately transform the way buildings are constructed (see Table 10).

20. See *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* for more information (IEA, 2013a).

Table 10: Policy assessment of major elements to pursue energy-efficient buildings

Policy level	***Governance***	***Energy prices***	***Infrastructure and human capacity***	***Materials at commodity prices***	***Voluntary programmes***	***Mandatory building codes***
Low	No active government agency promoting efficient construction.	Subsidies in place or below market prices.	Limited test capability and knowledge of buildings, unproven buildings programme.	No local access to efficient materials and high price premiums.	Limited to a few demo projects without lasting impacts.	An agency is pursuing or has been granted authority to pursue.
Medium	Shared responsibility between construction and energy departments.	Market-based prices without environment impact.	Ability to test some products and university expertise.	Some products are widely available and cost-effective.	Educational materials and advanced programmes introduced.	Mandatory building codes are in place but lack infrastructure.
High	One agency has responsibility and is active with funding.	Tariffs in place to account for non-energy impacts.	Rating organisations, policy and enforcement personnel, in place.	Mature markets with many cost-effective products available.	Energy savings calculators, simulation tools and incentives in place.	Building codes demonstrate efficient construction.

Individual countries and regions should conduct self-evaluations in accordance with these criteria to establish benchmarks for programme development. The IEA in collaboration with several experts is providing its evaluation as a starting point for discussion by policy makers (see Table 11). Large variations exist within countries and regions, however, so this assessment should not be seen as static but rather as a general perspective of the situation in the particular country and/or region.

Table 11: Building envelope policy assessment of major regions

Policy \ ***Region***	***ASEAN***	***Brazil***	***China***	***European Union***	***India***	***Japan/ Korea***	***Mexico***	***Middle East***	***Australia/ New Zealand***	***Russia***	***South Africa***	***United States/ Canada***
Governance	L	M	H	H	M	M	M	L	M	L	M	M
Energy prices	L	M	M	H	M	H	L	L	M	L	M	M
Infrastructure and human capacity	M	L	M	H	M	H	M	L	M	M	M	H
Commodity of efficient materials	L	M	H	H	M	H	M	L	M	M	L	H
Voluntary programmes	L	L	L	M	L	L	L	L	L	L	L	L
Mandatory building codes	L	L	M	H	L	M	M	L	M	M	M	H

Note: H: high, M: medium, L: low.

Optimal building envelopes and systems based on LCC

The vast majority of building envelopes being constructed or renovated around the world are much less efficient than they could be, because they are not optimised in accordance with LCC analysis, which takes into account all costs of acquiring, owning and disposing of a building across its lifetime. EU Directive 2010/31/EU (EU, 2010) specifies the need for minimum energy performance requirements "set with a view to achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the life-cycle of the building". The directive provides flexibility to encourage states to pursue policies for construction that may be more efficient and costly than cost-optimal. While "cost-optimal" is not fully defined and is subject to different interpretations, a typical understanding is that it represents the lowest LCC. However, another alternative is one that maximises energy savings while not increasing LCC (for more details on LCC, see Annex B).

LCC analysis can enable increased installed cost, at time of construction, to be compared with the value of the energy savings over the life of the installed product (typically 30 or more years for building envelope materials). Key economic factors include the discount rate that is used to account for future savings being worth less than current investments, and the price of energy over the entire analysis period. The primary factors that determine LCC are climate, the cost of energy, the heating and/or cooling equipment type and efficiency, and the installed cost of the insulation. Expected future energy prices are an important consideration but are beyond the scope of this roadmap.

Energy savings can vary significantly based on occupant behaviour (e.g. thermostat set points), climatic conditions and real energy performance compared with standardised test procedures or energy simulations. When a large set of integrated components is analysed, final energy savings are often reduced due to diminishing returns of competing technologies. Capital investment premiums above standard construction practice vary based on general overall economic market conditions, regional variations and maturity of the technologies being considered.

Many of these variables have a range of data and can be considered by policy makers. If a policy being considered is a mandatory building code, then the likely set of variables chosen will often be more conservative and the lowest LCC will be higher with less energy savings, although still significant. If a policy being considered is for a voluntary incentive programme, such as for deep renovation, then policy makers may be less conservative and could consider the potential of future mature capital investment costs rather than the current cost today of systems that are only being installed on a niche basis. Many recommendations of this roadmap will result in lower LCC, and will reduce variability through better performance metrics of emerging technologies.

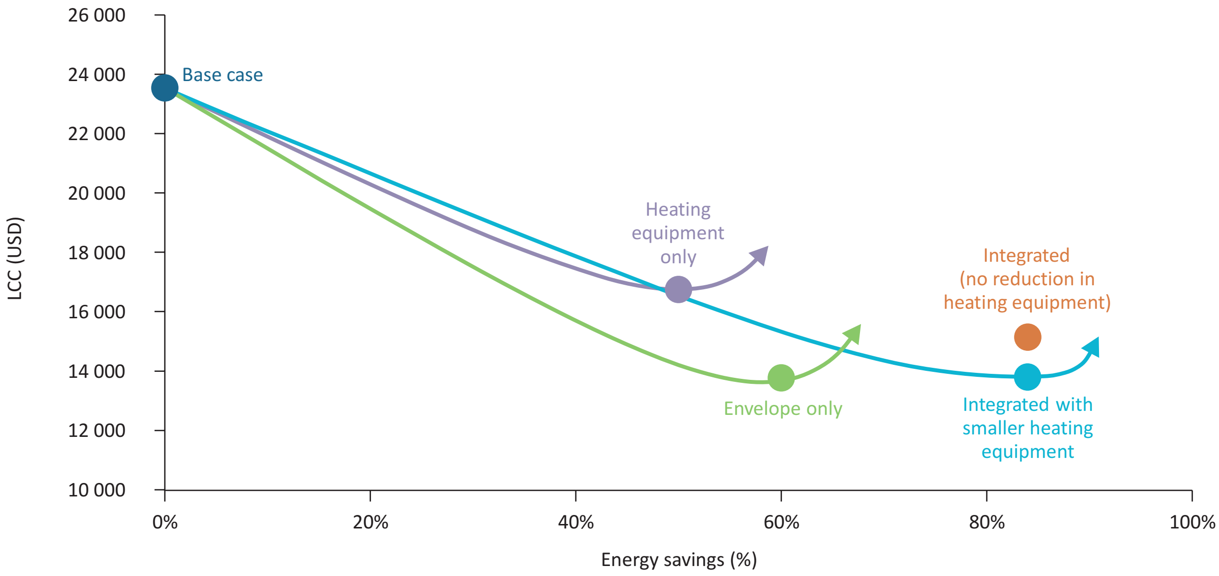
A major consideration for policy makers and consumers is whether energy efficiency measures are cost-effective for their economies and specific applications. While these decisions are best made at the country or local level, it is useful to look across many regions and countries to see what technologies are cost-effective. Detailed data are not available from enough countries to do extensive quantitative analyses for the large array of efficient envelope measures, but by looking at existing market assessments, established policies and current best practices, qualitative perspectives can be provided (see Table 12).

An example of a cold-climate building upgrade using LCC analysis is provided here using the typical technologies that are widely available and cost-effective in mature markets (see Figure 17). The features include low-e glass, greater insulation and air sealing, as well as the replacement of electric resistance heaters with heat pumps (air source). The analysis shows heating equipment upgrades only, envelope upgrades only and an integrated approach with both measures. The integrated approach shows the lowest LCC when reduced capital costs are considered by downsizing the heating equipment. If heating equipment is not downsized, then LCC is higher (more details are found in Annex B). The integrated approach with capital cost reductions has the lowest LCC, which is 42% lower than the base case and saves over 80% of the heating energy.

Table 12: Cost-effectiveness: Perspectives for energy-efficient building envelope measures

Envelope measure	***Widely cost-effective (moderate energy prices and/or moderate climate)***	***Niche market cost-effective (high energy prices and/or severe climate)***	***R&D and economies of scale needed to be cost-effective***	***Comments/ benefits***
		Opaque envelope		
Typical insulation	✓			All types of applications widely available.
Advanced insulation		✓		Only being used in niche applications.
Phase change material			✓	Very few installations, more R&D needed.
Air sealing (new construction)	✓			Many locations and low cost.
Air sealing (retrofit 25% improvement)	✓			Many locations and affordable.
Air sealing (retrofit 50% or higher)		✓		Can be expensive, more effort to expand.
Cool roofs	✓			Cost-effective in hot climates with mature market.
Advanced roof systems			✓	More R&D needed.
		Window systems		
Double glaze low-e windows	✓			Many locations and low cost once mature market.
Highly insulated U-value less than 1.1 W/m^{2}K		✓		Significant progress but more effort on systems benefits needed.
Highly insulated - value less than 0.6 W/m^{2}K			✓	More R&D to become market viable.
Window film	✓			Widely available for solar control, low-e just beginning, safety benefits.
Low-e storm or interior panels		✓		Could be very affordable in mature markets.
Insulated shades (low U-value)		✓		Benefits go beyond efficiency such as privacy, room darkening.
Exterior shading	✓			Cost-effective and becoming popular.
Automated exterior shading		✓		Provides improved comfort and some offer security.
Dynamic glazing			✓	Greater maturity needed to become cost-effective.

Figure 17: LCC curves for heating only, envelope only, and integrated solution in a moderate cold climate



Note: illustrated example based on 120 m² floor area poor performing building, USD 0.10 per kilowatt hour, 30 year service life, second heat pump replacement in 15 years, 30% capital cost reduction due to smaller envelope heating load and no escalation in energy prices or cost for second heat pump replacement.

KEY POINT: integrated solutions offer the greatest energy and cost savings.

New construction

The predominant policy path intended to ensure the energy efficiency of new buildings is the development, promulgation and enforcement of mandatory building codes. Such codes may differ widely depending on climate, economic prosperity and overall maturity of the market for energy-efficient building materials. The IEA in collaboration with the United Nations Development Program (UNDP) has issued a new Policy Pathway, *Modernising Building Energy Codes to Secure our Global Energy Future* (IEA-UNDP, 2013), which describes a detailed process of designing building codes that promote and encourage the construction of buildings that consume very little energy. This process involves looking at local conditions, building orientation and adapted behaviour to obtain much lower energy consumption for heating and cooling than with traditional approaches. China is working on energy efficient buildings with advanced building envelopes (see Box 6).

Due to rapid economic growth and increasing population, in many developing countries there will be a very large increase in construction in the coming decades. Many buildings in these countries are still being constructed with older designs and inefficient products, and without the use of optimised perspectives. Furthermore, designers and installers lack skills and access to training, and workforce development activities are limited. While zero-energy buildings should be the ultimate goal for all countries, they may be unrealistic for many countries until efficient building materials become widely available at affordable, commodity-based prices. Fundamental work is needed in these countries to develop and implement more stringent building codes, to ensure that technologies widely available and cost-effective in other countries soon become standard. As well as overcoming the institutional and market barriers discussed earlier, three core elements are essential for effective energy building codes: code development, infrastructure and enforcement (Figure 19).

Box 6: In China, a passive low-energy residential high-rise with energy-efficient building envelope

China has been pursuing pilot passive low-energy residential buildings that include energy-efficient envelope features. The Zaishuiyifang project, a Sino-German collaboration on a residential high-rise building (18 storeys, 6 500 m^2) was completed in 2012, and energy consumption was monitored in two apartment units (see Figure 18). The project is in a heating-dominated climate, in Qinhuangdao City, Hebei Province, so a key objective was to reduce heating energy consumption. The test results showed that energy consumption for heating was ≤ 17 kWh/m^2 per year, while maintaining high levels of comfort that were demonstrated by comfort requirements being satisfied over 90% of the time. The regular municipal heating supply was not utilised. The units also had small variations in indoor temperatures (≤ 3°C). Energy consumption for cooling was also low, at ≤ 15 kWh/m^2 per year. Overall, the passive low-energy building consumed less than one-third the energy of a building-code-compliant structure. The price premium for the high-performance building was estimated at USD 165/m^2. The following key energy-efficient building envelope measures were implemented:

- energy-efficient wall and roof insulation, including exterior insulation (25 cm EPS) with U-values of approximately 0.15 W/m^2K
- highly insulating windows with triple-glazed, low-e glass, and low-conductive frames, with an overall U-value of approximately 0.9 W/m^2K, and G-value (SHGC) > 0.5
- low air infiltration through air sealing with leakage measured at below 0.6 ACH at 50 Pa
- heat recovery (75%) from exhaust ventilation air that reduced the heating penalty associated with ventilation air, while maintaining high air quality (CO_2 concentration ≤ 1000 parts per million).

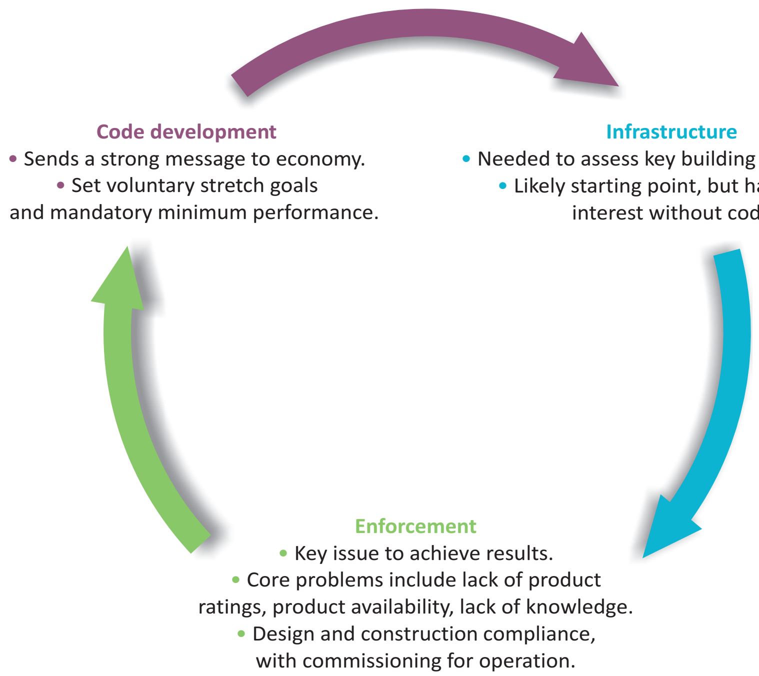
Source: Zhang, (forthcoming).

Figure 18: Chinese near-zero-energy residential high-rise building and high-performance windows

Source: Zhang, X. (forthcoming), "Near Zero Energy Residential Building", Energy Foundation, Center of Science and Technology of Construction, Beijing, China.

KEY POINT: low-energy buildings are possible in urban areas and need to move from niche pilot projects to mainstream construction.

Figure 19: Building code development and implementation activity



Source: adapted from LaFrance, M., (2012), "Overview of DOE Envelope R&D", presented at US DOE Building Envelope R&D Program Stakeholder Engagement Workshop, San Antonio, Texas, 26 June.

KEY POINT: building energy codes need to be developed with proper infrastructure while planning for enforcement.

This roadmap recommends the following actions:	*Milestone timeline*	*Stakeholder*
Promulgation of progressive building codes striving for zero-energy buildings, especially in mature, well-established markets with widely available efficient building envelope materials.	2014-20	Government, manufacturers, builders.
Market introduction of advanced building materials to achieve cost-effective commodity-based prices in emerging markets.	2014-25	Manufacturers, government, non-government organisations.
Development and promulgation of building codes in emerging markets, with efforts to increase compliance, which promote efficient building materials, such as low-e glass, insulation, air sealing, and reflective technology in hot climates.	2014-25	Government, researchers, manufacturers.

Deep renovation

Deep renovation of inefficient existing buildings is a crucial way to achieve a much more sustainable future. It leads to considerable reductions not only in energy consumption but also in capital costs, as upgrading all major end-use equipment and building envelope components together allows synergies that enable smaller heating and cooling systems to be used. About 1% of buildings are renovated each year (BPIE,2011), but the overwhelming majority of these renovations do not lead to deep energy-use reduction. Immediate action is needed to change this through policies that encourage deep renovation while a building is undergoing planned major refurbishment. A key immediate policy to enable the establishment of a self-sufficient market is the use of financial incentives linked to total efficiency improvements.

The best-known and most effective retrofit programme that has achieved significant improvements has been run by KfW, a development bank owned by the German government. Over 20 years, 61% of buildings in the former East Germany have been refurbished with EUR 61 billion of funding provided through 877 000 loans (KFW, 2013a). To qualify for the deep retrofit grants that result in energy consumption approximately 45% less than in a benchmark building, renovation plans have to base efficiency measures on holistic overall performance and include significant envelope and heating equipment improvements. The programme also specifies several lower levels of incentives for more modest improvements (KFW, 2013b).

To make sure that deep renovation happens, financial incentives should only be offered for improvements that reduce energy consumption by at least 50%, or achieve specific criteria such as very low-energy consumption per floor area. Sliding scales that favour reductions of 75% to 80% should be the primary goal of financial incentives; less expensive policies such as education or labelling are more suitable for modest energy-saving programmes.

Once deep renovation is established as a viable programme with widespread appeal and market uptake, the next key step is to motivate investors and building owners to renovate buildings that are not currently scheduled for renovation. These buildings may need refurbishment for aesthetic reasons or because energy bills are too high. Refurbishment is often delayed because of the large capital cost, so a key policy goal should be to establish technical and performance benchmarking that can establish a business case for deep energy renovation earlier rather than later. Policy makers should also aim to double the renovation rate to at least 2% per year (IEA model assumptions); many organisations are calling for an increase to 3% per year (European Voice, 2013). The European Union has already instituted requirements for a public building renovation rate of 3% per year (EU, 2012), although the level of performance is not specified and does not appear to be consistent with deep renovation definitions (GBPN, 2013).

To help justify deep renovation policies, decision makers need to consider the multiple benefits to the broader economy that these policies have been shown to deliver, including public health benefits, job creation and tax revenue, in addition to conventional energy considerations. Building owners can be encouraged to take into account non-energy benefits such as personal health and well-being improvements, increased occupant productivity, added market value and demonstrated greater capital return on investment. The IEA is currently conducting a study exploring such non-energy benefits (IEA, 2012d) (IEA, 2013b) (see Box 7). The goal is to establish a business climate that places greater value on high-performance buildings that can provide a beneficial return on investment for owner-occupied buildings and greater leasing revenue for leased spaces.

Box 7: Consumer impacts including health benefits from large scale insulation programme

Improvements to building envelopes can be driven by focused policies such as the recent New Zealand "Warm Up New Zealand: Healthy Homes" programme that targeted low income citizens living in older homes. The programme included 178 259 insulation retrofits and 60 635 heating equipment replacements from 2009 through 2013, with a total investment of NZD 330 million. An independent evaluation of the programme documented an average return on investment ratio of four to one when health benefits were included, with health benefits contributing the majority of the total. Private sector investment was also stimulated in addition to the public investment (IEA, 2013b).

Several other studies have linked inferior envelopes including south facing facades with clear glass, lack of insulation and non-reflective roofs to higher mortality rates during periods of excessive heat conditions (Hope, 2012). With the data obtained from these types of studies, the need for greater investment in energy efficiency in buildings appears overwhelming. These non-energy outcomes have the potential to deliver benefits in policy areas beyond energy efficiency and to increase the call for the large stock of building renovations.

Although the general aim is to renovate the majority of existing buildings by 2050, early renovation may be cost-prohibitive for some buildings whose operating systems and envelopes have useful remaining life. Once policy mechanisms have been formulated and successfully implemented over the next 15 or 20 years, then more details will be known about the mitigation cost of upgrading these buildings. This is an area that is recommended for more technical and policy analysis, along with case studies. Once the mitigation cost is fully refined, it can be compared with other areas within the economy to achieve the lowest abatement costs. Despite the uncertainty regarding these buildings, however, deep renovation of the overwhelming majority of buildings is or will be market-viable and should be pursued immediately.

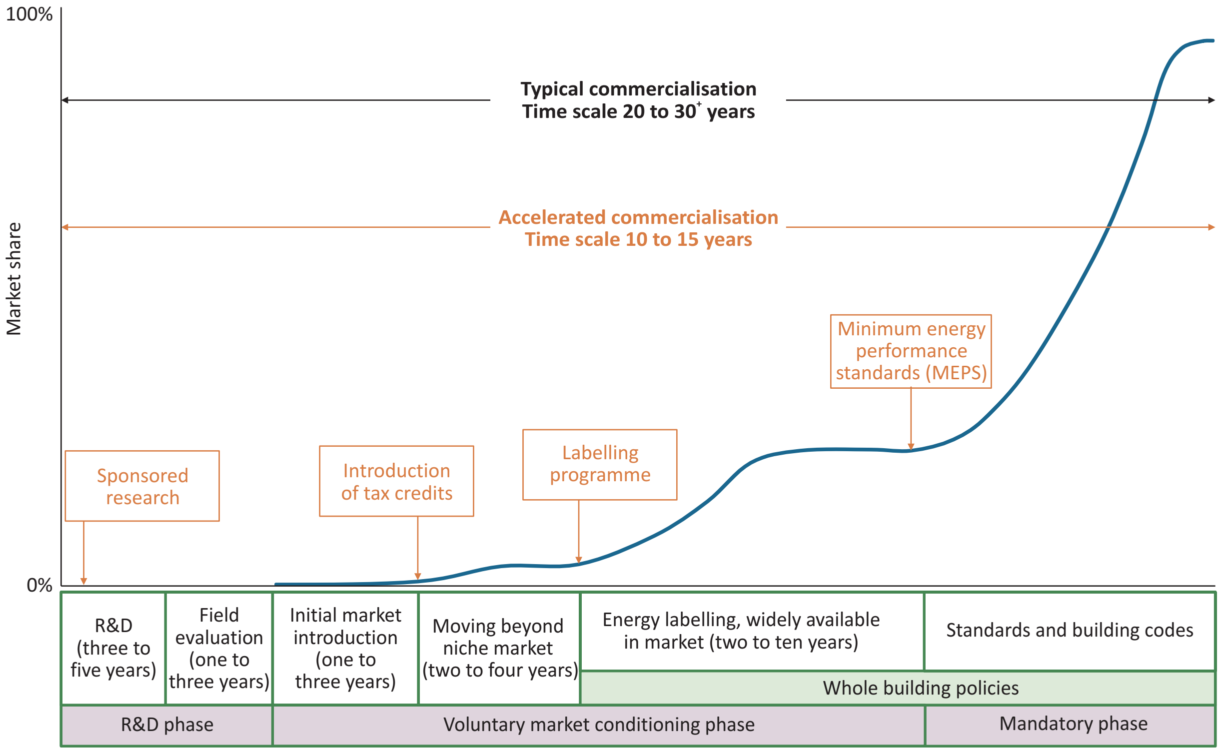
This roadmap recommends the following actions:	*Milestone timeline*	*Stakeholder*
Pursue deep renovation as part of normal building refurbishment, initiated with incentives with the goal of 75% to 80% reduction in energy consumption.	2014-20	Government, non-government organisations, political leaders.
Develop business case studies to promote deep renovation within a fully functioning private-sector market.	2015-20	Builders, investors, government.
Once deep renovation rate is well-established, increase annual renovation rate to 2%.	2020-50	Builders, investors, government.
Develop case studies and cost-abatement assessments to consider early deep renovation prior to full building utilisation.	2020-30	Researchers and governments.

New materials and technologies

New building envelope materials and technologies could increase energy efficiency and energy savings at much lower cost than is possible today. If we look at building technology over the last half-century, new materials have played a critical role in saving energy. Insulation is widely available and affordable, low-e glass has reduced typical energy consumption of double-glazed windows by 50% for only a few dollars per m^2, and simple approaches are available to add air sealing at very low cost during new construction.

To fully develop new technology into fresh products and achieve market saturation, appropriate policies will be required along the entire market maturity path. From the outset, however, a few core policies are essential to encourage the development of innovative technologies by fostering R&D, case studies and market incentives, and by making system benefits visible (see Figure 20) (IEA, 2013a). Many building material suppliers serve the world market, so product innovation is needed on a global scale. As lower economic growth persists in highly developed economies, wider global markets can offer manufacturers and investors greater potential. For example, the combined cold-climate market of China, Europe, Japan, Korea, Russia and North America is significant, and offers the largest potential for saving heating energy in residential buildings (see Figure 8).

Figure 20: Accelerating the product commercialisation path by mandating new technology



Source: IEA, 2013a. IEA (2013) *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*, OECD/IEA, Paris.

KEY POINT: accelerating the commercialisation of new building envelope materials will require integrated policies.

Significant unrealised energy savings are possible using existing building materials and technologies, so many policy makers argue that further extensive R&D is not needed. But lower-cost, better-performing, more market-viable materials and technologies are needed to improve the business case for such programmes and to reduce LCC. Future innovative materials and technologies will also reduce the risk associated with realising the large energy-saving potential, especially in areas with lower energy prices and with less severe climates. Vast building markets of the world are still resistant to the higher capital costs associated with more energy-efficient building envelopes, even if they provide significant return on investment.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Conduct competitive R&D with funding from public entities to pursue highly insulating dynamic windows that become net energy-plus windows in cold and mixed climates; high-performance insulation; and other innovative new materials.	2013-25	Government, utilities, and other public interest organisations.
Conduct case studies and demonstrations of value-added high-performance insulation; advanced windows; shading systems; and innovative roofing systems to show overall greater system energy efficiency and monetary effectiveness.	2013-25	Governments, utilities, researchers, and manufacturers.
Formulate integrated policies focused on promoting advanced materials and technologies that contribute significantly to deep renovation and zero-energy buildings.	2013-25	Governments, utilities, and other public interest organisations.

Conclusions: Near-term actions for stakeholders

The nature of the building envelope determines the amount of energy needed to heat and cool a building and hence needs to be optimised to keep heating and cooling loads to a minimum in accordance with LCC analysis. A high-performance building envelope in a cold climate reduces the energy demand required to heat the average building in the OECD to only around 20% to 30% of what it is today. In hot climates, advanced building envelope technologies can significantly reduce the cooling energy demand, and in some building segments, may render cooling equipment unnecessary.

The IEA 2DS attributes more than 40% of the savings expected in heating and cooling energy demand under a low-carbon scenario directly to improvements in the building envelope. This represents energy savings of almost 6 EJ in 2050, equivalent to the current energy consumption of the United Kingdom. Lower heating and cooling requirements will also help offset envelope investments since avoided capital cost for equipment can be used to fund envelope efficiency measures.

To achieve these savings, actions are required from all key stakeholders. The IEA lists here the highest-priority recommended actions per entity to ensure efforts can be focused on the critical areas in the near term, since resources are expected to be limited by competing priorities and budgetary constraints.

Stakeholder	Action items
Governments	• Fund and conduct competitive R&D for high-priority technologies such as highly insulating and dynamic windows, lower-cost high-performance advanced insulation, and improved approaches for validated air sealing in existing structures • Establish or further develop incentives for very high-performance products and deep renovation • Sunset incentives and promotion efforts for modest improvement (reduce "free riders") and reallocate to areas with greater energy-savings potential • Provide initial "seed" funding to help establish test infrastructure and building code mechanisms; consider governance over the mandating of building codes • Fund collaborative international research to assist in the establishment of new harmonised test mechanisms and to ensure that independent organisations beyond the manufacturing community can play a key role in developing market-neutral procedures • Support workforce development activities and specify contractor qualifications.
Manufacturers/ trade associations	• Conduct R&D on promising advanced materials and products with global market potential • Work to establish sustainable business models that allow independent rating and building code organisations to function efficiently but with reduced long-term burden on governments (funding predominantly from manufacturers and builders via competitive rating and certification processes) • Re-enforce and expand trade association charters to build market infrastructure and reduce barriers to establish a fair and harmonised market for energy-efficient building materials that will result in greater overall value for all entities • Provide initial "seed" funding to help establish test infrastructure and building-code mechanisms • Develop workforce development programmes and qualification schemes for building practitioners.
Researchers/ academia	• Investigate and find new innovative materials • Collaborate with researchers internationally and with leading manufacturers to assist with product development and infrastructure development • Participate in standard organisation deliberations to ensure that test protocols are fair and market-neutral, and in the interest of consumers • Educate designers and architects about the latest, state-of-the-art building science, product development, and building integration opportunities.

Stakeholder	Action items
Utilities	• Offer incentives for innovative products and deep renovation with a long-term perspective to avoid added capacity while developing viable markets for the future • Offer incentives for new construction that minimise impacts on peak electricity generation and that promote zero-energy buildings with “added value” to grid load management.
Non-government organisations	• Lead third-party testing and rating organisations • Initiate educational programmes; adopt deep renovation and zero-energy building programme criteria.
Architect and designers	• Stay current with the latest building science advances, obtain sustainable design credentials and assist in educating other building practitioners • Help present a business case for going beyond traditional efficiency measures, through experience gained on value-added projects.
Builders	• Increase total business revenue by pursing deep renovation in addition to added value for new construction activity • Participate in the dissemination of educational information that show how value added high-performance building envelopes lead to low-energy, more comfortable buildings • Attempt to correlate high-performance advanced facades to occupant perceived increased value • Invest in training and qualification of staff.
Building code officials	• Work to establish more stringent and easy to implement advanced building codes with a long-term vision of zero-energy buildings. Where possible, seek government governance for mandating policies for new and existing buildings undergoing upgrade • Provide data and knowledge to researchers and manufacturers to assist in code improvements.
Standard organisations	• Lead harmonisation efforts and adoption of new standards for innovative materials • Adopt programmes that provide incentives for developing markets to gain access to proactive standards at reduced rates • Consider programmes to more actively pursue the development of new standards for unique emerging markets when global standards are inappropriate.

Annexes

Annex A: Building envelope technologies

www.iea.org/publications/freepublications/publication/name,45205,en.html

Annex B: Life-cycle cost analysis

www.iea.org/publications/freepublications/publication/name,45205,en.html

Abbreviations, acronyms and units of measure

Abbreviations and acronyms

2DS	ETP 2012 2°C Scenario
6DS	ETP 2012 6°C Scenario
ACH	air changes per hour
BAT	best available technology
BIPV	building-integrated photovoltaic
BREEAM	Building Research Establishment Environmental Assessment Method
CCS	carbon capture and storage
CO_2	carbon dioxide
COP	co-efficient of performance
EIFS	exterior insulation finishing system
EPS	expanded polystyrene
ETP	Energy Technology Perspectives
GSEP	Global Superior Energy Performance Partnership
HVAC	heating, ventilation and air-conditioning
IEA	International Energy Agency
ISO	International Organization for Standardization
KFW	KfW Bankengruppe (Germany)
LBNL	Lawrence Berkeley National Laboratory (United States)
LCC	life-cycle cost
LEED	Leadership in Energy and Environmental Design
Low-e	low-emissivity
NREL	National Renewable Energy Laboratory (United States)
NZD	New Zealand dollar
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory (United States)
PCM	phase change material
PV	photovoltaic (solar)
R&D	research and development
SHGC	solar heat gain coefficient
SIP	structurally insulated panel
SR	solar reflectance
UNDP	United Nations Development Programme
USD	United States dollar
US DOE	United States Department of Energy
UV	ultraviolet
VIP	Vacuum-insulated panel
WUFI	Wärme und Feuchte Instationär
ZEB	zero-energy building
λ	thermal conductivity

Units of measure

EJ	exajoules (10^{18} joules)
Gt	gigatonnes (10^9 tonnes)
kWh	kilowatt hour (10^3 watt-hour)
m^2	square metre
Mt	megatonne
Pa	pascal
µm	micrometre (10^{-6} metre)
W/mK	watts per metre Kelvin
W/m^2K	watts per square metre Kelvin

Glossary

Aerogel: a micro-porous, translucent, silica-based, ultra-lightweight insulating material that has low thermal conductivity.

Dynamic shade control: refers to window attachments that are installed on either the exterior or interior of the building to modulate sunlight.

Dynamic solar control: the ability to modulate the sun's energy that enters a building to optimise performance, including dynamic glazings and dynamic shade control.

Economiser: the part of a heating and cooling system that pre-heats or pre-cools incoming ventilation air from exhaust air, or "free cooling" using outside air when appropriate.

Energy-plus buildings: refers to buildings that exceed zero-energy (*see zero-energy building*) and result in additional energy being contributed to the electricity grid on an annual basis generally from photovoltaic cells. Co-generation using fossil fuels are excluded from this class of buildings.

Exterior insulation finishing system (EIFS): a type of exterior cladding that includes insulation (board stock such as EPS) over a structural wall that is then covered by various layers of cementitious material. It is usually applied directly to masonry substrates or over a drainage plane for organic substrates.

Integrated façade system: also referred to as advanced façade systems that integrate daylighting benefits along with heating, cooling and artificial lighting controls. Technical approaches include exterior shading, special glazing characteristics, size of windows and orientation.

Low-emissivity (low-e): microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window or skylight glazing surface used primarily to reduce the U-factor by suppressing radiative heat flow. For the roadmap, low-e also refers to a general type of advanced glass that includes multiple coatings (e.g. spectrally selective) that can be tuned to high or low SHGC.

Retrofit: refers to the replacement of existing equipment, construction modification or upgrade of existing buildings and components.

Sash: the portion of a window that includes the glass and framing sections directly attached to the glass, not to be confused with the complete frame into which the sash sections are fitted.

Solar heat gain coefficient (SHGC) or g-value: the fraction of solar radiation admitted through a window (both directly transmitted, absorbed and subsequently released inward). It is expressed as a number between 0 and 1. The lower a window's SHGC, the less solar heat it transmits and the greater its shading ability.

Solar thermal collector: absorbs the sun's energy to provide heat or hot water to buildings and includes multiple types, with glazed collectors being the most common. Building-integrated solar thermal uses building envelope components as part of the collecting system.

Structural insulated panel (SIP): a prefabricated building panel that usually includes facers, such as oriented strand board or plywood, and insulated core, such as EPS insulation.

Thermal break: an element of low conductance placed between elements of higher conductance to reduce the flow of heat, often used in aluminium window frames.

Thermal mass: refers to mass (furnishings or building structure) that absorbs energy and can reduce extreme temperature impacts through the material's moderating impact. It also is used to store passive energy gains from the sun.

Vacuum glazing: an insulating glazing composed of two glass layers, hermetically sealed at the edges, with a vacuum between to eliminate convection and conduction.

Vacuum insulated panel (VIP): an advance insulation that uses a variety of core materials that are evacuated in a sealed enclosure, which is often a thin film with metallic coatings.

Whole-building perspective: refers to a systems approach through which integrated building systems are implemented to achieve the highest energy efficiency at the lowest cost. This typically includes smaller heating and cooling equipment with the elimination of perimeter zones in office buildings as well as distribution systems near windows when high performance building envelope components are integrated.

Zero-energy building (ZEB): refers to a building that on an annual basis is fully self-sufficient with respect to energy consumption, usually through the sale of electricity generated from PV cells equal to or greater than purchases of electricity from the grid.

Regional groupings

ASEAN (Association of the Southeast Asian Nations): Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.

China: refers to the People's Republic of China, including Hong Kong (China).

EU 28 (European Union (28)): Austria, Belgium, Bulgaria, Croatia, Cyprus*, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.

Middle East: Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates and Yemen.

Africa: Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Zambia and Zimbabwe.

Other developing Asia: Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Chinese Taipei, Cook Islands, DPR of Korea, East Timor, Fiji, French Polynesia, Hong Kong (China), India, Indonesia, Kiribati, Laos, Macau (China), Malaysia, Maldives, Mongolia, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Tonga, Vanuatu and Viet Nam.

* The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

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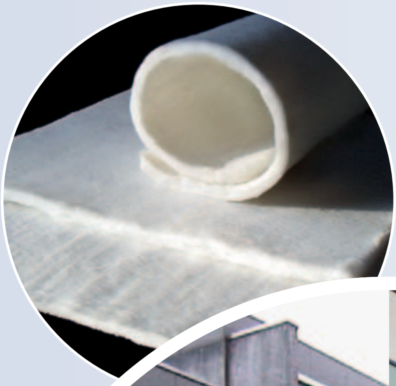
2015

2020

2025

2030



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Annex A: Building envelope technologies

This annex provides additional technical background regarding various building envelope technologies as a supplement to the roadmap, although it does not cover the full complement of technologies by itself. Further information regarding a wide range of building technologies including building envelopes and policies can be found in IEA publication, *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013).

Insulation

The overall thermal performance of a building element such as a wall, roof, floor or window is specified as thermal transmission (typically described as a U-value). It is a measure of the rate at which heat flows through an element when a temperature difference is maintained across the element. Its measurement involves difficult concepts and techniques, and includes conduction, convection and radiation heat transfer. Another common term is thermal resistance (typically shown as an R-value), which for all practical purposes is the inverse of thermal transmission. R-value is mostly meant to be a performance metric of building materials (e.g. insulation) and it is easier to understand by less sophisticated practitioners and consumers. In short, the higher the R-value, then the lower the heat flow will be. Conversely, lower U-values are best.

Thermal conductivity (λ) is a metric that is used to measure the rate at which heat flows through a material. It can be used to estimate the U- and R-values of an insulation product at a given thickness (see Table A.1). Insulation materials are tested on small apparatuses, while whole building assemblies and windows are usually tested in a "hot box" (large scale calorimeters) (see Figure A.1).

Figure A.1 Three-chamber climate simulator "hot box"

KEY POINT: establishing testing and performance rating infrastructure is critical but can be expensive.

Source: Fraunhofer IBP (Institute of Building Physics) (2010), "Three Chamber Climate Simulator", www.ibp.fraunhofer.de/content/dam/ibp/en/documents/Fl-174-05-Flyer-3Kammer-Klimasimulator-Sep2010-HT-E_tcm1021-29997.pdf.

Table A.1 Insulation types, thermal conductivity and typical applications

Thermal performance level	Highest		High	Moderate	Low	Applications/Comments
Thermal conductivity (W/mk)	0	0.01	0.02	0.03	0.04	0.05
Vacuum insulated panel (VIP)						Research underway in EU and North America to embed VIPs in EPS or XPS as part of EIFS systems with adhesives to avoid fastener penetrations. High material cost.
Aerogel						For highly constrained space and thermal bridges, such as stud caps. Case studies underway for interior installations with wall board to reduce labour and offer lower systems level cost. High material cost.
Polyurethane boards and spray						Wide applications for value-added performance with space limitations. Roof decking, cathedral roof structures, wall cladding, SIPS, basement, slab edge, and spray foam for cavities also offers air sealing benefits. Higher price premiums with many cost effective applications.
Extruded polystyrene (XPS)						Wide applications for value-added performance with space limitations. Roof decking, wall cladding, SIPS, basement, slab edge, and also offers air sealing benefits. Moderate price premiums with many cost effective applications.
Expanded polystyrene (EPS)						Wall cladding and a dominant choice for EIFS, SIPS, ICFs, and interior applications. Moderate price premiums with many cost effective applications.
Glass fiber						Widely used as cavity insulation alone or with spray foam ("flash and batt") to offer more affordable but sealed applications. Used in attics with less space constrained applications, generally lower cost and lower performing applications.
Stone fiber						Used as cavity and in attics with less space constrained applications, generally lower cost and lower performing applications.
Cellulose						Used as cavity and in attics with less space constrained applications, generally lower cost and lower performing applications. New formulations doped with phase change material and passed fire rating tests but has very limited market.
Wood fiber, flax, hemp, cotton, other						Variety of generally lower cost and lower performing insulation applications.

Notes: EIFS = exterior insulation finish systems; SIPs = structural insulated panels; ICFs = insulated concrete forms; PCM = phase change material. W/mK = watts per metre Kelvin. Thermal conductivity testing can be complex and involves many technical considerations that are beyond the scope of this roadmap, such as radiation within material cell structures and "apparent thermal conductivity" as determined in accordance with several ASTM test standards.

Source: Adapted from EST (Energy Savings Trust) (2010), "Insulation Materials Chart – Thermal Properties and Environmental Ratings", *CE71*, London.

Walls and roofs

In most developed countries, insulating walls is common practice and is generally done fairly well. There remain concerns about proper workmanship and not installing optimal levels of insulation, but for the most part, new buildings are far more thermally resistant to heat flow than the old stock of buildings. There are efforts to increase insulation levels, and the most effective approach to date is applying added insulation to the entire wall. Ideally, this added layer of exterior insulation is applied to the structural sheathing before the rain screen or cladding is added. A very common approach on most recent buildings in Europe and on services sub-sector buildings in North America and other parts of the world is to add Exteior Insulation Finishing Systems (EIFS), also called External Thermal Insulation Composite Systems (ETICS), which embed insulation under a stucco or cementitious type of finish (see the back of the roadmap cover for a photo of an EIFS retrofit).

Exterior insulation is very effective and can be applied to existing buildings. However, it requires re-cladding of the building and is rarely cost effective unless doing a major refurbishment or a full "deep" renovation through which other system benefits can be realised, such as significantly reducing the capacity of the mechanical equipment. EIFS can be installed on old as well as modern buildings and are widely available in mature markets. They offer significant efficiency improvement by eliminating thermal bridges and adding additional insulation to the entire wall.[1] Other types of viable retrofits include blowing insulation into cavities that are not insulated. This can be done with insulation that functions as an air barrier or one that does not serve this function. Interior insulation can be added but generally requires extensive interior renovation. It is often the only option for renovating historic, classified buildings. In all cases, the impacts on moisture migration within the altered structure need to be carefully managed.

Thermal mass

While insulation is the primary material used to reduce heating and cooling loads, thermal mass provides a significant role in reducing peak loading conditions and it results in energy savings. The primary approach to providing thermal mass benefits is the construction of masonry buildings that are very common in many regions of the world. Light weight construction (studs and sheathing) is very common in North America and has limited thermal storage capacity. Research is underway with advanced insulation that has been doped with phase change material to offer thermal mass benefits, although this has achieved limited market entry and represents only a small niche market. Thermal mass also helps retard heat gains in hot climates. A recent study suggests that cooling savings potential range from 7% to 25%, depending on building component, applications and operation of HVAC systems (Kosny et al., 2013).

Clay or concrete tiles are very common in many parts of the world. The tiles usually offer several advantages. First, they provide thermal mass that helps mitigate solar energy, and second, they are usually installed on counter battens that provide a vertical ventilation path below the tile. Thermal mass retards the heat gain, and much of it can be removed by ventilation. As the sun sets, remaining stored energy will flow back out to the environment. In addition, unglazed clay tiles, which are common in many regions and are red in colour, have a naturally high solar reflectance. These tiles also store moisture that can have an added cooling benefit since the moisture needs to be evaporated. China is doing significant research on evaporative building materials for walls and roofs that offer cooling benefits similar to unglazed tiles with significant water absorbing properties.

[1] Termite protection can be a concern and needs to part of the design.

Radiant barriers and coatings

Radiant barriers are usually a metal surface or coating with metal particles that have a low-e surface (a scale of 0 to 1) and reject long wave radiation. They are commonly used in attics but they also are found as a facer on various types of insulation. The thermal performance of an insulating product, such as board stock with a low-e facer, will have its full performance included in the insulation metric (e.g. R–value). However, a key consideration is the product's ability to reflect radiation, or not emit it, which is highly dependent on the radiant surface being adjacent to an air gap. If the product is installed tightly to another material, the radiant benefits are highly diminished. Barriers usually refer to materials that have very low emissivity around 0.05 (they must be below 0.10 to qualify per ASTM 1371 standards). By contrast, "interior radiation control coatings" or low-e paints have higher emissivity, around 0.20 with a requirement to be less than 0.25, and are usually spray applied, thus providing an easier installation technique. Performance of these coatings is not as effective due to higher emissivity (RIMA, 2013).

Garden "vegetative" roofs

In addition to insulation, radiant barriers, and cool roofs, there are other approaches to reducing heat gained through roofs. Garden, vegetated or green roofs refer to roofs that have soil or planting media that hold various types of vegetation. The roofs serve as a cool roof through transpiration, (similar to evaporation), which provides cooling of the area. Most garden roofs have enough soil to serve as additional thermal mass, so they also function as a higher level of insulation. A primary benefit is that they store rain water and prevent storm water run-off. Generally, garden roofs have high price premiums compared to typical cool roofs, and are pursued for environmental or aesthetic reasons. They tend to not be cost effective from an energy efficiency perspective.[2] A more common approach that is growing mostly in Europe is to have garden walls. While these offer many environmental benefits beyond energy efficiency, they would not be pursued for purely economic or energy efficiency reasons.

Foundations and floors

Foundations include a variety of basic configurations, including full basements, crawl spaces and slabs on grade (ground). All configurations exist in all climates, but certain configurations are more prevalent in certain regions. While it is important to consider adding insulation in all applications, it is most important in colder climates. In hotter climates, foundations offer ground coupling and can actually be a source of heat rejection. The portions of the basement, crawl space or slab that are exposed to the environment above the grade are the greatest concern.

Similar to walls, adding exterior insulation to floors and foundations is a preferred option and is included in mandatory building codes in many cold countries. However, compliance is problematic because adding insulation during foundation backfilling can be labour intensive. Adding insulation to slab edges can also be difficult for buildings that may not be adding exterior insulation to above-grade wall sections. The interface between the slab edge and the wall is an important construction detail and includes additional considerations such as termite concerns that need to be carefully addressed.

The vast majority of crawl spaces and basements in cold climates are in need of retrofitting. Insulating on interior walls is viable, but careful attention has to be taken to mitigate any moisture

[2] See information in the roadmap about global warming reduction potential of cool roofs. Unfortunately, garden roofs do not reject solar energy back to space, whereas reflective cool roofs do.

problems. This concern has been the subject of continuing debate among global building researchers and is receiving more attention as problems with other components of the building envelope have been solved.

Insulating floors that are over basements or crawl spaces is an easy measure for new construction and in some retrofits. This turns the basement into semi-conditioned space, which serves as a buffer zone. However, if the space is used and conditioned, then the insulation value will be wasted. Prior to insulating, any floor penetrations should be properly sealed. Similar to attics, if ductwork is located in the basement or crawl space, then it should also be properly sealed and insulated.

Windows

The most effective way to improve windows is to replace them with new products with superior performance. A significant advance in window technology over the last 20 to 30 years has been the development of low-e window coatings that are very thin, transparent metal films. Low-e coatings have the ability to reduce the thermal loss from windows and also to reflect solar energy. As recommended in the roadmap, the IEA is calling for all new windows installed in the world to be equivalent to the performance of double glaze low-e with low conductive frames, and in cold regions, equivalent to triple glaze with two low-e surfaces and low conductive frames.

Beyond replacing windows, there are ways to upgrade existing window systems when replacement is not possible (e.g. historic buildings) or cost effective. For instance, reducing solar heat gain in hot climates is much easier than reducing U-values in cold climates because the sun's energy can be reflected. Shading materials perform best when they are installed on the exterior of the building and can include shutters, awnings, solar shades and a variety of other shading devices. Interior shading with highly reflective surfaces, such as a bright white colour, can also be effective but have less of an effect if low-e glass is installed.

Window films are a very effective technology and can significantly reduce solar heat gain while maintaining a view to the outdoors. New low-e coated window films can reduce U-values by as much as 42% when installed on single glazed clear glass windows (LaFrance, 2012). In the United States, window films have full product performance ratings in the National Fenestration Rating Council's rating system,[3] but more work is needed on the full complement of window attachments globally.

Insulated cellular shades (that look like a honeycomb) can also reduce U-values on windows and are more effective in cold climates. However, proper installation is essential to minimise air flow between the shade and window to ensure that full improvement is achieved. Another well-known method to improve the performance of existing windows is to add an exterior storm window panel or an interior panel with low-e glass. Performance of a single glazed clear glass window with a low-e panel is very close to the performance of a new double glazed low-e window with a low conductive frame. This is important since the large stock of inefficient single glazed windows can be modified to perform comparably to the performance of new typical building code-compliant windows and still be very cost effective (Quanta, 2012).

Highly insulated windows – beyond triple glaze low-e

Many researchers and manufacturers have worked on multiple glazed windows (triple or quadruple) with multiple low-e coatings, exotic inert gases (e.g. krypton and xenon), advanced

[3] The National Fenestration Rating Council is a voluntary non-profit programme in the United States that rates windows and also has an international partner member programme. See www.nfrc.org for more information.

insulated frames and innovative edge seals to develop very high-performance windows. These windows have been promoted as having performance comparable to many wall assemblies. To date, these windows have generally not been able to achieve economic viability.

Vacuum glazing systems have been looked at as a way to achieve dramatic performance improvement while maintaining a thin, easy-to-install glazing unit. Japan is the only country with an established market for this technology and has been selling vacuum glazing systems for many years, although there are limitations on size and restrictions in severe cold climates due to concerns with thermal expansion. While Japan's vacuum glazing windows are high performance, they do not exceed that of conventional triple glazed windows.[4]

Researchers in Germany have worked on vacuum glazing systems and have invested EUR 10 million in the technology. Despite this, a high-performance market-viable vacuum glazing system has yet to be developed (ZAE BAYERN, 2013). In the United States, several research efforts are under way with the objective to develop a vacuum glazing process that will be compatible with the main manufacturing processes found in window production and that will be viable in all climates. So far, a successful product has not been developed. China similarly has been working on vacuum glazing systems, but there are limitations on product applicability and large-scale production has not been initiated. More research and development (R&D) therefore is needed to commercialise market viable, high performance, vacuum glazing systems.

Advanced solar heat gain

Advance glazing systems with low-e, spectrally selective glass significantly outperform older conventional glass, such as clear, tinted and reflective glass. Many occupants will be highly satisfied with these advanced coatings, and significant energy can be saved. However, these windows with static (fixed) solar heat gain coefficients (SHGCs) are still sub-optimal for energy performance for most climates. For instance, having a high solar heat gain in cold climates will provide needed benefits in winter months but may also lead to excessive indoor temperatures on hot summer days. By contrast, passive designs, with proper building orientation and large overhangs on equator-facing exposures that only allow direct sunlight to enter the space in winter months, can avoid this problem of summer overheating while also providing needed winter heat gain benefits. At the same time, there are many existing buildings for which this option is not possible or practical.

Similarly in hot climates, buildings with modest (or appropriate) window-to-wall ratios combined with advanced window glazings with very low SHGCs and the highest possible visible transmittance can provide energy benefits, but these windows may still prove to be too dark. When direct sunlight is not hitting the glass (e.g. on overcast/rainy days), these low SHGC windows may require lots of artificial light to be used, thereby increasing overall building energy consumption.

Glass manufacturers are continually trying to increase the visible light to SHGC ratio to address this concern, but there are physical limitations as to how much the technology can be improved. What appears to be the best solution today is to incorporate automatic exterior shade control, with advanced low-e spectrally selective glass that has higher visible transmittance and with appropriate window-to-wall ratios, as demonstrated in many low-energy buildings. These designs usually require building simulation software to assess annual energy impact, including overall heating, cooling and lighting energy consumption.

Automated exterior shades have very good energy performance but they can be expensive to install and maintain due to operable motors and control systems. Automated shading systems are widely

[4] Conventional triple glaze windows with low-e coatings and efficient frames have performance of approximately 1.1 Watts per square metre Kalvin (W/m^2K), whereas very efficient windows approach 0.6 W/m^2K.

available in Europe, where energy prices are high and penetration rates of air conditioning are very low. If these systems are planned during the design stage with full building control systems and the elimination of cooling systems, their economics can be viable in locations with moderate energy prices. Interior shades offer very good visible light control but do not achieve very low SHGCs. All of these options can be integrated with automatic dimming lights to save lighting energy. Effective automated controls for all dynamic systems are at a state that could benefit from more development to reduce installed costs. Today, these are the best widely available solutions and they represent a mature market in various regions. However, roadmap workshop participants believe consumer and building operators would prefer additional options.

One such solution to allow for optimal solar heat gain control in all climates and under all seasonal and diurnal conditions is dynamic solar glazings. Dynamic solar glazings allow for variable light and heat transmission through the glass. Researchers have been working on this for well over 30 years, but recently there has been significant progress.

The current market leader for dynamic solar glazings has been selling commercial products for over five years and opened a large new factory in 2013. Many demonstration buildings have been constructed with product from early production lines, and several companies are working on R&D, including a second company that has also built a new factory to produce electrochromic glass coatings, which is just starting to enter the market. Private sector investment in this new technology over recent years exceeds USD 250 million.

Thermochromic coatings that change optical properties based on the temperature of the glass are another viable option also available on the market. These coatings do not have active control, which may limit their optimal savings, although they do have the simplicity of having less systems equipment. If the temperature point of tinting can be tuned to different climates, significant savings may be realised compared to static glazings.

Windows – air leakage beyond improper installation

Windows, especially in older buildings, are responsible for a major portion of air leakage. New operable windows generally have much tighter seals than old existing windows. There are concerns that as windows age, air leakage increases. This is predominately due to thermal cycling from high-temperature exposure under direct sun conditions in the summer and large diurnal temperature differences during cold winters. Materials such as vinyl, which are becoming very prevalent and have low thermal conductivity, unfortunately also have high thermal coefficients of expansion. Many manufacturers consider this when developing window designs, but not all manufacturers, and window durability can suffer. Performance metrics that show “aged” or long term predicted air leakage rates would be helpful to ensure that expected energy savings are realised. Some window designs, mostly in Europe, include a locking gasket system that has very low air leakage and long-term performance is generally very good. However, because these windows are so tight, many manufacturers have incorporated vents in windows that waste energy (see roadmap section on air sealing where it describes a preferred approach to have very low air leakage for buildings while controlling for fresh air ventilation).

Integrated roof systems

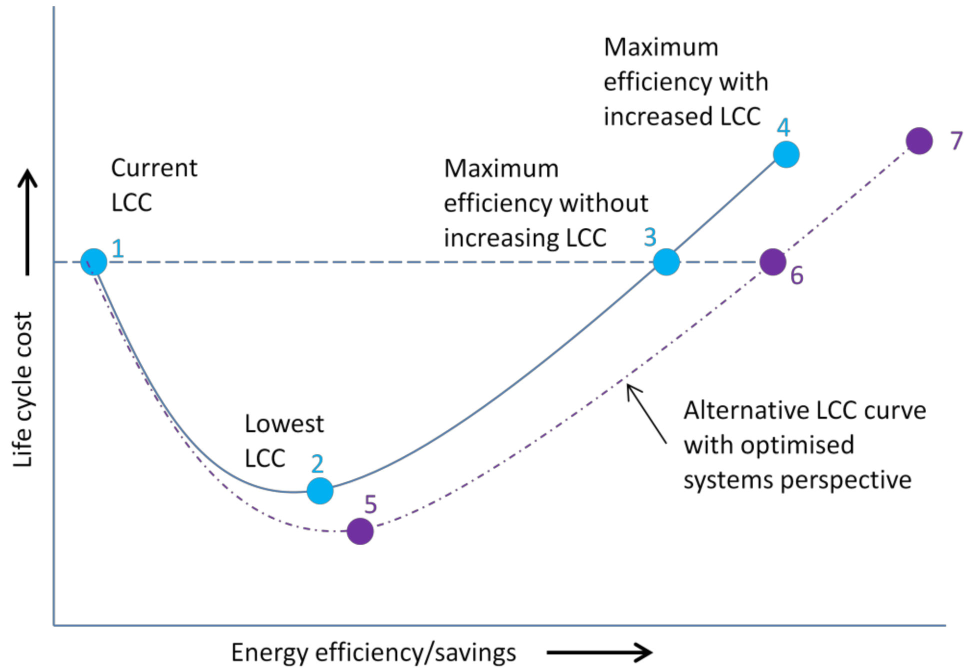
Increasingly, there are many interests associated with roof space, including solar photovoltaic (PV), building integrated PV (BIPV), solar thermal systems and cool roofs. For instance, a well established, efficient approach is the installation of skylights in buildings to provide daylighting benefits. These systems need to be designed to minimize cooling load impacts while also maximising lighting savings through proper artificial lighting design and operation. These systems can be very effective if implemented correctly, and with improved glazing technology (discussed above), they can offer low U-values while increasing visible light transmissions and avoiding unnecessary solar heat gain. The best roof systems therefore employ a balance of advanced technologies that are tailored for the particular building type, design and climate.

Annex B: Life-cycle cost analysis

This annex provides a more detailed discussion regarding life-cycle costs (LCC) to improve the knowledge base among policy makers. This section does not include extensive analysis on the large set of varying data that exists, but rather focuses on the need for local and regional policy makers to consider LCC when implementing new policies tailored to increase the investment associated with energy efficient building envelopes (see BPIE, (2013) for more discussion on this subject).

Transitioning typical construction practices to lowest LCC is represented by moving from point “1” to point “2” (see Figure B.1). Adding additional efficient envelope measures to increase total energy savings will increase cost, but will still be cost effective compared to the existing typical practice (moving from point “2” to point “3”). Incorporating the highest available efficiency that will have a higher life cycle cost is represented by point “4” and generally would not be recommended unless it were subsidised as part of an early adoption programme (e.g. a voluntary programme to move niche products into the mainstream) or if it were offsetting environmental benefits (e.g. through carbon credits).

Figure B.1 Life cycle cost analysis for energy efficient envelopes and integrated systems



Key point: LCC analysis is important to allow for greater investment in higher performing building envelopes and integrated systems.

Considering a full systems integrated perspective when other building end-uses are considered (e.g. heating, cooling and lighting equipment), an alternative LLC curve can be derived (points “1”, “5", and "7” in Figure B.1). Point “5” represents a new low LCC that has greater energy savings. This point will likely have less building envelope measures but will be the best economic opportunity. Furthermore, with assertive energy policies, point “6” could be justified since it does not increase LCC and has greater energy savings.

Establishing robust, accurate LCC curves for energy efficiency measures is challenging due to the lack of data, uncertainty and large variability of key inputs. Establishing adequate analysis that will result in policies to promote lowest LCC (*i.e.* point “2” or “5”) is much easier than policies to drive efficiency to the maximum that is cost effective (*i.e.* point “3” or “6”). A key desired result of this roadmap is to get policy makers to start assessing LCC in the policy setting process in order to achieve more value added and high efficiency building construction.

LCC example for integrated building envelopes

This section is a supplement to the results provided in the roadmap (see Figure 17 of the roadmap). This includes four core options (see Table B.1):

- Electric resistance heating upgrade to a heat pump
- A set of envelope measures that include insulation, low-e glass and air sealing
- An integrated approach with envelope measures and heat pump without capacity reduction[5]
- An integrated approach that expands the envelope measures and heat pump with a reduction of the capacity of the heating equipment.

In this analysis (using one set of data and assumptions, shown in Tables B.2 and B.3), an integrated approach results in the lowest LCC with the largest energy savings. However, a full analysis for public policy should include a wide range of data and assumptions for energy pricing, energy savings and costs.

Table B.1 Summary of energy savings and LCC for efficiency upgrade options

Options	Capital cost (USD)	Annual Energy (kWh)	% Energy Saved	LCC (USD)
Baseline		12 000		23 521
Heat pump only	3 000	6 000	50%	16 686
Envelope only	6 542	3 751	60%	13 894
Integrated without capital cost reduction	9 542	1 875	84%	15 144
Integrated with capital cost reduction	8 642	1 875	84%	13 666

Source: Unless otherwise indicated, all figured and tables are derived from IEA data and analysis.

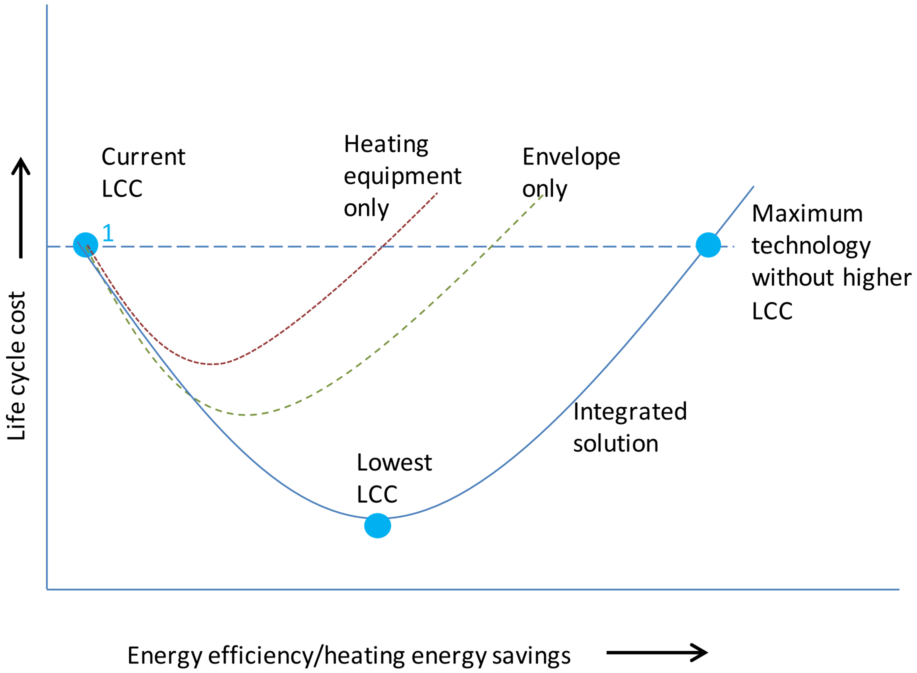
This example provides a simplified theoretical perspective that is then supported by actual real cost, energy prices and the assumptions provided below. It represents a real world case study that is reflective of an inefficient building with a poorly performing building envelope and that is heated by inefficient electric resistance heat. It depicts a highly beneficial scenario that may not be representative of the typical housing stock in the world but that is nonetheless representative of millions of housing units across the globe. The example is intended to illustrate key policy issues so to encourage more robust analysis by local and regional policy makers and building implementers.

Three separate LCC curves representing only heating improvements, only envelope improvements and the integration of both heating and envelope improvements are shown (see Figure B.2). These curves represent numerous energy efficiency measures that can be combined or considered separately and that would not fit a perfect curve. However, the most viable set of incremental measures would resemble a similar path so that initial energy saving opportunities would have modest LCC and modest energy savings until a lowest LCC optimal point is reached. Further savings

[5] Often heating contractors have standardised sizing criteria and may not conduct new sizing calculations. Furthermore, a common practice is to replace existing equipment with the same capacity to avoid cost, delay in installation, and liability concerns with under sizing equipment.

are likely to be more expensive and would produce higher energy savings, although at a greater marginal investment.[6] Ultimate maximum energy savings (e.g. extremely high levels of insulation and highly insulating windows with U-values below 0.6 W/m^{2}K in locations with moderate energy prices today) would likely result in LCCs that are higher than not upgrading typical housing stock.

Figure B.2 Typical LLC curves for a set of energy efficiency measures



Key point: Integrated solutions will result in the lowest LCC.

Detailed data to support roadmap example of integrated approach

Assumptions and data used for the analysis of the four scenarios described here are reflective of a mature market (Tables B.2 and B.3). The choice of upgrading from electric resistance heating to heat pumps (as applied in this analysis) is generally more competitively advantageous than many other applications. However, from a building envelope perspective, such an option is a very conservative assessment since other heating options, depending on specific conditions, may not be as economically favourable. For instance, moving from electric resistance to heat pumps with a coefficient of performance (COP) of 2.5 improves efficiency by 150%, whereas moving from a conventional boiler to a condensing boiler improves efficiency by around 15%. By using the example of electric heat pumps, this particular analysis illustrates heating and envelope improvements as being comparable. In reality, building envelope improvements may offer a greater opportunity at lower LCC (e.g. compared to boiler efficiency improvements). As stated extensively in the roadmap, an integrated approach needs to be considered based on the local situation and available data. Overall, significantly greater investment in efficient building envelopes is possible with favourable return on investments.

[6] This is representative of most energy efficiency opportunities, although large displacement technologies may not follow this model.

Table B.2 Case study assumptions

Characteristic	Metric
Discount rate	3%
Electricity rate	USD 0.10/kWh
Life of analysis	30 years
Floor area (m^2)	120
Windows % of floor area	15
Story	1
Dimensions	10m x 12m
Heating intensity	100 Kwh/m^2/yr
Annual heat load (base)	12000
Wall height	2.5 m
Heating equipment life	15 years

Table B.3 Building characteristics, data and assumptions

Baseline	Metric	Upgrade	Metric	Savings potential	Used for analysis	Price premium (USD)	Installation
Electric resistance	Efficiency 100%	Heat pump	COP 2.5	40% - 70%	50%	3 000/ house	Installed cost
Single glaze clear windows	U-value 5.6 Wm^2K	Low-e film to double low-e	U-value 2.4 Wm^2K to 1.8 Wm^2K	42% - 65%	42%	75/m^2	Installed cost
Wall insulation	U-value 0.7 Wm^2K	Add exterior rigid insulation (2.5 to 5 cm)	+ U-value of 0.56 Wm^2K, results in U-value of 0.31 Wm^2K	56%	56%	16/m^2	30% added labour cost to material cost, at time of re-siding
Floor[7] insulation	U-value 0.7 Wm^2K	Add 13 cm batt insulation	+ U-value of 0.43 Wm^2K, results in U-value of 0.27 Wm^2K	5%	5%	5/m^2	50% added labour cost to material cost, additional measure
Roof insulation	U-value 0.37 Wm^2K	Add batt or loose fill insulation (~24 cm)	+ U-value of 0.19 Wm^2K, results in U-value of 0.12 Wm^2K	68%	68%	6/m^2	50% added labour cost to material cost, additional measure
Air sealing	10 ACH at 50 Pa	Air sealing	1 ACH at 50 Pa	20% to 30% of heating energy	25%	20/m^2	Installed cost

Source: NREL (National Renewable Energy Laboratory) (2013), "National Residential Efficiency Measures Database", www.nrel.gov/ap/retrofits/index.cfm. Home Depot (2013), Insulation Prices. www.homedepot.com.

[7] Represents a raised structural floor, foundation insulation would likely use insulated board stock but would be more expensive with a lower thermal load (below grade application).

Abbreviations and acronyms

BIPV	building-integrated photovoltaic
COP	coefficient of performance
EIFS	exterior insulation finishing system
EPS	expanded polystyrene
ETICS	external thermal insulation composite system
IBP	Fraunhofer Institute of Building Physics (Germany)
ICF	insulated concrete forms
IEA	International Energy Agency
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory (United States)
LCC	life-cycle cost
Low-e	low-emissivity
NREL	National Renewable Energy Laboratory (United States)
ORNL	Oak Ridge National Laboratory (United States)
PCM	phase change material
PV	photovoltaic (solar)
R&D	research and development
SHGC	solar heat gain coefficient
SIP	structurally insulated panel
VIP	vacuum-insulated panel
USD	United States dollar
XPS	extruded polystyrene

Units of measure

kWh	kilowatt hour (10^3 watt-hour)
m^2	square metre
Pa	pascal
W/mK	watts per metre Kelvin
W/m^2K	watts per square metre Kelvin

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