Technology Roadmap

Energy-efficient Buildings: Heating and Cooling Equipment

International Energy Agency

INTERNATIONAL ENERGY AGENCY

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.
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Foreword

Current trends in energy supply and use are unsustainable – economically, environmentally and socially. Without decisive action, global energy-related greenhouse gas (GHG) emissions will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. In the building sector, the global number of households will grow by 67% and the floor area of service sector (commercial and institutional) buildings by almost 195%. We can and must change our current energy and climate path; energy-efficient and low/zero-carbon energy technologies for heating and cooling in buildings will play a crucial role in the energy revolution needed to make this change happen. To effectively reduce GHG emissions, numerous items will require widespread deployment: energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies. Every major country and sector of the economy must be involved and action needs to be taken now to ensure that today's investment decisions do not burden us with sub-optimal technologies in the long-term.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To address these challenges, the International Energy Agency (IEA), at the request of the G8, is developing a series of roadmaps for some of the most important technologies needed for achieving a global energy-related Carbon dioxide (CO_2) target in 2050 of 50% below current levels. Each roadmap develops a growth path for the technologies covered from today to 2050, and identifies technology, financing, policy and public engagement milestones that need to be achieved to realise the technology's full potential. These roadmaps also include special focus on technology development and diffusion to emerging economies, to help foster the international collaboration that is critical to achieving global GHG emissions reduction.

Buildings account for almost a third of final energy consumption globally and are an equally important source of CO_2 emissions. Currently, both space heating and cooling as well as hot water are estimated to account for roughly half of global energy consumption in buildings. These end-uses represent significant opportunities to reduce energy consumption, improve energy security and reduce CO_2 emissions due to the fact that space and water-heating provision is dominated by fossil fuels while cooling demand is growing rapidly in countries with very carbon-intensive electricity systems.

The *Energy-Efficient Buildings: Heating and Cooling Equipment* Roadmap sets out a detailed pathway for the evolution and deployment of the key underlying technologies. It finds that urgent action is required if the building stock of the future is to consume less energy and result in lower CO_2 emissions. The roadmap concludes with a set of near-term actions that stakeholders will need to take to achieve the roadmap's vision. It is the IEA hope that this roadmap provides additional focus and urgency to the international discussions about the importance of energy efficiency as a technology solution.

Nobuo Tanaka
Executive Director, IEA

This roadmap was prepared in 2011. It was drafted by the IEA Sustainable Energy Policy and Technology directorate. This paper reflects the views of the International Energy Agency (IEA) Secretariat, but does not necessarily reflect those of individual IEA member countries. For further information, please contact: technologyroadmapscontact@iea.org

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The *Energy-Efficient Buildings: Heating and Cooling Equipment* roadmap has been developed in collaboration with governments, industry, experts and the IEA energy technology network, of which the Implementing Agreements are the most important asset (see www.iea.org/techno/index.asp).

Roadmap Workshop Participants

A full list of participants can be found online at www.iea.org

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Key findings

- Low/zero-carbon and energy-efficient heating and cooling technologies for buildings have the potential to reduce CO_2 emissions by up to 2 gigatonnes (Gt) and save 710 million tonnes oil equivalent (Mtoe) of energy by 2050. Most of these technologies – which include solar thermal, combined heat and power (CHP), heat pumps and thermal energy storage – are commercially available today.
- An additional USD 3.5 billion a year needs to be made available for research, development and demonstration (RD&D) by 2030. R&D efforts should focus on reducing costs and improving the efficiency and integration of components. R&D into hybrid systems could lead to highly efficient, low-carbon technologies (*e.g.* integrated solar thermal/heat pump systems, CHP). Beyond 2030, R&D needs to focus on developing technologies that go beyond the best that are currently available.
- Governments need to create the economic conditions that will enable heating and cooling technologies to meet environmental criteria at least cost. Policies need to be "broad" to address specific barriers (*e.g.* lack of installer awareness) and "deep" to reach all of the stakeholders in the fragmented building sector.

Key actions in the next 10 years

- Policy working groups should be convened that include stakeholders from all areas of government to develop policy and ensure that energy-efficient and low-carbon technology priorities are aligned with environmental policies and do not face barriers because of conflict with other policy goals (*e.g.* fire, equipment safety and local planning).
- Governments should develop national roadmaps, tailored to local circumstances, to help to drive market expansion, advance systems development and integration, shape supportive policy and enhance collaboration. Policies should set measurable and meaningful targets, such as CO_2 emissions reductions, or ensure that programme effectiveness is verified regularly.
- Governments should implement systems to collect comprehensive and timely data on energy consumption by end-use in the buildings sector, as well as data on building characteristics, technology deployment, market breakdown, costs and efficiency. This will help improve policy development and allow the monitoring of progress towards roadmap goals
- A wide variety of standardised information packages, tailored to individual decision makers' needs, should be developed to allow decision makers to compare the potential of technology alternatives, identify performance targets and energy and CO_2 savings at the time of design or purchase.
- Governments should improve standard education of key professionals, such as architects, designers, engineers, builders, building owners and operators/users in the potential of existing and soon to be commercialised heating and cooling equipment.
- Policies such as minimum energy performance standards, labelling, utility programmes and financial incentives are needed over the next 10 years to address market barriers – such as high initial costs and low priority of energy efficiency in decision-making – and market failures (*e.g.* principal-agent problems, transaction costs, search costs, compliance issues). Governments need to highlight the role of technologies in reducing financial risks, such as energy and carbon price volatility.
- Over the next 10 years governments should expand and/or implement mandatory quality assurance and certification schemes for equipment and installers (including training). These should be harmonised across the heating and cooling technology industry, so that decision makers are faced with a simplified decision process.
- Industry and governments need to work together and share information on an international level to help lower costs, accelerate technology deployment, and provide quality and performance assurance for installed systems. Key areas for collaboration include research, market deployment, performance and test procedures, setting of energy and CO_2 emissions reduction targets/standards, harmonisation/comparability of heating and cooling system tests, and policy development.

Rationale and scope

Roadmap rationale

In *Energy Technology Perspectives 2010,* the IEA outlines a business-as-usual Baseline scenario and a scenario in which energy-related CO_2 emissions are reduced by 50% in 2050 from 2007 levels, the BLUE Map scenario (IEA, 2010a). In the Baseline scenario, global final energy demand in buildings increases by 60% from 2007 to 2050 (Figure 1). CO_2 emissions from the sector, including those associated with electricity use, nearly double from 8.1 Gt of CO_2 to 15.2 Gt CO_2. This increase is driven by a 67% rise in the number of households, a near tripling of the service sector building area,[1] higher ownership rates for existing energy-consuming devices and increasing demand for new types of energy services.

The BLUE Map scenario charts an entirely different future for the buildings sector, in which aggressive policy action reduces energy consumption and CO_2 emissions and improves energy security. In this scenario, global building-sector energy consumption is reduced by 1 509 Mtoe in 2050 (Figure 2), while CO_2 emissions are 83% lower than in the Baseline scenario. This can only be achieved by retrofitting existing buildings.

In the BLUE Map scenario, energy consumption in the buildings sector is reduced by around one-third of the Baseline scenario level in 2050.

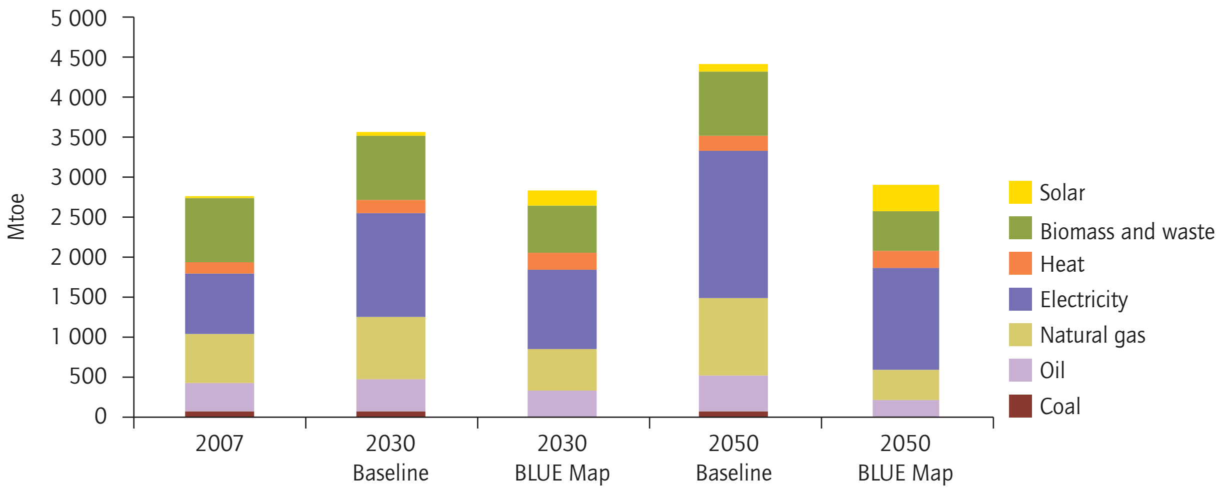
1. For simplicity, service sector buildings are also referred to as commercial buildings in this roadmap.

Energy consumption in 2050 is only 5% higher than in 2007, despite an increase in the number of households by 67% and in the service sector floor area of 195% over that time. The consumption of fossil fuels declines significantly, as well as that of traditional biomass. The residential sector accounts for 63% of the buildings sector's energy savings from the Baseline scenario in 2050.

Energy-efficient and low/zero-carbon heating and cooling systems[2] and building shell improvements account for 63% of the energy savings in the BLUE Map scenario and play a central role in reducing CO_2 emissions and increasing system flexibility. The reduced oil and gas consumption as the result of a switch to these technologies improves energy security and may also improve a country's balance of payments by reducing imports of energy. The increased use of thermal energy storage technologies in buildings will help improve demand flexibility, while real-time pricing and dynamic communication with smart energy networks will enable the building sector to provide very cost-effectively some of the increased flexibility required in the BLUE Map scenario (to accommodate an increased share of variable renewables), helping to reduce the need for expensive electricity storage.

2. The terms "air conditioning" and "cooling" are used interchangeably in this document. They refer to the conditioning of a building's internal area where desired internal temperatures are being reduced. It can include dehumidification or humidification. This roadmap does not deal with other internal air quality issues.

Figure 1: Buildings sector energy consumption by fuel and by scenario



Source: Unless otherwise indicated, material in figures and tables derive from IEA data and analysis.

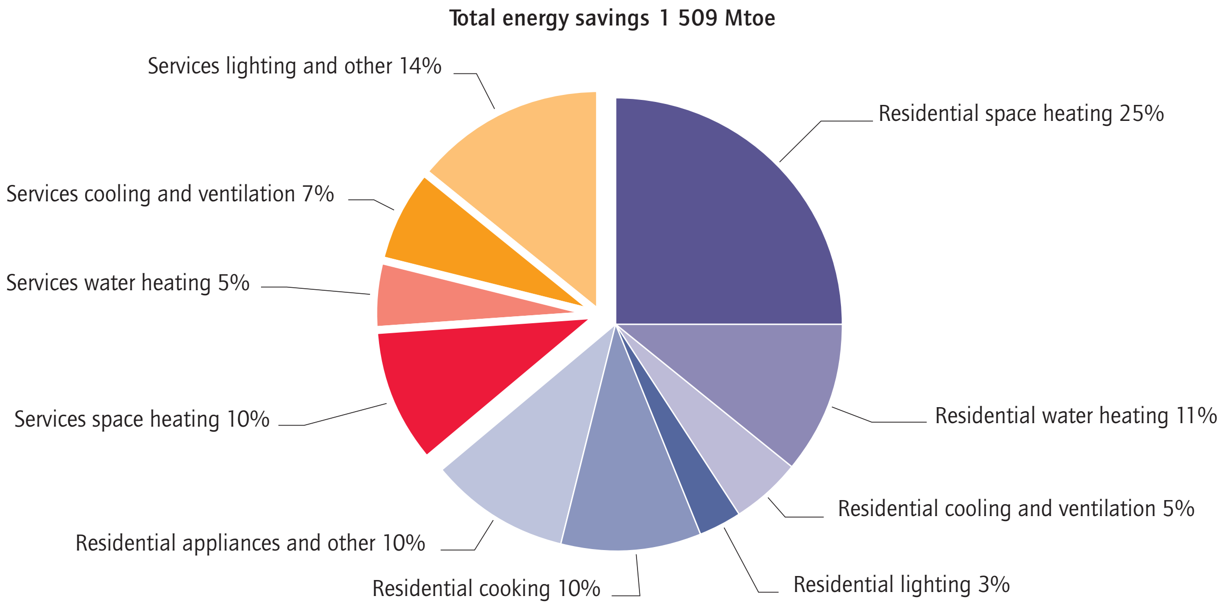
KEY POINT: Energy consumption in the building sector is 5% higher in 2050 than in 2007 in the BLUE Map scenario.

Box 1: *Energy Technology Perspectives 2010* BLUE Map scenario

This roadmap outlines a set of quantitative measures and qualitative actions that define one global pathway for heating and cooling technology deployment to 2050. This roadmap starts with the IEA *Energy Technology Perspectives 2010* (ETP) BLUE Map scenario, which describes the role of energy technologies in transforming the buildings sector by 2050 in line with an overall goal of reducing global annual energy-related CO_2 emissions to half that of 2007 levels. The model is a bottom-up MARKAL model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources and technology progress. The ETP model is a global 15-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 1 000 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 MARKAL model is supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

It is important to note that some of the rates of change (*e.g.*, annual change in equipment sales) in the BLUE Map scenario are unprecedented historically. To achieve such a scenario, strong policies will be needed from governments around the world. The BLUE Map scenario is predicated on strong policies to accelerate energy R&D, deploy energy efficient and low/zero-carbon energy technologies and put a value on CO_2 abatement (the BLUE Map scenario necessitates a marginal abatement cost in 2050 of USD 175/t CO_2). The scenario also assumes robust technological advances (*e.g.* higher-efficiency components for heating and cooling systems) that, if they do not occur, will make achieving the targets even more difficult or expensive. On the other hand, some unforeseen advances may assist in achieving the scenario or certain aspects of it (*e.g.* a more rapid fall in lithium ion battery costs, or breakthroughs in fuel cells).

Figure 2: Buildings sector energy savings by sector and end-use



KEY POINT: Two-thirds of the buildings sector energy savings in the BLUE Map scenario come from the residential sector.

Carbon dioxide emissions savings in the buildings sector in the BLUE Map scenario total 5.8 Gt CO_2 in 2050, with 2 Gt CO_2, or around 35%, coming space heating and from cooling, ventilation and hot water equipment. The decarbonisation of the electricity sector accounts for the remaining 6.8 Gt CO_2 of savings, but also allows electrification, notably through heat pumps, to become a viable abatement option.

Roadmap scope

This roadmap establishes a "big picture" vision for stakeholders in the buildings sector[3] and provides concrete advice on how to achieve the savings in the BLUE Map scenario. This vision is needed to address the fragmented nature of the industry, the long-term nature of the goals and the barriers that these create. The roadmap highlights the key technology options, the barriers they face and the policy options to address these barriers. It provides stakeholders with a structured and comprehensive vision of the long-term goals for the sector, as well as identifying specific milestones and packages of policies to achieve these goals.

An integral part of the roadmap is identifying the roles and contributions of different stakeholders and how they will need to work together to reach the shared objectives outlined in the BLUE Map scenario. The key areas addressed in this roadmap are:

- The status, costs and future developments in selected heating and cooling technologies.
- The areas where specific R&D needs have been identified, as well as technology development goals and milestones.
- Specific deployment goals for heating and cooling technologies in the building sector.
- Policy recommendations, to overcome existing and future barriers to heating and cooling technologies, and their timing to ensure the BLUE Map scenario results are achieved.

3. The building sector is defined as the buildings of the residential and service sectors. The service sector includes activities related to trade, finance, real estate, public administration, health, food and lodging, education and commercial services (ISIC codes 50-55 and 65-93). This is sometimes also referred to as the commercial and public services sector. The energy savings potential in industrial buildings is not covered in this roadmap, although the technologies described in this roadmap are those also applicable in these buildings.

The key technology options for heating and cooling in buildings have been narrowed down to those with the greatest long-term potential for reducing CO_2 emissions. This roadmap covers the following technologies for space and water heating, heat storage, cooling and dehumidification:

- Active solar thermal.
- Combined heat and power (CHP).
- Heat pumps for space heating and cooling, and hot water.
- Thermal storage.

This roadmap on heating and cooling technologies[4] is the first to be published for the buildings sector. Future efforts will look at the building shell, lighting and system issues. Buildings require a holistic, "whole-building" approach to maximise savings and minimise costs, so although these roadmaps are published separately, they have been developed within a "whole-building" outlook.[5]

4. This roadmap covers heating and cooling equipment, their controls and operation in buildings. Savings in energy used to operate ventilation systems (predominantly electric motors) are included in the totals in this section, but are not discussed in this roadmap.

5. For instance, district heating is included in power generation in the IEA framework, and so is not considered here. In 2007 district heating provided 123 Mtoe of energy to the building sector (5% of the total). Another key technology for buildings that is treated in a separate roadmap is solar photovoltaics.

Status of heating and cooling technologies today

Overview

This roadmap covers several key building technologies for space and water heating, heat storage, cooling and dehumidification.[6] They are:

- **Active solar thermal (AST)** can provide space and water heating, as well as cooling needs. This roadmap focuses on building integrated systems, but it can equally be used in district-heating schemes.
- **Combined heat and power** systems of building scale (1 kW_e to 1 MW_e) and "campus" scale (1 MW_e to 5 MW_e) are the focus of this roadmap. Traditional CHP systems are mature and a useful transitional technology, while micro-CHP, biomass CHP and even fuel cell systems (using CO_2-free hydrogen) may emerge as an important abatement option.
- **Heat pumps for cooling and space and water heating** are mature, highly efficient technologies that take advantage of renewable energy.
- **Thermal storage** includes sensible (hot water, underground storage) and latent ("phase change" ice storage, micro-encapsulated phase-change materials) and thermo-chemical storage. Thermal storage can maximise the energy savings and energy efficiency potential of other technologies, facilitate the use of renewables and waste heat, and improve flexibility, helping to minimise the overall system cost of the BLUE Map scenario.

Heat pumps, active solar thermal and CHP can all be installed in almost all building types to provide space and water heating. For cooling, active solar thermal and CHP require thermally driven chillers,

6. Other technologies play an important, but smaller contribution and won't be covered in this roadmap. These include efficient fossil fuel technologies, such as condensing boilers, biomass and biofuels.

Table 1: Key characteristics of heat pumps, CHP and active solar thermal

	Typical size (kW) SFD	MFD/ service sector	Efficiency (%)	Capital costs (per kW)	Fuels	Fuel cost
Heat pumps (electric)	2.5-10	10-500	200-600	Low-medium (air conditioning)/medium-high (space/water heating)	Electricity,	Medium-high
Heat pumps (gas-engine driven)	15	15-150	120-200	Low-medium	Gaseous fuels	Low-medium
CHP	1-15*	15-500	70-90	Medium-high	Coal, liquid fuels, gaseous fuels, bioenergy, hydrogen	Low-medium
Solar thermal	2.5-10	35-130	100	Low-high	Solar	n.a.
Absorption/ adsorption chillers	n.a.	15-500**	70-120	Medium	Gas, oil, bioenergy, solar, waste heat, etc.	Low-medium

* kW_e

** Few manufacturers make available sub-50 kW systems, with most products being in the several hundred kW range.

Note: capital costs are relative to incumbent technologies and are provided as a guide only, see Tables 2, 3, 4 and 5 for more detail. Efficiency for heat pumps is final efficiency, not primary efficiency taking into account losses from electricity generation, transmission and distribution. MFD= multi-family dwellings and SFD= single-family dwellings.

while heat pumps are the standard for stand-alone space cooling today. Heat pumps and CHP systems come in a range of sizes from as small as 1 kW up to MW scale and are very modular. In larger buildings, multiple units can be installed to improve operational flexibility, allow optimal operation for efficiency and provide an element of redundancy/back-up. Active solar thermal systems are modular and different permutations of solar collector area and thermal energy storage are possible that mean systems can meet a wide range of demands, although systems in OECD countries generally cannot meet all space and water heating demand today at reasonable cost.

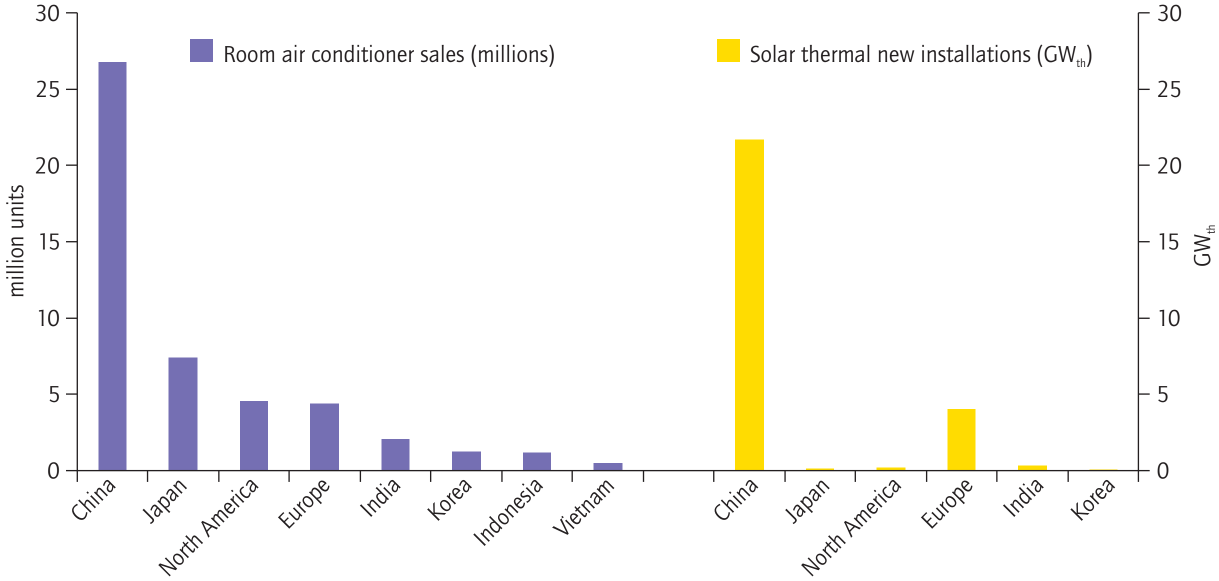
The importance of space heating and cooling varies by country and region depending on climate and income. In OECD countries, most energy in the building sector is used for space and water heating, while the energy consumption for cooling is generally modest.[7] In hot countries, with little or no space heating needs, cooling is much more important and given the largely immature market for cooling in these countries, represents a significant source of future energy demand growth.

Many criteria must be taken into account in the complex process of choosing heating and cooling technologies, including:

- annual heating profile for water and/or space heating, and annual cooling profile;
- relative timing of thermal and electric loads;
- space constraints;
- emission regulations;
- utility prices for electricity, and availability and prices of other fuels;
- initial cost and the cost of financing;
- the seasonal efficiency of the equipment;
- complexity of installation and operation;
- reputation of the manufacturer;
- architect/engineer/builder/installer's knowledge of available technologies and models.

7. In the US residential sector, a mature air-conditioning market, energy consumption for cooling is only around 8% of the residential energy consumption, while in commercial buildings the figure for cooling and ventilation is around 13 %. US DOE/EERE (2009).

Figure 3: Sales of residential air conditioners and active solar thermal systems in 2008-09 by country



Source: IEA Heat Pump Programme and Weiss, 2010.

KEY POINT: China is the most important market for room air conditioners and solar thermal systems.

The global market for heating and cooling is very large, with the market for cooling worth as much as USD 70 billion in 2008.[8] The value of the residential boiler market in 22 EU countries was estimated to be EUR 5.6 billion in 2004 at manufacturers' prices, not installed cost.[9] OECD countries dominate the market for space and water heating, but not for cooling, or for individual technologies. For instance, China leads the world for annual installed capacity of solar thermal systems and residential (room/unitary) air conditioners (Figure 3).

The market for micro-CHP is still in the early stages of development.[10] Global sales were worth USD 346 million (EUR 269 million) in 2009, however this represents just 37.8 MWe of capacity.[11]

8. www.bsria.co.uk/news/global-air-conditioning-sales-reach-us70-billion-in-2008/.

9. Based on data in VHK (2007).

10. Assumed to be 50 kWe and under.

11. See www.delta-ee.com/downloads/Delta_Micro-CHP%20Annual%20Sales_jul10.pdf.

Active solar thermal

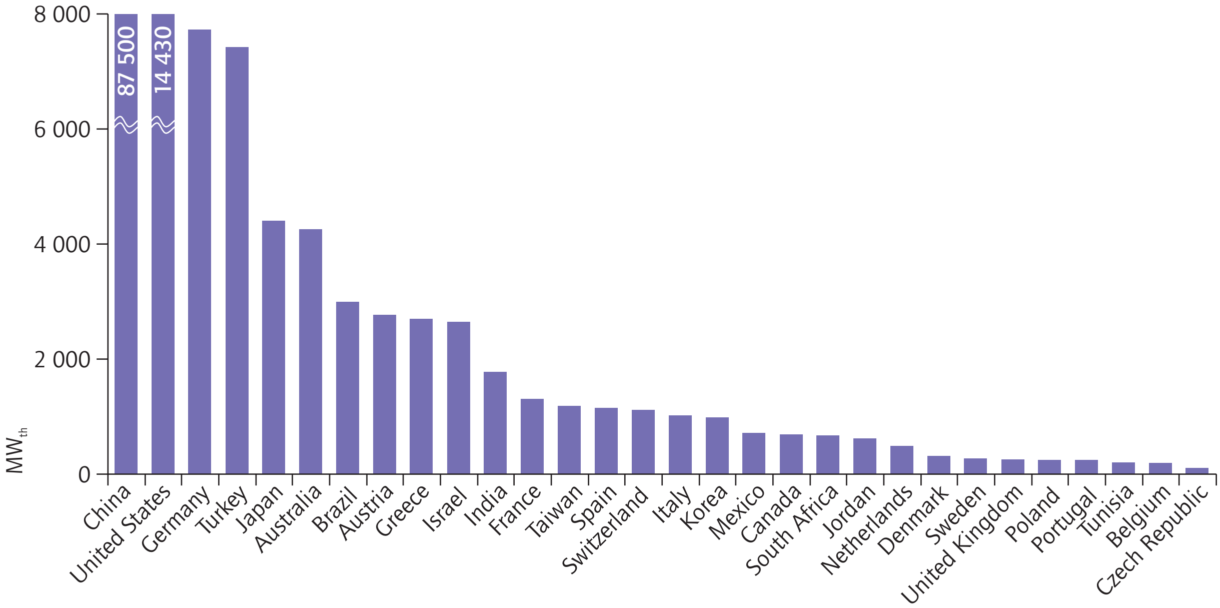
Overview

Solar thermal technologies provide heat that can be used for any low-temperature heat application in buildings, including space and water heating, and cooling with thermally driven chillers. The global installed capacity in 2008 was estimated to be 152 GW_{th}, with additions in that year of 29 GW_{th} (Figure 4).[12] They include a range of commercial technologies and systems that are competitive for water heating in markets where low-cost systems are available, energy prices are not low and solar radiation is good throughout the year. However, for solar to meet a larger share of the building sector's space heating and cooling needs, costs will have to come down and performance improve.

Cost reductions and improved performance are likely as there is substantial room for innovation and for improving existing technologies and applications, as well as commercialising emerging technologies such as solar cooling. In the BLUE

12. Weiss, *et al* (2010). These estimates are thought to represent 85%-90% of the actual installed global capacity, as some data gaps exist.

Figure 4: Installed solar thermal capacity by country (MW_{th}), 2008



Source: Weiss, 2010.

KEY POINT: China has 39% more installed capacity of active solar thermal systems than the rest of the world combined.

Map scenario, costs come down and low-cost[13] compact thermal energy storage becomes available allowing active solar thermal (AST) systems to play an important part in the transition to a sustainable energy profile for the building sector.

AST systems have several advantages. They can be applied almost anywhere and do not require any energy infrastructure. They are either carbon-free or have very low emissions, associated with their electricity use for pumping and controls. Owners and operators of AST systems do not have to consider the risks of changing energy prices and potentially, carbon prices.

Active solar thermal systems and their performance

AST systems collect the incoming radiation from the sun by heating a fluid (generally a liquid, but occasionally air). The heated fluid in these collectors is used either directly (*e.g.* to heat swimming pools) or indirectly with a heat exchanger transferring the heat to its final destination (*e.g.* space heating). The amount of heat energy provided per square metre of collector surface area varies with design and location but typically ranges from 300 kWh/m^2/yr to 900 kWh/m^2/yr.

13. The target for high-density energy storage for solar systems is that investment costs (after deployment) will be twice that of today's sensible energy storage systems.

Current solar water-heating systems for single-family dwellings are relatively small, with collector areas of 4 m^2 to 6 m^2, and meet 20% to 70% of average domestic hot water needs with a 150 litre to 300 litre storage tank. Solar combi-systems for single-family dwellings, which provide space and water heating, are larger, with current systems typically having a collector area of around 12 m^2 to 15 m^2 associated with a 1 000 litre to 3 000 litre storage tank. Combi-systems can meet 20% to 60% of the space heating and water heating needs of a single-family house. In both cases, an auxillary heating system is currently required to meet the balance of demand. However, as low-cost compact thermal storage becomes available it will remove the need for these auxillary systems in many applications. Where district heating systems exist, solar thermal energy can be produced on a large scale with low specific costs, even at high latitudes, as successful examples at the MW scale in Sweden and Denmark show.

An emerging application for AST systems is solar thermal air conditioning. Two main technologies can use solar thermal collectors for air conditioning in buildings:

- **Thermally driven chillers** are used to produce chilled water in closed cycles, which may then be used with any space conditioning equipment.
- **Open cycles** are also referred to as desiccant evaporative cooling systems (DEC) and are used for direct treatment of air in a ventilation system.

Table 2: Solar thermal system characteristics and costs for single-family dwellings, 2007

	Single-family dwelling		
	OECD Europe	OECD North America	OECD Pacific
Typical size: water heating (kW_{th})	2.8-4.2	2.6-4.2	2.1-4.2
Typical size: combi systems (kW_{th})	8.4-10.5	8.4-10.5	7-10
Useful energy: water heating (GJ/system/year)	4.8-8	9.7-12.4	6.5-10.3
Useful energy: space and water heating (GJ/system/year)	16.1-18.5	19.8-29.2	17.2-24.5
Installed cost: new build (USD/kW_{th})	1 140-1 340	1 200-2 100	1 100-2 140
Installed cost: retrofit (USD/kW_{th})	1 530-1 730	1 530-2 100	1 300-2 200

Source: IEA Solar Heating and Cooling Implementing Agreement; ESTTP, 2007; Navigant Consulting, Ecodesign Hot Water Task 4; and NEDO, 2009.

Table 3: Solar thermal system characteristics and costs for multi-family dwellings, 2007

	Multi-family dwelling		
	OECD Europe	OECD North America	OECD Pacific
Typical size: water heating (kW_{th})	35	35	35
Typical size: combi systems (kW_{th})	70-130	70-105	70
Useful energy: water heating (GJ/system/year)	60-77	82-122	86
Useful energy: space and water heating (GJ/system/year)	134-230	165-365	172
Installed cost: new build (USD/kW_{th})	950-1 050	950-1 050	1 100-1 850
Installed cost: retrofit (USD/kW_{th})	1 140-1 340	1 140-1 340	1 850-2 050

Source: IEA Solar Heating and Cooling Implementing Agreement; ESTTP, 2007; Navigant Consulting, Ecodesign Hot Water Task 4; and NEDO, 2009.

Coupling solar thermal collectors with thermally driven chillers would enable systems to meet space heating and cooling, as well as hot water demands. The dominant technology of thermally-driven chillers is based on sorption. The basic physical process consists of at least two chemical components, one of them serving as the refrigerant and the other as the sorbent. Many sorption chillers are available commercially at different capacities, but few at 100 kW_{th} or less.

Solar cooling is attractive because solar radiation usually coincides closely with cooling loads, while many service-sector buildings also have simultaneous heating and cooling requirements. However, costs will have to come down and a wider range of technology packages will have to be developed, particularly for single-family dwellings, before solar cooling is likely to be deployed on a large scale.

Combined heat and power

Overview

Combined heat and power is the simultaneous production of electricity and heat (for space and/or water heating), and potentially of cooling (using thermally driven chillers). CHP technologies can reduce CO_2 emissions in the building sector today in a wide range of applications, depending on the fuel chosen, its overall efficiency and the avoided CO_2 from central electricity generating plant. But like the electricity generation sector, CHP will have to decarbonise almost completely in the BLUE Map scenario. CHP can reduce transmission and distribution losses, and improve energy security and the reliability of energy supplies, particularly when combined with thermal energy storage.[14]

Typical CHP efficiencies in operation range from 75% to 85%, with state-of-the-art plant achieving efficiencies of 90%. Typical CHP capacities for single-family dwellings are 1 kW_e to 10 kW_e, while for multi-family dwellings or housing estates, systems are generally 30 kW_e to 500 kW_e. In the service sector, most opportunities for CHP fall in the 30 kW_e to 500 kW_e range. Larger systems are considered in this roadmap, up to 5 MW_e, but commercial buildings or office parks capable of supporting CHP above 1 MW_e represent only a small share of energy consumption.

Combined heat and power plants consist of four basic elements: a prime mover (engine or drive system), an electricity generator, a heat recovery system and a control system. CHP units are generally classified by the type of application, prime mover and fuel used. There are several mature CHP technologies, including reciprocating engines and turbines. Newer CHP technologies that are not yet fully commercialised, such as fuel cells and Stirling engines, are beginning to be

14. Several studies are under way to evaluate the operation of distributed CHP to help with load shifting. The European project Smart-A (www.smart-a.org) has highlighted some results.

deployed. Small-scale plants – so called mini-CHP or micro-CHP – can meet the needs of individual buildings or houses.

Today's total installed capacity in countries for which data is available is estimated to be 360 GW_e (IEA, 2008), representing a replacement cost of USD 630 billion to USD 700 billion. Although data are not available for the proportion of this CHP installed in residential and commercial buildings, the figure could be in the order of 10 GW_e and perhaps 17 GW_{th}. In the BLUE Map scenario, given the decarbonisation of electricity generation, CHP will need to shift to fuel sources that are carbon-free (biomass, biogas, hydrogen from CO_2-free sources, etc.) or largely carbon-free after 2030 if it is not to be a transitional solution to climate change. Building-scale applications using fuel cells (powered by CO_2-free hydrogen) and biomass CHP systems play an important part in the BLUE Map scenario after 2030. But achieving such an outcome for fuel cells will depend on cost reductions and improvements in performance and durability in the next 20 years.

CHP systems and their performance

CHP systems are generally more efficient, from a systems perspective, than the separate, centralised production and distribution of electricity and local production of heat, as CHP requires less primary energy. However, CO_2 savings are highly dependent on the specific energy system and the CHP system specifications.

A wide range of CHP technologies are already available, with different performance characteristics and costs. There are a number of mature technologies available, as well as some that are not widely deployed and others that still require further R&D. Recent and future technological developments may expand the range of cost-effective applications for CHP in buildings. The main CHP technologies are:

- **Microturbines** have not been widely deployed, despite having existed since the 1990s. They are smaller versions (typically 25 kW_e to 250 kW_e) of gas turbines and can use recuperators to preheat combustion air. Recuperated microturbines in the 30 kW_e to 100 kW_e capacity range typically achieve electrical efficiencies of about 23% to 29%, and overall efficiencies of 64% to 74%.
- **Fuel cells** use an electrochemical process that releases the energy stored in natural gas or hydrogen fuel to create electricity. Heat is a by-product. Fuel cells that include a fuel reformer can utilise the hydrogen from any hydrocarbon fuel. There are four main types of fuel cell: molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC) and polymer electrolyte membrane fuel cells (PEMFC). Fuel cells offer the advantage of nearly 1-to-1 electricity-to-heat ratios, making them well suited for modern low-energy buildings.
- **Reciprocating engines**, in the form of spark (Otto cycle) or compression-ignited (diesel cycle) internal combustion engines (ICE), are the most common CHP type today. They are a mature technology, available in a wide range of sizes, with electrical efficiencies of 25% to 48% (typically rising with size)[15] and total efficiencies of 75% to 85%.[16]
- **Stirling engines** are external combustion engines, as opposed to ICEs. They are not yet widely deployed, although a growing number of commercial units exist and more are being developed. They can use a wide range of energy sources and can have high overall efficiencies (up to 95%), albeit with relatively low electrical efficiency (8% to 20%).
- **Gas turbines** use high-temperature, high-pressure hot gases to produce electricity and heat. They can produce heat and/or steam as well as electricity, and come in the megawatt size-range. Typical electrical efficiency is 20% to 45%, while overall efficiencies are 75% to 85%.

While all CHP units perform the same broad task, the heat and electricity ratio differs from device to device. Conventional CHP technologies with an internal or external combustion engine or a turbine prime mover have high overall efficiencies but tend to provide more heat than electricity.

Fuel cells, an emerging technology, provide a higher proportion of electricity than other CHP technologies. However, the only fuel cell systems to have been widely commercially deployed are PAFC and PEMFC, with 5 000 PEMFC fuel cells

15. All efficiencies in this report are quoted in lower heating values.

16. Close to 100% efficiency can be achieved by certain systems with the use of a condenser in the external flue gas outlet.

having been installed in Japan in 2009 alone (JGA, 2010). Operational experience is therefore limited to these fuel cells, although there is significant R&D (both public and private) in the other fuel cell systems, while demonstration projects are providing valuable operating experience.

There remain challenges to the widespread uptake of CHP technologies in the residential sector, however, including their high first costs, scaling issues,[17] and regulatory and information barriers. In the service sector, some sub-sectors have proportionately larger water and space heating and cooling loads, with more stable loads throughout the year, which significantly improves the competitiveness of CHP solutions.

17. Sizing to meet hot water demand allows higher load factors, but at an individual building level means that space heating demand will need to be met to a greater or less extent by other heat sources.

Table 4: Technology and cost characteristics of small- and large-scale CHP technologies in 2007

	Reciprocating engines	
	Large-scale	***Small-scale***
Size range (kW_e)	100-3000	1-100
Economic life (years)	15-20	15-25
Electrical efficiency (%)	30-40	20-40
Total efficiency (%)	75-85	75-85*
Installed cost (USD/kW_e)	1 000-1 600	1 500-12 000
Fixed O&M (USD/kW/year)	1.5-10	Varies
Variable O&M (USD/kWh)	0.008-0.017	0.011-0.017
	Gas turbines and micro-turbines	
	Large-scale	***Small-scale***
Size range (kW_e)	1 000-5 000	30-250
Economic life (years)	15-20	10-20
Electrical efficiency (%)	25-40	25-30
Total efficiency (%)	70-80	65-70
Installed cost (USD/kW_e)	1 050-2 000	2 000-2 700
Fixed O&M (USD/kW/year)	10-40	20-67
Variable O&M (USD/kWh)	0.004-0.005	0.011-0.017
	Fuel cells	
	Large-scale	***Small-scale***
Size range (kW_e)	200-2 500	1-100
Economic life (years)	8-15	8-10
Electrical efficiency (%)	40-50	30-37
Total efficiency (%)	70-80	70-75
Installed cost (USD/kW_e)	5 000-11 000	8 000-28 000
Fixed O&M (USD/kW/year)	2.1-6.5	Varies
Variable O&M (USD/kWh)	0.03-0.04	Varies

Note: *Condensing units can have test efficiencies close to 100%.

Sources: Discovery Insights, 2006; Japan Gas Association, 2009; Marcogaz, 2009.

Heat pumps

Overview

Heat pumps provide space heating and cooling, and hot water in buildings. They are the predominant technology used for space cooling, either in simple air conditioners, reversible air conditioners or chillers. Heat pumps are highly efficient, although their overall primary energy efficiency depends on the efficiency of electricity production (or other energy source) they use. They are proven, commercially available technologies that have been available for decades. Annual sales of air conditioners were estimated to be worth more than USD 70 billion in 2008 (BSRIA, 2009),[18] with sales of room air conditioners in China alone estimated at 27 million units in 2009, a 35% increase over 2005 sales. Globally, an estimated 800 million heat pump units are installed (including room air conditioners, chillers, and heat pumps for space heating and hot water).

Heat pumps use renewable energy from their surroundings (ambient air, water or ground) and "high-grade" energy, *e.g.* electricity or gas, to raise the temperature for heating or to lower it for cooling. If certain criteria are met, the European Union credits heat pumps as using renewable energy.[19] They achieve point-of-use efficiencies greater than 100%, i.e. they provide more useful cold or heat (in energy terms) than the electricity input.[20] The heat pump cycle can be used for space heating or cooling; reversible systems can alternate heating and cooling, while hybrid systems (depending on the system design) can provide heating and cooling simultaneously. Heat pumps for space and water heating are mature technologies, but their share of the global heating market is small.

18. See www.bsria.co.uk/news/global-air-conditioning-sales-reach-us70-billion-in-2008/

19. The European Union credits the heat pumps use of "aerothermal", "hydrothermal" and "geothermal" energy as part of its Directive to promote the use of renewable energy (EU, 2009), as long as they result in reduced primary energy consumption (primary energy efficiency of 115%). In the EU this means a COP of around three or more is required.

20. Heat pump efficiencies can be described by their performance under test conditions by a coefficient of performance (COP). For example, a heating COP of three is equivalent to 300% efficiency, *i.e.* three units of useful heat for one unit of commercial energy input. Test procedures vary, with many being based on operation under estimated actual operating conditions, for instance over an entire year or heating season. These are then often referred to as seasonal performance factors (SPF) or seasonal COPs.

Heat pumps for heating and cooling buildings are described by the medium from which they extract energy (air, water or ground), the heat transport medium they use (air or water) and the service they provide (cooling, space heating and/or water heating). Hybrid systems with higher efficiency are also possible, for instance those that couple heat pumps with conventional boilers or solar thermal collectors.

In the BLUE Map scenario, the buildings sector deploys heat pumps widely for space heating and hot water, and very high-efficiency heat pump systems for cooling. This, together with the decarbonisation of the electricity sector, results in very significant savings compared with the Baseline scenario. More efficient heat pump cooling systems and their use for space and water heating result in 1.25 Gt of CO_2 savings below the Baseline level in 2050. When combined with thermal storage, heat pumps could also help reduce the costs in the BLUE Map scenario of integrating a high share of intermittent renewables into the grid by enabling loads to be shifted out of peak periods.

Heat pump systems and their performance

Heat pumps can provide space heating and cooling as well as sanitary hot water with the possibility of providing all three services from one integrated unit. Most heat pumps use a vapour compression cycle driven by an electric motor, although other cycles exist and some heat pumps are driven directly by gas engines.

The following are the most common forms of heat pumps in the residential sector:

- **Air-to-air central, split and room air conditioners** are the standard technology for air conditioning (either one room, or the entire dwelling/building) in many regions. They can be reversible, allowing them to also provide heating.
- **Air-to-water heat pumps**, often called air source heat pumps (ASHPs), provide sanitary hot water and space heating, and can operate down to -25°C, while avoiding the need for expensive ground or water loops.
- **Water-to-water and water-to-air** heat pumps take advantage of an available water source as the heat source or sink and are typically more efficient than ASHPs.

Table 5: Technology and cost characteristics of heat pumps for heating and cooling in single-family dwellings, 2007

	North America	China and India	OECD Pacific	OECD Europe
Typical size (kW_{th})	2-19	1.5-4	2.2-10	2-15
Economic life (years)	15-20	15-20	8-30	7-30
Costs				
Installed cost: air-to-air (USD/kW_{th})	360-625	180-225	400-536	558-1 430
Efficiency (%)	250-450	220-350	250-650	250-350
Installed cost: ASHP (USD/kW_{th})	475-650	300-400	560-1 333	607-3 187
Efficiency (%)	250-440	250-440	250-500	250-440
Installed cost: GSHP (USD/kW_{th})	500-850	439-600	1 000-4 000	1 170-2 267
Efficiency (%)	280-500	280-500	280-500	280-500

Sources: IEA Heat Pump Programme; Navigant Consulting, 2007; IEA, 2010a.

- **Ground-source heat pumps** (GSHPs) utilise brine-to-water or brine-to-air heat pumps coupled with a heat exchanger loop buried in the ground. Direct exchange with the heat sink/source systems is also possible. They have higher efficiencies in cold weather than ASHPs.

In the commercial sector, the basic technologies used are similar to those in the residential sector, although usually on a larger scale. For heating and cooling, small offices often use reversible air-to-air systems in temperate climates, while in large commercial buildings GSHP in combination with thermal storage technologies offer the possibility of both heating and cooling, with extremely high seasonal performance factors when using "free cooling". Whenever heating and cooling is required at the same time, heat-pump technology can be particularly cost-effective, as only one appliance is necessary.

The key cooling technologies for service-sector buildings are:

- **Packaged air conditioners** are standardised products, with a packaged central unit containing the heat exchanger and compressor – and sometimes the evaporator and condenser as well – all in one cabinet, usually placed on a roof.
- **Chillers**, either water- or air-cooled, produce chilled water to cool the air in buildings.
- **Thermally driven "adsorption or absorption" chillers** (using fossil fuels, solar thermal, waste energy, biomass, etc.) are a mature technology and use a similar cycle to that of conventional air conditioners. Their efficiencies are lower than electrically driven heat pumps (with coefficents of performance typically in the range 0.7-1.2).
- **Desiccant dehumidification**: Uses materials, or other solutions, that attract and hold moisture (desiccants) in an air conditioning system to dry air before it enters a conditioned space. They remove moisture (latent heat) from outdoor air, allowing conventional air conditioning systems to deal primarily with "dry" (sensible) temperature control.[21]

In commercial buildings, the situation tends to be more complicated. Integrated heating, ventilation and air conditioning (HVAC) systems are often the norm in OECD countries. The integrated design of the building shell and the HVAC system, including ducting and controls, is a vital area of building design.

21. This allows significant efficiency improvements, as heat pumps systems providing dehumidification need to operate around 6°C-7°C (below dew point), while without humidity control they can provide space cooling at higher temperatures (perhaps 16°C-17°C), thus reducing the temperature "gap" to be bridged.

Heat pumps have become more efficient, but room for improvement still remains.[22] For instance, the coefficient of performance (COP) of the best air conditioners has increased to between 6 and 7.[23] Similar progress has occurred with heat pump water heating systems, with the COP of these devices in Japan increasing from around 3.5 in 2001 to 5.1 in 2008. These performance improvements have been achieved through advances in individual components and better overall system integration. The incorporation of inverters in heat pumps has allowed high COPs to be achieved when operating at part loads.

The efficiency of a heat pump depends on several factors, but the most critical is the temperature lift or reduction that is being sought. The higher the differential is, the lower the efficiency of the system. On a like-for-like basis, GSHPs have higher seasonal heating efficiencies than ASHPs, although their installation costs are higher.

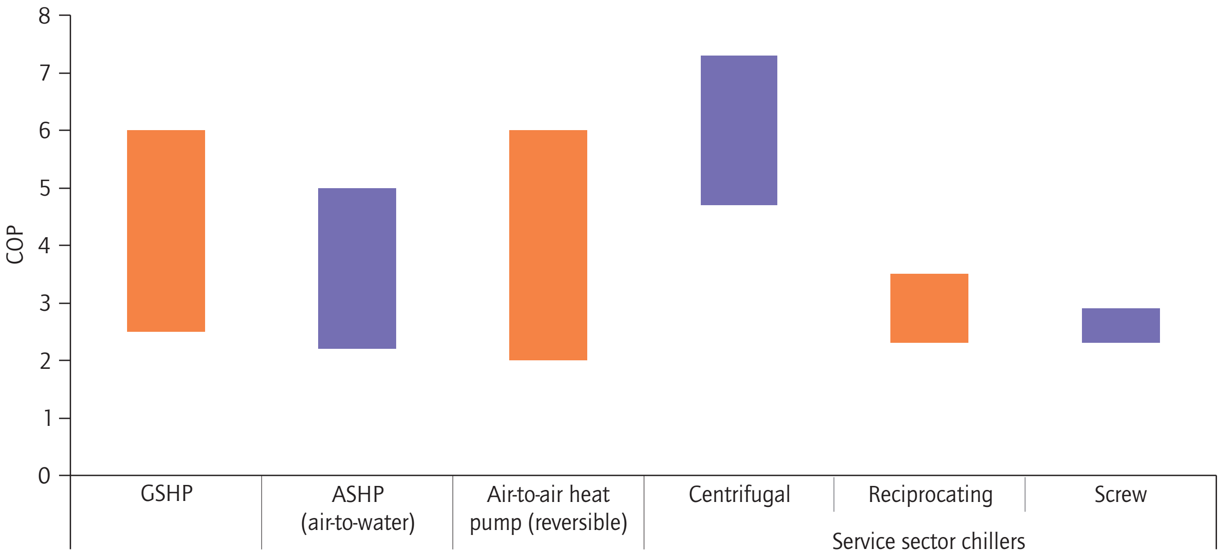
Figure 5 presents indicative seasonal performance factors (SPF) for heat pumps for space and water heating as well as cooling.[24] The wide range of values reflects the differences in technology specification, climatic conditions and the temperature lift required. Monitoring programmes are under way to determine the actual in-use SPF values in different countries in order to help evaluate performance and help optimise system integration, operation and performance.

22. Current heat pump designs have not yet approached theoretical limits of performance, although there will be restrictions on how close to the theoretical limit systems can get for economic and technical reasons.

23. COPs are not directly comparable across countries due to differing climate, technical specifications and test procedures, but Japan's COP for small air conditioners has increased from 4.3 in 1997 to 6.6 in 2008. In the United States the minimum performance standard for the seasonal cooling COP was 3.8, but will be raised by between 10% and 15% in 2014, while systems with a seasonal cooling COP greater than 6 are already available in this market.

24. The standards and names used to express annual energy performance differ between Asia, North America and Europe. The International Organization for Standardisation (ISO) is working on a global standard for SPF calculation (called APF, Annual Performance Factor).

Figure 5: Typical current efficiency ranges for heat pumps in heating and cooling modes by technology



Source: IEA Heat Pump Programme and US DOE/EERE (2009).

KEY POINT: Heat pumps have high end-use efficiencies that vary significantly depending on technology and climate.

Thermal energy storage

Overview

Thermal energy storage (TES) systems can be charged with heat or cold and hold this energy over time. The most common example is sanitary hot water tanks, which are usually insulated to reduce losses. These systems are cheap and can store heat for days or even a week or two at acceptable cost. But they are bulky and not an ideal solution for long-term storage. The key parameters of thermal energy stores are their capacity, power rating (ability to discharge), efficiency (losses over time and with charge/discharge) and cost (Table 7). In the building sector, there are three major reasons for using thermal energy storage:

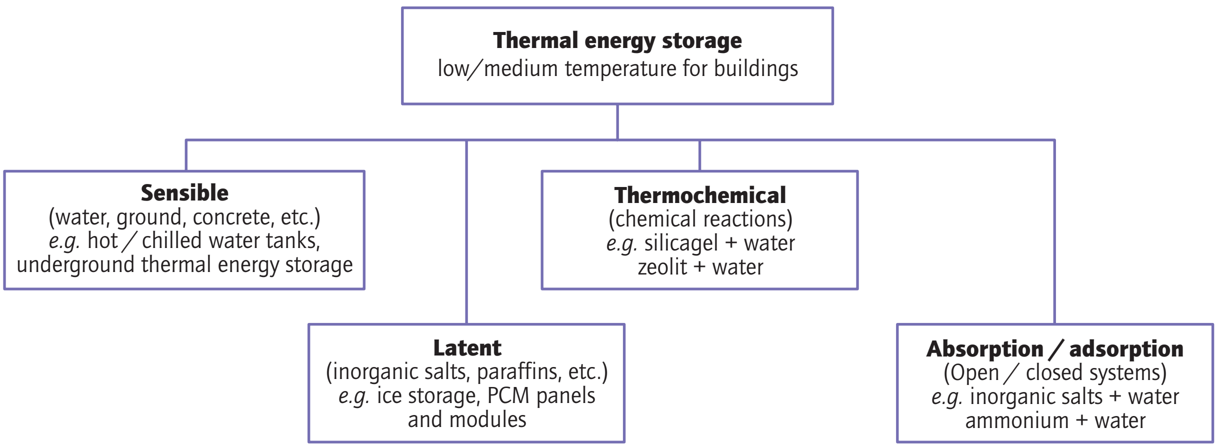
- Improving system efficiency by avoiding partial load operation or operation at other sub-optimal times or by taking advantage of waste energy (*e.g.* heat released from chillers). This can involve storage over hours, days or months.
- Shifting demand over time to reduce peak loads. This can help improve overall energy system efficiency, reduce investment in energy infrastructure and reduce costs. Storage is typically required for hours, or several days.
- Facilitating the greater use of renewable energy by storing the energy produced so it can coincide with demand (storing solar thermal energy over days, weeks or months to match water and/or space heating demand).

The importance of the last two points will increase in the BLUE Map scenario as the share of variable renewables in electricity generation increases – and hence the need for greater system flexibility – and as efforts to decarbonise fuel use in buildings accelerate.

Thermal energy storage can be categorised based on the underlying physical principles of the storage technique (Figure 6).

The installation of larger-scale ice and chilled water storage is growing rapidly in some countries as utilities seek to reduce peak loads and customers seek to reduce peak load charges. Integrated ice storage typically allows systems to reduce chiller capacity by 50%, with a similar reduction in the electrical peak demand for chilled water production. Thermal energy storage will also be the key to solar systems providing a larger share of household space and water heating and cooling, when low-cost compact thermal storage systems or centralised large-scale thermal storages systems become available. This will allow much larger solar systems than are used today, with surplus heat being stored until the winter enabling 100% of space and water heating needs to be met depending on system design. The BLUE Map scenario assumes that low-cost compact thermal energy storage begins to be deployed beyond 2020, although the challenges to achieving viable economics remain significant.

Figure 6: Thermal energy storage characterisation



KEY POINT: There are a number of different thermal energy storage routes.

Table 6: Energy capacities, power, efficiency and storage time of thermal energy storage technologies

TES technology	***Capacity kWh/t***	***Power kW***	***Efficiency (%)***	***Storage time***	***Cost (USD/kWh)***
Hot water tank	20-80	1-10 000	50-90	day-year	0.1-0.13
Chilled water tank	10-20	1-2 000	70-90	hour-week	0.1-0.13
ATES low temp.	5-10	500-10 000	50-90	day-year	Varies
BTES low temp.	5-30	100-5 000	50-90	day-year	Varies
PCM-general	50-150	1-1 000	75-90	hour-week	13-65
Ice storage tank	100	100-1 000	80-90	hour-week	6-20
Thermal-chemical	120-150	10-1 000	75-100	hour-day	10-52

Source: ECES and Roth, K. Zogg, R. and Brodrick, J. (2006).

Note: ATES stands for aquifer thermal energy storage and BTES stands for borehole thermal energy storage.

Thermal storage technology

There are three major types of thermal energy storage:

- **Sensible heat storage** uses a storage medium that is heated or cooled (*e.g.* hot or chilled water in tanks). This has a relatively low energy density. Large-scale stores (in the MWh scale) are often placed underground in order to use the ground as insulation. Aquifer thermal energy storage (ATES) exchanges heat through boreholes, with a natural water-saturated and permeable underground layer as a storage medium.
- **Latent heat storage** uses the phase change of a substance (*e.g.* from ice to water) to store and then release energy without any change in temperature. These offer storage densities 5 to 15 times greater than sensible stores.
- **Thermo-chemical storage**, which uses reversible chemical reactions to store energy, can achieve densities 5 to 12 times greater than sensible stores and perhaps up to 20 times greater, while being able to deliver thermal energy at different discharging temperatures, dependent on the properties of a specific thermo-chemical reaction.

Sensible heat storage systems (*e.g.* hot and chilled water) and some latent heat stores (*e.g.* ice storage) are mature technologies. However, developments in advanced phase change materials (PCM) and chemical reactions are creating new application possibilities, such as PCMs embedded in building materials such as bricks, wall boards and flooring. PCMs are well suited to cooling because of the relatively low temperature change required for release of energy. [25] Hybrid systems are also possible, for instance plastic PCM nodules can be put into a tank where the heat-transfer fluid (usually water) melts or solidifies the PCM. The storage density of this hybrid system is higher than that of water, but less than that of a pure PCM system.

Current R&D is focused on reducing the specific costs of high-density storage, which are still too high for many applications in buildings. Another key challenge is to verify and improve the number of cycles that can be achieved by emerging storage technologies. Integrating the storage volumes underground, particularly for large-scale stores, is still is a challenge for low-cost storage volumes especially in urban areas, with R&D in this area focusing on new materials and construction methods.

25. Additional applications for buildings include dehumidification, temperature control of electronic equipment, conservation of temperature-sensitive goods and cold/warm bags, medical wraps, etc.

Vision for heating and cooling technology deployment

Roadmap vision

The vision of this roadmap is to achieve the future outlined in the ETP BLUE Map scenario, whereby heating and cooling technologies reduce building-related CO_2 emissions by 2 Gt by 2050. This requires an acceleration in the rate at which these technologies are adopted worldwide. This transformation will reduce energy demand, CO_2 emissions and energy bills while improving energy security. Buildings are complex systems that are influenced by a wide range of factors but many "one-off" improvements can be implemented without affecting future abatement options; these often offer low-cost incremental savings.

The heating and cooling roadmap vision

To accelerate the widespread adoption of energy-efficient heating and cooling technologies worldwide between now and 2050 in order to achieve significant reductions in energy, CO_2 and other pollutant emissions, and energy bills and to shift the buildings sector to a more sustainable future.

BLUE Map scenario targets and assumptions

Energy efficiency options are available in the buildings sector that can reduce energy consumption and CO_2 emissions from heating and cooling equipment, lighting and appliances rapidly and at low cost. But achieving deep cuts in energy consumption and CO_2 emissions in the building sector will be much more expensive and faces significant barriers. It will require an integrated approach, with much more ambitious policies on building shells than are currently foreseen, particularly in the existing stock of buildings in OECD countries, and on decarbonising the energy sources used.

The most cost-effective approach to the transition to a sustainable buildings sector will involve three parallel efforts:

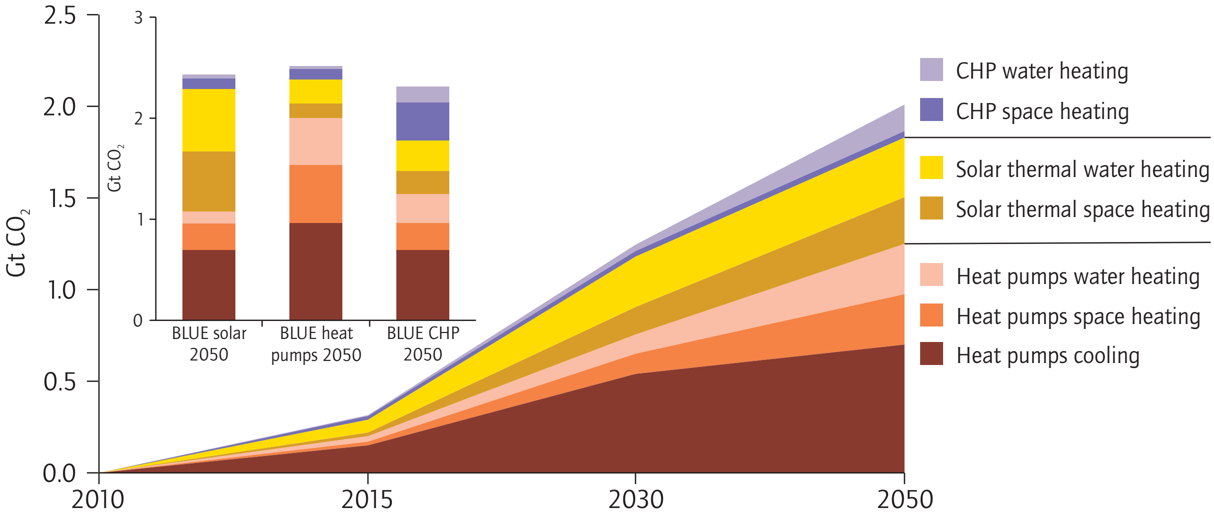
- The rapid deployment of existing technologies that are energy-efficient (including designing and building better building shells to minimise overall energy demand) to low-cost applications and the use of low/zero carbon technologies. R&D into new technologies will need to be increased and existing technologies optimised for new applications in the building sector.
- The deployment of existing technologies into applications with higher abatement costs, along with efforts to adapt the existing building stock in OECD countries, and the deployment of emerging technologies at modest scale.
- Maximising the deployment of energy-efficient technologies, substantially renovating 60% of the OECD building stock by 2050 and ensuring the widespread deployment of new technologies, particularly those that decarbonise energy use, such as electricity, hydrogen and solar in the buildings sector (in the BLUE Map scenario).

While an essential first step, energy efficiency alone will not be sufficient to meet ambitious climate-change goals which also require a significant shift in fuel use to low-carbon energy sources.

The consumption of electricity, district heat, heat from building-scale CHP and solar is higher in 2050 than in 2005 in the BLUE Map scenario. Solar grows the most, accounting for 11% of total energy consumption in the building sector as its widespread deployment for water heating (30% to 60% of useful demand today depending on the region) and, to a lesser extent, space heating (10% to 35% of useful demand today depending on the region) helps to improve the efficiency of energy use in the building sector and to reduce CO_2 emissions.

The increased deployment of heat pumps for space and water heating as well as the deployment of more efficient heat pumps for cooling account for 63% of the heating and cooling technology savings. Solar thermal systems for space and water heating account for about 29% of the savings. CHP plays a small but important role in reducing CO_2 emissions and account for 8% of the savings, and also assists in the balancing of the renewables-dominated electricity system in the BLUE Map scenario by adding increased electricity generation flexibility.

Figure 7: Heating and cooling technologies' contribution to CO_2 emissions reduction (BLUE Map and alternative scenarios)



Note: Excludes the impact of improved building shells on reducing heating and cooling loads.

KEY POINT: Energy-efficient and low/zero carbon technologies for heating and cooling save 2 Gt CO_2 by 2050.

These CO_2 emissions reductions stem from a dramatic transformation in the markets for these technologies which will take them from small-scale deployment (with the exception of heat pumps for air conditioning) to large-scale, mass-market technologies that are the incumbent technologies for heating and cooling from 2030 onwards.

Developing scenarios for the future is an inherently uncertain exercise. To explore the sensitivity of the results to different input assumptions, several variants of the BLUE Map scenario have been analysed. They are:

- **BLUE Heat Pumps**: this scenario looks at ultra-high efficiency heat pump air conditioners (COP of 9) for cooling and humidity control, and faster cost reductions for space and water heating applications. Heat pumps in this scenario save 2 Gt CO_2 in 2050.
- **BLUE Solar Thermal**: this scenario explores the situation where low-cost compact thermal storage is available by 2020 and system costs come down more rapidly in the short term. Solar thermal in this scenario saves 1.2 Gt CO_2 in 2050.
- **BLUE Buildings CHP**: this scenario explores the impact of more rapid declines in the cost assumptions for fuel-cell CHP units using hydrogen and their potential contribution to a higher penetration of distributed generation. CHP in this scenario saves 0.5 Gt CO_2 in 2050.

The main distinction between these scenarios is that in each case a specific technology is assumed to achieve significant cost reductions earlier than in the BLUE Map scenario. This technology, therefore, gains a higher share of installations than competing options. In the BLUE Solar Thermal and BLUE Heat Pumps scenarios, each of these technologies becomes the dominant technology in 2050 for space heating and hot water. In the BLUE Buildings CHP scenario, the share of useful energy for space and water heating provided by small-scale CHP in the buildings sector doubles.

Deployment goals

The BLUE Map scenario represents a complete transformation of the way space heating and hot water is provided, while the global average efficiency of cooling systems will have to more than double by 2050:

- The share of useful space and water heating demand met by fossil fuels will drop to between 5% and 20% (depending on region) from today's position of dominance.
- Heat pumps will dramatically increase their share of space and water heating. The total

number of installed units for in the residential sector for space heating and cooling, and hot water will reach almost 3.5 billion by 2050.

- Installed solar thermal capacity will increase by more than 25 times today's level to reach 3 743 GW_{th} by 2050.
- The installed capacity of distributed CHP in buildings will be 45 times greater than today's level, reaching 747 GW_e in 2050.
- Thermal energy storage will be associated with half of all space heating and hot water systems by 2050.

In 2008, an additional 26 GW_{th} of solar thermal capacity was estimated to have been installed (Weiss, 2010), but average total installed capacity will have to grow by an average of 8% per year on average until 2050 (80 GW_{th} per year), from around 152 GW_{th} today to 3 743 GW_{th}. At the same time, the availability of low-cost compact thermal storage will see average useful yields of solar energy per kW or m^2 grow over time, reducing the area of solar panels required to meet a given useful energy demand.

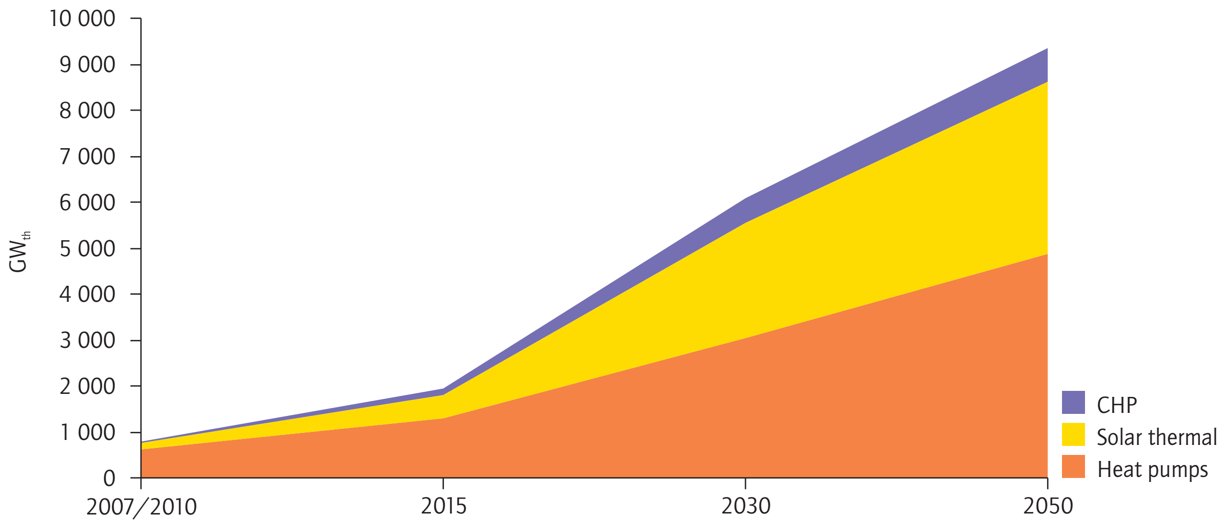
The starting point for total CHP in the residential and service sectors is very uncertain. Comprehensive data on installed CHP capacity is not available at a global level. However, the IEA has estimated that given the current data on installed capacity of all non-industrial CHP, around 17 GW_{th} or around 10 GWe (20% of the total installed capacity — excluding heat provision to networks and CHP in industry) could be in small-scale applications in hospitals or other campus-type installations.[26]

In the BLUE Map scenario, deployment ramps up slowly but accelerates from 2015 to 2030, as conventional systems come on-line and the large-scale deployment of the first generation of fuel-cell systems begins. Growth slows after 2030, but there is a significant rebalancing towards hydrogen fuel cell CHP and biomass CHP. This coincides with the widespread production and distribution of CO_2-free hydrogen and continued cost reductions for fuel-cell CHP systems. By 2050, CHP in the residential sector is projected to reach 747 GWe and provide 130 Mtoe of electricity and 116 Mtoe of heat.

Worldwide, the number of installed heat pump systems for heating and cooling in the residential sector in 2010 is estimated to be around 800 million. This will grow to 3 500 million

26. Note: This is based on data from 43 countries collected by the IEA, but comes from a variety of sources, including Eurostat for EU data, the U.S. Department of Energy for US data, and the Japan Gas Association and Japanese Ministry of Energy Technology and Industry (METI) for Japan, among several other sources. Not all countries surveyed by IEA are included; some countries do not collect capacity data, others do collect this data, but not all their CHP capacity can be fully counted because many plants operate for part of the year as conventional power plants). Total global installed electrical capacity was estimated to be 360 GWe, while for heat production from CHP it is in the order of 440 GWth.

Figure 8: Global deployment of energy-efficient and low/zero-carbon heating technologies in the BLUE Map scenario, 2007/2010 to 2050 (GW_{th})



KEY POINT: The deployment of energy-efficient and low/zero carbon technologies for heating and cooling needs to increase twelve-fold by 2050.

in the BLUE Map scenario.[27] Three-quarters of today's heat pumps are small air conditioning[28] or reversible units with a typical capacity of 2 kW to 3.5 kW. Their contribution to space heating in some markets is significant, but at a global level the contribution to hot water production is currently very modest. The estimated total installed capacity of heat pumps for space and water heating needs to grow to 6.6 times today's level, with installed capacity for water heating alone going from virtually nothing today to 1 300 GW_{th} by 2050 and total capacity for space heating and hot water reaching 4 876 GW_{th}.

In the BLUE Map scenario, the share of units providing space and water heating will rise to one-quarter of the total by 2050. In absolute terms, non-OECD countries drive the growth in the BLUE Map scenario. However, the greatest growth in heat pump use for space heating occurs in the OECD, Former Soviet Union and China. The growth in deployment includes a large increase in the share of heat pumps servicing more than one end-use. In hot climates, for instance, many of the simple air conditioners that are included in the Baseline scenario are replaced by heat pumps providing air conditioning and hot water for space heating and sanitary hot water. When combined with thermal storage, these hybrid systems can achieve significant energy savings.

Thermal energy storage is an integral part of the BLUE Map scenario, providing the flexibility to take advantage of energy and CO_2 emission reduction opportunities. In climates with a high cooling load in summer, coinciding with the peak load of the electricity grid, load shifting using chilled water or ice storage tanks is an evident option. Countries with a high rate of penetration of these storage systems include Japan, South Korea and the United States.

The primary areas where thermal energy storage is deployed in the BLUE Map scenario are:

- Integrated heat pump systems for heating and cooling, which use conventional storage (hot water systems), underground storage and compact thermal storage. These will provide three benefits:
  - In cooling mode, the heat generated can be used to produce hot water that can be stored for when it is needed.
  - In heating mode, the cold generated can be used to chill water that can be stored for when it is needed.
  - In space heating and cooling applications, heat pumps can be operated at the optimal time to maximise the efficiency of the system and avoid operation at very low or very high outside temperatures.
- Thermally driven chillers coupled with CHP, solar energy or waste heat sources can significantly reduce operating costs, and their combination with sensible energy storage can offer increased flexibility.
- Active solar thermal systems hold much potential for space and water heating. Today's sensible energy storage systems will still dominate in developing countries, where space-heating requirements are minimal. However, in the OECD countries, Former Soviet Union and China the availability of low-cost, high-density thermal energy storage is assumed to transform the active solar thermal systems installed from 2025. This will allow combination systems that meet hot water and space heating needs to have three times the collector area and cover up to 100% of space and water heating needs.

Thermal energy storage is an important facilitating technology that will allow greater use of renewable energy sources, increase efficiencies, capture waste heat and provide increased energy system flexibility at low cost. In total, half of all space and water heating systems in the BLUE Map scenario in 2050 are combined with thermal energy storage.

27. This is based on a mixture of actual installed capacity data (predominantly in the OECD); and sales data married with assumptions about product lifetimes. Although some confidence can be had in the order of magnitude of the total, better publically available data is still required. Today's figure is thought to be accurate to within 50 million units.

28. Cooling-only air conditioners rely on the heat-pump mechanism to reduce ambient temperatures.

Cost reduction and performance goals

Costs and performance vary widely among heating and cooling technologies and also for each individual technology because of differences in end-use applications, climate, technology specification, user requirements and building occupation profiles. Variations within each country are even more pronounced at a global level, so it is difficult to present meaningful results that are directly comparable at a highly aggregated level.

For these reasons, this roadmap looks in detail at the costs and performance of heating and cooling technologies in a relatively narrow range of applications and building types in several key countries[29] and then summarises the results (Table 7).

29. For most technologies examined this is the G8 countries plus China and India.

Table 7: Cost and performance goals for heating and cooling technologies, 2030 and 2050

	2030		2050	
Active solar thermal				
Installed cost	-50% to -75%		-50% to -75%	
Maintenance cost	0% to -40%		0% to -40%	
Delivered energy cost	-50% to -60%		-50% to -65%	
Thermal energy storage	PCM, thermal-chemical and centralised		PCM, thermal-chemical and centralised	
Installed cost	-50% to -75%		-65% to -85%	
Delivered energy cost	Depends on cycle regime		Depends on cycle regime	
Heat pumps	Space/water heating	Cooling	Space/water heating	Cooling
Installed cost	-20% to -30%	-5% to -15%	-30% to -40%	-5% to -20%
Coefficient of performance	30% to 50% improvement	20% to 40% improvement	40%to 60% improvement	30% to 50% improvement
Delivered energy cost	-20% to -30%	-10% to -20%	-30% to -40%	-15% to -25%
CHP	Fuel cells	Microturbines	Fuel cells	Microturbines
Installed cost	-40% to -55%	-20% to -30%	-60% to -75%	-30% to -50%
Electrical efficiency	35% to 40%	30% to 35%	35% to 45%	35% to 40%
Total efficiency	75% to 80%	70% to 75%	75% to 85%	75% to 85%
Delivered energy cost	-45% to -65%	-10% to +5%	-75% to -85%	-15% to +20%

Note: Improvements in costs or performance are expressed as a percentage relative to the base year (2010) specification. However, the electrical and total efficiencies for CHP are actual percentages, not improvements. For fuel cells, the delivered energy cost is for thermal energy and is based on a long-run cost of CO_2-free hydrogen of between USD 15/GJ and USD 25/GJ in 2050.

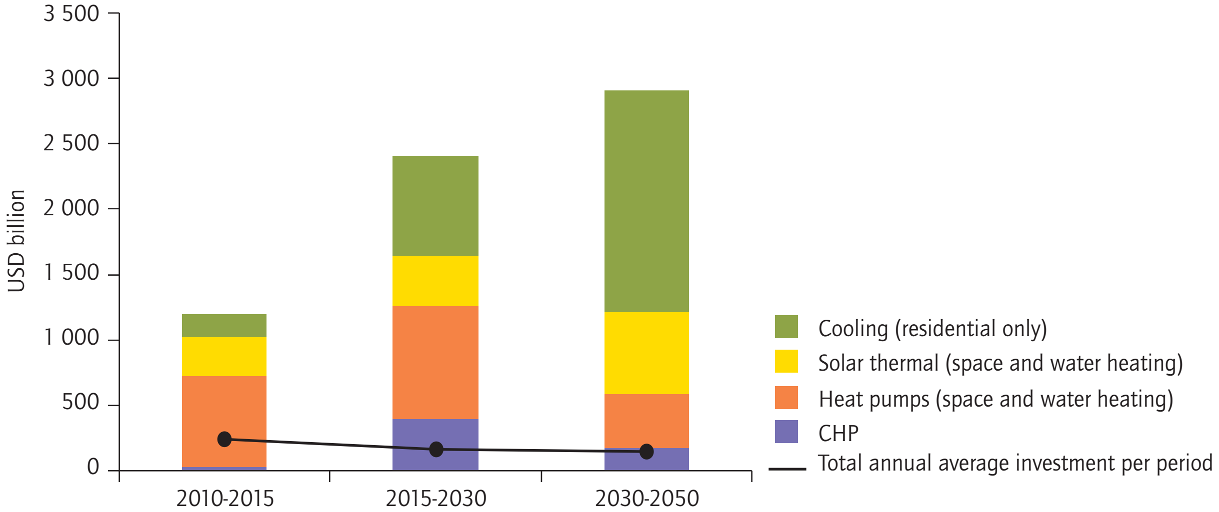
Additional investment needs and financing requirements

For space heating and hot water production, the cumulative investment additional to that in the Baseline scenario in the buildings sectors is estimated to be USD 3.8 trillion (Figure 9), but could be as high as USD 6.3 trillion if costs decrease less quickly than projected in the BLUE Map scenario.[30] For cooling capacities, data are less comprehensive, but the cumulative additional investment needs could reach USD 2.6 trillion just for the residential sector in order to meet this roadmap's deployment goals.

Incremental investment needs are high in the early period of deployment, as unit costs remain significantly higher than those for incumbent technologies. As costs start to come down, deployment accelerates, particularly from 2015 to 2030. Although the incremental investment costs for cooling are modest in the short-term, the transition to the best available technologies will be very costly in the longer term, driven by the very rapid expansion in demand for cooling, primarily in developing countries, compared with the slowing and even declining demand for space heating as building shells improve.

30. These scenarios are based on a set of equipment cost reduction assumptions, if a greater share of the savings can be achieved by improved application and integration of existing technologies, then the costs could be significantly lower. The area where this uncertainty is greatest is with regard to improved space cooling systems.

Figure 9: Cumulative and annual incremental investment needs in the buildings sector in the BLUE Map scenario, 2010-50



KEY POINT: Annual incremental investments decline over time as deployment helps to reduce costs.

Technology development: milestones and actions

Although many of the energy-efficient and low/zero carbon technologies for heating and cooling are commercially available in many applications, a significant number of improvements can be expected with increased RD&D efforts, particularly in terms of cost reductions and in optimising systems for a wider range of applications. These improvements are needed to achieve the energy savings and CO_2 emissions reductions envisioned in this roadmap in a timely manner.

Invest in additional research, development and demonstration

This roadmap recommends the following actions:	***Milestones***
Develop cross-stakeholder consensus on the importance of energy sector R&D to secure stable long-term funding. Increase RD&D expenditure on heating and cooling technologies by USD 3.5 billion per year over today's levels by 2030.	2011-30
Review existing RD&D investment in heating and cooling for buildings. Align funding priorities with long-term goals, specifically: rebalance current heating and cooling technology R&D funding to focus on energy-efficient and low/zero-carbon heating and cooling systems where this is not the case today.	2011-12
Develop national or regional integrated RD&D strategies for buildings, identifying short- and long-term priorities for investing in heating and cooling systems and integrating them into the smart energy systems of the future.	2011 onwards
Improve IEA statistics on public and private investment in RD&D for heating and cooling systems for buildings.	2011 onwards

Public and private sector investment in RD&D for heating and cooling technologies needs to increase by USD 3.5 billion per year above today's levels by 2030 if additional improvements to today's systems are to be achieved and demonstrated in a timely manner, while maintaining progress on developing solutions beyond the best available technology.[31] RD&D should focus on reducing system costs and improving performance as well as optimising existing technologies for all heating and cooling applications and market segments. If these programmes are successful, a reduction in funding could be envisaged by 2050, as the heating and cooling sector would be substantially decarbonised by then.

Governments, utilities, associations, industry and researchers should pursue national and international collaboration on RD&D, which helps to accelerate learning by sharing experiences and avoiding the need to "reinvent the wheel", while using scarce resources more effectively. The IEA multilateral technology initiatives, which bring together researchers from across countries and regions, are one example,[32] but other useful initiatives exist under the aegis of APEC, the United Nations, the World Bank, the Asian Development Bank and other organisations. The European Union has a wide range of projects covering the building sector that bring together universities, other research organisations and industry on specific projects linked to long-term priorities for the energy sector.

Government support of research and development is vital to enable specific heating and cooling technologies to cross the "valley of death" – the journey from initial scientific research to self-sustaining levels of market deployment.

The impact on heating and cooling systems of widely varying applications, consumer requirements, building characteristics and climate means that large-scale demonstration programmes will also be required to ensure adequate information is available to minimise the risks of deploying new technologies. Governments will need to partner with manufacturers, home-builders and energy utilities to ensure these demonstration programmes are as comprehensive and relevant as possible.

31. No reliable data exists on total current public and private RD&D spending on heating and cooling technologies.

32. Of the 41 technology initiatives, 11 have work programmes of direct relevance to the building sector. See www.iea.org/techno/index.asp.

Of the additional investment in RD&D needed, around 60% will be required to support accelerated R&D efforts to improve performance and reduce the cost of existing technologies,[33] with the balance for demonstration projects.

Large-scale demonstration projects of energy-efficient and low/zero-carbon technologies are needed to help reduce technical and market barriers by providing robust data to evaluate their performance in each market segment. This will allow designs to be adapted, or made more flexible, reduce costs, ensure they perform as consumers expect and deliver the energy and CO_2 savings anticipated. They can also be effective in educating local builders and installers.

An important first step, however, is to ensure that current RD&D funding is being spent wisely and effectively and in alignment with the goals identified for heating and cooling equipment; public funding should go primarily to energy-efficient and low/zero-carbon technologies, rather than to fossil fuels. Stable long-term funding commitments are critical to developing research capacity and achieving the maximum value from R&D investment. As such, a key part of any roadmap process is the development of consensus among stakeholders – including political consensus – on the importance of increased R&D investment. This will allow the development of stable long-term plans and funding commitments for country, or even region-level, R&D strategies that take into account local conditions, existing technological capability and available resources. Priorities can then be identified for market segments and individual technologies as well as for private sector participation. Continuity is vital in order to avoid wasteful situations where RD&D and funding are ramped up and then scaled back, with negative impacts on the industry, as has sometimes occurred.

Integration with the overall goals of the BLUE Map scenario needs to be an overarching goal. RD&D should aim at enabling energy-efficient and low/zero-carbon heating and cooling technologies to link seamlessly with the smart energy networks of the future, so that they can send, receive and respond to information upstream from utilities and grid operators, and downstream from home energy management and building operating systems. The more intelligent heating and cooling systems become, the greater the flexibility that will be offered to the energy system which should help to reduce costs.

33. Specific R&D goals for individual technologies will be highlighted in later sections.

Active solar thermal

This roadmap recommends the following actions on R&D:	*Milestones*
R&D into the integration of solar thermal collectors into building shells and the development of low-cost multifunctional building components incorporating collectors. R&D into alternative materials for use in collectors that can reduce costs and improve performance.	From 2011, deployment of new collectors between 2015 and 2030. Single-family dwelling cost: 2020 -30% 2030 -50%
R&D for desiccant and sorption systems, and high-temperature solar collectors for solar cooling (reduced costs, improved performance, development of small-scale thermally-driven chillers).	2012-20
Development of systems and designs suitable for large-scale mass production that incorporate the latest materials.	2011-20
RD&D into customisable, optimal control systems capable of exchanging information with energy networks and building management systems. Optimising hybrid systems (*e.g.* solar thermal/heat pump systems) to achieve very high efficiency heating and cooling systems, with large CO_2 emissions reductions.	2012-25

Note: For RD&D requirements for compact, low-cost thermal energy storage, see the thermal energy storage recommendations.

Mature solar thermal technologies are commercially available, but further development is needed to provide new products and applications, reduce the cost of systems and increase market deployment. Depending on location, new buildings constructed to low-energy or passive house standards could derive all of their space and water heating needs from solar thermal by 2030 at reasonable cost. Solar thermal renovations resulting in a solar coverage of well over 50% should become a cost-effective refurbishment option for single- and multi-family houses and smaller-scale commercial buildings. These goals are ambitious but realistic if the right mix of RD&D, industry development and consistent market deployment programmes are applied.

To reach these goals the following technologies need to be developed:

- **Integration of solar collectors in building components**. Building envelopes need to become solar collectors themselves, so both the performance of collectors and their direct integration into buildings needs to be improved. This should lead to the development of multifunctional building components which act as elements of the building envelope and as solar collectors.
- **Alternative materials**: The development of new components for use in collectors – such as polymers or plastics, the coating of absorbers (optimised to resist stagnation temperatures) and new materials to tackle deterioration resulting from UV exposure – could help to reduce the cost and improve the economics of solar thermal systems.
- **Solar cooling systems**: Solar thermal systems will require more compact thermally-driven cooling cycles (sorption chillers and desiccant systems), with higher coefficients of performance, operating at lower temperatures. This will require R&D into new sorption materials, new coatings of sorption materials on heat exchange surfaces, new heat and mass transfer concepts and the design of new thermodynamic cycles. This will need to be complemented by design guidelines and tools specifically developed for solar cooling systems and applications.
- **Low-cost compact thermal energy storage** will be critical to AST meeting a larger proportion of space and water heating and cooling.
- **Intelligent control systems** that communicate with building energy management systems will increase the useful solar energy available. These centralised and integrated control systems need to be able to benchmark and self-diagnose problems, while facilitating the integration of complementary systems (*e.g.* hybrid solar thermal/heat pump systems) and communicating upstream to utilities.
- **Improving the automation of manufacturing** will help to reduce initial system costs and expand the economic application to a wider range of customers, particularly for retrofitting existing buildings.

Combined heat and power

This roadmap recommends the following actions on R&D:	*Milestones*
Development of PEMFCs and SOFCs (around 1 kW to several hundred kW class for residential use) with higher efficiency and durability, and lower costs. R&D on lower-cost fuel cell stacks (membranes, bipolar plates and gas diffusion layers) and balance of plant (inverters, controls, etc.), as well as reduced parasitic losses.	2015- 20
RD&D to improve microturbine performance and efficiency, as well as reducing costs. Increase flexibility of systems to adapt to varying demand and electricity/heat demands.	2011-25
R&D to improve efficiency and costs of fossil fuel-fired reciprocating engines and gas turbines. Reducing local pollutant emissions, particularly for reciprocating engines.	2011-25
Development of large scale SOFC (hundreds kW class for commercial use) by establishing technologies for integration of cell- stack modules as well as R&D for hybrid fuel cell-gas turbine systems, with MW-scale capacities and very high efficiencies.	2015-25
Develop standardised CHP packages and operational strategies for different market sub-sectors and application profiles; provide professionals with simulation and optimisation tools.	2012-25

CHP includes technologies such as fuel cells, microturbines and Stirling engines that have yet to be widely deployed in buildings and have, in some cases, significant opportunity for reducing costs and improving performance.[34] The key challenges are optimising components and lowering costs, through more R&D but also through large-scale, high-volume production. In addition, further R&D into flexibility of operation and variable heat/electricity balance would improve their economics. Similarly, R&D and demonstration will be required on micro-CHP integration into smart grids and real-time data exchange with the network. For engines, the current upsurge in work on emissions reduction must continue and overcome several significant engineering and chemical engineering challenges.

The following areas need to be addressed by increased RD&D efforts:

- **Reciprocating engines** are a mature technology, but incremental improvements in efficiency, performance and costs should be possible. The US Department of Energy's Advanced Reciprocating Engine Systems programme (ARES) aims to deploy an advanced natural gas-fired reciprocating engine with higher electrical efficiency, reduced emissions and 10% lower delivered energy costs. Manufacturers of liquid fuel-fired reciprocating engines are incorporating design modifications and new component technologies to improve performance and reduce emissions.
- **Microturbines and gas turbines**: Technology development for microturbines is focused on improving efficiency (through higher temperatures and pressures, new materials such as ceramics and thermal barrier coatings), advanced blade design, recuperators (to boost electrical efficiency at expense of overall efficiency) and ultra-low emissions (through lean-pre-mix dry low-emission combustors and reduced-cost SCR systems).[35] Gas turbines are more mature, but there could be modest declines in capital and maintenance costs, while recuperated dry low-emission combustors could meet very low emissions standards without the need for exhaust gas clean-up.
- **Stirling engines** are at the market introduction stage and R&D to reduce their costs and improve their electrical efficiency is required. This can be achieved by increasing the working hot-end temperature by using high-temperature materials in the hot-end components; these exist today, but their costs need to come down. To help identify the best applications for Stirling engines, more demonstration programmes are required. The development of a wider range of systems will also help expand the range of applications in which Stirling engines can compete.
- **Fuel cells**: The R&D priorities are to reduce costs and improve durability and operational lifetimes. Better fuel-cell system design, new high-temperature materials and an improved understanding of component degradation and failure could considerably enhance the durability of fuel cells. Fuel cells and their balance of plant will need to have an operating life of 40 000 to 80 000 hours to be competitive in buildings; current designs are expected to meet the lower end of this range, but further progress is needed. Improving PEMFC tolerance to impurities is a priority, while the development of a wide range of commercial SOFC and MCFC designs is required. Lower-cost catalysts, membranes, bipolar plates and gas diffusion layers all need to be developed further. Balance-of-plant system costs can be lowered by reducing the costs of power conditioning systems (inverters) and the fuel pre-treatment system. Another important goal is to increase net system efficiencies by reducing parasitic loads.

34. Large-scale CHP technologies are generally mature and will not experience major improvements in either their performance or costs.

35. Many of these improvements will filter down from improvements in large-scale gas turbine development.

Heat pumps

This roadmap recommends the following actions on R&D:	*Milestones*
R&D into more efficient components and systems for heat pumps for heating and cooling applications, as well as to reduce first-costs for heat pumps for heating and cooling.	20% improvement in COPs by 2020; 50% by 2030 15% reduction in costs by 2020; 25% improvement by 2030
More efficient integrated heat pump systems (capable of simultaneous space/water heating and cooling) capable of meeting needs of low-energy buildings and interfacing with smart grids/home energy management systems.	Begin deployment in 2015, widespread deployment from 2020
Efficient low-temperature space heating systems and high-temperature space cooling systems integrated with heat pumps.	All new buildings capable of accepting low-temperature heating/high-temperature cooling by 2020 in OECD
Development of hybrid heat pump systems (*e.g.* with solar thermal) with very high efficiency and CO_2 savings	Widespread deployment from 2020-25

RD&D priorities for heat pumps are to continue improving the components and systems of existing technologies, and design systems that maximise COPs across a wide range of applications, climates and operator behaviour, to widen their potential market. This will require improving the design and sizing of systems, their integration with the building design and in their operation and control. The development of hybrid systems (*e.g.* heat pump/solar thermal systems) offers the potential for very high year-round COPs. R&D also needs to focus on developing packaged integrated heat pump systems capable of providing cooling and space and water heating simultaneously for small-scale applications. These goals will also require extensive demonstration programmes to refine designs and optimise systems for different applications and customers.

Improved performance is important, but efficiency will increase more slowly now that highly efficient systems are available. Just as important is the technology effort to reduce costs of systems, so that they are competitive in a wider range of applications.

Research is needed on the following technical areas:

- **Equipment and components**: Decrease costs and increase reliability and performance through more efficient components. The key component areas are:
  - Heat exchangers;
  - Compressors;
  - Expansion devices/valves;
  - Fans, circulators and drives;
  - Heat pump cycles;
  - Variable speed compressors;
  - Defrosting strategies;
  - Advanced system design (including for colder climates);
  - Smart controls.
- **Systems/applications**: Optimise component integration and improve heat pump design and installations for specific applications to achieve higher seasonal efficiency in wider capacity ranges. Improve optimisation with ventilation systems in larger applications.
- **Control and operation**: Develop intelligent control strategies to adapt operation to variable loads and optimise annual performance. Develop automatic fault detection and diagnostic tools. Improve communication with building energy management systems and upstream to smart energy grids.
- **Integrated and hybrid systems**: Develop integrated heat pump systems that combine multiple functions (*e.g.* space-conditioning and water heating) and hybrid heat pump systems that are paired with other energy technologies (*e.g.* storage, solar thermal and other energy sources) in order to achieve very high levels of performance.

- **Improved design, installation and maintenance methodologies**: Develop and promulgate information defining and quantifying benefits for good design, installation and maintenance of systems in order to realise the full efficiency potential of the heat pumps.

In parallel, improvements in building design and operation that reduce the temperature lift performed by the heat pump will increase the average operating efficiency (the seasonal or annual performance factor).

Thermal energy storage

This roadmap recommends the following actions on R&D:	*Milestones*
Foster collaboration on basic science (thermodynamics and material development) and applied R&D (system integration, and centralised and building applications) for sensible, PCM and thermal-chemical stores.	2012 onwards
Invest in R&D to develop promising materials for compact thermal energy stores, particularly phase change materials and thermo-chemical stores. Validate stability of materials, performance characteristics and cycle life.	2012- 2020
Establish R&D collaboration with end-use technologies that will benefit from thermal energy stores (improved performance, reduced cost, greater CO_2 reductions). Key technologies are AST, heat pumps and CHP in buildings.	2013 onwards
Develop and demonstrate heating and cooling systems with integrated, advanced compact thermal energy storage systems (based on PCMs or chemical reactions) in order to optimise performance and identify pathways to reduce costs for compact thermal energy storage.	2015-25

RD&D for thermal energy storage should focus on reducing costs and improving the ability to shift energy demand — for electricity, gas, etc. — over hours, days, weeks or seasons and facilitating the greater use of renewable energy. Both central and decentralised energy storage systems are likely to play a role. As well as ongoing R&D into the underlying science of thermal energy storage, the integration and optimisation of storage with heating and cooling technologies still needs to be perfected. This optimisation relates both to the storage itself (size, materials, etc.) as well as the operation and control of the overall system, including storage and interaction with the building occupancy profile.

A high number of charging and discharging cycles is critical for most TES applications, so the stability of materials in the systems is very important – not only the storage medium itself but also materials used in systems components such as containers, heat exchangers and pipes.

Once thermal energy storage technologies have reached the level for prototype or demonstration, further improvements will be necessary to bring them to market. Better materials are the most promising way to achieve this, but cost barriers may prevent otherwise effective solutions from being implemented.

More R&D into the real boundary conditions of material properties in TES systems is also necessary, given that it is essential to have very high confidence in the stability of materials and the number of charge/discharge cycles that systems can achieve. Operating conditions and hence performance are sometimes quite different from the assumptions made during early development. Worldwide R&D activities on novel materials for PCMs and thermo-chemical approaches are insufficiently linked at the moment and this needs to change. Many projects are focused on material problems related to one specific application and potentially miss wider opportunities for material applications in storage.

Over the last few years, the emphasis of co-operative RD&D efforts has shifted towards storage technologies that improve the manageability of energy systems or facilitate the integration of renewable energy sources.

Meeting the strategic goals for the BLUE Map scenario will require research focused on key areas of technical advancement:

- Phase-change materials and other material advancements;
- Stability of materials and system components over lifetime charge/discharge cycles;
- Analysis of system-specific storage parameters for different applications;
- Optimised control and operation;
- High-temperature energy stores.

The key performance expectation for the household sector is that low-cost compact thermal energy storage will become available for small-scale applications in heating and cooling systems by 2020-25. This will allow initial deployment between 2020 and 2025 and large-scale deployment from 2030. The most promising areas of R&D are in PCMs and thermo-chemical stores, with hybrid systems (combining PCM and sensible heat systems) likely to allow early deployment of systems at a reasonable cost.

Heating and cooling technology policy: strategic goals and actions

If consumers are not given adequate incentives to address the environmental costs of energy use, they are unlikely to make optimal decisions from an economic and environmental perspective. However, even if the environmental costs are built into energy prices, many non-cost market barriers[36] to more efficient and low/zero carbon heating and cooling technologies remain. These market failures can be grouped into categories (Figure 10). The building sector is very fragmented, with numerous decision makers (architects, engineers, builders, developers, home-owners, etc.) and applications (by market segment), so policies need to be "broad" in order to tackle all the barriers, and "deep", in order to ensure the barriers faced by all those in the decision-making chain are addressed.

The key barriers identified in this roadmap that need to be addressed are:

- Higher initial costs;
- Market risks for new technologies;
- Imperfect information;
- Uncertainty (technical, regulatory, policy, etc.).

Uncertainty is an issue that cuts across all areas. Decision makers faced with significant uncertainty are likely to delay investment decisions or opt for incumbent technologies where uncertainty is minimal and there is an expectation — perhaps not achieved in reality — that the risks involved are quantifiable and therefore manageable. Policies need to be designed to systematically address uncertainty.

Strong policy co-ordination is required to overcome the limited planning horizon of many consumers and industry players given the long-term nature of the transition for the buildings sector which needs to be co-ordinated over 40 years if the costs of meeting the BLUE Map goals are to be minimised. All stakeholders need to understand their roles in the long-term vision for the sector so that technologies and industry support structures are put in place in a timely fashion to meet deployment goals.

36. See IEA, 2007 for a brief description of these barriers and a detailed analysis of principal-agent barriers.

Figure 10: Barriers to energy-efficient and low/zero-carbon heating and cooling technologies

Cost effectiveness	Fiscal barriers	Regulatory barriers	Statutory barriers	Intellectual property barriers	Other barriers
High costs	Unfavourable fiscal policies	Unfavourable regulations	Unfavourable statutes	IP transaction costs	Incomplete and imperfect information
Technical risks	Fiscal uncertainty	Regulatory uncertainty	Statutory uncertainty	Weak international patent protection	Policy uncertainty
Market risks				Anti-competitive patent practices	Industry structure
External benefits and costs				University, industry, Government perceptions	Misplaced incentives
Lack of specialised knowledge					Infrastructure limitations

UNCERTAINTY

Source: Based on ORNL, 2007.

KEY POINT: Energy-efficient and low/zero carbon technologies for heating and cooling face many barriers.

Strategic policy goals

The challenge laid down in the BLUE Map scenario requires strong national and international commitments to improving energy efficiency and reducing CO_2 emissions. A long-term view is required to ensure that policy positions are not eroded in the face of changing short-term fiscal or political priorities. Creeping delays in implementation raise the long-term cost of a given goal and could eventually preclude certain levels of CO_2 reduction at a given point of time at reasonable cost. Policy action is therefore urgent.

Achieving the energy and CO_2 emissions reductions from the level of deployment in this roadmap will require strong, consistent, stable and balanced policy support in the following four main areas:

- Increased technology R&D, significant demonstration programmes and the development of beyond best available technologies (BAT). An additional USD 3.5 billion per year is needed by 2030.
- Improved information for consumers and agreed, robust metrics for analysing the energy and CO_2 savings of heating and cooling technologies as well as their life-cycle financial benefits.
- Market transformation (deployment) policies, which are ideally technology neutral in the long run, to overcome the current low-uptake of the many energy-efficient and low/zero-carbon heating and cooling technologies.
- Greater international collaboration in R&D, best-practice policy packages and deployment programmes to maximise the benefits of policy intervention, as well as the transfer of technical knowledge between countries and regions.

Stable long-term policies will be required to give actors in the sector the confidence to invest. Achieving the roadmap's ambitious goals and overcoming existing barriers will require targeted action all along the chain, from basic research to demonstration and deployment.

The deployment levels of heating and cooling technologies will be influenced by a range of factors, including awareness of the technology's benefits among consumers, builders and policy makers; the implementation of financing mechanisms to mitigate up-front cost barriers; and the availability of performance standards and certification programmes. Given the well-documented non-market barriers that energy-efficient and low/zero-carbon technologies face, active government policy developed in partnership with consumers, building developers, architects, manufacturers, industry associations and local and regional governments will be essential to unlocking the potential these technologies have to reduce energy consumption and CO_2 emissions.

Specific policy recommendations

Ensure policy co-ordination and engage stakeholders

This roadmap recommends the following actions:	***Milestones***
Convene a policy co-ordination working group to develop regulatory and policy framework for heating and cooling systems in buildings. Should include all regulatory and policy-making bodies with an influence over the building sector at a national, regional and local level (*e.g.* ministries of finance, energy, housing, environment/climate and urban planning, as well as regional and local governments).	Begin 2011
Enlist stakeholders into a consultation or steering committee. Engage these stakeholders at the beginning of the policy development process, then: • Review existing policies and measures for heating and cooling systems in buildings (including safety, standards, energy efficiency, climate, energy poverty). • Develop a shared vision and pathway for achieving energy-efficient and low-carbon heating and cooling systems for buildings within an overall framework for energy efficiency and CO_2 emissions reductions in buildings. Set specific goals in terms of deployment and savings (develop national and regional plans, with policies for R&D, demonstration and deployment).	2011-13

A large number of policy areas affect the building sector, from fire and electrical safety, to local planning regulations and energy efficiency policy, and many different parties develop and/or implement policy and regulation, so poor policy co-ordination is a real risk for the sector. The absence of some stakeholders, or their failure to understand long-term goals, would hinder the transition outlined in this roadmap and could even make its achievement impossible if serious misalignments in policy occur. A first priority therefore needs to be ensuring that all of the relevant national, regional and local government agencies co-ordinate their policies for buildings. Similarly, all stakeholders need to understand the ultimate goals of the policy framework and the pathway required to get there, and be able to contribute to developing the policy packages for buildings. The involvement of all stakeholders will also help them to develop a sense of ownership in a shared vision.

Switzerland's efforts to promote heat pumps offer an example of how such co-ordination can work. In 1993, the Swiss Federal Office of Energy (SFOE) started a strategy to promote heat pumps and established an international network with other institutions (Rognon, IEA HPP 2008). The first important act was the foundation of the Swiss Heat Pump Association which serves as a platform for engineers, contractors, manufacturers, energy suppliers and government organisations. The SFOE set the rules and provided financial incentives while the association had the responsibility of co-ordinating national and international R&D collaboration, demonstration, statistics, market analyses, education and the promotion of the quality label for heat pumps. Today, heat pumps have a significant market share for retrofits and new buildings in Switzerland. These types of examples have inspired similar efforts in China (see Box 2).

Box 2: Heat pumps in China

In China, the Ministry of Finance and the Ministry of Housing and Urban-Rural Construction released a paper on "Implementation Opinion about Promoting the Renewable Energy Utilization in Building Application and Temporary Management Measures with Special Funds for Renewable Energy". The following areas are strongly supported by the government:

- Heating and cooling using water-source heat pumps in areas rich in surface water and ground water;
- Heating and cooling with seawater-source heat pumps in coastal areas;
- Heating and cooling using ground-coupled heat pumps (geothermal heat pumps);
- Heating and cooling using sewage-source heat pumps.

In response to the country's initiative, several ministries, commissions and local authorities have formulated corresponding policies for energy conservation and energy efficiency in buildings. Many cities have also provided subsidies to encourage the application of ground-source heat pump systems.

During the last three years, the central government of China has promulgated a series of policies and regulations about energy conservation and environmental protection so that local governments and the nation will pay more attention to energy efficiency and renewable energy. Heat pump technologies, providing both heating and cooling for buildings, are becoming more attractive, resulting in a fast-growing market.

The Chinese state encourages the application of solar energy and geothermal energy in new and retrofit buildings. Geothermal energy is considered a renewable energy according to the Chinese Renewable Energy law. Geothermal pilot projects are provided special subsidies. Booming real estate construction, rapid economic growth and increasing living standards will inevitably make China the world's largest heat pump market.

Source: China Academy of Building Research. XU Wei, ZHANG Shicong.

Policy development in related areas that affect buildings have created some regulatory barriers to deployment of new technologies – building codes that prohibit the installation of solar thermal collectors on roofs, for example, or local regulations that discourage innovative building solutions. Better co-ordination can help avoid these unintended policy conflicts.

Market transformation

To achieve the goals set out in this roadmap, the market will have to be transformed. This will require the removal of market barriers – such as lack of prioritisation of energy efficiency, capital market barriers and absence of external costs – and market failures such as an inadequate number of market participants, a lack of perfect information, principal-agent problems, transactions costs and delays, and inadequate financial mechanisms. This roadmap recommends specific policies to:

- Improve information availability and relevance for decision makers;
- Improve the knowledge and competence of heating and cooling system actors – such as architects, engineers and installers – with regard to energy-efficient and low-carbon technologies;
- Implement policies to accelerate deployment and reduce costs through economies of scale;
- Expand quality assurance schemes to encompass the entire sector and provide consumers with the confidence to invest;
- Remove regulatory, policy, fiscal and other barriers.

Achieving complete market transformation in the building sector is an extremely challenging policy goal due to the large number of individual decision-makers and the fact that the building sector is large, diverse and fragmented. In the United States alone, nearly 500 000 homebuilders operate each year, but the five largest of these accounted for less than 7 percent of new homes constructed (DOE, 2003). The number of builders is just the tip of the iceberg in terms of the building sector's complexity, however, decision-makers influencing investment decisions also include owners, occupants, investors, trades people, equipment manufacturers, suppliers, architects, lenders, insurers, codes and standards setters, zoning officials, realtors and others.

In many cases, the principal-agent problems further complicate matters, as decision-makers (*e.g.* developers) minimise first-up construction costs and don't have the long-term interest of building owner-occupiers in mind when they make design decisions. The principal-agent problem also applies when landlords purchase heating and cooling equipment for tenants without regard to life-cycle costs (Murtishaw and Sathaye, 2006).[37] These barriers are estimated to be significant and widespread in many end-use markets in IEA countries (Prindle, 2007) and could slow the transition to energy-efficient and low-carbon buildings. In addition, builders often face greater market risk when they incorporate new technologies as buyers and future owners seldom have adequate information with which to value these features.

37. The scale of this problem is huge; given, for example, 32% of households rent their accommodation in the United States (DOE, 2008). This is a particular problem in multi-family dwellings, as the share of renters is even higher.

Improve information availability, quality and impact on decision makers

This roadmap recommends the following actions:	*Milestones*
Identify what drives choices by heating and cooling system decision-makers (architects, engineers, consumers, installers, etc.). Identify what information, at what time, and in what form will have the most impact on their decision-making process.	Begin 2011.
Develop standardised information/metric packages of life-cycle costs and benefits for heating and cooling technologies. Mandate their distribution, including estimated lowest CO_2 emissions and life-cycle cost solutions, at point of sale and in documentation supporting quotes/system designs. Packages should highlight financial risks of fossil fuel systems (energy and CO_2 pricing).	Begin 2011, with information available in the OECD by 2014 and the rest of the world by 2018.
Harmonise international test procedures to ensure transparency for comparison of heating and cooling options. Work with existing organisations such as the International Standards Organisation.	Some work already under way; accelerate work in OECD by 2015 and extend to rest of world by 2025.
Develop effective communication policies to: • Ensure that stakeholders in the building sector and consumers are aware of the information available and are educated in the use of the information, particularly the importance of life-cycle costs; • Raise the importance of energy efficiency and low/zero-carbon technologies in the hierarchy of factors influencing the purchase selections of decision-makers.	Begin 2011, to be ongoing.
Introduce efficiency labelling schemes for all residential and service sector heating and cooling systems. Phase out voluntary schemes and replace them with mandatory schemes. Incorporate heating and cooling system labelling into home energy performance labelling as a separate item, with supporting documentation made available on replacement and retrofit opportunities.	Begin 2011. All OECD countries to have comprehensive mandatory labelling by 2015, developing countries by 2020.

The market for heating and cooling systems is characterised by imperfect information.[38] Policies are required to ensure that consumers, policy makers, governments, utilities and other agencies understand the potential of energy-efficient technologies to save energy and reduce CO_2 emissions. The provision of objective information on the performance of available technologies can boost customer acceptance and accelerate deployment. Standardised national and international testing and evaluation procedures for specific technologies can increase understanding among developers, architects and installers and accelerate the maturity of local industry more broadly.

The information required to make informed decisions about energy-efficient and low/zero-carbon technologies is often incomplete, unavailable, difficult to obtain and/or expensive. The lack of independent information that is perceived as trustworthy, comparable and unbiased is a major barrier to the uptake of energy-efficient and low/zero-carbon technologies. Addressing this lack of data needs to be a policy priority. For example, as part of their wider strategy for promoting solar thermal, Austria ran a promotional and training campaign from 2004 to 2008 that included information and promotional events (including trade fairs); training measures for installation and technical staff, planners, and energy consultants; planning support for large solar thermal systems; expert workshops; presentations; an information website; information brochures; and a free solar thermal consultation hotline.

38. The problem is often one of asymmetric information. That is to say that one party, usually the seller, has better or more complete information than the buyer.

In the building sector, the purchase of heating and cooling equipment is often given little consideration by architects, builders and home owners; the industry standard is usually fitted. This is rarely the lowest life-cycle cost option, and is unlikely to factor in future energy and CO_2 price risk. For replacements, this decision is often made as the result of deteriorating performance or failure, leaving little time to evaluate alternatives.

Policies are required that ensure that decision makers are provided with standardised information (that goes beyond current labelling schemes) about the energy efficient or low/zero carbon technology best suited to their building and operational requirements. This information must be tailored to ensure that it is as relevant as possible and meets the needs of stakeholders, as research has shown that different consumer groups respond to information about energy savings opportunities differently (Barr, Gilg, and Ford, 2005). This will require:

- Research into the requirements of different decision makers (builders, architects, installers, home owners, etc.) and the presentation of information most likely to successfully influence their purchase decision.
- Development of standardised information packages in consultation with stakeholders, which should include information on efficiency, CO_2 emissions, life-cycle costs and scenarios that evaluate energy/carbon price risks.
- A phased introduction of the information packages that will allow trial groups to be identified and the effectiveness of the packages to be surveyed. Adjustments can then be made before the final roll-out of the programme.

Current policies that address information barriers include product energy performance labelling, which can be either voluntary or mandatory. The effectiveness of this depends a lot on the decision maker having a good understanding of what the information really means. These policies therefore need to be complemented by educating consumers and ensuring that those presenting the information are well-versed in the implications for consumers. There are two main types of labels: comparison labels and endorsement labels. Comparison labels provide information on relative efficiency using some kind of rating/index system, but may include absolute energy consumption information and/or energy cost information. Endorsement labels identify the best performing models in a product class (*e.g.* the "Energy Star" programme); participation is generally voluntary.

Mandatory efficiency labelling schemes should be extended to all heating and cooling systems worldwide by 2020. Standardised information packages can build on labelling schemes for residential consumer appliances, while web-based simulation tools for instant comparison and evaluation of options could be introduced for professionals with stand-alone workstations in retail outlets for consumers. Complementary policies must be put in place for monitoring, verification and enforcement of labelling and minimum energy performance standards, if savings potentials are to be realised.

More detailed information will be required for commercial appliances and for building sector professionals, however. Building professionals should have access to detailed and customisable tools to help evaluate heating and cooling technologies and their performance under various simplified operating and financial scenarios. For example, Canada's Office of Energy Efficiency has produced the web-based RETScreen tool, that is a free download, and provides ongoing training and support in its use.

The information provided needs to include relative efficiency (potentially based on existing labelling schemes), energy consumption, annual running costs, life-cycle costs and CO_2 emissions. Standardised scenarios that look at energy price and CO_2 price risk should also be included. This information will need to be integrated into buildings' energy performance certificates as separate items, which is not usually the case today, so consumers understand the balance of opportunities between equipment and the building shell. The information should be made available to decision makers at the time of purchase of equipment, as well as being required to be shown to people commissioning new building projects and purchasers of new or existing buildings.

Studies have shown that consumers need to have a basic understanding of the meaning and usefulness of the information provided if they are to act on it.[39] The dissemination and uptake of these information packages will therefore need to be supported by policies to educate consumers about the availability, correct interpretation and relevance of the information available.

39. A study in California showed that being able to correctly interpret information in home energy performance data and understand the usefulness of that information was a prerequisite to consumer interest in home energy performance (Robert Mowris and Associates, 2004).

Deployment regulatory and policies

This roadmap recommends the following actions:	*Milestones*
Introduce a stable, long-term regulatory framework aligned with the high-level goals for energy and CO_2 savings in buildings in order to provide decision makers the confidence to invest long-term (*e.g.* legislation that ring-fences policy and funding to provide long-term certainty).	2011-13
• Remove/modify current regulatory, fiscal or local planning policies that inhibit the uptake of energy-efficient and low/zero-carbon heating and cooling technologies.	2011-15
• Reduce transaction costs by utilising innovative mechanisms for pooling purchase requirements.	2012 onwards
• Require that all energy efficiency and CO_2 reduction programmes treat equally electric and thermal energy technologies.	2011 onwards
• Develop innovative financing solutions based on a combination of financing options (using a common platform) and delivery mechanisms to ensure as broad a reach as possible.	2012 onwards
Introduce a portfolio of deployment incentives to help reduce first-cost barriers and other market-based barriers. A portfolio mixing regulatory (minimum energy performance standards, utility obligations, etc) with fiscal or financial incentives (tax rebates, cash incentives, etc) is required, as well as complementary policies to reduce market risk. Public procurement can also help develop nascent markets and raise awareness.	Begin 2011-13 in OECD and by 2020 in non-OECD; phase-out will depend on global progress in cost reduction.
Introduce minimum energy performance standards (MEPS) for heating and cooling equipment in the residential and service sectors. The system should transition from efficiency-based metrics to CO_2-based metrics over time. A clear plan for continuous tightening of these MEPS should be implemented.	MEPS for heating and cooling equipment in OECD countries by 2015 and by 2020 in rest of the world.

More efficient or low/zero-carbon technologies generally have higher initial investment costs than incumbent technologies so reducing such costs will improve the uptake of these. Complementary policies on providing information on the life-cycle costs will help allow an accurate assessment of their competitiveness and reduce the first-cost barrier problem to some extent, but will not be enough by themselves to achieve a market transformation. Deployment policies can take various forms and can be grouped into three categories: energy service contracting models, white certificate obligations and financial or fiscal incentives.

It is important to review the existing regulatory framework on heating and cooling systems in buildings to ensure that conflicts do not occur among the myriad regulatory regimes for buildings (*e.g.* fire, health and safety; local planning regulations; electrical and gas regulations; and those directly related to heating and cooling equipment). Co-ordinating and aligning the regulatory framework to remove any barriers while still meeting other policy goals (fire, safety, etc), is an important pre-requisite for a successful deployment programme. Similarly, it is important that energy is priced at full cost for all consumers, so that price incentives are as strong as possible and that all billing is based on metered consumption where practical.

An important policy opportunity exists in public procurement policy. Governments can lead the way by ensuring policies are in place to mandate or incentivise the public procurement of efficient and low/zero-carbon heating and cooling technologies.

The higher capital costs of many energy-efficient and low/zero-carbon heating and cooling technologies and other bariers means that clear, long-term, effective, efficient and predictable deployment incentives are required to help transform the market to the point where support policies are no longer needed. A portfolio of policies will be required to take into account all the various actors and their decision-making criteria in the residential and service sectors. Tailoring deployment policies and the complementary policies to address information barriers will require careful research and consideration of the best policy levers for each market segment. A range of policy tools are available, including:

- **"White" certificate markets**: These could be for energy efficiency and/or carbon reductions in buildings, with a specific heating and cooling sector component.[40]
- **Feed-in tariffs**: These have been typically applied to electricity and could be used for CHP, but could also be extended more holistically to the heating market.
- **Obligations**: Subject to certain criteria (either economic or technical), developers, builders, or home renovators could be required to install energy-efficient and low/zero-carbon heating and cooling technologies (*e.g.* the Spanish federal solar thermal ordinance, the Technical Building Code).

40. The white certificate market could have co-benefits in terms of expanding the market for energy service contracts and other energy efficiency/optimisation consultancy services. France has trialed a white-certificate system to help develop capability and is in the process of raising the energy savings requirements.

- **Financial/investment incentives**: Cash subsidies or purchase cost reductions, grants, "*bonus-malus*"[41] systems and low/zero-interest loans for the purchase of energy-efficient and low/zero-carbon heating and cooling technologies.
- **Fiscal incentives**: Accelerated depreciation for businesses or tax credits, variable value added taxes, etc.
- **Minimum energy performance standards**: These can be used to eliminate the worst-performing products and shifting to a CO_2 standard could allow these to be used like fleet fuel economy standards with continuous tightening of the average sales value.

Innovative financing policies must be developed in conjunction with other deployment policies in order to ensure that they are effective. These should be integrated as seamlessly as possible into the deployment policies to reduce transaction costs. Options include schemes where consumers are not required to pay the additional first-cost premium, which is recovered over time through utility bills, or other energy service contracting models.

41. This system is used in France with the purchase of new vehicles. Those under a certain emissions limit receive a cash bonus, while those over the limit must pay a penalty. This can theoretically be scaled to be self-funding, but experience has shown this to be challenging.

Box 3: Solar thermal in India

The Government of India, under the National Action Plan for Climate Change (NAPCC), recently announced the Jawaharlal Nehru National Solar Mission (NSM). The mission is setting an ambitious target for ensuring that domestic and industrial applications below 80°C are solarised, which means installing 10.5 GW_{th} (15 million m^2) by 2017 and 14 GW_{th} (20 million m^2) of solar thermal collectors by 2022. The key strategy of the mission will be to make necessary policy changes to meet this objective:

- Make solar heaters mandatory, through building bylaws and incorporation in the National Building Code;
- Ensure the introduction of effective mechanisms for certification and rating by manufacturers of solar thermal applications;
- Facilitate measurement and promotion of these individual devices through local agencies and power utilities;
- Support the upgrading of technologies and manufacturing capacities through soft loans, to achieve higher efficiencies and further cost reduction.

Another option is to pool many of the small-scale investment decisions of residential and service sector customers into large portfolios to allow sophisticated assessment of future risk and benefits. This would facilitate larger-scale projects, minimise the cost of capital and the transaction costs involved in acquiring funding. However, the challenges are different in developing countries, where immature financial markets or institutional frailty might be a barrier (IEA, 2010b).

Some simple measures could help improve the prospects for financing energy-efficient and low/zero-carbon heating and cooling technologies, by raising their profile with banks and other fund providers. Requiring landlords to disclose monthly energy costs for all new leases, and requiring underwriters of mortgages and new construction loans to consider energy costs, and to factor in the energy and carbon price risks in loan repayment risk, could all help.

Improve building sector and installer knowledge

This roadmap recommends the following actions:	***Milestones***
Including the heating and cooling technologies as well as emerging technologies as part of standard education of architects, engineers and heating and cooling technology installers.	Begin assessment of implementation in 2010. Enforce by 2015.
Ensure building sector professionals are aware of the importance of energy costs and future operating cost risks for tenants.	Ongoing.
Develop programmes to ensure installed heating and cooling systems are accurately matched to the loads of the building. Develop and distribute accurate simulation tools to identify heating and cooling loads in new buildings and train buildings professionals in their use.	From 2012.
Consolidate heating and cooling system design, installation and training and certification schemes into a single overarching programme that gives consumers a simple, unambiguous guarantee of confidence. Start the process of harmonising systems across countries/regions.	From 2015.

Governments, utilities and other entities should provide education to home-builders, architects, engineers and commercial building owners and operators. Reliable, tailor-made, "easy to understand" information for end-users is important. Ensuring that a qualified installer base expands to meet the potential deployment growth of energy-efficient technologies will be essential to ensuring the technical potential is realised. Addressing the general issue of the oversizing of heating and cooling systems in residential and small-scale commercial applications will be important. Certification and labelling of equipment helps boost consumer confidence in a product and can improve competition and reliability of the systems if effective monitoring verification and enforcement programmes are in place.

An example of efforts to offer clearer information on quality assurance to consumers is the EU-CERT. HP Project, a European training and quality campaign for installers in the field of heat pump technology that was supported by the European Commission. This was succeeded in July 2009 by the more comprehensive *QualiCert* project, which goes further by extending a quality certification and accreditation system for installers of small-scale renewable energy systems. The sharing of experiences from countries with mature markets (*e.g.* training and certification of installers in the United States) can be very useful.

International collaboration

Engage in international collaboration efforts

This roadmap recommends the following actions on R&D:	***Milestones***
Develop websites and have regular international meetings for information and research sharing.	2011 onwards
Identify countries (including developing countries) that are candidates to significantly expand technology deployment, and help to get them involved.	2011 onwards
Convene workshops and co-ordinate activities.	2011 onwards
Publish periodical reports and scorecards on progress; report on best practices, issues arising and how these can be overcome.	2011 onwards

Governments around the world must work together to ensure sufficient co-ordination of activities and avoid working at cross-purposes, to accelerate technology development and adoption in the most efficient way. There are several key areas for information sharing and collaboration:

- Research programmes;
- Codes and standards;
- Setting of market development targets, such as market penetration;
- Alignment of heating and cooling system infrastructure;
- Policy development and experience in implementing different approaches.

A number of activities can help improve international collaboration and information-sharing. Governments should maximise the use of websites to publically share information and learning and identify best practices. Regular international meetings can help governments learn from experiences in other countries and increase contacts. Multi-stakeholder workshops – including governments, utilities, manufacturers and others – are also important to improving collaboration and sharing best practices in areas such as standardisation, system integration, innovative applications and consumer behaviour. Information should also be shared about policies that are particularly effective or ineffective to avoid duplication of mistakes and encourage repeat successes across countries. Early involvement of developing countries in international collaboration and information sharing should be ensured to overcome unique but surmountable barriers in emerging markets.

Technology and research should also be shared. Expertise sharing and exchanges of experts should be explored. Common research agendas can address shared problems (*e.g.* systems integration and performance, seasonal performance). In the European Union the Technology Platform on Renewable Heating and Cooling is one such example of international collaboration.[42]

The IEA Secretariat can play a role in convening workshops and in co-ordinating activities, including planning, data collection, international analysis and research methodologies. Through its roadmapping efforts, the IEA can help co-ordinate planning in linked areas around the world. The IEA Implementing Agreements play an important role in running joint research programmes. Countries and private organisations can join for specific projects.

Encourage governments to address policy and industry needs at a national level

National roadmaps can show how stakeholders can better set appropriate targets, guide market introduction, understand end-use needs and behaviour, integrate energy-efficient technologies into heating and cooling systems, craft supportive

42. See www.rhc-platform.org/cms for more details.

policy and collaborate where possible. In addition to making recommendations about how governments, researchers and equipment manufacturers and suppliers can identify their route to increased deployment of energy-efficient technology by 2050, this roadmap strongly encourages stakeholders to formally develop and share their own national roadmaps. By formulating common goals, the global community can work toward the significant CO_2 reductions enabled by energy-efficiency technologies.

Conclusions: near-term actions for stakeholders

This roadmap has responded to government leaders' requests for more detailed analysis regarding future deployment of energy-efficient heating and cooling technologies. It outlines a set of strategic goals, actions, and milestones to reach higher levels of market penetration around the world by 2050.

The existence of a roadmap document is not enough on its own. This roadmap is meant to be a process that takes into account new developments from research breakthroughs, demonstration projects, new types of policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure development and deployment efforts are on track to achieve the greenhouse gas emissions reductions that are required by 2050. As such, the IEA will report regularly on the progress that has been made in achieving the roadmap's vision.

To ensure co-ordination and harmonisation of activities, there needs to be a clear understanding of the roles of different stakeholder groups, along with commitments to achieving various objectives and targets over time. Table 8 identifies near-term priority actions for the full set of stakeholders that will need to be taken to achieve this roadmap.

The IEA has benefited from major inputs from representatives from government agencies, industry, the buildings sector and other experts. These groups should continue to collaborate, along with others, to work together in a harmonised manner in the future. Specifically, the IEA proposes to develop a Roadmap Implementation and Monitoring Committee that would work together in an ongoing fashion. The Committee could undertake various data collection and monitoring activities, as well as co-ordination activities. It could build on — and include participants from — existing efforts.

For more information about the ongoing roadmap process and progress in implementation, visit www.iea.org/roadmaps/index.asp.

Table 8. Near-term actions for stakeholders

Stakeholder	Action item
Economics/finance ministries	• Give manufacturers incentives to ramp up to large-scale production quickly in order to reduce costs (depreciation rules, investment incentives, etc). This requires stable, medium- to long-term policy frameworks, allowing companies to better plan their investment, R&D and deployment strategies. • Remove barriers to heating and cooling technologies in the existing domestic taxation system and import and export tariff/quota structure. • Develop innovative financial models and programmes to address cost barriers (*i.e.* repaying additional investment through utility bills, make low/zero-carbon heating and cooling technology installation costs deductable from local rateable value, not additive). • Use policies to help address first-cost barriers and higher life-cycle costs to achieve rapid early deployment of heating and cooling technologies during a fixed transition period that will achieve market transformation (grants, feed in tariffs, fiscal incentives, etc.). • Require regulatory regimes that give utilities incentives to look at system-level savings potential and that share financial rewards among beneficiaries, or at least don't expropriate benefits from decision makers. • Ensure government procurement policy, backed by adequate funds, facilitates the purchase of energy-efficient and low/zero-carbon heating and cooling technology systems. • Ensure the long-term stability of overall policy framework and funding streams for programmes to ensure actors have the confidence to invest. • Ensure regulatory framework is not overly complex and does not result in unintended consequences. • Ensure rigorous ex-post analysis of policy incentives is conducted to ensure that programmes deliver their intended benefits. • Define key milestones that will allow policy support to shift as the market enters different stages (*i.e.* to identify when specific deployment support can be phased out as the market gains critical momentum).
Training/science ministries and universities	• Allocate additional support to RD&D programmes for energy-efficient and low/zero-carbon heating and cooling technologies. • Include energy-efficient and low/zero-carbon heating and cooling technologies (existing and emerging) as part of standard education of architects, engineers and heating and cooling technology installers. • Work towards standardisation of test methods, establish appropriate metrics and empirically verify performance via in-use testing, including for customised systems. • Design, implement and make a strong commitment to ongoing RD&D programmes, ensure better co-ordination between programmes for different energy-efficient and low/zero-carbon heating and cooling technologies in order to develop hybrid technologies and ensure better integration of systems. • Develop mandatory education and certification schemes for installers and equipment.

Table 8. Near-term actions for stakeholders (continued)

Stakeholder	Action item
Environment/energy/ resource ministries and regulators	• Improve the collection of statistics, including the greater use of common methodologies harmonised internationally, on end-use energy consumption and energy indicators. • Improve and refine regional and national market potential estimates for energy-efficient and low/zero-carbon heating and cooling technologies. • Co-ordinate efforts to bring together all stakeholders to create a shared vision of deployment and policies to achieve greater penetration of energy-efficient and low/zero-carbon heating and cooling technologies • Develop ambitious national/regional/local roadmaps with targets for energy-efficient and low/zero-carbon heating and cooling technologies between now and 2050. • Collect better data on what motivates building sector decision makers and consumers design and purchase decisions. • Develop programmes to make energy costs more visible. Highlight the cost implications of exposure to volatile fossil fuel prices. Require mandatory metering (including tenant sub-metering). • Develop outreach and information programmes to help consumers understand the benefits of energy-efficient and low/zero-carbon heating and cooling technologies and increase their interest in adopting them. • Establish appropriate codes and standards for energy-efficient and low/zero-carbon heating and cooling technologies, including their harmonisation at an international level through ISO. • Clearly define the roles and responsibilities of different actors (governments, regulators, building sector professionals, equipment manufacturers, utilities and consumers); develop co-operative and collaborative strategies among multiple levels of government and building sector stakeholders in the national plan for energy-efficient and low/zero-carbon heating and cooling technologies. • Base CO_2-related policy incentives on life-cycle CO_2 emissions where possible. • With utilities, work co-operatively to develop synergies between the building sector and the management of energy networks (the concept of smart energy networks) in order to minimise overall system costs. • With science and research ministries, design, implement and make a strong commitment to ongoing RD&D programmes. • Ensure the regulatory framework for utilities rewards investment in energy efficiency, distributed generation and renewable energy sources. Remove regulatory or fiscal barriers to utilities' investment in these technologies.

Table 8. Near-term actions for stakeholders (continued)

Stakeholder	Action item
Manufacturers, designers, architects, developers, etc.	• With governments, ensure that all national targets can be met, if stable long-term policy frameworks provide the incentive to scale up manufacturing capacity. • Identify and implement policies to ensure adequate industry service capability is in place to meet the projected growth in deployment. • Take part in monitoring, verification and enforcement programmes at international level to share information. • In partnership with other stakeholders, develop national or international programmes for product and installation certification and quality assurance. • Governments and industry must include consumers in the planning process and ensure that their needs and desires are understood/met. • Develop outreach and information programmes to help consumers understand the benefits of energy-efficient and low/zero-carbon heating and cooling technologies and increase their interest in adopting them. • Develop innovative financial models/programmes for the technologies with high first costs. • Help identify sub-markets that can serve as early adopters/examples for large-scale deployment.
Non-governmental organisations	• Promote public awareness on energy efficiency and on low/zero-carbon technologies. • Legitimise the benefits to be gained by the measures outlined in this roadmap through endorsement, promotion and educational programmes. • Work with standards organisations like ASHRAE and builders' groups to develop more performance-based standards and guides. • Work with environmental and energy groups, trade associations and energy/environment ministries to develop and present consistent greenhouse gas accounting on renewable energy and energy efficiency.
Utilities	• Work with governments and consumers to develop policies and plans for increased deployment. • Develop innovative financial models/programmes for the technologies with high first costs. • Develop outreach and information programmes to help consumers understand the benefits of energy-efficient and low/zero-carbon heating and cooling technologies and increase their interest in adopting them. • In partnership with other stakeholders, develop national or international programmes for product and installation certification and quality assurance. • Explore system designs where the buildings sector can help minimise the overall system costs (demand-shifting, the use of thermal energy storage, etc). • Governments and utilities should co-operatively develop infrastructure development plans, particularly in order to future proof networks and the integration of energy-efficient and low/zero-carbon heating and cooling technologies into the smart energy networks of the future.

Table 8. Near-term actions for stakeholders (continued)

Stakeholder	*Action item*
State, provincial and local governments	• Implement the above policies through local code authorities and energy agencies. • Provide equal compensation and incentives to utilities to invest in distributed and efficiency technologies as they receive to invest in generation, transmission and distribution. • Require all state, local and utility programs to provide equal treatment to thermal and electric technologies in greenhouse gas reduction programmes. • Promote public awareness initiatives and campaigns, in co-operation with NGOs and industry. • Lead by example, by applying energy-efficient and low/zero carbon technologies in public buildings, adapting public procurement rules accordingly. • Use expertise of industry and other stakeholders (including NGOs) on the development of local initiatives (awareness raising, training or re-qualification).
Supranational organisations (*e.g.* the IEA)	• Co-ordinate sharing of hardware, software and research among countries. • Monitor and evaluate the launch and ramp-up of energy-efficient and low/zero-carbon heating and cooling technologies among national governments. • Identify countries (including developing countries) that are candidates to become early adopters, and help to get them involved. • Convene workshops and co-ordinate sharing of expertise, R&D, lessons learned from policy programmes, etc. • Publish periodical reports and scorecards on progress; report on best practices and issues arising (including how to overcome them). • Remove barriers to the international trade in and adoption of energy-efficient and low/zero-carbon technologies, using ISO as one possible means in some areas, and international organisations in general.

Appendix I: References

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Appendix II. Abbreviations, acronyms and units of measure

ASHP	air source heat pumps
AST	active solar thermal
ATES	acquifier thermal energy storage
BAT	best available technology
BAU	business-as-usual
BTES	borehole thermal energy storage
CCS	carbon capture and storage
CHP	combined heat and power
CO_2	cabon dioxide
COP	coefficient of performance
EIA	Energy Information Administration (United States)
EPA	Environmental Protection Agency (United States)
ETP	IEA Energy Technology Perspectives publication
EU	European Union
GHG	greenhouse gas
GSHP	ground-source heat pumps
HSPF	Heating Seasonal Performance Factor
IA	Implementing Agreement (IEA)
ICE	internal combustion engine
IEA	International Energy Agency
ISIC	international standard industrial classification
ISO	International Organisation for Standardization
MEP	minimum energy performance
MCFC	Molten carbonate fuel cell
OECD	Organisation for Economic Co-operation and Development
PAFC	phosphoric acid fuel cells
PCM	phase change materials
PEM	proton exchange membrane
PEMFC	polymer electrolyte fuel cells
PV	photovoltaic power
R&D	research and development
RD&D	research, development and demonstration
SOFC	solid oxide fuel cells
SPF	Seasonal Performance Factor
T&D	transmission and distribution
USD	United States dollars

Units of measure

°C	degrees Celsius
g	grammes
GJ	gigajoule = 10^9 joules
Gt	gigatonne = 10^9 tonnes
GW_{th}	gigawatt of thermal capacity= 10^9 watts
kW_e	kilowatt electrical capacity
kWh	kilowatt-hour = 10^3 watt x 1 hour
kW_{th}	kilowatt thermal capacity
m^2	square metre
Mt	megatonne = 10^6 tonnes
Mtoe	million tonne of oil equivalent = 10^6 tonne of oil equivalent
TWh	terawatt-hour = 10^{12} watt x 1 hour
W	watts

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