EFFICIENT HEATING AND COOLING SYSTEMS FOR LOW-ENERGY HOUSES

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INTRODUCTION

Buildings account for a large amount of land use, energy and water consumption, and atmospheric pollution. For example, in the United States, they use 40% of the total national energy consumption (56% by residential dwellings), produce 38% of the total carbon dioxide emissions, and account for 12.2% of the total quantity of water consumed (2006). In this context, buildings with considerably reduced energy consumption are a key strategy to achieving energy savings and climate protection targets in both the residential and commercial/institutional sectors [1]. This article reviews a number of heating and cooling systems—existing and/or under development—available for residential buildings and briefly outlines some research projects and initiatives, as well as technical achievements in Canada and other developed countries over the last few years.

KEYWORDS

low-energy house, building integrated photovoltaic thermal system, energy efficiency, heat pump, heat recovery

LOW-ENERGY HOUSES

Since the mid-90s, energy consumption in the residential sector has successfully been lowered by using improved insulation, energy-efficient windows and lighting, existing or new efficient appliances, and integrated heating, ventilating, and air conditioning (HVAC) systems. Low-energy homes (LEHs) are being promoted as potential solutions to reduce our dependency on fossil fuels and to lower global carbon emissions.

Definitions

The definition of low-energy houses varies from one country or continent to another according to national/regional codes and standards, and to specific energetic and environmental targets.

Green houses

A green (sustainable, natural) house (or building) means a construction which focuses on increasing resource use efficiency (energy, water, and materials) while reducing, during its life-cycle, the impacts on human health and productivity and on the environment. The goal of

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such homes is to bring together several practices and techniques in order to use resources more efficiently through better siting, design, construction, operation, maintenance, and the use of locally available natural materials. To reduce energy use a few percentage points below the minimum required by law, renewable energies (i.e., passive thermal and active photovoltaic solar techniques, wind, geothermal) can be used. Green houses also have to take advantage of (solar) orientation, natural ventilation, plants and trees on green roofs, day lighting, thermal mass, and night time cooling. During construction, one goal is to reduce the amount of materials used. Materials being considered include rapidly renewable plants (e.g., bamboo and straw), lumber from sustainably-managed forests, recycled stone and metals, and other non-toxic, reusable, and/or recyclable products such as coal, combustion products, foundry sand, and construction demolition debris. Finally, wastewater from dishwashing or washing machines can be used for irrigation, flushing toilets, and washing cars.

Low- and ultra-low-energy houses

There are no clear or unique definitions for low-energy houses (LEH) and ultra-low-energy houses (ULEH). In Canada, *low-energy houses* are considered to be houses that were built to meet the Canadian *R-2000 performance standard* requiring about half the energy consumed by a conventional house. In the United States, homes that are at least 15% more energy efficient than homes built according to the 2006 International Energy Conservation Code qualify as ENERGY STAR homes. That includes a variety of energy-efficient features, such as energy-efficient insulation, high-performance windows, tight construction and ducts, energy-efficient heating and cooling equipment, and approved lighting and appliances. In most European countries, the typical characteristics of a low-energy house include the area-specific heat load (W/m^2) and the annual specific energy required for space heating ($kWh/m^2 \cdot year$). As an example, Table 1 shows a comparison of typical measures and values for low- and ultra-low-energy houses as defined by Switzerland's MINERGIE label [1]. In Germany, the KfW 40 program defines a *passive house* as *a building, where thermal comfort can be kept by only reheating the hygienic necessary air volume flow rate* [1]. To get certification for such a house, the area-specific heat load must not exceed ~10 W/m^2, the annual energy required for space heating has to be below 15 $kWh/(m^2 \cdot year)$, and primary energy consumption for both space and DHW heating must be lower than 60 $kWh/(m^2 \cdot year)$. In Austria, low-energy houses are defined as houses

TABLE 1. Switzerland's typical requirements for low- and ultra-low-energy houses according to MINERGIE label [1].

Requirements	Low-energy house	Ultra-low-energy house
Renewable energy (solar, geothermal, etc.)	Recommended	Recommended
Space heating energy requirement	40–50 $kWh/m^2 \cdot a$	15 $kWh/m^2 \cdot a$
Thermal insulation	15 to 20 cm	25 to 35 cm
Glazing	Double layer	Triple layer
Heat distribution system	Usual systems	Air heating possible
A-label electrical appliances	Recommended	Required
Mechanical ventilation	Recommended	Required
Specific heat load	20–40 W/m^2	10 W/m^2

with a specific heat load lower than 40 W/m^2 and a space heating energy requirement of about 50 kWh/m^2. In Norway, typical needs of low energy houses include a heat load of 20 W/m^2 and a space heating energy requirement below 30 kWh/(m^2·year) [1].

Net (or near) zero energy houses

The net (or near) zero energy house (NZEH) is a term applied to a residential building with zero (or near zero) net energy consumption and zero carbon emissions annually. In other words, a NZEH is a house that produces the same amount of energy as it consumes on an annual basis, thus implying on-site energy generation. Such a house is consequently not dependent on the energy grid supply. It tends to have a much lower ecological impact *green buildings* that require imported energy and/or fossil fuels. However, this definition mostly refers to the operation of the house and not to its total lifetime. It doesn't include the emissions generated in the construction of the house and the embodied energy of the structure.

Benefits and drawbacks

Compared to conventional buildings, low-energy houses (LEH) present multiple advantages such as improved indoor comfort, lower environmental impacts, and economic benefits. Increased comfort is due to more uniform indoor temperatures, no draught thanks to air-tightness, and better air quality provided by the mechanical ventilation systems, including air filtration (pollutants, pollen), as well as cooling and dehumidification. LEHs are environmentally sound due to significantly reduced energy and supply temperature requirements for space heating. They also present economic benefits, including savings in operating costs, independence from fossil and electrical energy prices, improved energy efficiency and relatively limited additional investment for the new construction. Moreover, home owners may benefit from a higher resale value because of the electrical energy transferred (or sold) to the grid. Possible disadvantages of LEHs include potentially higher initial costs compared to those of average conventional houses. Lack of trained home designers and builders could be another potential drawback in some countries.

Main targets

The strategies used to build houses offering low energy consumption, improved comfort, and economic benefits differ from one country to another. The main energetic target is to reduce energy use in the winter as well as in the summer. In the winter, LEHs have to reduce conduction/convection/infiltration heat losses through high thermal insulation, avoidance of thermal bridges, and an air-tight construction. This can be provided by using high-efficiency windows and better insulated walls, ceilings, and floors. Effective window placement can provide more natural light and lessen the need for electric lighting during the day. Optimizing passive solar gains through house orientation and the use of a thermal mass to store and buffer peak gains may further help reduce the energy used for space heating, especially in cold and moderate climates. LEHs must also be designed to make use of energy gained from other sources such as exhaust air, drain water, and combined heat and power devices. In the summer, LEHs have to reduce heat gains mainly through high thermal insulation, air-tight construction, oriented windows and walls, awnings, porches, and trees to shade windows and roofs. External gains can also be reduced by minimizing make-up fresh air, while internal gains can be lowered by using energy-efficient appliances. Efficient energy use also reduces energy costs and/or the need for new power plants and/or energy imports. It facilitates the replacement of non-renewable resources with renewable energies—often the most economical solution to energy shortages—and represents a more environmentally-friendly alternative to increasing energy production. However, because energy used in houses can dramatically vary with the occupants' behavior, particular attention must be paid to this important issue.

TECHNOLOGIES FOR LOW-ENERGY HOUSES

Many conventional and new HVAC technologies can be integrated in low-energy houses. They can use renewable energies such as solar, wind, and geothermal energies, as well as heat recovered from the home exhaust air and drain water. This section reviews a number of the most efficient heating, ventilating, and air-conditioning (HVAC) devices and systems available today for low-energy houses.

Micro-generation using solar cells

Individual low-energy houses can use photovoltaic (PV) solar cells to provide both electricity and heat. Such systems are commonly called *building-integrated photovoltaic/thermal systems* (BIPV/T). Their main advantage is that the initial cost can be offset by reducing the cost of building materials and labor that would normally be used to build conventional roofs. BIPV/T must be connected to the electricity grid to export electricity when there is a surplus and draw power from the grid when not enough electricity is being produced. A typical photovoltaic module has an ideal conversion efficiency rate in the range of 15%. The remaining energy produced is heat. By recovering heat and using it for space and hot water heating, the total solar efficiency may increase to over 50%. However, grid-tied PV systems still have a high initial cost and are generally sold only under incentive programs.

Micro-generation using wind turbines

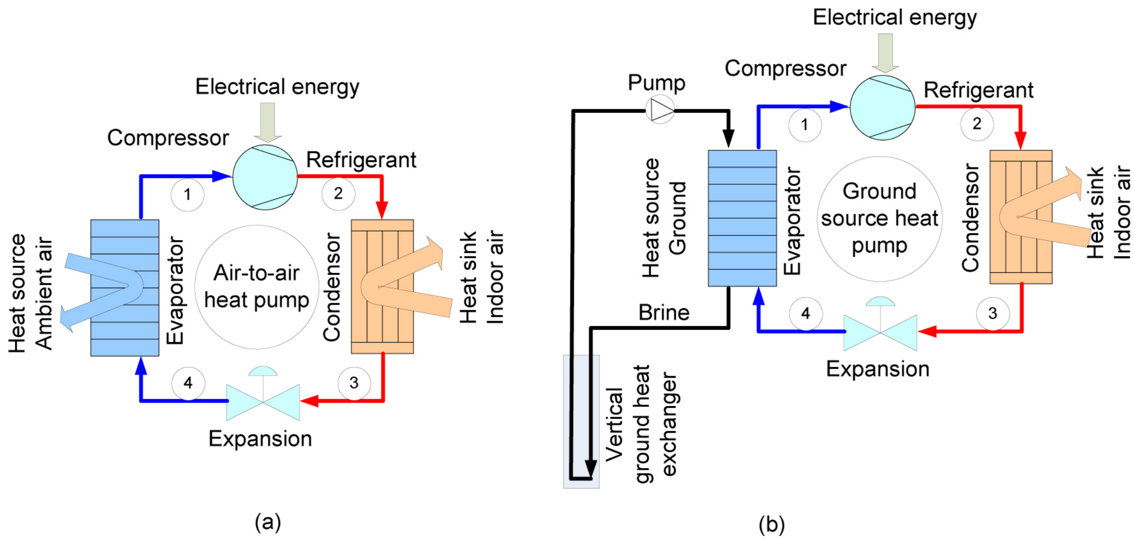
Wind turbines connected to the electricity grid (Figure 1) seem more appropriate for large complexes of low-energy residential houses that can generate their own energy to meet electricity needs. However, for individual residences, small-scale wind turbines seem less interesting because of potential noise emissions, high costs, and aesthetic issues.

FIGURE 1. View of a residential wind turbine [2].

Heat pumps

Heat pumps draw abundant, free, and renewable energy from the air or the ground. Air-, ground-, and water-source heat pumps are the most energy efficient, environmentally clean, and cost-effective space conditioning and domestic hot water heating systems available. They can help reduce energy consumption and power demand by up to 69%. This was the reason why the IEA HPP's Annex 32 project [1] focused on the development of new heat pump integration solutions in LEHs. Air-source heat pumps (Figure 2a) extract heat from the outside air and transfer it to the inside air. They are relatively easy to install and inexpensive. However, they have limitations due to the use of outside air as a heat source or sink. At outdoor temperatures below approximately

FIGURE 2. (a) Air-to-air heat pump; (b) Ground-source heat pump with vertical ground heat exchanger.



–8°C or over 30°C, their heating and cooling performance may drastically decline. Ground-source (or geothermal) heat pumps (GSHP) (Figure 2b) extract heat from the ground (soil, rock) or similar sources (groundwater, lake, river, etc.) and transfer it to the house indoor air. They typically have higher efficiencies than air-source heat pumps. This is because GSHPs draw heat from the ground which is at a relatively constant temperature all year round below a depth of about 2.5 m.

The most common type of residential heat pumps uses a mechanical vapor-compression refrigeration cycle. In such a cycle, the low pressure and temperature refrigerant (state 4) enters the evaporator where it evaporates by recovering heat from the ambient air (Figure 2a) or from the ground (Figure 2b), both being renewable heat sources. The low pressure and temperature vapour (state 1) produced within the evaporator is compressed by the compressor up to state 2 at higher pressure and temperature. During this process, the compressor consumes electrical energy. The vapour at state 2 leaving the compressor at high pressure and temperature enters the condenser where it condenses and transfers heat to the indoor air. The amount of heat transferred to the house indoor air is equal to the heat recovered from the ambient air or from the ground, plus the equivalent heat of the electrical energy consumed by the compressor. The liquid refrigerant leaving the compressor (state 3) at high pressure and temperature enters the expansion device where its pressure and temperature are reduced down to the initial state 1, and then the cycle is repeated. A reversing valve (not shown in Figures 2a and 2b) can switch the direction of the refrigerant flow through the cycle and therefore the heat pump may deliver either heating or cooling to a low-energy house. In the heating mode, the coefficient of performance (COP) is defined as the ratio of the useful thermal power supplied to the house to the input electrical power. In mild weathers, the average COP of air-source heat pumps over seasonal variation is typically 2.5–2.8. Ground-source heat pumps are generally more efficient than air-source heat pumps with seasonal COPs of 3.5 or higher. In the cooling mode a heat pump's operating performance is described by the Seasonal Energy Efficiency Ratio (SEER). In North America, it is defined as the cooling output during a typical cooling season, expressed in Btu (1 Btu = 1.055 kJ), divided by the total electric energy input during the same period, expressed in watt-hours (Wh).

Heat recovery ventilators

In recent years, improved practices in the construction of new low-energy houses have resulted in more energy-efficient, but also more air-tight homes. These homes generate several pollutants coming from household contents and materials, people and their activities, as well as family pets (Table 2). The moisture comes from cooking, washing, showering, and breathing. At excessive levels, moisture condenses on windows and can cause structural deterioration. Areas of excessive moisture are also breeding grounds for mould, mildew, fungi, dust mites and bacteria. Mold spores and dust easily become airborne and circulate freely throughout the house, possibly causing a range of symptoms and allergic reactions.

In addition to excessive moisture and biological contaminants, combustion appliances have the potential for allowing gases, including carbon monoxide, and other pollutants to escape into the air. Home products used to build new houses can also give off gases that are less favourable to the occupants' comfort and health. In many areas there's also a concern about radon seeping from the ground. In many LEHs, air infiltration through the doors, windows, and other openings does not always provide adequate ventilation. Even when there is an acceptable air exchange rate, fresh air may not be getting to the rooms where it is needed. As a result, mechanical ventilation is needed in most LEHs in order to distribute fresh air throughout the home, maintain a healthy living environment, filter the incoming fresh outdoor air, complement the house air-tightness, and ensure a healthy living environment. The need for heat recovery ventilators (HRV) has become obvious because this technology offers fresh air, better climate control, and energy efficiency by reducing the heating (or cooling) requirements. There are two types of energy recovery systems: heat recovery ventilators (HRV) and energy recovery (or enthalpy recovery) ventilators (ERV). Both types include a heat exchanger, two separate blowers to push the air through the machine, and some controls. The main difference between a heat recovery and an energy recovery ventilator is the way the heat exchanger

TABLE 2. Common pollutants and their sources [3].

Pollutant	Source
Excess moisture (humidity) and mould	A crawl space with an exposed earth floor, people, clothes drying indoors, cooking and washing, plants, firewood stored indoors, etc.
Urea-formaldehyde	Some types of particle board, panelling, carpeting, furniture, textiles, etc.
Radon	Soil and ground water
Tobacco smoke	Smoking
Household chemicals	Cleaning products, certain hobby supplies, paints and solvents, aerosols, etc.
Odours, viruses, bacteria and dandruff	People and pets
Combustion by-products (including carbon monoxide, nitrogen oxides, carbon dioxide and particulates)	Fuel-burning appliances, including furnaces, heaters, range/ovens, gas clothes dryers, fireplaces, wood stoves, etc.

works. With an energy recovery ventilator, the heat exchanger transfers a certain amount of latent heat along with sensible heat, while a heat recovery ventilator only transfers sensible heat. HRVs and ERVs can be stand-alone devices that operate independently, or they can be built-in or added to existing HVAC systems.

A heat (or energy, enthalpy) recovery ventilator is a ventilation system that uses a counter-flow heat exchanger between the inbound and outbound air flow. It consists of two separate air handling systems. One collects and exhausts stale indoor air while the other draws in outdoor air and distributes it throughout the home (Figure 3).

In Figure 3, the flow of air in and out of the house takes place simultaneously. The two air streams are always kept separate and fresh outdoor air is filtered before it enters the heat exchanger core. A circulation fan (blower) distributes the air throughout the home via ductwork. A separate ductwork system draws the stale indoor air back to the HRV, where it is filtered and pushed by another blower through the heat exchanger core. Here, the stale air releases heat that is transferred to the fresh air being drawn into the house. During the heating season, an HRV recovers heat from the outgoing, stale household air and uses it to preheat incoming fresh outdoor air. Because an energy recovery ventilator transfers some of the moisture from the exhaust air to the usually less humid incoming winter air, air humidity within the house remains more constant. This also keeps the heat exchanger core warmer, minimizing freezing problems. During the air-conditioning season, the HRV reverses this heat exchange process, removing some of the heat from the incoming air and transferring it to the outgoing air. In that season, an energy recovery ventilator may help control humidity in the house by transferring some of the water vapor in the incoming air to the theoretically drier air that is leaving the house. The energy recovery ventilator generally offers better humidity control than a heat recovery system. It can help keep excess moisture *out* of the home by extracting it from the incoming fresh air and transferring it to the exhaust air. Since less energy is required to lower the temperature of dry air compared to moist air, an ERV can reduce the load on the air conditioner and thus save energy and money. Most energy recovery ventilation systems can recover about 70%–80% of the energy in the exiting air and deliver that energy to the incoming air. However, they are most cost effective in climates with extreme winters or summers, and where fuel costs are high. In mild climates, the cost of the additional electricity consumed by the system fans may exceed the energy savings from not having to condition the supply air. Energy recovery ventilation systems operating in cold climates must have devices to help prevent freezing and frost formation because cold supply air can cause frost formation in the heat exchanger, which can reduce the ventilation effectiveness.

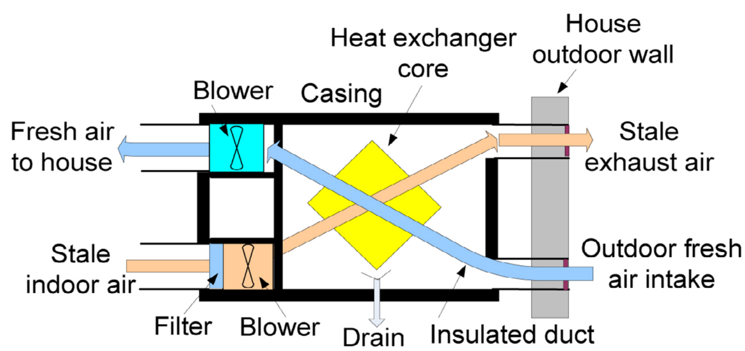
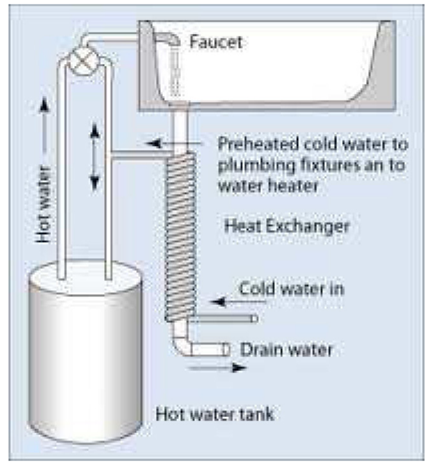


FIGURE 3. Principle of a heat recovery ventilator. Note: All the parts shown may not be found on all HRVs.

Drain-to-water heat recovery

After space heating, domestic water heating is the second most costly form of energy demand in LEHs, accounting for 20–30% of total annual energy consumption. However, up to 90% of this energy is wasted out to the sewer. Drain-water heat recovery (DWHR) systems can re-capture some, or most, of this valuable energy and use it to preheat cold, fresh water. A typical DWHR unit consists of a simple inner copper drainpipe with soft copper tubes wrapped very tightly around an inner pipe (Figure 4). As warm water flows down the drainpipe, incoming cold water flows through the outer copper tubes. Such a device can bring the cold water temperature from 10°C to as much as 24°C and save between 25% and 40% on annual water heating energy consumption. They also may reduce greenhouse gas emissions by about 200kg/person/year when replacing natural gas used for domestic water heating.

FIGURE 4. Principle of a drain-to-water heat recovery device [4].



CANADIAN MARKET AND PROJECTS

During the early 90s, the Canadian Federal Government undertook several initiatives aimed at reducing the amount of energy consumed by buildings. Many of them supported the development of higher efficiency standards and codes, and energy efficient technologies. As a result, recently built new housing is on average 13% more energy efficient (mainly space heating and hot water usage) than the housing built about 15 years ago [5]. This section provides a short overview of the Canadian energy market and national and provincial building initiatives.

Energy end-users

In Canada, residential and commercial buildings use together 30.3% of the total national energy consumption (2004). Prevailing energy sources are natural gas (46%) and electricity (37%). Major end-users are space (55%) and domestic hot water (24%) heating [6].

Features of Canadian LEHs

The most common type of low energy houses (LEH) in Canada is the two-storey cottage. Its construction is based on 2' × 6' (R-20 or equivalent) wood framing for walls, generally with an exterior continuous layer of insulation and high levels of insulation in the ceiling/attic. Roof slopes commonly vary in the range 30–50° and can accommodate insulation over R-40. The Canadian National Building Code requires low-emissivity, double-glazed argon windows, preferably with thermally broken frames. More thermal insulation is added in the form of concrete basement floors (5–10 cm), often insulated to R-12 and covered with ceramic, or of interior vertical brick or concrete walls. In provinces where natural gas is the primary space-heating fuel (Ontario and Western Canada), either direct vent or condensing furnaces constitute the majority of heating systems. Saskatchewan, Alberta, and British Columbia mainly use direct-vent furnaces, while Ontario and Manitoba mainly use condensing furnaces. Electric baseboard systems are the dominant heating system in Québec and the Maritimes (Eastern Canada), while flame retention oil systems predominate in the Territories.

Heat recovery ventilator systems are well established as an essential component of a ventilation system necessary to provide good indoor air quality. In Eastern Canada (Québec, New Brunswick, and Newfoundland), about 90% of new houses comply with the ventilation system requirements of the National Building Code, while compliance in the rest of Canada (British Columbia, etc.) is much lower, 20% to 60% typically. Generally, major market barriers to widespread adoption of low-energy housing practices include the lack of builder skills, poor workmanship, and lack of on-site inspection. Variable contractor and subcontractor skills make it difficult to ensure that a high-quality airtight envelope will be constructed. Limited builder know-how about new technologies, particularly advanced windows for passive solar design, as well as poor coordination between the installation of the HVAC systems and the building envelope may also be a barrier for the LEH market. On the other hand, many home builders do not usually employ full-time architects or engineers. They offer several existing designs to the customer and don't explain the available energy efficiency options.

Certification programs

The Canadian certification programs (R-2000, Novoclimat, and ENERGY STAR) are *voluntary* and contain various combinations of *required* and *optional criteria* that must be fulfilled to meet the desired certification level. Most of them have a range of *certification levels* (Silver, Gold, and Platinum) that offer builders a means to differentiate and improve the performance of their products. These *national* programs primarily focus on energy efficiency and have performance categories that also address water use, site issues (storm water management, site location), indoor environment, construction (erosion, traffic management), human waste, and materials. R-2000 is a program launched in 1981 and run by Natural Resources Canada's Office of Energy Efficiency. The technical requirements of the R-2000 standard include measures for the efficient use of energy, improved indoor air quality, and better environmental responsibility in the construction and operation of a house. These requirements give builders flexibility in the selection of construction techniques, building products, mechanical equipment, lighting, and appliances. A major aspect of the R-2000 standard is the energy target, which is based on the combined energy consumption for space heating and domestic water heating. The energy target is calculated for each house based on its size, location, and fuel type. In 1991, at least 15,000 additional homes (about 1.5% of the new home construction market) had been built according to the R-2000 standard. NOVOCLIMAT (2003) is a program of the Agence de l'efficacité énergétique of Québec (Eastern Canada) based on the R-2000 standard aimed at improving the thermal resistance and air-tightness of the building envelope, maintaining good indoor air quality through the selection of healthy building materials and the maintenance of adequate ventilation through a heat recovery ventilator, improving occupant comfort and the durability of the building envelope, and training the builders. ENERGY STAR is promoted by Natural Resources Canada's Office of Energy Efficiency (OEE) and by major manufacturers and retailers of energy-efficient products, utilities and energy retailers, as well as interest groups from Australia to Europe. Products that display the ENERGY STAR symbol have been tested according to prescribed procedures and have been found to meet or exceed higher energy efficiency levels without compromising performance. *Mandatory* programs are much less common in Canada and tend to occur in new developments where requirements can be tied to land purchase or lease, or as a required rezoning condition.

Market players and stakeholders

A large number of national players and stakeholders are active in the low-energy home sector in Canada. For example, the *Canadian Home Builders' Association* (CHBA) represents more than 6800 member firms across Canada, including new home builders and renovators, land developers, trade contractors, product and material manufacturers, building product suppliers, lending institutions, insurance providers, and service professionals. The *Canada Mortgage and Housing Corporation* (CMHC) is a government-owned corporation providing mortgage loan insurance, mortgage-backed securities, housing policy and programs, and housing research. *The Heating, Refrigeration and Air Conditioning Institute of Canada* (HRAI) is the national trade association comprised of manufacturers, suppliers, wholesalers and contractors in the Canadian heating, ventilation, air conditioning, and refrigeration industry. Finally, Natural Resources Canada's *Office of Energy Efficiency* (OEE) is Canada's information centre on energy conservation, energy efficiency, and alternative fuels. It helps Canadians save energy while contributing to a healthier environment and provides practical energy conservation advice to consumers. Some of the main provincial market players and stakeholders in the low-energy housing Canadian market are listed in Table 3.

TABLE 3. Provincial market players and stakeholders in the Canadian provinces [5].

Player	Province	Profile	Activities
Hydro-Québec	Québec	Electric utility	Provides climate change solutions by linking up with ENERGY STAR. Offers residential energy use diagnostic tests to customers.
BC Hydro	British Columbia	Electric utility	Has launched an ENERGY STAR pilot program for residential households. Offers financial incentives.
Manitoba Hydro	Manitoba	Electric utility	Has launched the *Power Smart New Home Program* and offers financial incentives.
Gaz Métro	Québec	Gas utility	Works in partnership with ENERGY STAR and encourages customers to save energy while helping the environment.
Barrie Hydro	Ontario	Electric utility	Has launched an ENERGY STAR pilot program and provides financial incentives and rebates.
Union Gas	Ontario	Major Canadian gas utility	Helps customers make energy-efficient improvements to their homes. Promotes ENERGY STAR approved heating equipment to contractors and customers.
SaskEnergy Inc.	Saskatchewan	Gas utility	Promotes ENERGY STAR approved gas furnaces and boilers and is raising customer awareness of the benefits of energy efficiency.
SaskPower	Saskatchewan	Electric utility	Educates both customers and employees on how to make choices about their electricity use and help protect the environment. Actively promotes ENERGY STAR approved products.

Canadian initiatives and projects

In 2004, a multi-stakeholder group launched the *Net Zero Energy Home Coalition,* aiming at financing large-scale demonstration projects by introducing tax breaks or other financial incentives. Their goal was to have all new home construction designed by 2030 to meet net zero energy standards for severe Canadian climactic conditions. The *Solar Buildings Research Network* (SBRN), launched in 2005 and led by Concordia University (Montréal), has helped advancing research in solar buildings by coordinating the research efforts of ten other Canadian universities. Other partners were Natural Resources Canada, the Canada Mortgage and Housing Corporation (CMHC), and Hydro-Québec. The network's vision was the construction of a solar building operating in Canada as an integrated advanced technological system that approaches the net zero energy target.

CMHC and its national partners launched in 2006 a competition entitled EQuilibrium Sustainable Housing Competition [7] whose main objectives were to develop grid-tied homes with net zero energy consumption over a twelve-month period, and affordable homes that are highly resource efficient during construction and operation, with high quality indoor environments. EQuilibrium housing is a national housing initiative that brings the private and public sectors together to develop healthy homes that produce as much energy as possible. Focusing on the core principles of occupant health and comfort, energy efficiency, renewable energy production, resource conservation, reduced environmental impact and affordability, EQuilibrium homes offer potential buyers such benefits as lower energy bills in every season, healthier and more comfortable homes, a reliable, renewable supply of power, a greatly reduced environmental impact, as well as vital and sustainable communities for generations to come. Eleven zero-energy and near-zero-energy demonstration projects across the country had been built by the end of 2008 [7].

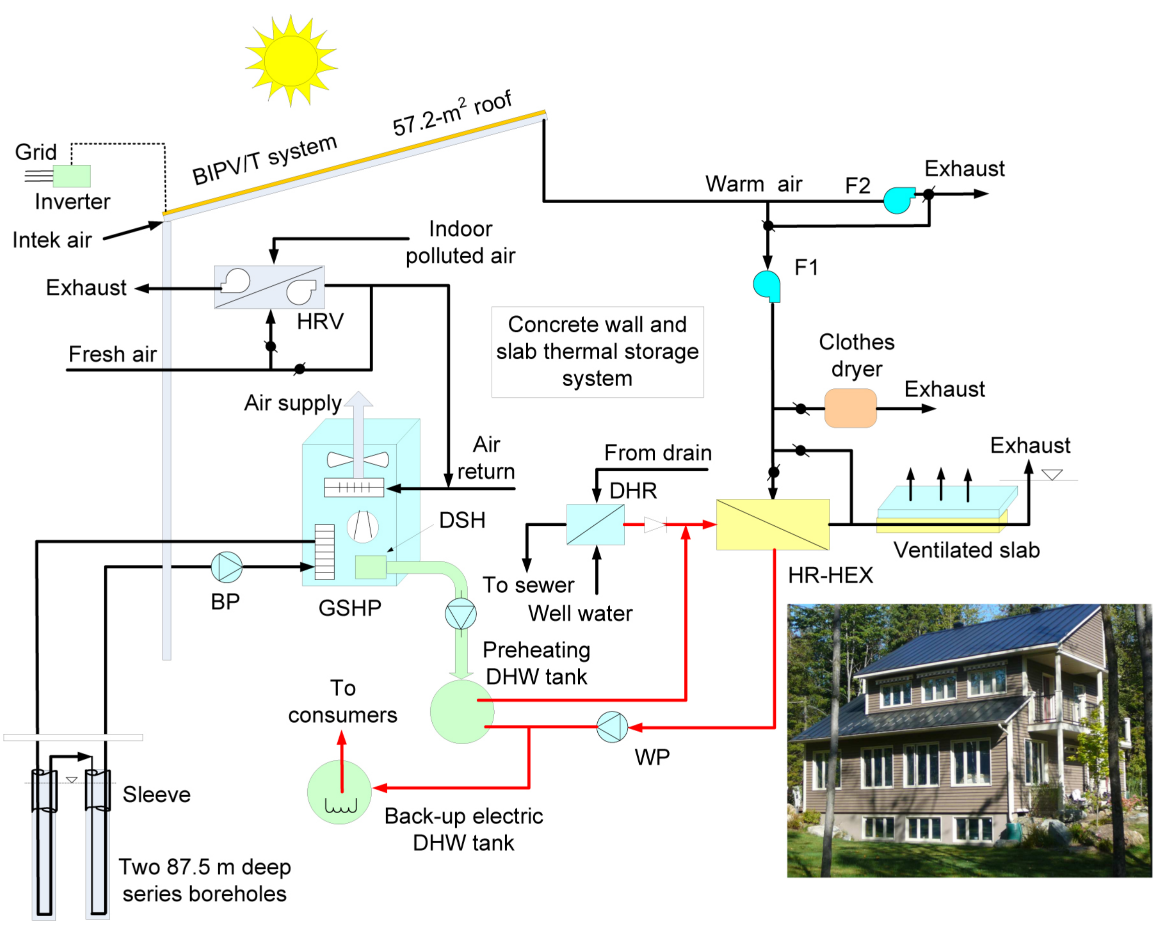
The *Abondance* building is a multi-family triplex located in Verdun, Quebec. It uses GeoExchange heat pumps, solar thermal vacuum tubes, grey water heat recovery, and 84 solar PV panels, while improving indoor air quality and moisture control. Among other innovative elements, the triplex features toilets that run solely on captured rainwater – conserving water and reducing demand on the municipal sewer system by 75%. The *Avalon Discovery III* built in Red Deer, Alberta, is a grid-tied, solar-powered, single-family home. It features a super-insulated building envelope, integrated renewable solar and space heating, a grey water recycling system for the laundry, bathroom and irrigation purposes, and innovative wall and window systems. The home was tied to the utility grid, allowing power to be bought or "sold" back into the grid system. The *Echo Haven* is a complete community of 25 low-impact homes in Calgary, Alberta. The main features of the project are shared amenities, equipment, and renewable energy sources, including solar hot water heating and grid-tied PV array, several wind turbines, 100% storm water retention on-site, grey water treatment, and rainwater harvesting. The Inspiration – The *Minto EcoHome* built in Ottawa, Ontario, is a single-family home featuring a highly-insulated building envelope (double wall), triple-pane low-e argon filled windows, HRV ventilation system, and solar thermal and PV systems. The *Riverdale NetZero Project* located in Edmonton, Alberta, is an energy-efficient duplex including renewable solar electric and solar heating systems, air-tight construction with high R-value windows, and a 60% reduction in indoor potable water use. The *Now House* in Toronto, Ontario, is a 60-year-old wartime house retrofitted with energy-efficient and sustainable features and technologies such as upgraded insulation, windows and Energy Star appliances, more efficient hot water and wastewater heat recovery, and renewable solar PV arrays. The *Top of the Annex*

TownHomes in downtown Toronto, Ontario, consist of three energy-efficient and affordable townhouses. They include sustainable and affordable infill housing, a highly insulated building envelope, high specification glazing, and ground source heating powered by solar PV panels. The *Urban Ecology,* located in Winnipeg, Manitoba, consists of two semi-detached homes with photovoltaic and geothermal renewable energy systems, in-floor radiant heating, snow-proof pitched roofs, and rainwater storage tanks.

EcoTerra home

The EcoTerra home is a 234 m^2 (including a 90 m^2 basement), two-storey, factory built wood-framed modular detached home (Figure 5). It is a rural single-family home located in Eastman, Quebec, designed by the Mackintosh School of Architecture and engineered by the Concordia University research team [8, 9, 10, 11]. Approximately 30% of the south façade area of the house is glazed with triple-pane, argon-filled, low-emissivity windows. A south-facing, roof-mounted, 57.2 m^2 building-integrated photovoltaic/thermal system (BIPV/T) converts solar energy into electricity (maximum 2.86 kW_e) and heat (maximum 12 kW_{th} at a

FIGURE 5. Simplified configuration of the EcoTerra house HVAC integrated system [9, 10]. BIPV/T: building integrated photovoltaic/thermal; BP: brine pump; DHR: drain heat recovery; DHW: domestic hot water; DSH: desuperheater; GSHP: ground-source heat pump; HR-HEX: heat recovery heat exchanger; HRV: heat recovery ventilator; F: fan WP: water pump.

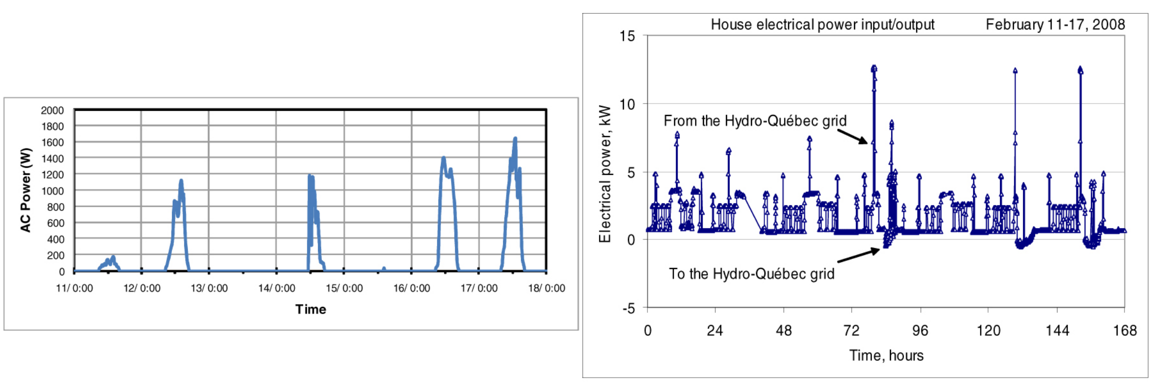


236 L/s air flow). It consists of 21 UniSolar, amorphous-silicon, 136 W modules fastened to a sloped (30.3°) metal roof. Outdoor air is drawn under the PV cells by the variable speed fan. The PV system is tied to the grid so that any surplus electricity generated is sent via an inverter to the grid. Depending on the exit temperature and heating demand, the solar-heated air can be used for drying clothes by circulating warm air through the clothes dryer, for preheating domestic hot water via an air-to-water heat exchanger, or for actively heating the thermal mass of a ventilated concrete slab in the basement. The preheated water is stored in a domestic hot water (DHW) tank where it is further heated by the heat pump's desuperheater. A second backup electrical DHW tank then raises the hot water temperature up to 60°C prior to its use. The cold water coming from the well is first heated by a drain water heat recovery system, prior to entering the preheating DHW storage tank. Finally, a heat recovery ventilator HRV recovers heat from the outgoing, stale household air and uses it to preheat the incoming, fresh outdoor air. During the air-conditioning season, the HRV removes the heat from the incoming air and transfers it to the intake air.

The main heating system uses a geothermal heat pump and an exhaust air heat recovery ventilator. The nominal cooling capacity of the geothermal heat pump with a two-stage compressor and R-410A refrigerant is 7.6 kW. It is linked to a vertical closed-loop ground heat exchanger made up of two vertical series-connected U-tubes filled with a 25% water/methanol mix. The depth of both 150 mm diameter boreholes is 87.5 m. As noted, the heat pump desuperheater heats the domestic hot water stored inside the DHW preheating tank. The energy performance of the main components of the EcoTerra house are succinctly presented here [8, 9, 10, 11].

Figure 6a presents the PV gross electrical power generated during each sunny day of a typical cold climate week (February 11–17, 2008). Figure 6b shows the net power drawn from and exported to the local (Hydro-Québec) electrical grid. It seems that even with cold ambient temperatures and some snow on the PV arrays it was possible, generally around noon, to transfer excess electrical power (about 1 kW) to the grid. On warmer days (e.g. May 5th, 2008) (Figure 7a) and weeks (e.g. July 7–13, 2008) (Figure 7b), the net (about 1.5 kW) and gross (around 2.3 kW) electrical power transferred to the grid and generated by the BIPV/T system increased.

FIGURE 6. (a) PV system power production; (b) EcoTerra house weekly net input/output electrical power (February 11–17, 2008).



(a) (b)

FIGURE 7. (a) EcoTerra house daily net input/output electrical power (May 5, 2008); (b) BIPV/T system gross power generation (July 7–13, 2008).

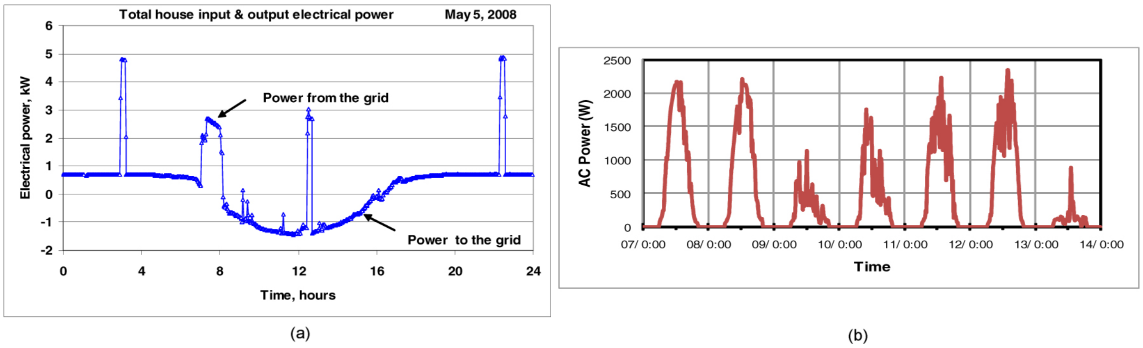
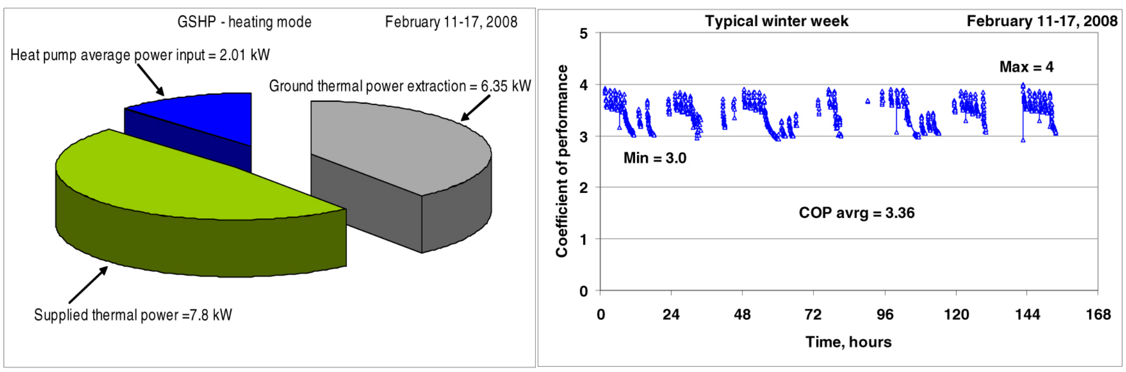


FIGURE 8. Ground-source heat pump weekly energy balance (a) and coefficient of performance (b) (February 11–17, 2008).



During a typical winter week (February 11–17, 2008), the ground-source heat pump extracted 6.35 thermal kW (Figure 8a) from the ground with coefficients of performance (COP) varying between 4 (maximum) and 3 (minimum) at the beginning and the end of each running cycle respectively (Figure 8b).

During the same typical cold winter week (February 11–17, 2008), the indoor air entered the heat recovery ventilator at around 22°C (Figure 9a) prior to being exhausted. The heat recovered heated the outdoor fresh air from entering temperatures as low as –15°C up to 15-20°C prior to entering the GSHP (Figure 5). The overall energy efficiency of HRV, based on these measured temperatures as per ASHRAE *Standard* 84, varied around 85%.

Finally, as can be seen in Table 4, the annual electrical energy consumption of the occupied low-energy house (11,077 kWh in 2010 and 11,993 kWh in 2011) was 56.8% lower than the average consumption of conventional houses, which in Eastern Canada ranges around 26,700 kWh/year. This number doesn't account for the electrical energy generated by the BIPV/T system about 58% of which was estimated to be supplied to the grid each year.

TABLE 4. EcoTerra house annual electrical energy consumption.

Year	House	Electrical energy consumption (kWh/year)
2010	Occupied	11,077
2011	Occupied	11,993

Figure 10a shows the monthly energy consumption profile of the unoccupied and

FIGURE 9. Exhaust (a) and outdoor fresh make-up (b) air temperatures entering and leaving the heat recovery ventilator (February 11–17, 2008).

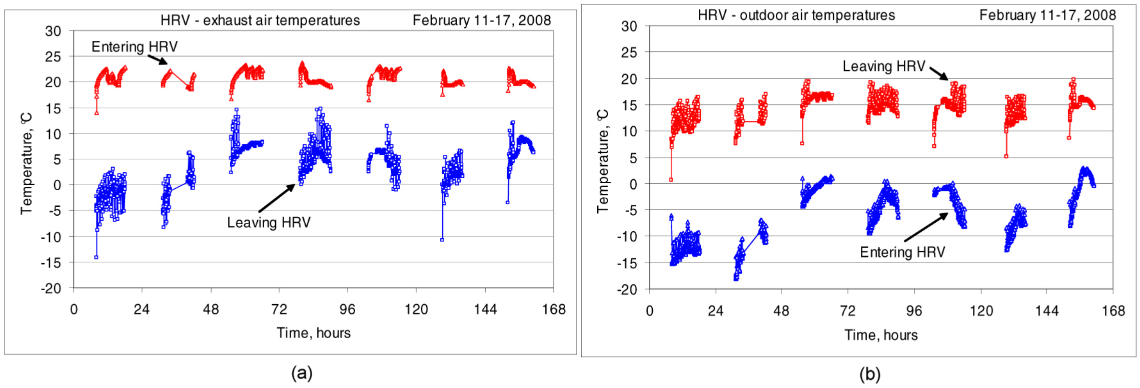
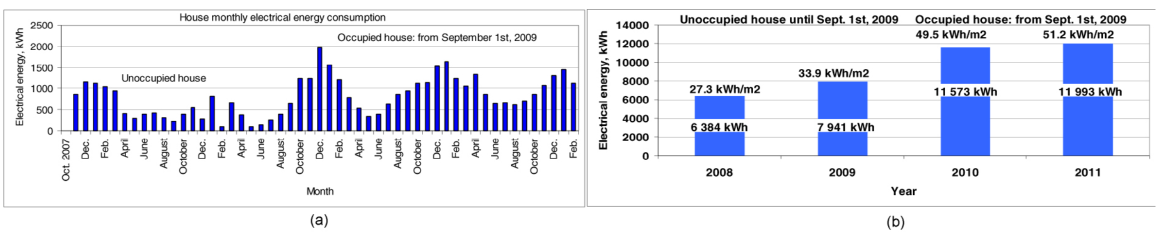


FIGURE 10. Domestic electrical energy consumption; (a) monthly; (b) annual total and specific (i.e., vs. total floor area).



occupied low-energy houses, while Figure 10b presents the annual total and specific energy consumptions. The annual specific electrical energy consumption (versus the total area) varied between 27.3 kWh/m^2 in 2008 (unoccupied house) and 51.2 kWh/m^2 in 2011 (occupied house). The geothermal heat pump (i.e., compressor, fan, and brine-circulating pump), which was the main heating and cooling device, consumed 8.2 kWh/m^2 (in 2008), 8.8 kWh/m^2 (in 2009), 10.8 kWh/m^2 (in 2010), and 9.9 kWh/m^2 (in 2011). The last two numbers exceed the annual energy consumption target by 50% for air-conditioning (both heating and cooling) of the occupied house, which was 15 kWh/m^2.

OTHER NATIONAL PROJECTS

A survey of low-energy housing markets, several HVAC system developments, and field monitoring of integrated heat pump systems for low-energy houses has been carried out as part of the IEA HPP Annex 32 project [1].

In Austria, there were about 1700 passive houses at the end of 2006. Since that time, Graz University of Technology has developed several small-capacity (3–5 kW) air-to-air and air-to-water heat pumps using natural refrigerants, such as carbon dioxide and propane, ready to be integrated into future low-energy houses [1, 12]. Simultaneously, Arsenal Research has conducted field monitoring of combined heat pump systems for space and DHW heating. The main systems under study were: (i) an air-to-air reversible heat pump where the outdoor fresh air is preheated by a ground-to-air collector buried at a depth of about 1.5 m prior to entering the air heat recovery coil; (ii) a non-reversible brine-to-water heat pump for floor space heating and cooling where a ground collector is used as a heat source in the heating mode, and partially as a heat sink in the cooling mode. The second system was chosen for further development because in Austria hydraulic heating systems are most popular, and residential building cooling demand can be met using passive cooling systems, without any heat pumps. Figure 11 presents the Austrian brine-to-water heat pump using CO_2 as a refrigerant. Central buffer storage has also been studied by the Austrian R&D team (Figure 11) [1, 12]. With this concept, in the first part of the gas cooler (GC1), the water drawn from the bottom of the storage tank is heated up to 30–35°C, supplied to the floor heating system, and then returned to the middle part of the storage tank. Water from the middle part of the storage tank can be heated by the second part of the gas cooler (GC2) up to about 50–55°C, and then supplied to domestic hot water consumers (showers, etc.). This configuration makes it possible to operate the system in the space heating only, DHW only or simultaneous space heating and DHW modes.

In Japan, R&D projects have focused on the integration of several heat pump systems in low-energy houses located in both moderate and cold climate regions. In that country, 80% of the population lives in the moderate climate areas (e.g. Tokyo, Osaka), where both space heating and space cooling requirements exist. Reversible heat pumps for space heating in the winter and air-conditioning in the summer are very popular. They have been further developed for application in low-energy houses in terms of capacity range and control issues for different building types. Feasibility studies and field testing of ground-source heat pumps for the cold climate area have been conducted as well [1]. A first low-energy house has been built and monitored near Sapporo (Hokkaido), a relatively cold Japanese region (Figure 12).

This house has a total floor area of 200 m^2 and is inhabited by two persons. The total window area is 83 m^2, 63% of which is south-oriented. The overall heat transfer coefficient, including the wooded frame, is about 1.3 $W/(m^2K)$. The overall heat loss coefficient is 0.96 $W/(m^2K)$, including ventilation heat losses (about 0.5 h^{-1}). The large windows and thermal mass maximise passive solar gains in the winter, while the roof provides shading in the summer. The HVAC system (Figure 13) has four heat pumps: one for space heating (SH) and cooling, one for domestic hot water (DHW) heating and two for snow melting on the pavement. The heat pumps are connected to four 75 m double U-tube vertical borehole heat

FIGURE 11. System layout of the Austrian prototype system. DHW: domestic hot water GC: gas cooler; HX: heat exchanger; P: pump [1, 12].

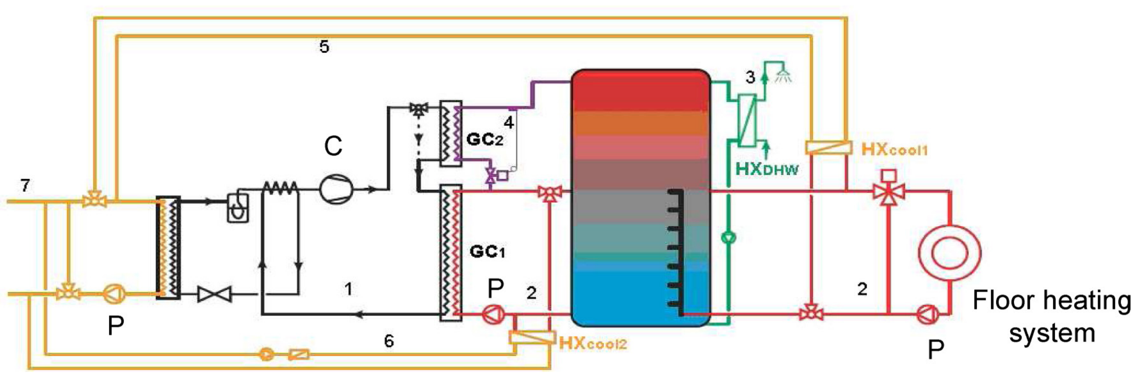
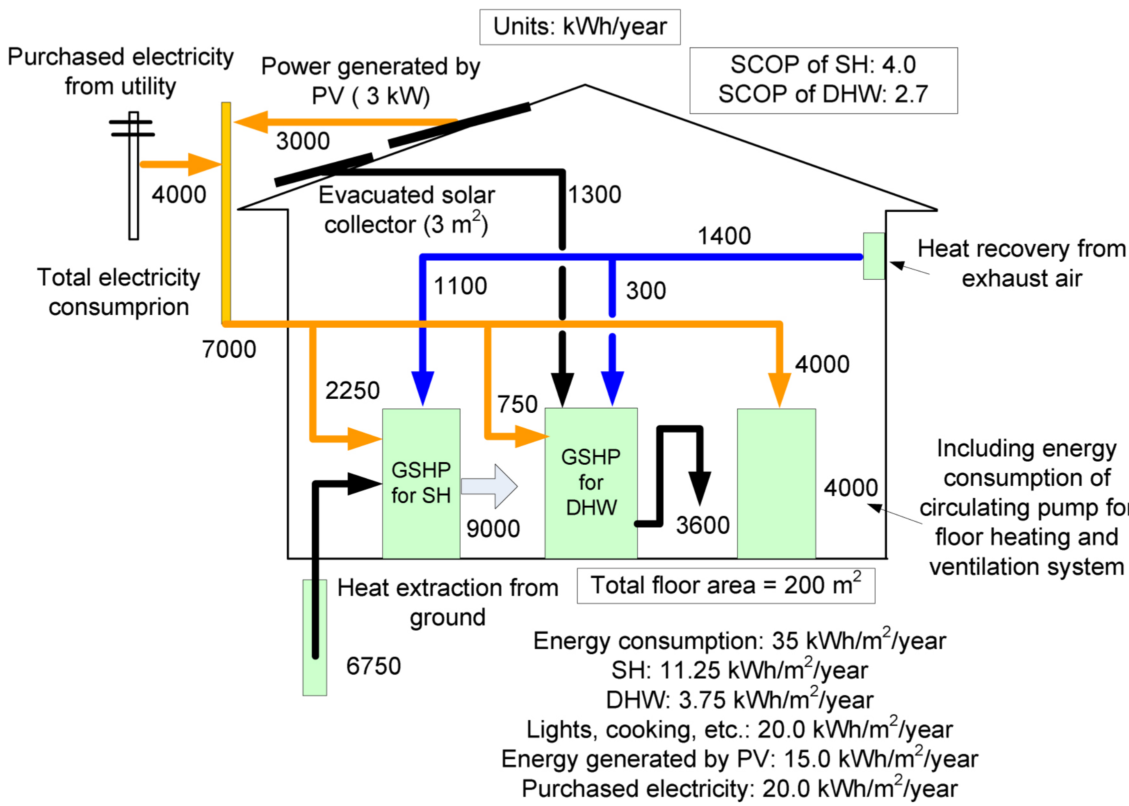


FIGURE 12. View and basic features of the first field monitored Japanese low-energy house [1].

	Insulation	Area [m²]				
Ceiling	240 mm	132				
Outer walls	186 mm	E	W	S	N	Total
		47	38	55	94	234
Floor	50 mm (with concrete slab of 300 mm)	200 (Base: 23, First: 132, Second: 45)				
Windows	Low-E Triple filled with Argon gas (1.3 W/(m²K))	E	W	S	N	Total
		6	9	53	14	82
Q value	0.96 W/(m²K)					
C value	0.42 cm²/m²					

FIGURE 13. Configuration of installed system for second field test [1]. DHW: domestic hot water; GSHP: ground-source heat pump; PV: photovoltaic cell; SCOP: seasonal coefficient of performance; SH: space heating.



exchangers. Free cooling is provided by the vertical borehole heat exchangers through concrete slabs and/or convectors. A 3 kW_p PV system generates electrical power to the grid. An additional 6 m^2 thermal solar collector preheats the incoming cold water and stores it in a 350 liter tank prior to entering the DHW heat pump. The total specific annual electrical energy consumption of this house was 47 kWh/m^2, about 24 kWh/m^2 of which came from the grid and the rest (about 50%) from the PV system [1].

In Norway, there were over 10,000 low-energy houses in 2007. Norway's R&D projects have focused on the assessment of heat pump technologies for low-energy houses, as well as on the performance evaluation of exhaust air heat pumps in the Norwegian cold climate [1, 13, 14, 15]. Different configurations have been studied: (i) heat pump with condenser and desuperheater; (ii) heat pump with condenser, desuperheater and subcooler; (iii) heat pump with condenser, desuperheater and suction gas heat exchanger; (iv) CO_2 heat pump with three-part gas cooler. In the last concept, the incoming cold water is preheated in gas cooler A, the low-temperature space heating system is connected to gas cooler B, and the DHW is reheated in gas cooler C (Figure 14). In the combined operating mode, about 45% of the total heating capacity of the gas cooler was used for domestic hot water (DHW) heating.

Switzerland's MINERGIE standard, initiated in 1998, is now widely accepted in new residential dwellings. It has reached a market share of approximately 30% and about 9000 units have been certified (2008). Switzerland's R&D has focused on design guidelines for energy-efficient heat pump systems for space heating and cooling and field tests integrated systems [1, 16]. The field monitored building (http://www.cosyplace.ch) was a 3-story multi-family, 5-flat building located in the Basel canton [1, 16]. In this case, the main component is a 15.5 kW (heating capacity) ground-coupled heat pump for space heating and DHW production. The buidling has triple glazing windows, a net living space of 741 m^2, a design heat load of 11.8 kW, and 110 m^2 radiant floor space heating. Space cooling is provided by a passive cooling system including a two-pipe ground-to-air heat exchanger buried at a depth of 1.3 m. In the winter, the heat pump generated 14% of the heat required for DHW, corresponding to 29.8 l/person/day. The remaining 86% of the heat generated was used for space heating. 70% of the total electrical energy was consumed by the heat pump in the space heating mode, 19% by the DHW heating system, and 12% by the circulation pumps. Energy

FIGURE 14. Layout of the B/W CO_2 heat pump prototype and comparison of a prototype with an improved state-of-the art CO_2 heat pump [1, 13, 14, 15].

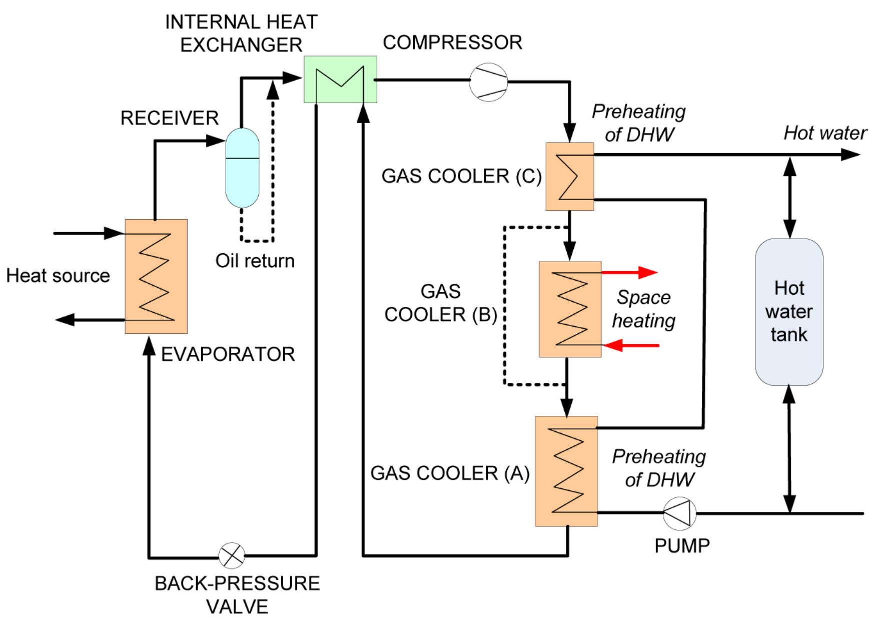
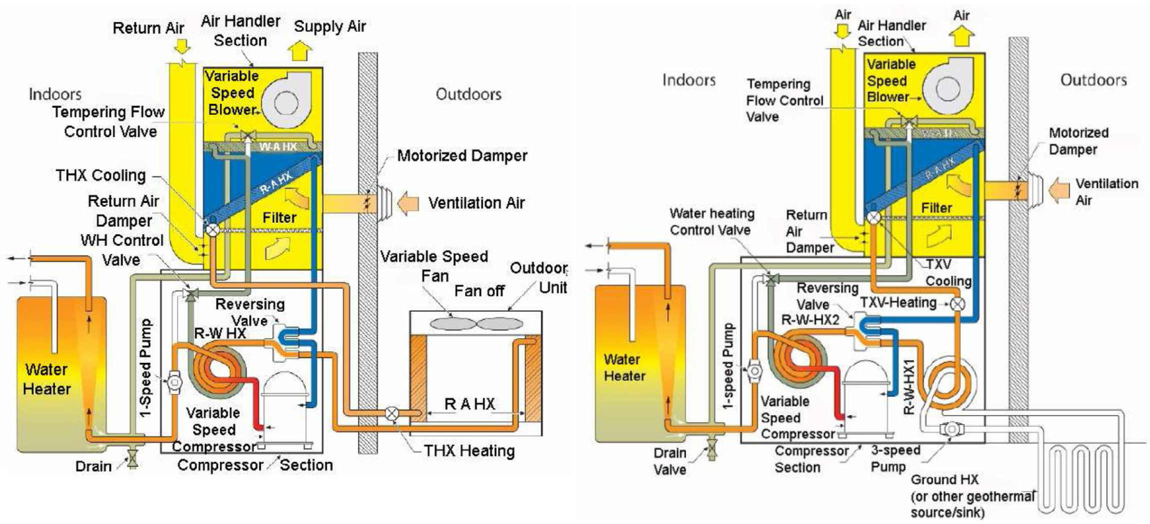


FIGURE 15. Air-source (left) and ground-source (right) integrated heat pump for US low-energy houses [1, 17].



Star is the common standard for low-energy houses in the United States, which guarantees a 15% reduced energy consumption compared to a standard building. There were 150,000 such single-family houses in 2005.

R&D projects in the United States have focused on the development of a highly-integrated heat pump for net-zero energy house (NZEH) application as part of a co-operation project between the space conditioning program of the U.S. Department of Energy (DOE) and the Oak Ridge National Laboratory (ORNL). The strategic goal of the DOE is to have net-zero energy technologies available on the market by 2020. R&D has included the development of multifunctional heat pump systems for space heating, cooling, DHW and ventilation, including dehumidification, as well as prototyping, lab-testing, simulations, and system field tests [1, 17]. The proposed integrated heat pump concepts for U.S. low-energy houses may include air-source (Figure 15, left) or ground-source heat pumps (Figure 15, right). Both layouts are similar but for the air-source system the ground coil loop including the pump and the heat exchanger are replaced by an outdoor refrigerant-to-air heat exchanger and a variable speed fan.

CONCLUSIONS

This article reviews a number of benefits, drawbacks and targets, and some common definitions of low-energy houses. Also presented are several Canadian initiatives and national projects (e.g., EcoTerra house), as well as other developments and field demonstration projects carried out under IEA HPP Annex 32. The article demonstrates that low-energy houses may significantly reduce energy consumption and improve indoor comfort by using renewable energies such as solar, ambient air, and geothermal energy. Photovoltaic cells, air- and ground-source heat pumps, as well as integrated waste heat recovery devices are the most promising systems aimed at reducing energy consumption in the residential sector. The future development of low-energy houses will be made possible by further development of such HVAC and power generation technologies, and also by providing more public incentives, improving building code regulations and standards, or as a result of significant increases in the cost of conventional energies. In spite of these requirements, the market for such systems is growing in many countries, and it will continue to grow in the future.

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