energies

Editorial

The 4th Industrial Revolution Brings a Change in the Design Paradigm for New and Retrofitted Buildings †

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† This special issue is about the next generation of new and retrofitted buildings and three co-editors are to ensure broad scope and high quality of papers in this issue.

Highlights:

- Water-sourced heat pumps with hot and cold tanks or a connection to District Energy Systems may be the most economical solution.
- Concrete interior walls and floors may be the most ecological solution in many cases.
- Pandemics show that both the EU's and the US's ventilation strategies need to be modified.
- Monitoring using building automatics allows HVAC optimization in the occupancy stage.
- Historic buildings with "*classic form and ultramodern function*" may reach zero energy/emission.

Abstract: The Fourth Industrial Revolution forms a smart grid with diverse sources of energy through the interconnectivity of data. Buildings that were previously the biggest users of energy are now becoming energy producers. Yet, buildings are also continually changing. The ecological definition of buildings, in addition to the building itself, includes solar panels and geothermal energy storage. The need for decarbonization and energy-efficiency brought about the implementation of heat pumps in buildings. The most economic type of heat pump is a water-sourced heat pump with hot and cold tanks or a connection to the District Energy System. Monitoring using building automatics allows HVAC optimization in the occupancy stage. Until the SARS-CoV-2 pandemic, the EU and the US differed in their air handling methodology, but the pandemic showed the limitations of both approaches and led to the creation of a new, integrated approach. These new ventilation systems, based on filtration instead of dilution, come together with decarbonization and the demand for new and retrofitted buildings to be smart, have zero emissions and excellent indoor environments, and be affordable. To fulfill these conditions, design teams must extrapolate experience with passive houses and introduce expertise in building automatic controls (BAC). The authors analyze the heating cooling and ventilation aspects of dwellings in a technology called Ecological Thermo-Active (ETA) technology that can also be applied to the interior retrofitting of buildings, including those with historic facades. The building "*with classic form and ultramodern function*" is an example of this changing design paradigm.

Keywords: energy efficiency; field energy use; monitoring and modeling; building automatic control; affordable; deep retrofit; historic buildings

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1. Foreword

New technology, whether passive or active always requires a trade-off. In the case of Ecological Thermo-Active (ETA) technology being introduced by the authors as an extension of a new passive housing technology, it is the use of water as medium for cooling solar panels, delivering heat from the heat pump to the heat exchangers in walls and to the thermal storage and controlled utilization of thermal mass that eliminates the use of an electric water heater and reduces the overall thermal loads. To understand the development of the current knowledge, we divide the information flow in this field into a few parts, the first one explains the need for the integration of solar panels with geothermal energy storage.

2. Part 1: Zero-Energy Built Systems Include Solar Panels and Geothermal Storage

This paper starts with the first principles [1] and builds on the complexity we have learned since the mid-1970s.

2.1. For any Technology to Succeed, There Must Be a Need and Understanding of the Market

In 1976, researchers at Illinois university (Urbana, IL, USA) designed, and engineers in Saskatchewan Canada (1977–1978) built, ten commercial houses and one to demonstrate house a new house system approach [2]. The design and construction shown in Figure 1 represented the ideas of building science leaders in North America, but the construction industry was not prepared to follow because the gap between building science (building physics) and builders was then, and is today, far too large. This is also the most important issue that slows progress in energy efficiency and climate-change-oriented research [3]. In a nutshell, four decades ago, we had a concept of modern technology but a lack of understanding of the building performance [4].

Figure 1. Saskatchewan Energy Conservation house designed by the Illinois U. demonstrated passive technology in 1978 (Regina, SK, Canada). Solar-exposed surfaces with large windows are inclined. Evacuated solar pipes are placed on the attic level. It was provided with an air–air heat pump and polyethylene-based heat recovery ventilator. Courtesy of Harold Orr.

In 1978, builders liked the idea of an airtight, well-insulated house, but to make this house affordable, they applied an economic trade-off, namely using electric heating instead of air-borne heating and ventilation. The heating chimney was eliminated, yet, they did not realize that eliminating the chimney also changed the airflow pattern and therefore the indoor environment. Sick buildings (not enough fresh ventilation air) and wet attics (increased humidity and condensation on top floors and in attics) were problems introduced by the elimination of the chimneys [5]. Yet, the understanding of interactions between the different functions of a building came in steps:

- In 1985, mechanical ventilation became mandatory in all residential buildings in Canada.
- The design process was changed to the integrated design process (or protocol, IDP), where a whole team started collective work in conceptual stages.
- Discovery of interstitial air pressure fields and observations that there may be several airflow paths between any two points in a building [6–8]. Furthermore, observations

that local airflow resistance varies with changes in the frequency and direction of the wind gusts.

- Introduction of air–barrier systems that affected heat and moisture flows.
- Introduction of exterior insulating sheathing to reduce moisture condensation in exterior walls [9].
- Air-tight and highly insulated houses introduced summer cooling needs [4].

Currently, with a better understanding of building science, we can use the passive house methods in different countries, however, with varying investment efficiency. Yet, to further increase energy efficiency, one must further advance the technology to use active and dynamic systems [10]. This involves the integration of solar panels with underground thermal storage. In other words, we need both renewable energy sources and new means of energy storage.

2.2. Buildings with Active Thermal Systems without External Heat Capacity

The need for active renewable sources was understood from the very beginning of the energy conservation movement. The initial concept of solar engineering was to use large, solar-oriented windows that were shaded to avoid overheating and heavy floors to accumulate solar radiation. It could have worked if we had stratified ventilation at night collecting thermal energy accumulated on the floors and delivering it to other parts of the building; it could also work with modern hydronic floor heating to capture the energy surplus and deliver it to other areas of the building, but the real question is how much energy can be saved in this manner.

The answer to all these questions can be found in the award-winning project Harmony House Equilibrium^{TM}, designed in 2010 by Chris Mattock in Vancouver, British Columbia, Canada [11], and shown in Figures 2 and 3.

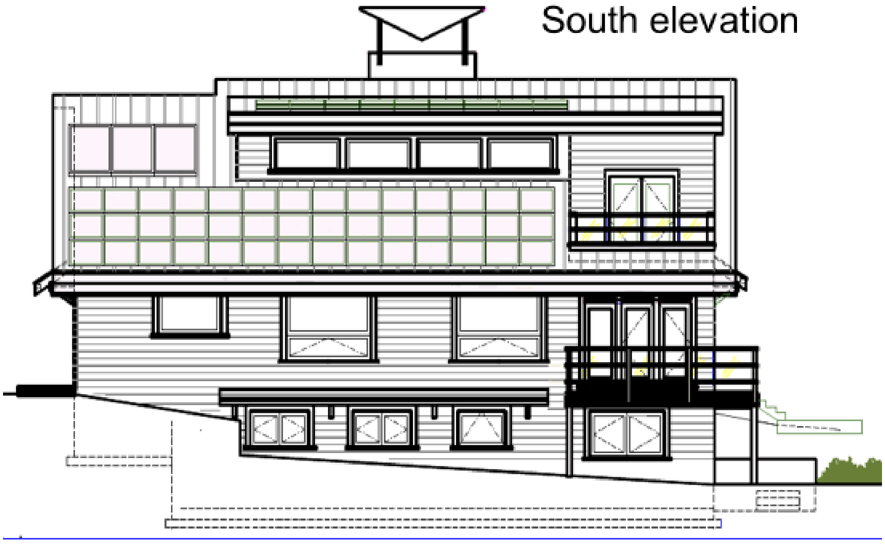


Figure 2. South elevation shows plenty of windows and two levels of solar panels placed on two roofs with different slopes (see later text) and two levels of slab on the ground, because of the sloped terrain on which the house is located. Courtesy of Chris Mattock.

Figure 3 shows a cross-section of the house showing clerestory windows for daylighting and passive solar gain dividing two slopped roofs. While the windows on the north walls are triple, those on the south are double and serve to catch as much winter sun as possible. The extended roofs, as shown on the south elevation, provide summer solar shading. Highly insulated walls, including basement walls Rsi 7 $(m^2\ K)/W$ and a roof with Rsi 10 $(m^2\ K)/W$, as well as Rsi 3.5 $(m^2\ K)/W$ under a slab foundation make an extremely well-insulated house with maximized solar gains. The large part of the space above the living room is open and connected with a wind tower that is equipped with a skylight and aerodynamical cap providing air suction for any direction of wind blows.

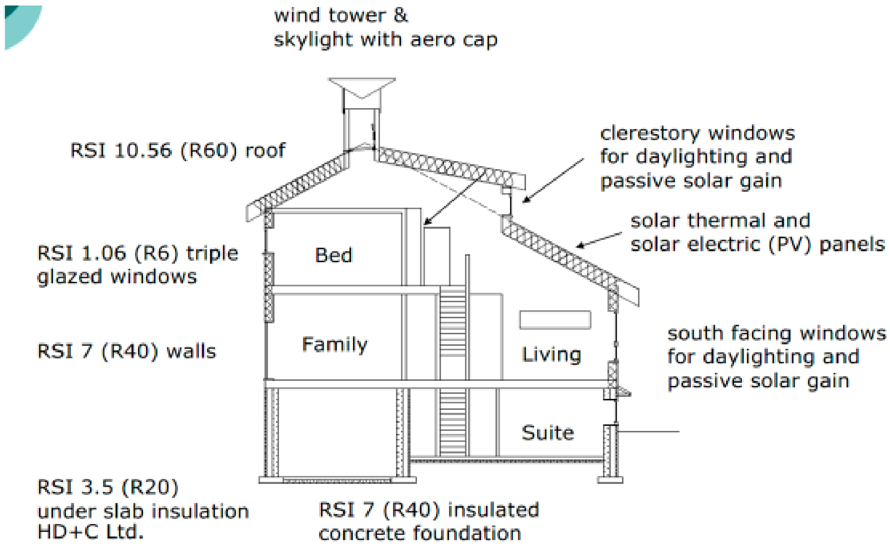


Figure 3. An award-winning house design in a competition for a zero-energy house (2009) using only solutions readily available in the marketplace. Source: Slide presentation of Chris Mattock.

In winter, the solar gains from all windows are extracted by the air circulation system, while in summer, the excess heat is removed through the exhaust ventilation and wind tower. The large area of the thermal and photovoltaic panels and the mild climate of Vancouver make the energy balance at zero net energy. Table 1 below shows the energy predictions.

Table 1. Predicted Energy Performance.

- Envelope only, Energuide Score 86
- Envelope and Renewable Energy Systems, Energuide Score 100
- Passive Solar Heat Gain 4056 kWh/yr
- Auxiliary Space Heating Demand 2833 kWh/yr
- Space Cooling Energy Demand 0 kWh/yr
- Solar Domestic Water Heating Supplied 2462 kWh/yr
- Auxiliary Domestic Water Heating Demand 936 kWh/yr
- Appliances and Lighting Demand 8633 kWh/yr
- PV power production 12,400 kWh/yr

This case highlights that, even in a mild climate region, when using an air-borne, combined heating and ventilation system and utilizing all internal thermal mass with the best possible space design, the yearly contribution of passive solar gains is only about 25% of the building's energy demand and a large area of solar panels is needed.

The above example supports a typical estimate of a 50 to 60 percent cost increase if one wants to bring a traditional wood-frame technology to zero energy. As we select a high affordability level and require that additional cost for achieving a net zero energy level cannot be higher than 10 percent of the standard house, we must accept two elements of improvement: separation of ventilation and heating/cooling and the use of geothermal energy storage for days and perhaps the seasons of thermal energy.

2.3. Buildings with Active Thermal Systems and Geothermal Storage of Energy

The term "active" thermal insulation was introduced in a common language to highlight the presence of a heat source/sink. While it does not affect the insulation performance, the term “active” contradicted the term “passive house”, and the patent relates to a hydraulic linkage between the heat exchanger in the ground to the one in the building’s enclosure.

A concrete demonstration house had a floor area of 187 m^2, a wall area of 573 m^2, an area of hydronic tubing in the walls, and a roof of 393 m^2 [12]. Thermal storage was designed as a separate construction and placed under the building as shown in Figure 4.

Figure 4. Hydronic tubing installation in the ground-floor slab. Courtesy Thamas Barkanyi. (**a**) Hydronic tubing before concrete pouring; (**b**) Edge thermal insulation and covered tubing.

There was also mechanical ventilation with a capacity of 500 m^3/h and preconditioned air with a 75 m-long, 25 cm-wide ground–air heat exchanger placed on 1.6 m depth in addition to 20 m^2 of solar panels on the roof for domestic hot water and energy storage.

The calculated energy use for the building is 144.5 kWh/(m^2·yr), and primary non-renewable energy is 12.1 kWh/(m^2·yr). The overall heat transfer coefficient was calculated [12] at about 0.070 W/(m^2·K) in the winter, while without the contribution of thermal storage, the wall had a heat transfer coefficient of 0.28 W/(m^2 K).

2.4. Interim Conclusions from Part 1

In the moderate climate of Hungary, a direct linkage between the geothermal energy storage and heat exchanger in the building enclosure was not sufficient to satisfy the building code. Additional heating was provided in the ventilation loop. This indicates that a water-sourced heat pump should be placed in the main energy source loop, i.e., as part of the space heating or cooling system.

Extensive research on methods to precondition ventilation air [13–15] summarized in [16] explained the need for two independent sources of outdoor air and provided guidance on the use of an earth-to-air heat exchanger (EAHX). The need to select an air intake implies enhanced consideration of a building’s automatic control system.

3. Part 2: The Sustainable Built Environment Is Shaped by Economics and Social Traditions

Elsewhere [17], authors have highlighted that social tradition may use market forces to override the official reasoning behind a social initiative.

3.1. The Market Responds to the Social Needs of People but May Neglect Society’s Need

Figure 5 quoted from this paper highlights such an effect. Data from the U.S. Energy Information Administration compare components of residential energy between 1978 and 2005. While the space heating fraction was reduced from 66% to 41%, the increase in comfort components took up all the savings, and the total energy consumption in the year 2005 was the same as in 1978.

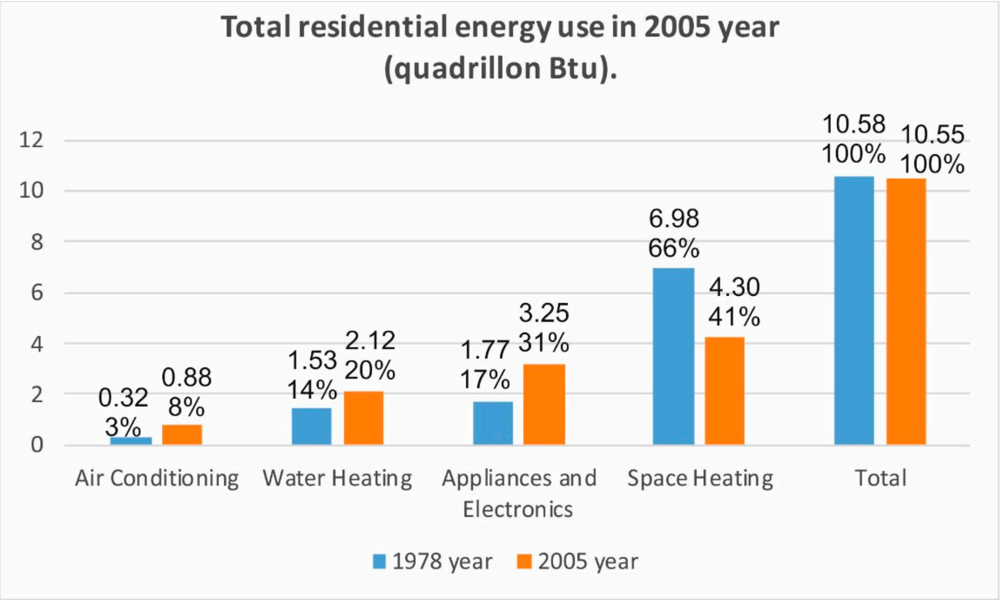


Figure 5. A comparison of the components in total energy use in the years 2005 and 1978.

Similar observations were reported in Canada by the authors of this paper [18]. An event denoted as an "energy conundrum" occurred in 2002, wherein it was observed that large residential buildings in the city of Vancouver used the same amount of total energy as in 1929, namely, 250 kWh/(m^2·yr). This highlights the role of thermal mass, indicating that switching to the adaptable indoor comfort approach [19] in a building with an adequate thermal mass (providing a phase shift of 12–14 h) could allow a shift in the peak loads to the night time when the grid has an excess of energy.

In other words, this observation implies that external thermal storage for buildings with light construction may bring them into the same class as buildings with inner concrete walls and floors. In terms of thermal impedance (thermal response factor), the exterior walls play a secondary role. Another conclusion from Figure 5 relates to using components instead of total energy per unit of floor area. It is obvious that measures such as the U-value or R-value of walls can be misleading.

We will return to this issue later, but an issue highlighted here is that the goals of technology must be congruent with the social needs of people. Yet, many social issues may not be translated to individual market demands. A good example is achieving zero energy or zero carbon emissions.

To alleviate a conflict between society and investors, we propose a two-stage construction process. In the first stage, one achieves the highest performance level possible for the selected initial cost, while the second stage continues to optimize cost for the selected performance level. In the first stage, the building is completed at a minimum performance level that is acceptable to both the building code and the investor. The designer then predicts the continuation to a zero-energy level that may be initiated a few years later.

Another area where the market did not respond is the field of interior retrofitting.

3.2. *An Analysis of the Interior Retrofitting of Existing Buildings*

We must understand why the progress in energy efficiency was restricted to new construction and why the return-on-investment thinking prevailed in retrofitting. The breakthrough was achieved by designers of a Montreal settlement, "Atelier Rosemount" [20].

3.2.1. Atelier Rosemount in Montreal

By planning the new construction in several stages, starting with an inexpensive building to later be retrofitted in stages until reaching zero energy, the designers combined new construction and retrofitting. These designers introduced a risk-free mortgage system for all stages following the first stage.

The critical steps in their process were:

1. Design the process of construction or retrofitting to zero-energy level and divide it into two or more stages. Set the period of the first mortgage short, 10 years or less. Stage 1 must satisfy the codes and standards.
2. When stage one is completed, use the physical value of the property as the basis for the next step of financing, i.e., re-mortgage payment on the anniversary, add the second mortgage, and freeze the new mortgage payment again to accumulate savings in your mortgage saving account. The amount of your monthly contribution will not be changed.
3. Perform the second stage of construction or retrofitting and increase the mortgage on your property, but instead of increasing the monthly payment, extend the duration of the mortgage. The difference between what you pay to the account and what is transferred from the account to the bank is your savings for the mortgage down payment.
4. If you have reached 90% reduction in the space heating/cooling, ventilation, and air conditioning cost, you have achieved the needed objectives. If not, continue to the next stage.

In the actual case in Montreal, the re-financing lasted 10 years when the difference between the cost of servicing the capital investment and the actual payment was growing with time, allowing the owners to perform improvements on the building settlement that, in the current system of construction, would require 30 or more years if the simple return on investment was applied.

In other words, this model of financing was leasing the energy cost to the owners of the properties and the bank. This approach permitted achieving zero energy for social housing! The Montreal project was completed in 10 years and satisfied both the economic requirements of the bank and the requirements of society. We are giving the specific details of this economic model because in some communities, user-friendly banks are giving a lower interest rate to schemes involving property improvements.

Stages of improvements from 2008 to 2018 in Atelier Rosemount, Montreal (Figure 6):

- High-Performance Enclosure, common water loops, and solar wall resulted in a 36% reduction in energy use per square meter and year.
- Gray water power pipes increased total reduction in energy use to 42%.
- Heat pump heating (planned with a horizontal heat exchanger) increased the total reduction to 60%.
- Renewable 1: evacuated solar panels for hot water increased the total reduction to 74%.
- Renewable 2: photovoltaics brought the total energy reduction in 2018 to 92%.

The Atelier Rosemount project deals with a full district of three-story houses, where some are luxurious, with cross-ventilation between north and south, and others are social buildings. It shows that with a good design where non-renewable measures reduce energy consumption by 60 percent, one may reduce total energy use to 92% of the initial energy consumption in social dwellings.

This project, which started in 2008, included many details typically not considered in standard Canadian construction, e.g., heat recovery from hot water pipes when delivering it to the gray water container. Furthermore, this project breaks many boundaries used in the construction industry: namely, it shows that there is no difference between new construction and retrofitting, between a single house or cluster of houses. It actually shows that designing a cluster of buildings with a significant volume of soil makes it easier to organize the heating/cooling and ventilation, social functions, and even rainwater collection. Advanced water management become a strong point of the sustainably built system.

Figure 6. An affordable, low-rise, energy-efficient multi-unit residential building, "Atelier Rosemount", in Montreal. Note the rain retention basin in the bottom right (credit Nikkol Rot).

Interim conclusions: The new economic model developed in this project became a key to the next generation of technology removing the difference between new construction and retrofitting.

Furthermore, despite the different conditions, the Rosemount project in Montreal [20], Harmony House Equilibrium in Vancouver [11], Hungarian house [13], and older examples such as the High Environmental Performance House in Syracuse, NY, USA [21–23] or the Regina Conservation house [4] show that passive measures reduce total energy by up to 60%. One may further reduce the next 30% by using renewable energy. The only question is the cost.

3.2.2. Review of the Deep Energy Retrofits in the USA

With permission of the authors, we quote some of the key elements of the 2021 report from Lawrence Berkeley National Laboratory written by Iain Walker, Brennan Less, and Nuria Casquero-Modrego [24], which provides a detailed review of home energy upgrades targeting deep energy reductions (i.e., Deep Energy Retrofits, or DERs) from 30% to >50% site energy savings:

> *Key changes in project design noted in this review include the: (1) electrification of dwellings with rapidly improving heat pump systems and low-cost PV technology, (2) shift away from high-cost super-insulation strategies and toward more traditional home performance/weatherization envelope upgrades, (3) recognition of the importance of when energy is used and from what fuel sources in terms of both energy cost and carbon emissions, and (4) emerging smart home technologies, such as batteries or thermal storage, smart ventilation and HVAC controls, and energy feedback devices. Promising program design strategies covered in this review include (1) end-use electrification programs, (2) novel financing approaches (e.g., Pay-As-You-Save and local lender networks), (3) Pay-for-Performance incentive structures, (4) securitization of portfolios of upgraded homes as investment products, and (5) One-Stop Shop programs that integrate financing, project management, design, and support services.*

Key barriers that provide opportunities for modification:

- ***Projects focused solely on energy savings are not appealing***

There is a need to emphasize other metrics, including health, resilience, affordability, maintenance, and environmental aspects. Energy upgrade projects must address the actual needs and goals of homeowners, and these projects must be profitable and enjoyable for the contractors and trade workers implementing them.

- ***The workforce remains inadequate***

The emergence of new technologies, metrics, and processes makes this inadequacy even more evident, as no centralized databases exist of contractors who have experience with electrification or low-carbon projects, for example.

- ***The costs remain too high***

Finding the lowest cost is likely to include PV, thermal storage, simple weatherization, and electrification, rather than high-cost envelope upgrades. One may leave existing heating systems in place and augment them with higher-performance systems to save the cost of existing system decommissioning. Efforts are needed to reduce these soft costs to levels equivalent to or less than the general remodeling industry.

- ***Economic justifications are challenging and possibly inadequate***

Approaches, such as net-monthly cost and Pay-As-You-Save programs, are making progress in this area, but more work is needed to incorporate health and environmental costs that are typically ignored.

We want to highlight that the LBNL report discusses strategies such as electrification programs and methods of financing (***Pay-As-You-Save, Pay-for-Performance, retrofit as investment product***) Perhaps the most important is the ***One-Stop Shop*** program that integrates project financing with design management and support services.

3.2.3. Decarbonization of Buildings Is Critical for Tomorrow's Built Environment

We distinguish between three different areas of concern [25]:

(1) **Direct emissions** are the greenhouse gas (GHG) emissions from controlled sources such as combustion in boilers, furnaces, and equipment (including fugitive GHG emissions such as refrigerant leaks).
(2) **Indirect emissions** are indirect GHG emissions associated with purchased media, such as the electricity and district heating/cooling used in buildings.
(3) **Activity-related emissions** include embodied emissions within materials and resources used or consumed by the organization—paper used, waste produced, coffee consumed, and emissions of any suppliers. Embodied carbon includes mining, processing, manufacturing, transportation, and installation of materials.

The atmospheric GHGs typically associated with buildings are carbon dioxide, methane, and a few refrigerants used in cooling. An index, called global warming potential (GWP), that compares the global warming impact of a mass unit of a given material to the same mass unit of carbon dioxide is used to quantify the GWP effect.

From the ASHRAE task group, we repeat the following definition of a zero-carbon building (ZCB): a zero-carbon building is a highly energy-efficient building in which carbon-free renewable energy or high-quality carbon offsets are used to counterbalance the annual carbon emissions from building materials and operations, so that, with time, it offsets the carbon emissions embodied in the original construction process. One needs to use this definition of ZCB to compare different construction strategies. Without an accepted ZCB definition, one cannot analyze the building as a system.

For instance, some people talk about a ban on the use of concrete. Obviously, concrete has huge, embodied energy, yet when it is used with a controlled effect of thermal mass, it may be a material of choice in many applications. The highest ASHRAE green award in 2020 went to a concrete building in Tokyo using Thermo-Active Technology. Therefore, the discussion of embodied carbon without a comparison of initial and operational carbon emissions is a misunderstanding of science.

We realize that the analysis of a building as a system is not easy: it requires technical proficiency higher than used today in construction. Furthermore, models of building performance and cost–benefit analyses are much broader than the current energy modeling. To optimize for net zero gas emissions, one must use modeling of the building operation under actual weather and occupancy conditions, as well as considering carbon emissions from the electrical grid.

3.3. Retrofitting Historic Buildings with a View to a Classic Form and Ultramodern Function

It is generally agreed that buildings related to history must keep their appearance. Their façade cannot be changed, and preservation implies that any surface cleaning may not alter their appearance. This is, perhaps the only principle of historic building preservation that is not questioned. The questionable part of historic buildings relates to their functionality. Some people say we need to reserve their function as it was years ago; others say that if the Roman bath centuries ago was preparing temperature and steam conditions for several hours but we can do it in 30 min today using a computer, either we call it a museum and use it as it was before or we call it a historic building implement a modern function. In the following section, we support the second point of view.

3.3.1. The Principles of Historic Building Preservation

The first principle of historic building preservation is generally agreed upon and can be called:

1. *Preservation of exterior appearance.*

The second principle relates to their function and can be called:

2. *Preservation of the functional equivalency.*

Here, the interpretation may differ. For instance, a heating system with underfloor stone channels and a wood fireplace in the adjacent room was installed at the beginning of the 16th century in a famous Polish family castle to preserve the first books ever printed by the Gutenberg press. Should one use the wood fireplace today, or is it enough to preserve the appearance from the 16th century but use the air conditioning as we do in a modern museum?

In the actual case, we have three more principles (rules) to guide us in making the decision:

3. *Preservation of environmental features;*
4. *Preservation of environmental harmony;*
5. *Minimal alterations.*

It appears that the principal rule 5 makes it clear: keep the wood stove and underfloor channels as they were but use an invisible air conditioning machine (rule 4 makes it invisible) to fulfill rule 3.

This example was related to a single function, namely, the heating of the room. However, typically, one deals with multi-dimensional processes, e.g., surface cleaning involves not only appearance but also future performance. In the past, one used a slacked lime dissolved in water that was drawn by capillary forces into the surface of the masonry. After several applications, it provided enough lime to tighten the wall. More experienced craftsmen were adding small particles of clay alone or mixed with micro-silica to reinforce the physical bonding with the electro-osmotic effect and to reduce the number of applications needed for adequate tightening of the old masonry. Others used a mixture of hydraulic lime and bentonite that relies more on physical settlement than on the micro-crystallization of lime, but still, they did not alter the traditional treatment of masonry.

Today, people have started to add white cement to the mixture of hydraulic lime and bentonite to improve the look of the surface. Yet, the addition of white cement will change the hardness of the mortar, the equilibrium of the water contained in the material, and the rate of water absorption. These changes will modify the risk of brick spalling in freeze–thaw conditions. This example highlights the second principle. Functional equivalency may require a deep understanding of the many functions that are interacting in the assessment of durability or long-term material or assembly performance.

We will give the reader another example of the *Preservation of the functional equivalency*. Mortar, in middle-age masonry castles, typically used a slacked lime with the addition of animal fur (equivalent to fiber reinforcement, 5–10 micron in diameter, glass fiber, hemp fiber), ground bones (equivalent to fly ash, ground clay bricks, or other pozzolanic admixture), and some animal blood (equivalent to a super-plasticizer). How can we produce functionally equivalent mortar today?

Today, in addition to the above-listed equivalent admixtures, one adds natural and chemical re-dispersing and bonding polymers to improve the compatibility of recycled organic materials mixed with inorganic fibers and powders. Moreover, as lime recrystallization requires many years of service, an important question is if one could use cement instead of lime. The theoretical answer is yes, providing that one will reduce shrinkage and increase the freeze–thaw resistance of the mortar. To this end, one may need to increase tightness with the use of fly ash, use a water-retaining admixture, and ensure a minimum fraction of micropores. In practice, this implies that we prefer lime–cement or cement–lime mixtures in which part of the cement is replaced by pozzolanic materials. In practice, there may be several different mortars that can be used instead of the old mortar. Yet, in practice, after selecting a mortar with given physical and rheological characteristics, one will have to make a small masonry wallet for a one-sided, one-directional freeze–thaw test to establish the risk of spalling bricks under specified climatic cycling. The criterion of the freeze–thaw test depends on the climate for which the test is performed. Today, we do not have the capability to predict long-term interaction between the brick and mortar under field conditions. Furthermore, testing the clay bricks alone does not give us the correct answer.

3.3.2. Air Flow Control and Durability in Historic Buildings

In many retrofitted or historic buildings, there is no place for a mechanical room or access to the ground. The options are as follows: (a) in the cellars as the cold climate building always had them; (b) in an adjacent structure, e.g., tower or a service building; or (c) making a small district heating/cooling connection to another active and functional building and designing an HVAC system for both of them. The mechanical room must have a place for a water-to-water heat pump and a hot water tank, several valves, and controls for water and air. The cold water tank may or may not be in the same room to facilitate dealing with water condensation or freezing of the water in the cooling mode.

There are also a lot of devices related to air handling. There are connections to two independent ventilation air intakes, one from a direct fresh outdoor air intake and one from either the earth-to-air heat exchanger (EAHX) or a hot or cold water tank. There can be a humidifier or a dehumidifier (or both for some climates) and a Merv 13 filter for the central delivery of fresh air. As discussed elsewhere [26], one needs two independent sources of fresh air for automatic mixing to achieve the required temperature. When overpressure of air is possible, the hybrid ventilation system will work with the DOAS (dedicated outdoor air system) to periodically deliver a supply of air with a pressure about 10 Pa higher than that in a staircase or outdoor air.

For occupant health and viral control, one recommends the relative humidity in dwellings to be in the range of 40 to 60% RH. In a severe cold climate, this may be too high (winter window condensation). In such a case, the delivery pressure may be lowered and a small ventilator (a computer-type one) may be added on the exhaust.

There is one critical comment that we need to make about the airtightness of buildings: there is no magic number that can be used for different climates because the critical factor is the durability of the exterior wall and not the energy saving. Making walls too tight requires using mechanical ventilation when it is not needed [27]. Furthermore, the minimum air ventilation is required only in the period of extreme weather, and larger ventilation is advised for other periods of the year.

If the exterior walls are used for heating or cooling, then the water management system in the internally retrofitted buildings would rely on the control of the relative humidity of the centrally delivered air to avoid water condensation in the air cavity between the old and new part of the wall. The safest solution is to use interior partitions for heating/cooling or ventilation and, after ensuring that an air barrier function of the existing drywall is ensured, simply add a layer of thermal insulation under the drywall. Often, when dealing with old masonry one can use a frame to position drywall and fill a poured polyurethane foam behind the drywall.

When increasing the thermal insulation level of the exterior wall, one must perform a freeze–thaw durability assessment. This can be performed using the extreme boundary of the freeze–thaw process, called the critical moisture content of the masonry. Using a calibrated (verified material properties) and a reliable hygrothermal model (e.g., a 2D model of WUFI or Delphin), one can calculate the maximum moisture content in masonry brick subjected to 3 to 5 years of random rain events in the actual climate and the actual walls. Continuous calculation is needed for simulating the coincidence of freezing temperatures after rain events with the previous history of wetting/drying and to compare it with the critical moisture content for the laboratory test on the actual brick (taken from the field) The procedure to determine the critical moisture content of clay bricks is well documented in the technical literature (see: [28,29]).

Often, examination of the existing surface of masonry allows for adding a small increase in thermal resistance, such as 1 unit of SI, without the freeze–thaw assessment. In doubt, one can apply surface spraying of silane/siloxane-penetrating agents [30] to reduce water intake without blocking the evaporation from the brick, as the latter leads to an increase in the risk for surface damage.

3.4. Towards Quantifying the Hygrothermal Aspects of the Internally Retrofitted Walls

An engineer is told that the durability of masonry was achieved by the tradition of many generations, and now, when the indoor environment and service conditions are different, it is your role to formulate methods of evaluating durability and to consider the factors affecting an indoor environment that will permit the interior thermal upgrade of buildings.

The first step in resolving the environmental functions in historic buildings was made at Dresden Technical University by introducing the concept of the capillary active layer. As the Thompson (Kelvin) law explains, pore sizes lower than 10^{-7} m reduce the vapor pressure of water. In pores smaller than 10^{-8} m, water vapor condenses at 90% RH. Thus, capillary action moving water to the surface where it evaporates was termed as capillary active by Grunewald [31] and Häupl [32] (Figure 7).

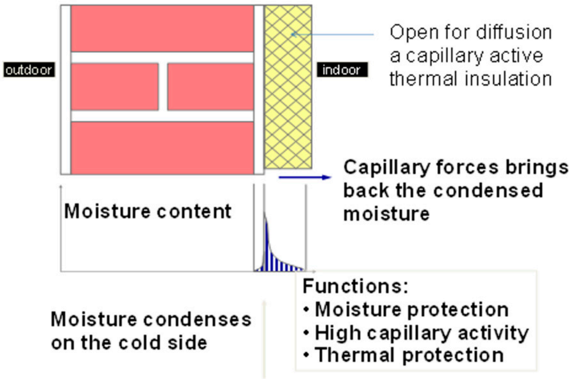
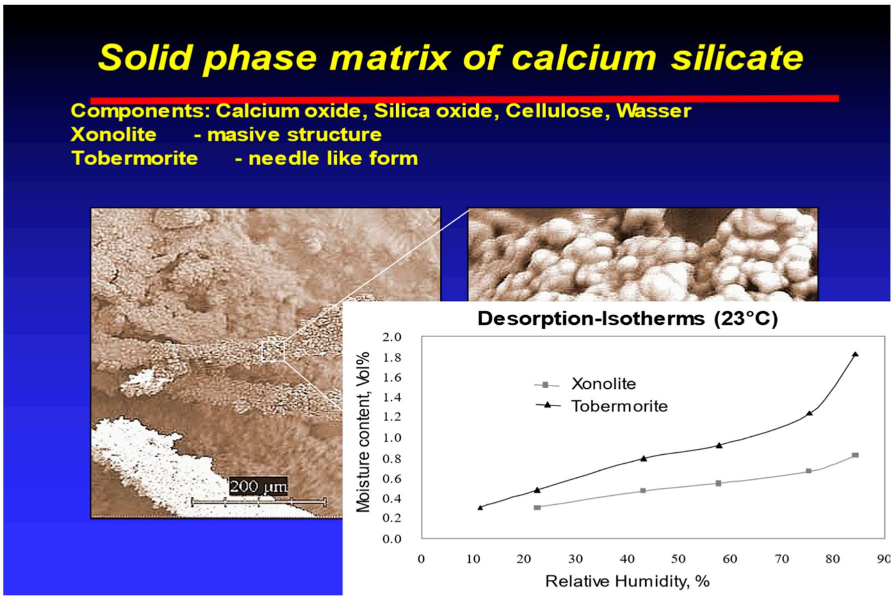


Figure 7. The capillary active layer brings the liquid water to the surface of the material, allowing evaporation to the interior air (Häupl [32] reprinted with permission).

The first capillary active layer was developed using calcium silicate by Grunewald [31] by trial and error, involving industrial pilot manufacturing, the determination of water transport characteristics at a university, and then additional pilot manufacturing. The observation that Tobermorite, one of the two basic minerals forming calcium silicate, had a higher sorption curve (i.e., contained more micropores with nominal diameters lower than 10^{-8} m) led to the optimization of the mixture of these two components to improve the overall hygric performance of the material (Figure 8).



Solid phase matrix of calcium silicate

Components: Calcium oxide, Silica oxide, Cellulose, Wasser
Xonolite - masive structure
Tobermorite - needle like form

Figure 8. Basic components of calcium silicate (from Gruenwald et al. [31]).

In principle, capillary active material technology is an extension of traditional materials such as lime plasters and wood cement boards used in the interior of buildings. A low-density, cement-bonded wood strain (CBW) was used in masonry breathing walls that were highly water-vapor-permeable and also have high sorption. CBW [33] had a WV permeance similar to that of lime plaster (i.e., about 10 times higher than wood). The sorption of CBW, however, of water in equilibrium with humid air (for instance, 50% RH) is about six times greater than that of lime plaster. While under a stepwise change in humidity, this material is much slower than wood, yet after 10 h of exposure to new conditions, the amount of water stored by CBW exceeds that of an unpainted log house. In conclusion, CBW and strawbale walls were found to provide a good solution for breathing walls.

While CBW material represents historic development, the capillary active layer became the next step in the process of moisture management. Work in Japan on clay-plaster and Chechia (Fort et al. [34]) expanded applications of capillary active materials. Yet, the latter research had different objectives. Exterior thermal insulation and the composite system typically use expanded polystyrene foam and the softening of the foam by fire causes the delamination of the protective lamina layer. With evacuation ladders limited to 10 floors, the only suitable exterior insulation above 11 floors is high-density mineral fiber insulation (MFI). Generally, this is a self-draining material, except for the bottom 20 cm layer for aged material. However, it does not have the required impact resistance. The work of Fort et al. [34] alleviated both shortcomings of mineral fiber boards. With a small modification to MFI production (an increase in perpendicular fiber orientation) and a capillary active layer cap that provides impact resistance and catches condensed water, the composite material was ready for the marketplace. Furthermore, this paper modifies the hygrothermal model of Kuenzel [35], bringing it closer to the soil science model of de Vries (see the analysis in the Ph. D thesis of Bomberg [36]). A laboratory experiment to determine temperature and moisture fields served as a basis for the model calibration and identification of unknown parameters. The calibrated model is then used for a hygrothermal assessment of the studied detail.

Another application of calcium silicate as a capillary active layer occurred in the reconstruction of Our Lady Church in Dresden [37]. One had to catch water from the air in the top cupola and remove it later, when the weather permitted, to avoid the condensed water from dropping down. To check the capability of the capillary active layer, one had to determine all climate parameters in the cupola. To this end, an integrated program of testing and modeling has been used.

Incidentally, the concept of capillary active material was critically reviewed [38]. We take a moment to explain that any use of the passive storage of thermal energy or water coming from the environment is restricted to a thin material boundary. To use them for engineering purposes, one needs an active driving force, such as a thermal gradient or a water content gradient. The capillary active material is used to catch water more than to transport it.

Speaking about hygrothermal modeling also raises the question of its credibility. Experience [39–41] indicates that either co-simulation [42] or verification of material characteristics (calibration) [43] is used. Today, we have three different methods for model calibration:

(1) During the experimental work, as used by Fort et al. [36];
(2) Using one of the material properties' verification methods (see: Bomberg and Pazera [43]);
(3) Emerging approach of using system monitoring and statistical analysis of the acquired data [44] for performance evaluation (MAPE modeling, [45,46]).

Each of the three above methods of hygrothermal model calibration have been shown to work well.

The applications of the active capillary materials to the systems opened a new chapter of building science, namely, the capability to control the water content in exterior walls. Thus, in 2010, Bomberg, who worked in the hot and humid climate of China and needed thermally induced movement of water, introduced a second air gap (cavity) in the exterior wall [10]. This ventilated air cavity allowed the use of renewable energy as a source or sink located between the old and new parts of the retrofitted wall. This decision was based on experience from the repairs of moisture-damaged walls in the lower mainland of BC (Vancouver), where only passive measures of moisture barriers were used. In humid climates, one had to use active means of humidity control because moisture storage in combination with space ventilation proved to not be reliable as the second line of defense. Using mechanically driven dehumidified ventilation air was the only reliable means of water management.

We must continue the discussion on the control of air flows inside buildings, as it is one of the most misunderstood areas of building science. Traditionally, our residential buildings were leaky, and only since 1990s, when air tightness became a part of modern construction, have we started paying attention to it. The discovery of interstitial air pressure fields by Lstiburek [6–9] completed our understanding of air flows in buildings. We have four interconnected air pressure fields:

1. Exterior (caused by wind);
2. Interior (HVAC operation and ducts);
3. Across the walls (stack effect);
4. Interstitial (connectivity walls, rooms, staircases, ventilation plenum).

The presence of an interstitial field implies several different airflow paths between two points in a building. The total resistance to airflow is the sum of all local airflow resistances. As mechanical equipment operating at one location may, through the interstitial connections, alter air pressure in another location, we have a new variable affecting the flow of humid air or even modifying the thermal performance of walls.

The effect of many different paths in the building is evident when comparing criteria used in different airtightness tests. The typical criterion in a material laboratory test is 0.02 L/(s m^2), measured at an air pressure difference of 75 Pa, while that for a laboratory test on wall assembly is 0.2 L/(s m^2), measured at the same pressure difference, indicating that most air will pass through junctions, joints, and connections. Yet, for the same test performed in situ, the criterion is the 10 times larger, namely, 2 L/(s m^2) at a 75 Pa difference or 1.5 L/(s m^2) at a 50 Pa pressure difference, indicating that the pressure difference measured on both sides of the wall may not be the actual force driving the airflow through the wall.

While airtightness criteria relate to the surface of walls, without other house descriptions, we cannot recalculate airtightness to the rate of ventilation. Figure 9, prepared by Proskiw [47], compares airtightness recalculated to a reference pressure difference (either 4 or 10 Pa) measured over a period of time (from 1981 to 1995) to highlight the increase in the airtightness with time and severity of the climate. From the moderate climate of British Columbia in 1990–1995, the average reference value was 4 ACH (air changes per hour). Moreover, the average reference values for Quebec and Ontario were near 3 ACH, and in the most severe climate of the Prairies, the average airtightness went down to 2 ACH.

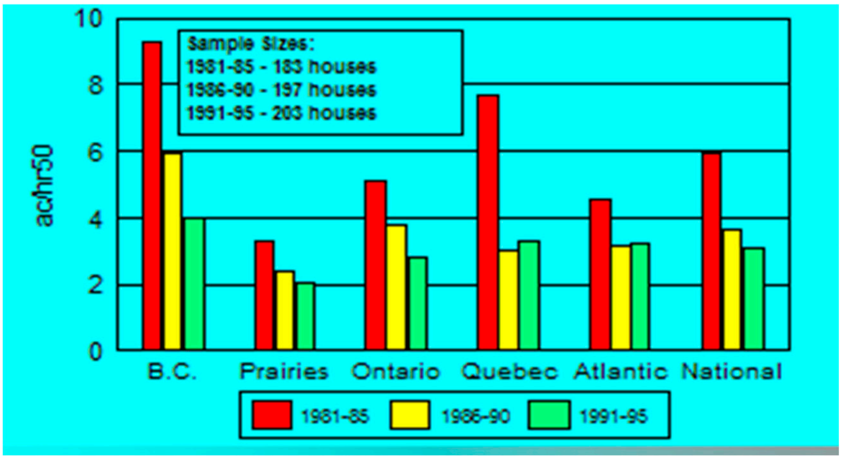


Figure 9. Field measurements of airtightness in Canada recalculated by Proskiw [47] to a reference pressure difference (published with permission).

Figure 9 shows that in the 1990s, the reference air tightness in the severe climate of the Prairies is perhaps 25% higher than a benchmark for near-zero-energy houses; in Quebec and Atlantic provinces, this value is 100% higher; and in British Columbia, it is 266% higher. Thus, from the builder's perspective, the issue of airtightness is restricted to the cold climate and does not exist in moderate or warm climates. The airflow control inside the building was brought up when the world leading research centers existed in Canada and Sweden. However, national institutes of Canada or Sweden, by the decision of their governments, became focused on local, industrial problems and disappeared from knowledge creation. The currently leading Europe universities are Leuven, Belgium, and Prague, Chechia, which are located in a moderate climate, and most of the new construction ideas are coming from warm regions of Europe, the US, or Asia. The culture of southern countries includes more outdoor life, and opening windows became "a policy" in green movements. Airflow control is a key issue in building physics but would have never been recognized in construction practice without the SARS-CoV-2 pandemic.

The pandemic showed that current European and American methods of ventilation dramatically increased the risk of viral infection. After two years of increasing the rate of unfiltered air, we came to the situation described by a famous statement of the British Prime Minister at the time, Lord Churchill: "*Americans always find the best solution, after they tried everything else*". This time, the American solution comes from California and implies a variable rate of hybrid ventilation based on filtration (and not on the traditional dilution).

3.5. Air Flow Control and Durability Are Key Factors for the Retrofit of Residential Buildings

It has been established that leading builders can provide scientifically correct solutions. In the 1970s, the author had been living in a Swedish cooperative provided with a separate, filtered air intake on a side of a window, stratified mechanical ventilation, night air cleaning, and automatically controlled hydronic radiators. After emigrating to Canada, he was living in a condominium provided with a forced air system that included both heating and cooling lines coming to the dwelling and a valve to set the mixing proportions. These technical solutions were standard for middle-class professionals, but their cost was higher than average. So why are they not popular today? The answer is simple: market globalization without the popularization of building science brings us to the lowest common denominator.

There is only one way to break the trend to the lowest common market denominator: set goals far above the current technology's reach. When, in the 1960s, the Swedish government decided to lower energy use in housing, it modified mortgage rates, and industry followed. When, in the 2010s, the US government set the energy goal at zero, typical construction was struggling to reach the low energy level. Yet, one generation later, the industry has no problem with the massive production of zero-energy buildings. Thus, today, our goals are "*zero greenhouse gas emission and zero increase in the risk for viral infection by the indoor ventilation air*". We will continue postulating a new way to achieve these two objectives.

3.6. Sustainable Built Environment Requires a Focus on Climate Change

The main goal of a conference published as "Energy efficiency and durability of buildings at the crossroads" [3] was to increase the impact of future designs by Architects active in Building Enclosure Councils in 34 large American cities. This paper stated:

> *"Yet, it is not clear how to achieve the major change that is required. However, it is clear, based on past successful programs, that only a systems approach will achieve those goals in the future. We are past selling magic new materials and miraculous one-issue solutions. Every building, old or new, needs to be treated as a system in which every component is a piece of the puzzle. The green value is determined by the resulting building performance, not by the perception that the action is green."*

Figure 10 of this paper, presented at this 2008 conference [3] by Dr. Selkowitz, highlighted that market forces must be supported by public/private initiatives. The 2030 objectives require actions in both new building and upgraded existing buildings, the latter of which should be thermally upgraded before 2030. Examining this Figure now, it appears that new construction is on schedule while retrofitting is a failure because the integrated design process was not used.

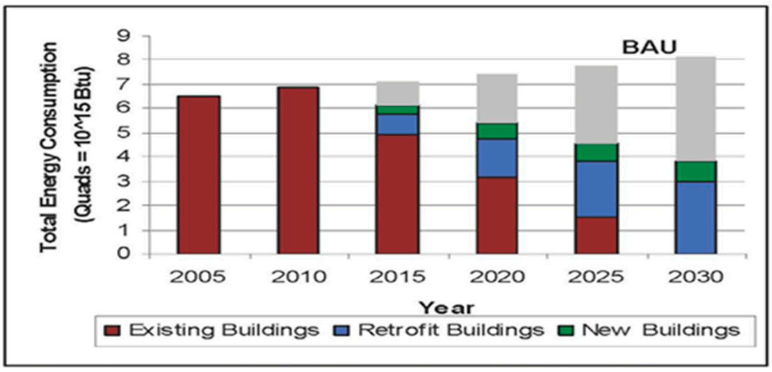


Figure 10. Two components in 2030 targets, LNBL [3] (reprinted with permission).

The fragmentary approach to construction started 5000 years ago. The building as a system was introduced 50 years ago, when the old system could not deliver energy-efficient buildings. The first step was to learn integration [48–50], and the second was to focus on control of the indoor environment [16,51,52], not forgetting about the buildability [53–55] and the analysis of passive houses [56,57] to arrive at a synthesis [58]. Finally, this integrated technology was demonstrated to function in Hungary [12], the USA [59], China [60], Poland [61], and Japan [62]. New modeling approaches have also been proposed [63].

While creating an integrated design process appeared to be a small change in the design paradigm, it was actually a major step forward. Kuhn [64] says this is an example of how technical revolutions take place. We observed that it took society two generations to build a full understanding of a technology proposed in 1976 by the leaders of the building science. Do we have another 40 years to become fluent in systems thinking, or do we have to deal with climate change in 2022? Social scientists [65] have advised using a transcending paradigm instead monetary savings. There are some academic papers [65] that are correct in the assessment of the future but do not mobilize society. Tony Blair, in his lecture on the Russia–Ukraine war, postulated that a constant goal of the nation is needed for at least 15–20 years to achieve a social change. Thus, what can we do to accelerate the change?

The methods of building evaluation are different today than they were four decades ago because, today, we understand the interactions between the different functions of the building. Yet, in this editorial overview, we highlighted that it is not the technology itself, but the manner in which we deal with technology that makes the socio-economic impact. Overdoing the intellectual part of technology in typical academic research or overdoing the commercial impact in the technology transfer stage (application of the technology) does not help. On the contrary, it often reduces the impact of the technology. Furthermore, if, for the sake of administration policy, one aspect, e.g., energy efficiency, is stressed while others are neglected, the whole technology becomes unbalanced. Our current system of supporting applied research requires a visible fragmentation, while socio-economic progress requires integration. As an example, if we want to develop an energy model based on the data collected from the actual building to optimize the system and later develop a more advanced model for HVAC operation, such a project does not fit into academic research as it is too practical, nor does it fit into applied research because one cannot estimate the monetary savings of this approach. Effectively, the whole world of academia is excluded as they rely on government research support.

4. Part 3: A Call for Action

As we have a transcendental paradigm of climate change and retrofitting is one of the means to slow the change in climate, we should use it. As engineers, we are also doers. If we obtain the support of leaders in the academic community and we produce a Special Issue showing the existing technology's readiness, we start the process of making an impact on future practice and create what the EU directives call a "wave of renovation".

Thus, we postulate that instead of talking about retrofitting without context, we set a national goal to slow climate change through retrofitting actions. In contrast to structural engineering, where new materials can come with an impact on construction, the management of environmental quality will require many small details to be thought through and built with adequate care. While the change in environmental control is urgently needed, this change requires an understanding of the building as a system and must come from the scientific community. For this to happen, the scientific community must have a vision of the next generation of buildings. Two critical issues in this vision are: (1) the occupant must be able to control the indoor environment and the building automatics must enable the occupant to do this, and (2) the design must be focused on the level of the components or assembly, while materials will be judged upon whether they fulfill the requirements for assembly and the subsystems.

Meadows [65] produced a list of the most important factors that modify people's motivation. In the first place, he lists transcending paradigms, and in the last (11th place), numerical parameters such as subsidies, taxes, or standards. She contradicts the currently used paradigms, saying:

> *"The shared ideas in the minds of society, the great big unstated assumptions, constitute that society's paradigm, or deepest set of beliefs about how the world works. These beliefs are unstated because it is unnecessary to state them—everyone already knows them, Notice, however, that most of the current sustainability research . . . is focused on the least effective leverage points like the economic aspects . . . politicians believe that sustainability is mainly an economic problem. So, "Numbers" . . . and parameters such as subsidies, taxes, and standards become the main focus".*

We fully understand the concerns of Meadows, who stressed that sustainability research has more in common with the change in the transcendental paradigm than the economics of construction. Kuhn [64] highlighted that a scientific revolution comes with a small step in the socio-economic situation when it is close to change. The authors claim that a change-of-thinking paradigm is needed for the next generation of building technology for slowing or reversing climate change. Understanding this should motivate all involved in building science (physics) to mobilize the public and explain to politicians that the important approach in the post-COVID-19 world is to invest in the renovation of our buildings. Now, after repeated waves of the pandemics, comes the realization that the next generation of new or renovated dwellings must provide an indoor space suitable for the quarantining of people infected with an air-borne virus, be it SARS-CoV-2 or influenza. A bedroom likely to be used by sick people should be underpressurized to guard against the spread of illness. A direct outdoor air system (DOAS) should be used [58]. Therefore, the requirements for retrofitting must be broadened to include adequate handling of DOAS ventilation with interior air circulation. In effect, one may summarize the above discussion as follows.

The scientific community must show the practical readiness of several integrated technologies to create pressure on politicians to restart the public–private consortia on multifunctional material or to develop assemblies for refitted buildings considered as a system.

Future Research

As each building may be a system different from the others, the first step in monitoring is characterizing the building in its real use conditions. The response factors for air exchange, heat exchange, and water/vapor exchange are different, so we will have to introduce three types of characterization. In this paper, we do not deal with durability; we discuss only the first two. Our priority is to develop a model of energy consumption related to the real operation time and the real climate. Models used today are parametric: they help in the design of the system but only partly relate to its performance. Without such models, we cannot design zero-emission buildings.

Item A: Monthly bill for electricity

1. The air response of a building is different for small, mid-size, and tall buildings, so we need to test the airtightness of dwellings on the first floor, mid-floor, and top floor using corridor pressurization (if such is used) for summer and winter.
2. Thermal response measurement has to be conducted two times (with and without the ventilation system working) and in two situations: with cooling and heating, both in the range 22–16 degree Celsius. The same dwellings should be used for testing.
3. The basic model for energy consumption may probably be based on artificial neural networks and include a linear interpretation of tests (1) and (2) to allow an increase in precision with more data coming to the calculation.

Item B: Efficiency of HVAC

Monitoring must include wall surface temperature in a master bedroom (high ventilation is required), outdoor temperature, and, estimated from the model “A”, energy used for conditioning the space in the dwelling. Calculations are made separately for winter and summer, disregarding the shoulder seasons.

Item C: Efficiency of the heating system and COP of the heat pump

If the flow and temperatures of the outgoing and incoming medium are monitored, one can calculate the energy delivered to the dwelling, and assuming that thermal panels are part of the heating system, compare it with the energy used in model “A”.

Item D: Optimization of HVAC

Either a model “A” or an addition “B” to this model can be used for controlling the automatics in a multi-variant space. In the real world, we will divide the use of solar thermal panels into two patterns: (a) heating hot water and (b) heating the ground or water in the underground tank used for the lower terminal of the heat pump, i.e., cooling in a heating climate. Similarly, we will be adding heat from the heat pump, and the switching process must be operated automatically when a near-freezing temperature approaches. You might ask what is the sense of heating the underground if the heat pump will cool it—the answer is simple: with the COP between 2 and 3, the heat pump will double or triple the energy put into the lower terminal. This is the reason we do not support the direct linkage of the geothermal storage with the building.

Item E: Developing a model for the operation of the optimized HVAC

While model "A" should be as simple as possible, the addition of "B" can be used for the fine-tuning of the Heating Ventilating and Air Conditioning (HVAC) system and lead to the final model for the operational control of the HVAC system. This model must have both components of air and energy and allow for the examination of variable ventilation rates on energy use.

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