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Perspective

Position Paper Introducing a Sustainable, Universal Approach to Retrofitting Residential Buildings

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Abstract: Protests during the 2021 Climate Conference in Glasgow exemplified our dilemma. The establishment perpetuates old thinking, while young people demand a new approach to mitigate the impact of climate change. The authors agree with the young people, and as a solution we propose to replace the current fragmentary approach with a new holistic one. The passive house approach that was conceptualized by the University of Illinois and built in Canada in 1977 showed us that energy consumption can be reduced about half of that used in the traditional design. Seventeen years later, a European passive house was built in Darmstadt. In 2008, a demonstration house in Syracuse, NY, showed that integrated passive measures produced energy use by about half of the NY state code for 2004. At the same time, some advanced houses in the USA showed total energy use of about 70 kWh/(m^2·y). In 2008, at the first Building Enclosure Science and Technology Conference, two equally important objectives for 2030 were proposed by the Lawrence Berkeley National Laboratory: (1) a 90% reduction of energy use in new buildings and (2) 50% for the retrofitting of existing buildings, i.e., to the level achieved in the 1980s. The first objective has recently been achieved in small buildings while the large residential buildings remain on the level obtained in the 2000s. Yet, the retrofitting of existing buildings (the second objective) has been a dismal failure. This paper acknowledges progress in hydronic heating and cooling involving electric heat pumps and hybrid solar panels, building automatics used for operation of HVAC, and modification of air distribution systems that comes from experience with the SARS-CoV-2 pandemic. Furthermore, it highlights that to accelerate energy efficiency and carbon emission reductions, there must be broad public-private educational programs with demonstrations of a new generation of retrofitting. Economically and ecologically retrofitted buildings will create a new approach to real estate investment.

Keywords: energy efficiency; residential retrofits; building automatics control; integrated HVAC; retrofitting technology

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1. Foreword

In science, a discovery or invention precedes application. This is not the case for building science. Years ago, Confucius (Lao Tse) highlighted the bond between buildings and culture. Modern building science was created by an analysis of traditions. The mighty cathedrals built in the Middle Ages in Europe were based more on scientific intuition than knowledge. Yet, since the development of the natural sciences, it is the tradition, and its failures demonstrated when trying to modify some concepts, that defined what became the mainstream of building technology. Therefore, today, when trying to develop a rapid solution for climate change, we cannot analyze the construction technology alone, but we must do it in the context of the socio-economic conditions of the country. Several behavioral studies showed that occupants want to actively participate in shaping their environment and several economic studies highlighted that the well-being and productivity of the building occupants are more important than the initial cost of building. Yet, the traditional structure of investments does not include these aspects of design. As we propose a market disruption with new technology, we must provide a cost-benefit analysis of all critical aspects of housing, not only the life-cycle cost analysis. In this context, the indoor environment and, related to them, the hygro-thermal considerations or indoor air quality are critical. We do not discuss other aspects of building science as they do not change during the proposed market disruption. We do not neglect their importance. Yet, dealing with a limit of 21 pages of text, we decided to examine only one approach. Furthermore, in a time of economic globalization, using examples from North America is not a problem and restricting the selection of technology to a potential winner is also justified. The environmental quality management (EQM) technology selected for this paper provides accessibility of environmental controls allowing occupants to correct unsatisfactory environments and is wide enough to include several different practical strategies. In contrast to strategies that eliminated other options, e.g., passive houses or solar houses, the EQM includes thermo-active buildings from Japan, or thermo-active thermal insulations from Hungary, or multi-stage construction methods applied in Canada. In a nutshell, the EQM is an aggregate of the best individual developments in different cases.

2. Limitations of Current Technology in Shaping the Indoor Environment

The following article considers history and forces the shaping of environmental progress in residential construction with the focus on retrofits. It proposes changes to residential buildings and formulates a universal retrofitting technology. Yet, to achieve progress one must first understand the limitations of the current technology.

2.1. Indoor Environment as Defined by an Architect

In 1970 Flynn and Segil [1] wrote,

But rather than a simple correction of climatic deficiencies, the environmental control function of building must be oriented toward the more extensive sensory demands of various occupant activities and experiences. This occupant perceives light as the surface brightness and color; he absorbs heat from warmer surfaces and warmer air; and he himself emits heat to the cooler surfaces and cooler air. He responds physiologically to humidity, to air motion, to radiation and to air freshness. He also responds to sound. A major function of the building, then, is to provide for all the sensory responses concurrently-to establish and maintain order and harmony in the sensory environment.

Why does this statement not represent construction practice? Because the design, construction, and commissioning professionals are thinking only about their individual fields. These experts do not have tests to ensure field performance of materials. The existing tests measure material characteristics and only after collecting enough field performance information may one correlate them with field performance to gain enough judgement value allowing a designer to select the material. Structural, fire, acoustic, lighting, and material experts are all qualified in their disciplines and have little understanding for “how to establish and maintain order and harmony in the sensory environment” when developing designs for a “durable and cost-effective building shell”. The current design process does not provide the facility for predicting the future performance of new systems, nor the means for quality assurance for the building. As we do not have a unified approach to design low-energy buildings, many demonstrations of monitored whole-building performance, e.g., the high-environmental-performance house in Syracuse NY [2–4] or the net-zero-energy equilibrium house [5], despite analyzing the monitored discussion and the demonstrated field performance that have limited impact in the marketplace.

2.2. The Role of the Architect Is Changing

While in the past, architects had a holistic view of occupants and the building, this is not the case today. There are two major reasons for this, namely (a) an increase in the number of materials, and (b) a lack of a two-way street between building science and building practice.

(a) Speaking about Swedish statistics, in 1900, there were about 500 different construction products to choose from and today we can find 55,000–60,000 different products. This highlights the growth of specialized expertise and the fragmentation of the design process that erased the capability of an architect to control all stages of the design and construction process. Today, more than in the past, the architect must be able to produce an integrated product satisfying all occupants and all aspects of building performance.

(b) The lack of real exchange between science and practice is demonstrated below. Previously, moisture was not a serious consideration because masonry is resilient to moisture (unless exposed to freezing and thawing). The masonry wall could wet and slowly dry and thus temper large changes in moisture level introduced by climate or people. Scientists knew about diffusion theory and the calculation of condensation as early as 1938 and five different books were published in Russian on calculating water vapor transport through walls before 1958, when Glaser described a simple method to calculate water condensation in layman's terms. But in the 1950s, commercially manufactured glass fiber insulation was typically placed in the wood-frame wall cavities reducing the cavity surface temperature and causing condensation. So, having visible problems in practice, the codes and standards embraced an easy-to-understand solution. Moisture transport by diffusion became a worldwide accepted concept. Despite computer modeling for simultaneous heat and moisture (water and vapor) being available in the early 1970s and showing shortcomings of the Glaser's method, the widespread models came only in the 2000s. The lead author in 2015, while giving a course on building physics at one of the EU Universities, was told, "Please include the Glaser theory because it is included in this course and approved by our government." He replied, "Of course, already 40 years ago I published the paper explaining why using it is wrong".

2.3. The Paths from Materials to an Exterior Wall Assembly

For the sake of discussion, we distinguish between four functions typically associated in standards for a material layer, namely (1) exterior cladding (façade), (2) exterior continuous insulation, (3) structure or structural layer for load transmission layer, and (4) interior trim and finish; see discussion in reference [6]. The façade layer (1) controls fire, rain, air and water vapor entry, light, sound, solar radiation, and vermin; the external insulation (2) controls heat, but may also control air, water vapor, and sound; the structural layer (3) provides strength and rigidity but may also control air, water, and vapor transports; and the interior finish layer (4) controls fire, air, water and vapor movements, and sound.

(1) The façade layer can be either directly attached or be a rain screen with an air gap behind it (e.g., brick veneer) to provide rain control. In this case, the layer on the interior side of the air gap should fulfill all other façade requirements.

(2) The thermal insulating layer should also control acoustics. Note that popular materials such as mineral fiber with wind protection or polystyrene boards with taped joints do not fulfill the many requirements for air, water vapor, and vermin entry.

(3) The structural design is not discussed here.

(4) The requirements for airtightness and fire resistance of interior finishes are fulfilled by gypsum board, which is water-vapor permeable but lacks the moisture buffer capability. Thus, in the next generation of technology we need to reintroduce materials with moisture buffering ability.

The summer overheating of rooms associated with airtight, well-insulated buildings is caused by a large area of glazing and a high precision of heating controls. One may re-distribute the energy gains caused by solar radiation with increased thermal mass, circulation of indoor air, night ventilation systems, or cooling.

2.4. Energy Use in the Building Systems of 1978 and 2005

Figure 1 from the U.S. Energy Information Administration shows total residential energy use in 1978 and 2005. The total energy consumption in the building sector did not change from 1978 to 2005; while the fraction of the space heating was reduced from 66% to 41%, the comfort components took all the savings.

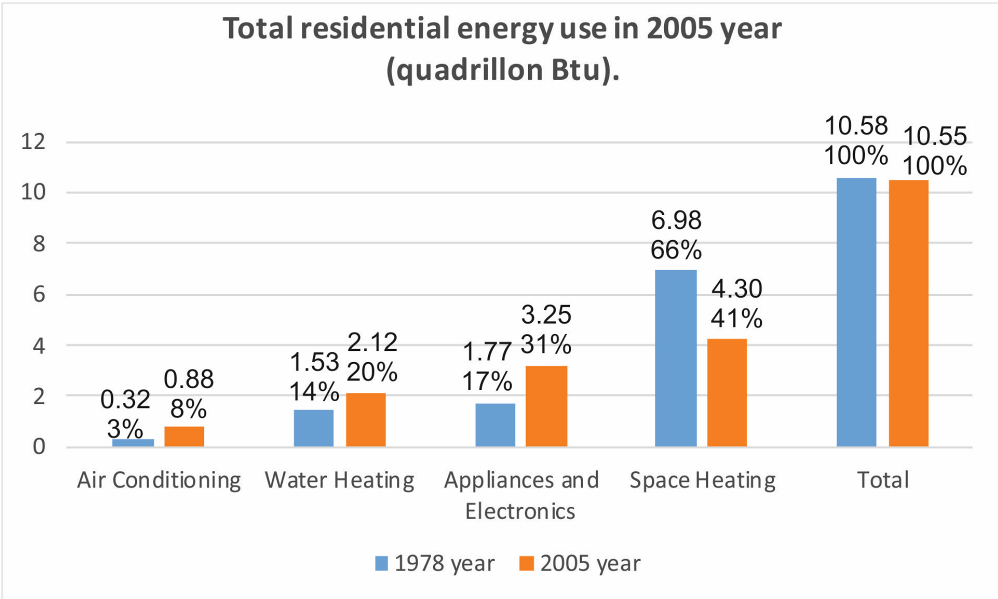

Figure 1. A comparison of energy use in 2005 with use in 1978.

Similar observations were reported in different countries and even by the authors of this paper [7]. An event that we call an "energy conundrum" was a discovery that in the years 1929 and 2002, large residential buildings in the city of Vancouver used the same amount of total energy, namely 250 kWh/(m^2·y). The fact that heavy masonry buildings without insulation could provide reasonable indoor climate highlighted the role of thermal mass that was later eliminated by use of automatic temperature controls. Yet, research on an adaptable comfort approach shows that one can modify the indoor air temperature by at least 6 °C, over a 6 h period and the change in human comfort does not exceed 4% of the comfort index [8]. This means that we should re-examine the approach to the design of low-energy buildings. If we want to reduce the use of air conditioning and use electrical energy during designated hours in a night, then add utilization of thermal mass and switch to the adaptable indoor comfort approach.

The second conclusion that one can draw from these comparisons is that only the total energy gives us a realistic measure for energy; measuring one of its components using metrics such as U-value or R-value may only introduce confusion and misjudgment. We recall the problem of log houses that did not meet the standard requirements, while providing a good indoor climate. This tradition was valid up to the 1950s when small but continuous changes in material technology started improving the performance of the whole system. Those changes became strongly accelerated in the 1970s when the concept of sustainability appeared. Sustainable building includes aspects related to reducing the consumption of natural resources [9–11], improving the external environment and ensuring the comfort of users [12–14].

2.5. Case Studies in Retrofitted Buildings

The examples below relate to summer overheating of masonry buildings with natural ventilation. In a renovated, four-star hotel, with high-ceiling rooms, located in Brussels, a room on the fifth floor in the summer afternoon showed a temperature of 26 °C when the day was cloudy and the outside temperature was 22 °C. After a window was fully opened, the temperature went down to 25 °C and when a huge fan (provided by the hotel concierge) was activated, the temperature remained at 25 °C, but the occupants felt comfortable.

The explanation is simple. Retrofitting included adding insulation and air-tight windows. In this way, retrofitting increased the impact of the stack effect (hot air rising because of buoyancy). The multi-unit masonry was built in the 1930s and as burning coal at that time required one chimney for each dwelling, the European tradition was to connect the exhaust from a ceramic stove to the same chimney stack at every second floor. Newly installed electrical heaters and natural ventilation all worked well, but the forgotten, hidden connections though an old chimney moved hot air from the first floor to the third floor and subsequently to the fifth floor. Note that these rooms had no air mixing and high ceilings facilitated a significant vertical gradient of temperature. Since level five was near the neutral pressure zone, opening or closing windows had no significant impact on air buoyancy and the additional heating delivered from the two lower floors kept the room temperature three degrees above the outdoor temperature.

A second example is from Canada, from a passive-solar design, an 18 story, concrete building with air pressurized corridors to compensate for the stack effect. The living room has a large heating and cooling unit located under the window and a leaky entry door (gaskets are worn). With closed windows, cigarette smoke coming from outside was smelt in the bathroom. During the summertime, this two-bedroom apartment had four different temperature zones. Of course, the occupants opened windows and used extra ventilators in the kitchen and living room.

With 192 apartments in the building and a total of 384 ventilators, the building used much more energy than was saved by the retrofitting measures. The design concept, however, worked well, keeping the average indoor temperature about two degrees above the outdoors in summer and on sunny days in winter, although in summer it caused excessive use of cooling. In effect, this design would be good if an indoor air circulation system was properly designed.

Another example is a case in Portland, Oregon where the best technical solutions were applied, and the post-retrofitting survey gave only a passing level of satisfaction with the indoor environment [15]. This reinforces the observation from the Canadian example that any indoor space without air flows between 0.1 and 0.3 m/s appear to American people as having a poor environment. Why American? Because the tradition here was air-borne heating that always included air flows in the space.

Elsewhere, we discussed an example where books became covered with mold while being kept in a closed desk during the winter in the warm and humid climate of Nanjing, China. Yet, books also became covered with mold in the corner of a basement room on an open bookshelf in the cold climate in Ottawa, Canada in a house with good mechanical ventilation when an adaptable comfort was used for temperature control [8]. This is a reminder that the universal approach to indoor environment during retrofitting must also *include air humidity management*.

Now, after repeated waves of the SARS-CoV-2 pandemic, one comes to the realization that the next generation of new or renovated dwellings must provide indoor space suitable for quarantining people infected with an air-borne virus, be it SARS-CoV-2 or influenza. A bedroom likely to be used for sick people should be underpressurized to guard against the spread of illness. A designated outdoor air system (DOAS) should be used [16]. Therefore, the requirements for retrofitting must be broadened to include an adequate handling of DOAS ventilation with interior air circulation and air humidity controls.

2.6. The Quest for a Sustainable Built Environment

The quest for sustainability resulted in dramatic changes in the process of residential construction. The new concepts of an integrated design team, building information modeling, commissioning of the building enclosure, and passive house standards have reached maturity. Global work on the development of new construction materials has not changed, but their evaluation is different from in the past when each material was considered on its own merits. Today, we look at the performance of a building as a system and on the material as a contributor to this system. Sustainability involves harmony between different aspects of the environment, society, and economy. Figure 2 shows the scope of considerations that broadens the field of building science in North America (building physics in Europe). Now, in the quest of improving building performance, building science merges concepts of passive houses with solar engineering and integrates building shells with mechanical services, but is still missing an overall vision. Physics does not tell us how to integrate people with their environment.

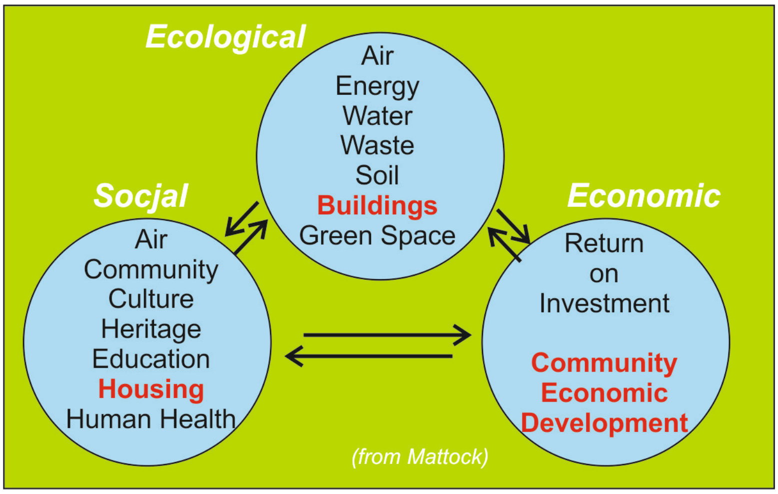

Figure 2. All three components must be satisfied for the sustainable built environment.

The authors introduced a new term, namely environmental quality management (EQM) for buildings, because the vision of building physics must be redirected toward occupants. In doing so, building physics will include the indoor environment with aspects such as energy efficiency, ventilation, indoor air quality, and thermal comfort on one side and added durability of the shell, affordability, and building resilience.

2.7. Case of Market Thinking Replacing System Thinking

Scientists demonstrated the system approach, highlighting the significance of passive measures in the design of energy-efficient buildings [17]. One may be surprised that 44 years ago one built with almost the current level of technology. This fact then begs the question: why was this technology not used in the marketplace? This occurred primarily because there was no real contact between the building science community and the socioeconomic forces driving the evolution of building construction. The design and construction shown in Figure 3 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, a critical issue that slows progress in climate-change reduction [18,19]. In a nutshell, 44 years ago we had a concept for a new technology, but not the understanding of the building energy performance. The current definition of energy performance is based on the 2005 U.S. Energy Act that talks about all factors affecting energy efficiency and the well-being of the occupants (specifically an occupant's productivity if this is a nonresidential construction).

Figure 3. Saskatchewan Energy Conservation house designed by the Illinois U demonstrated passive technology in 1978 (Regina). Solar-exposed surfaces with large windows are inclined. Evacuated solar pipes are placed on the attic level. It was provided with an air-sourced heat pump and polyethylene-based heat recovery ventilator. Reprinted with the permission of Harold Orr.

In 1978, builders liked the idea of airtight, well-insulated houses as shown in Figure 3 and, to make them affordable, they applied an economic trade-off. With much smaller heating loads, one could eliminate furnaces and replace them with electrical heating. Yet, the air-borne heating system had more functions than heating. The builders did not realize that eliminating the chimney also changes 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 [20].

Now we understand better the interactions between the different functions of a building. Yet, this understanding came in steps:

- In 1985, mechanical ventilation became mandatory in all residential buildings of Canada.
- Any residential building must be considered as a system with interacting subsystems.
- The design process was changed to the integrated design process (or protocol, IDP), where a whole team started collective work in conceptual stages [21]. Incidentally, bringing critical decisions to the initial stage of work reduced the cost of late changes in the design and therefore IDP was readily accepted in construction.

The following observations summarize the difference between then and now:

1. Heat, air, and moisture transports are inseparable and cannot be separately assessed. Today, we talk about "environmental control".
2. Often, when we modify a material or a construction detail, we find that the cost of repairs following these small changes is significant. This happens each time we analyze only one function without interaction with the other elements of the system. In other words, we fail when we lose track of the integrated approach.
3. The modification of building enclosures is slow but continuing. While old, leaky, and poorly insulated walls dry quickly, airtight walls that are insulated on the exterior dry slowly. If water enters around the window frames, then it will stay inside the wall.
4. Traditionally, building science followed the evolution of practice and lessons from any solution of the encountered problems enhanced understanding of construction performance. In the 1980s there was no practice of low-energy housing construction and Timusk (see [15]), when reviewing moisture control issues of the previous decade, stated:

"At the moment we are in a position where the traditional approach of learning from failures and copying what worked, has broken down. . . . it is extremely difficult to accommodate all of the new information in view of the rapid changes in materials, details and performance expectations."

The Canadian R-2000 and Build America programs as guides for housing design, highlighted that formal education must be complemented by seminars for consultants and building practitioners. Indeed, this became the widespread practice in the USA. Furthermore, one needed to expand the environmental control in two dimensions:

- Improve the tools of field monitoring and field diagnostics and integrate them with user-oriented, computer-based design tools.
- Stress the objective-based design process, much in the same manner as it is done in structural engineering.

One should highlight that the impact of the interstitial pressure field became significant only when the building enclosure became more airtight [22–24]. Figure 4 shows mold growth on an interior wall in Florida [22] as the effect of an interstitial air pressure field.

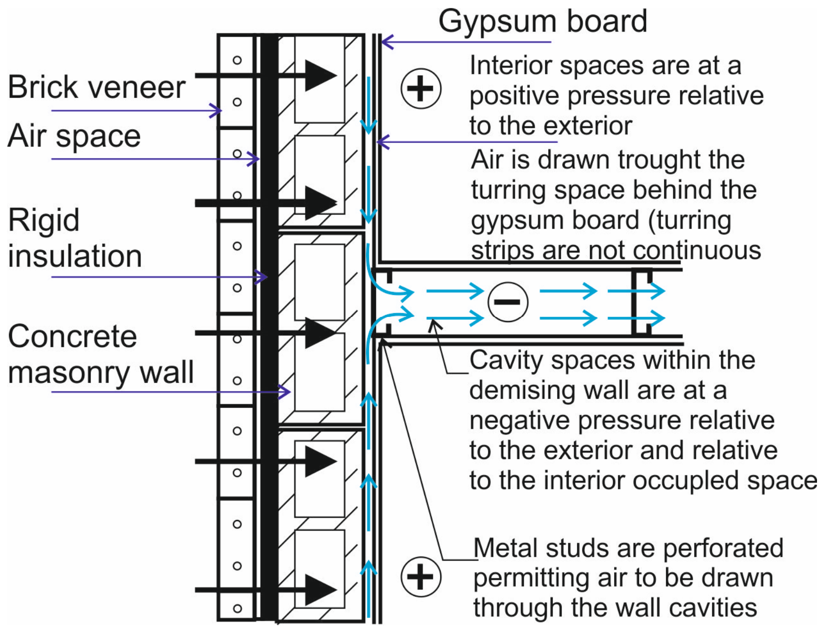

Figure 4. Interstitial airflow results in mold growth on the interior in a Florida hotel. With permission of J. Lstiburek.

The new performance expectations emerged slowly and mainly because of an accelerated pace of building science developments. Here are a few critical performance issues:

1. Discovery of interstitial air pressure fields and observations that several airflow paths are possible between any two points in a building. Furthermore, the total airflow resistance is a sum of all local airflow resistances and each of them varies with the frequency and direction of the wind gusts.
2. Introduction of air-barrier systems [25,26] affected heat and moisture flows.
3. The need for exterior insulating sheathing [27] to avoid moisture condensation within exterior walls.
4. Ecological considerations modified material choice and the wall-field performance [28].
5. Introduction of an integrated design process permits a system approach but also forces the making of critical decisions in the beginning of the design process.
6. With air-tight and highly insulted houses, one needs to modify humidity in indoor air [29] and the capillary active technology is developed.
7. Finally, in retrofitting, one may introduce a second air gap [30] and use it for several different functions, such as control of water content in the outer walls, as a means to modify air pressure in the indoor spaces, or even air recirculation in the dwelling.

The methods of building evaluation are different today than they were three decades ago because today we understand the interactions between the different functions of the building. The architectural design process includes four steps:

1. First, all passive energy measures and factors affecting indoor environment such as temperature, indoor air quality, acoustics, daylight, illumination, hot and sewer water management, aesthetics, and building resilience in disaster situations are addressed.
2. Second, the building's automatic control systems to integrate heating, cooling, ventilation, and other indoor climate controls including use of geothermal and solar means for energy generation and storage are addressed.
3. Next, an economic analysis to determine the level of investment for the initial building design or the initial stage of retrofitting. For example, one must decide to what extent photovoltaics should be included in stage 1 of the construction or retrofitting process.
4. Finally, one develops a comprehensive operational manual for the building and provides the design for stage 2 of new construction or retrofitting. This step also estimates costs for stage 2 of a project (see later text about two-stage design).

New elements in the above list are step 2 on building automatics and step 4 on the operational manual. The latter must be requested in the contract documents. Observe that there is no standard for a passenger car manual but all buyers expect to receive one. So, buyers should start expecting a manual for a smart house.

2.8. Review of the Deep Energy Retrofits (DER) in the USA

Published in a 2021 report from Lawrence Berkeley National Laboratory written by Iain Walker, Brennan Less, and Nuria Casquero-Modrego, entitled Emerging Pathways to Upgrade the US Housing Stock: A Review of the Home Energy Upgrade Literature [27] provides a detailed analysis of the state of the art.

With permission of the authors, we quote some of the key elements of the review.

This review addresses whole home energy upgrades targeting deep energy reductions (i.e., Deep Energy Retrofits, or DERs), from 30 to >50% site energy savings. The intent of this work is to characterize how energy upgrade projects and programs have evolved and improved over the past decade, and to identify what changes are needed to drive expansion of the U.S. retrofit market in such a way that addresses carbon emission from buildings, improves resilience and upgrades the housing stock for the 21st century. The topics covered in this review are wide-ranging, including trends in U.S. and European retrofit programs, measure costs (e.g., ductless heat pumps, heat pump water heaters, exterior wall insulation), emerging technologies, advancements in simulation tools, surveys of energy upgrade homeowners and practitioners, business economics (e.g., soft costs, gross margins), and health effects. 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 towards 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. In addition to these project- and program-innovations, the industry should adopt new project performance metrics, namely those for carbon, peak demand, and energy storage, along with metrics characterizing resilience and health. Market drivers are needed to spur widespread energy upgrades in the U.S. housing stock, which will require valuation of DERs by the real estate industry, reduced project costs (in part by cutting soft costs), and projects designed to appeal to homeowners' while being enjoyable and profitable for contractors.

Key barriers that provide opportunities for modification:

- Projects focused solely on energy savings are not appealing.

The past focus on energy efficiency or annual site energy savings is not enough. 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.

Despite market development efforts over the past decades and the presence of many dedicated and very skillful companies, the general workforce is inadequate to implement complex projects at scale. The emergence of new technologies, metrics and processes make 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 way to save energy and reduce carbon emissions is likely to include PV, thermal storage, simple weatherization, and electrification, rather than high-cost envelope upgrades. Other novel approaches may include leaving existing heating systems in place and augmenting with higher-performance systems to save the cost of existing system decommissioning. Another aspect of cost control is to invest in technologies that can more reliably reduce energy use (or CO_2 emissions) in homes to reduce financial risks for homeowners and post-retrofit home performance risks for contractors. Across the industry, soft costs are a substantial fraction of the total, and 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.

Due to low energy costs and the failure to appropriately price carbon emissions, the direct financial benefits of home-energy upgrades are difficult to prove using simplistic methods, such as the number of years it takes to pay back an investment. Other 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 also need to recognize that for many homeowners, their motivation and decisions regarding home energy upgrades are not purely based on simplistic financial analyses.

As our article does not deal with the financial side of retrofitting, we want to highlight that the LBNL report discuss strategy such as the electrification programs and methods of financing (pay-as-you-save, pay-for-performance, and retrofit as an investment product) and perhaps the most important from the system integration point of view is the one-stop shop program that integrates project financing and design management and support services.

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

We distinguish between three different areas of concern [31,32]:

(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 the purchased media such as electricity, district heating, or 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 the global warming potential (GWP), which 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.

We define a zero-carbon building (ZCB) as: 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 the definition of ZCB to compare different construction strategies. Without an accepted ZCB definition, one cannot analyze the building as a system and spend time and effort on useless talk. A good example is what many green people consider as an option, which is to ban the use of concrete. While concrete has huge, embodied energy, when used with the controlled effect of thermal mass it may be a material of choice in many specific applications. The highest ASHRAE green award in 2020 went to a concrete building in Tokyo using thermo-active technology (an equivalent of environmental quality management). Therefore, the definition of a zero-carbon building includes a comparison of initial and operational carbon emissions.

We realize that analysis of a building as a system is not easy; it requires technical proficiency higher than used today in construction. Furthermore, the modeling of building performance and cost-benefit analysis 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 consideration of carbon emissions from the electrical grid.

Including electric grid interaction with the building complicates modeling in a dramatic way because the GHG emissions depend on both location and time of the year. To minimize the GHG emissions from the generation of electricity requires re-evaluation of the way we do modeling and the way we design the building operation. As today decarbonization is not included in the cost calculations, one must be prepared for the inclusion of decarbonization in the next generation of buildings. This paper highlights the need for rethinking the fundamentals of the retrofitting technology.

2.10. Shaping the Internal Environment in Thermomodernized Buildings, Conclusion

Perhaps the single most visible limitation of the current design is fragmentation. The fragmented nature of the current approach often leads to results different than expected. As we started systematic work on energy conservation in the mid-1970s, it is interesting to examine Figure 1, which shows that between the years 1978 and 2005 the space heating component was dramatically reduced, but there were no changes in the total energy use. In effect, fragmentation often improves one aspect of field performance but may destroy others.

Figure 2 reminds us that sustainability includes three components and ecology alone does not make buildings sustainable. In effect, by including economic and social aspects, the concept of sustainability is opposite to fragmentation and brings another perspective to the construction process.

A failure of the integrated passive house system (Figure 3), when applied by builders in a simplified approach, demonstrates the role of interaction. Without understanding the interaction between heating and ventilation, builders changed the heating system, worsening the indoor environment. This example emphasized that reducing the gap between science and practice and creating a new generation of technology must proceed in parallel and that one must create *broad public–private educational programs*. In 2008, two equally important objectives were proposed by the Lawrence Berkeley National Laboratory, namely a 90% reduction of energy use in new buildings and the retrofitting of all existing buildings. The second objective, retrofitting, failed because it was not supported by a broad public–private educational program such as R2000 (Canada) or Building America (USA) that were introduced in the 1980s to support the sustainability approach.

Therefore, *if one wants to succeed with the climate-change* aspect of economically and ecologically retrofitted buildings, one must institute such programs again, as well as create a new approach to investment in building and city renovation.

3. An Example of the Next Generation of Low Energy Buildings

This section presents and discusses principles of *environmental quality management* (EQM), a generic public domain technology that we consider a next-generation technology. Several different practical examples are given of its application.

3.1. Thermal Storage Requires Transient Operation of Buildings

EQM technology includes thermal storage from geothermal sources and contribution from thermal mass that is controlled by the building automated system. Geothermal storage system has been discussed [33–37]. EQM integrates HVAC with the building structure, uses transient but controlled changes of indoor climate (adaptable indoor climate) to control the input of thermal mass and moisture buffers. To control the operation, one develops algorithms based on monitored information from field performance and uses them for system optimization.

3.2. Heating and Cooling Systems in the EQM Technology

Bomberg et al. [6] recommended using water-based heat-pump technology with coupling between thermal mass and a large surface of a hydronic heating or cooling system. This type of heating/cooling was found to be more efficient than air-borne systems (Brennan et al. [3]) or other air-based heat pumps because of the large thermal mass of water in the system. The most important aspect of water-to-water heat-pump use is, however, summer cooling. We know that highly insulated, air-tight buildings even with a window-to-wall percentage as low as 20 percent [29] will result in summer overheating in a typical mixed climate and we typically use 40 to 60 percent of glazing on the solar side of the building.

A reinforced polyethylene (PEX) tubing can be used in heating on the wall (Hu et al. [28], Fadiejev et al. [37]) and cooling on the floor. To improve control of the thermal mass, a hydronic heating on the surface of the interior walls is used. The impact of radiant panel location is significant (Table 1).

Table 1. Effect of location of the radiant panel on energy demand in dynamic operation mode.

Panel Location	Heating Demand (GJ)	Cooling Demand (GJ)
Wall vs. floor	58 vs. 98	24 vs. 31

These values were calculated using energy-plus with film coefficients typical for horizontal and vertical orientations. Hu also found that to achieve more than 90% efficiency in the desired heating, a thermal resistance of the insulation layer of at least 1 (m^2K)/W must be used.

Figure 5 shows that the integrated design process (IDP) may start with an initial lowering of utility bills without a cost increase and that all passive measures create only a small increase in the ownership cost that is here expressed as a mortgage. With a further increase of the ownership cost, this passes through a minimum. Another characteristic point on the curve shown in Figure 5 is the point of equilibrium where the use of photovoltaic (PV) panels is approximately the same as traditional passive measures. One may continue using PV panels until reaching zero energy at a substantial mortgage investment, typically about a 50–70% increase of the minimum cost. Currently, the typical investor stops after placing a few solar panels.

Thus, the rational design of low-energy buildings hinges now on the capability of selecting the reference point for the photovoltaic (PV) technology. In line with this need, the PHIUS selected reference buildings based on the ASHRAE/DOE climate zones [38,39] and considered 115 locations for cost optimization that included air tightness, window upgrades with a 15 °C minimum interior surface temperature, heating and cooling demands, and peak heating and cooling loads. Statistical models were fit so that the cost of the target properties can be generated for any location from parameters such as degree-days and design temperatures. In this manner, both the German and U.S. PH developments moved housing toward the goal of sustainable development. As we have selected the maximum period of return on investment to be 15 years, the energy level attained may be below the zero-energy building.

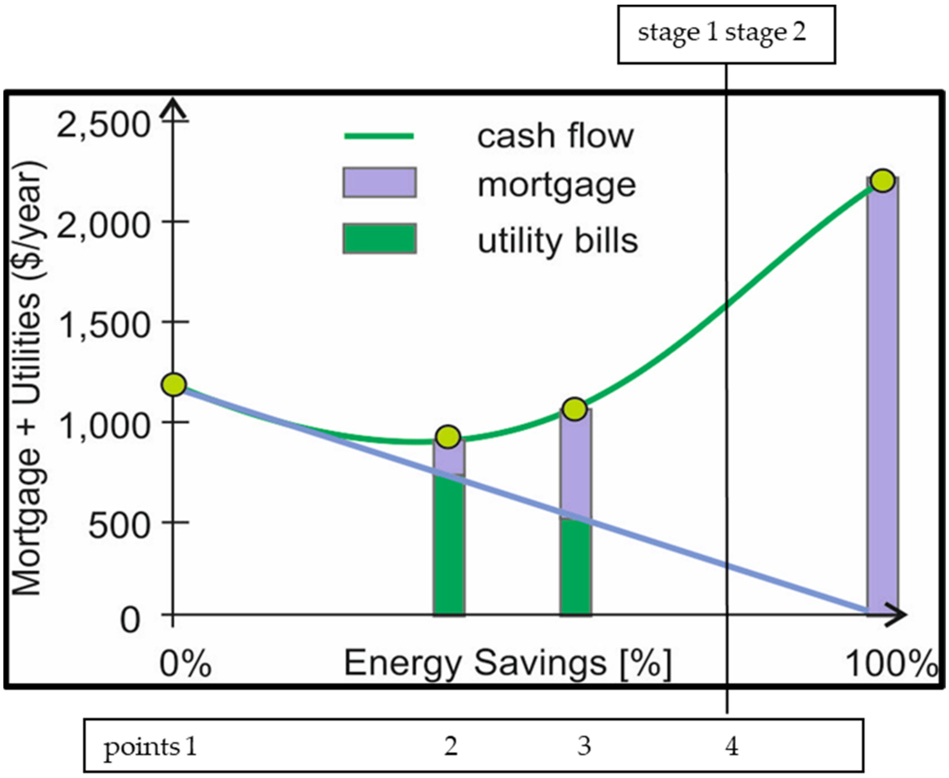

Figure 5. Costs of utilities (green) and mortgage (blue) versus energy savings from zero savings to 100% savings. Point 1 is the reference cost, point 2 is an optimum with passive measures alone, and point 3 is the price of photovoltaic (PV) when equal to passive measures, point 4 represent the end of the stage 1. Modified graph from PHIUS (own archives).

The proposed way to alleviate the conflict between the investor (with limited finds) and society (which wants to reach a net-zero energy level) is to introduce *a two-stage construction process*. In such a process, stage one is designed to achieve a performance level limited by the available funding, while stage two continues to 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, yet the design predicts continuation of construction to the zero-energy level.

Generally, the second stage would start a few years later and often will also include the charging of vehicles used by the household. For the two-stage solution to be successful, both stages must be designed at the same time, and only the construction process is divided to secure funds after the basic building exists.

3.3. Hybrid Ventilation Modified for SARS-CoV-2 Containment

The pandemic showed shortcomings of both the EU and U.S. approaches to indoor air handling in residential buildings. Therefore, one must capability to change ventilation rate between 0. and 3.0 air change per hour and either add filtration to the existing system or use pressure gradient within the habitable space. and used DOAS with exterior filtration In the latter a case one must resolve the management of air humidity, see the next section.

3.4. Over-Pressure Indoor Air Requires New Moisture Management Technology

Introduction of air pressure higher than outdoors is useful for controlling ventilation rates, but it also requires modifying the indoor humidity control and provision of moisture buffer capabilities that were lost with the elimination of lime from the interior plasters. To this end, an air gap between the old wall (exterior or interior) and panelized interior finish system is introduced. The panelized interior system has surfaces covered with a hygroscopic and capillary active layer called *eco-wrap* that will act as a moisture buffer.

This concept is based on research on dynamic walls in CRIR (Centre Recherché Industrielle de Rantigny), France, in the 1980s that showed the difference between static and dynamic performance of the wall is negligible. So, the wall acts as the heat exchanger and the energy loss is minimal. In this manner the ventilation and moisture management are integrated with the heating/cooling system.

There is a need to use a material with the capability to catch and release water, i.e., wetting and drying though an interaction with the passing air, this material was labeled eco-wrap. This material may also be a new subcategory of plaster/mortar because it must be continuous, strongly hygroscopic, and capillary active, as well as show field performance like an elastic plaster. Hygroscopic means attracting and holding water molecules from the surrounding environment by either absorption or adsorption, which is usually at room temperature. As the Thompson (Kelvin) law explains, a pore size lower than 10^{-7} m reduces the saturation value of the water vapor concentration above water meniscus. With the pore curvature corresponding to a size smaller than 10^{-8} m the condensation of water vapor takes place at 90% RH and at 10^{-9} m it would happen at 30% RH. Thus, wood is more hygroscopic than inorganic materials and using mortars that include organic fibers is a method to increase the hygroscopicity of the composite material.

The hygroscopic layer may also be drawing moisture from other materials with larger pores and this phenomenon was introduced under the name of the capillary active layer in the work of Grunewald and Häupl [40]. Figure 6 shows a capillary active layer that brings the condensed water vapor to the surface of the material, allowing evaporation to the interior air.

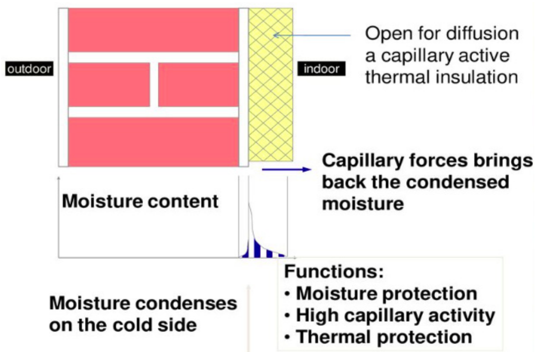

Figure 6. Capillary active layer brings the condensed water vapor to the surface of the material, allowing evaporation to the interior air (Reprinted with permission from Ref. [40]).

The first capillary active layer was developed in the application of calcium silicate by Grunewald [38] using a try-and-error sequence that involved a pilot manufacturing enterprise, determination of the moisture transport characteristics at a university, and a second round of pilot manufacturing. The observation that tobermorite, one of the two basic minerals forming the calcium silicate, had a higher sorption curve (i.e., contained more micropores with nominal diameter 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.

A clay-based plaster is another capillary active material used as the interior finish in historic caves in Japan. This plaster was developed to replace the mechanical control system that could not cope with opening and closing the entrance door by a highly variable number of visitors and changing weather conditions. In principle, the capillary active material technology is an extension of traditional materials such as lime plasters and wood-based cement boards used on the interior of buildings. A low-density cement-bonded wood fiber (CBWF) was used in masonry breathing walls that were highly water-vapor permeable and have high sorption. CBWF had a WV permeance like that of a lime plaster (i.e., about 10 times higher than wood). The sorption of CBWF, i.e., water in equilibrium with very humid air (for instance 50% RH), is about six times greater than lime plaster. While under a stepwise change in humidity, this material is much slower than wood, but after ten hours of exposure to new conditions, the amount of water stored by CBWF exceeds that of an unpainted log wood house. In conclusion, CBWF and strawbale walls were found to provide good solutions for a breathing wall.

In effect, cement-bonded wood fiber material represents a purely historic development, while the Dresden Technical University team added a next step in knowledge to improve the process of moisture management and complimentary work in Japan expanded the concept of capillary active technology. The next step was motivated not with the material but with the system level. Exterior thermal insulation and composite systems typically that use expanded polystyrene foam and cementitious lamina should not be used above the 11th floor, i.e., to the limit of evacuation ladders.

For higher buildings, the only suitable exterior insulation is high-density mineral fiber insulation (MFI). Generally, it is a self-draining material except for the layer at the bottom. For the fresh material, the water-retention strip is about 100 mm, but with aging (weathering) of the material this is increased to about 180–200 mm. Furthermore, the MFI does not have the required impact resistance. Both these shortcomings are alleviated by the work of Fort et al. [41], by providing a water-vapor diffusion to the surface of MFI, a capillary active layer is applied. While the main point of this research relates to a combined experimental-computational analysis of hygrothermal performance, the engineering solution addresses a known market need. This paper modifies the hygrothermal model of Kuenzel [42] closer to that used in soil science, e.g., de Vries, and see the analysis in Ph.D. thesis of Bomberg [38]. A laboratory experiment to determine temperature and moisture fields served as a basis for model calibration and the identification of unknown parameters. The calibrated model is subsequently used for a long-term hygrothermal assessment of the studied detail.

Hygrothermal properties of insulating materials, connecting layers, and their mutual interactions therefore belong to the main topics of recent studies aimed at interior thermal insulation systems (Fořt et al. [41], Vereecken and Roles [43]). Both computer modeling and testing are used in their work. Measurements were made in a real-time mode, but modeling is versatile. The results, however, are strongly dependent on the quality of input data and material characteristics.

We have three different methods for model calibration:

(1) During the experimental work as used by Fořt et al. [41]
(2) Using one of the material properties verification methods (see: Bomberg and Pazera [32]) or a new, emerging approach of the system-monitoring application of statistical analysis of data [44] and performance evaluation (MAPE modeling, see: Romanska-Zapala et al. [37]).

3.5. Next Generation of Capillary Active Materials

During pilot manufacturing in the USA, recycled wood with 100-micron diameter and unspecified cellulose fibers were used. In China, fibers from rice plants and rice hulls were used. The choice of different components in the fiber mixture is made with the view to: (a) ratio between strong and weak fibers, (b) ratio between inert and electrostatically charged, and (c) ratio between the micropores and the skeleton. Furthermore, to reduce shrinkage, the fraction of Portland cement, replacing it with pozzolanic material such as fly ash, or a mixture of fly ash with silica were limited. The choice of fillers in addition to the preselected size of sand is unlimited. To obtain the combability of different materials we use re-dispersing and bonding polymers, as well as polymers regulating the water retention of the mix by eco-wrap.

Generally, the eco-wrap mix is designed for demolding after 24 h and 48 h water retention to apply the next layer without prewetting the surface. Eco-wrap can be designed for application in either one or two layers. The base layer would have more of the coarse sand and bonding polymer than the interior finish layer. This also improves the control of the wetting and drying performance.

The mix design process takes a few stages. In the first stage we are looking for wet ting, drying, shrinkage, and workability performance and this is done purely on an experimental basis. One tries to develop a mix that behaves as a typical mortar with a reasonable workability, consistency, and critical physical properties. In stage 2 (Figure 7), one evaluates the basic hygric properties by comparison to the reference mortar/plaster, in our case a standard Portland cement mortar.

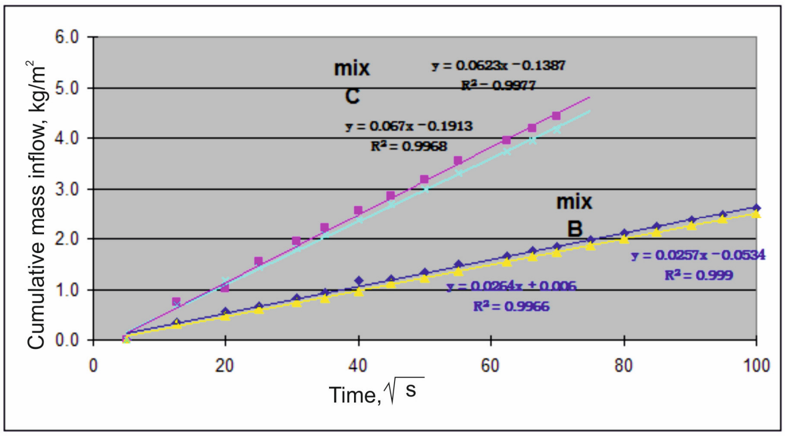

Figure 7. Lime-pozzolanic mix C shows wetting from free water surface faster than mix B, which is based on standard Portland cement. Note that an initial stage of the test is purposely discarded.

The outcome of the water absorption test is easily predictable. But the test is needed to determine the maximum liquid water conductivity of the material. Conversely, the drying rate permits better evaluation. Figure 8 shows clear differences between different eco-wrap mixes. The mix C shows a much better drying rate than mixes D and E. At this stage one may decide that mix C3 is more suitable for a one-coat application, while a combination of D2 and C3 will be better suited for the finishing interior surfaces.

Stage 3 is a repeat of stage 1 but with a rigorous framework of special mortar design and this includes review of the cost–benefit relation, early strength development, and use of a chemical addition to retain water for 48 h. The fraction of this admixture is different in hot or cold climates.

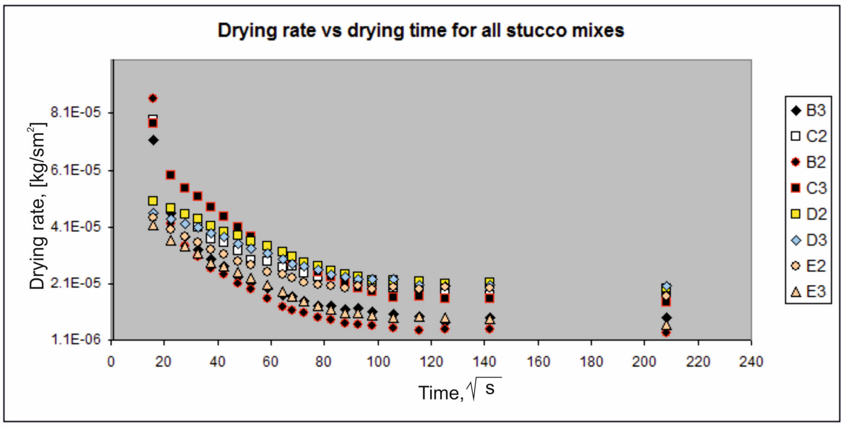

Figure 8. Drying rate versus drying time. Mix B is based on standard Portland Cement; mixes (C, D, E) represent eco-wrap based on lime with varying fractions of fibers (e.g., mix D has a density of 800 kg/m^3).

3.6. The Need for Building Automatic Control Network (BACnet)

EQM technology includes the development of an integrated control system that performs optimization of different subsystems such as the water-to-water heat pumps, solar thermal and photovoltaic panels, air intake ventilators, heat exchangers for pre-heat or pre-cooling of the ventilation and modification of its humidity level, heat exchangers for the exhaust air, instantaneous hot-water delivery systems (or hot-water tanks), cold-water tanks and rain- and/or gray-water tanks, illumination, and control of temperature, air flow and humidity in several spaces depending on their functions. Furthermore, it controls the use of surface heating/cooling that are integrated with building partitions to modify the contribution of thermal mass to the energy consumption. With an adequate steering algorithm based on the history of use and predicted values in relation to the outdoor climate, one can optimize the indoor climate for any type of use and climate (except for the extreme).

The above list explains why the building of an automatic control network (BACnet) is included and optimization during the post-occupancy stage. The system includes two subsystems: (a) a metering system to monitor the selected parameters with a view to discovering malfunctions of the separate units and provide information on their performance, and (b) the building management system to ensure the required quality of indoor environment. To this end, one may introduce the self-learning functions of the steering algorithms to permit optimization of these subsystems in the post-occupancy period. Yet, to optimize HVAC performance we need to have information collected over four different seasons, i.e., a minimum of one year of post-occupancy.

Figure 9 shows the concept of building automatic control in the EQM system.

Note that the charging of motor vehicles and PV systems are now common practices for residential properties; any combination of AC and low-voltage DC on the same grid may also affect the frequency distribution of the electrical current and associate with its loss of quality in the energy systems. Thus another, yet not discussed, function of the BACnet is to ensure the quality of the electrical current.

3.7. Rehabilitation (Retrofitting) of Old Buildings—A Continuum in Time

Another dimension of the EQM technology is that it allows use of the same approach for new low-energy buildings and for rehabilitation of the old. A project in Montreal, Canada demonstrates the power of planning the construction process for a longer period. Atelier Rosemont in Montreal, Canada is a cluster of buildings designed to be upgraded over a period of 10 years to demonstrate the power of integrated planning and execution from the standard neighborhood to near-zero-energy buildings that includes community areas. The Atelier Rosemont project highlights how vague the boundary between new constructions and retrofitting of old buildings can be and that the system integration proposed in dynamic EQM projects is not a dream. EQM technology is to make a double integration, in time and space, much easier to achieve.

Figure 10 shows the buildings to which different stages of energy reductions that were applied from 2008 (0% of total energy reduction) to 2018 (92% of total energy reduction).

Stages of improvements from 2008 to 2018 in Atelier Rosemount, Montreal,

- High-performance enclosure, common water loops, solar wall—36 percent reduction in the total energy use per square meter and year;
- Gray-water power pipe—42% reduction in energy use;
- Heat-pump heating (with horizontal heat exchanger)—60% reduction;
- Renewable 1: evacuated solar panels for hot water—74% reduction;
- Renewable 2—photovoltaic bring the total reduction to 92% (in 2018).

Thus, in the span of 10 years, these building reduced energy use by 92 percent of the original use.

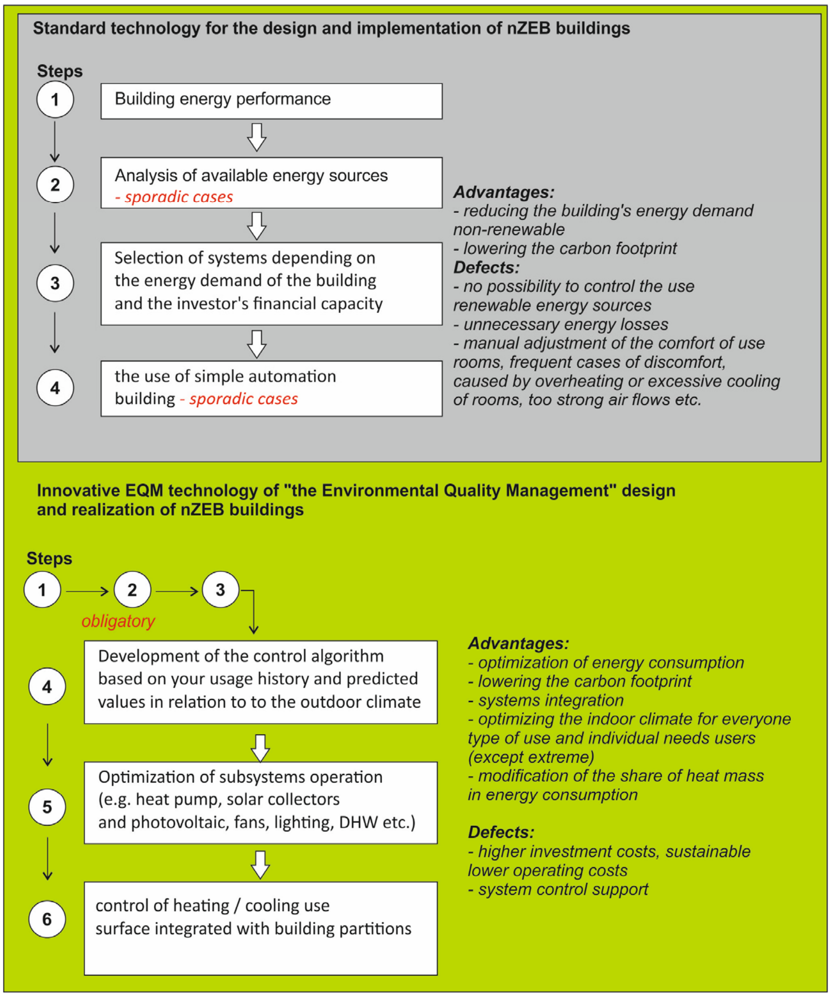

Figure 9. The concept of building automatic control in the EQM system. Source (MFC own study).

Figure 10. An affordable, low rise, energy efficient multi-unit residential building "Atelier Rosemount" in Montreal; rain retention basin in the bottom right (credit Nikkol Rot, reprinted with permission).

3.8. Thermal Storage Is Located in Ground Next to Building Foundations

Elsewhere, we analyzed earth–air heat exchangers for pre-conditioning air, postulating that efficient use of EAHX (earth–air heat exchanger) requires use of both: a fresh air inlet and EAHX. This paper explained that when outdoor air reaches a specific temperature, e.g., 19 °C, one should use outdoor air and switch back to the EAHX when the air temperature cools below 19 °C. To switch between two sources of air we need to know the following:

- Temperature of outdoor air;
- Temperature on exit from EAHX;
- Temperature required on entry to the indoor space;
- The need for heating or cooling of air to the temperature of entry to the indoor space.
- Electric energy needed for operating EAHX;
- Dynamics of temperature changes in the soil surrounding the EAHX pipes;
- Temperature of the air being removed from the indoor space and recuperation of energy.

The highest efficiency of interaction between EAHX and the ventilation center (mechanical room) is achieved when fully integrated control/steering systems for the low-energy building is used. In such a case, separate needs in different indoor spaces (different rooms), e.g., presence of people in the room are considered. Such a system will address optimization of both comfort and energy use.

In discussing this holistic approach to design, one must also consider resiliency of the building, i.e., what happens when the electrical supply is interrupted. Buildings must be airtight but not too tight because continuous use of mechanical ventilation requires a significant supply of electricity.

Experience from Finland indicates that the uncontrolled air leakage that may provide 60–70% of the minimum ventilation appears to be good guidance. We also suggest using 10 Pa overpressure of buildings if the walls are designed for adequate moisture management and the delivery of fresh air is restricted to 60% of time.

While use of a direct air pre-conditioning is restricted to small houses and in larger residential units water-based heat exchangers, the above discussed considerations are still valid. The preferred location for a water tank used as ground for the thermal storage is under the house or in the house's perimeter.

3.9. An Example of Hungarian Demonstration House

An extension of passive house technology (proposed by Bomberg [38] and Krecké, see [45]) was an introduction of pre-conditioned air or water tubing to produce an 'active insulation' layer. This would allow using energy from other sources and reduce heat transmission through external enclosure. The system requires only an ordinary pump to transport the heating/cooling medium that connects an active insulation layer with the earth heat exchanger. In a cold climate, the medium temperature is lower than the indoor space but higher than the outdoor air.

A patent introducing the concept for an active thermal insulation layer for buildings as a contrast to passive house technology was issued in 2012 and the demonstration building in the town of Nyiregyhaza in Hungary that has a direct coupling between ground and wall heat exchangers is described elsewhere [46]. Data recorded for eight years demonstrate that active thermal insulation regularly improves thermal performance of external walls. The equivalent thermal transmittance U_{eq} of the analyzed wall (dependent upon climatic conditions) varied from 0.047 W/(m^{2}K) in November to 0.11 W/(m^{2}K) in March, while the steady-state value without ground coupling was 0.282 W/(m^{2}K). In the tested building, the average heat loss reduction was 63% in relation to standard insulation.

In the demonstration house, a continuous circulation of the medium is used for the purpose of analysis. Indeed, the medium temperature varied from 12 to 23 °C with an average of 17.9 °C, while the average outdoor temperature was 11.9 °C, indicating the summer recharging the ground with energy from the walls. Figure 11 presents the daily temperature differences between the coil medium and the outside air. As the positive temperature difference (5843 degree-days) are much higher than the negative values (−493 degree-days), one sees large heating potential.

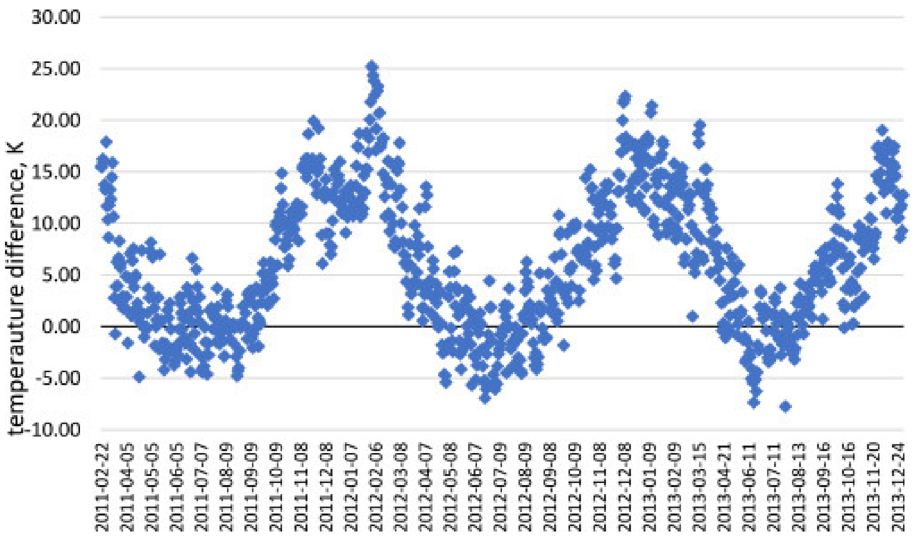

Figure 11. Temperature difference between fluid in coil and external air (Adapted from Ref. [46]).

In effect, if the system operated only in the heating fashion, one would see that the heat-loss reduction in the cold period was higher than 50%.

3.10. Next Generation of Low Energy Buildings, Conclusion

A comparison of residential buildings from 1929 to 2002 in Vancouver highlighted the need for a *transient operation* of buildings. In the next generation of buildings, large surface of hydronic heating or a cooling system coupled with a thermal mass and operated with a water-to-water heat pump will be used. The Hungarian demonstration house shows the possibility of 40–50% energy reduction.

To alleviate the conflict between the investor (limited finds) and society (wants net-zero energy level), we introduce *a two-stage construction process, where stage one is designed to achieve a limited performance level, though acceptable to* the building code, and a limited cost acceptable to the investor, while the second stage continues to the selected performance level. The Canadian (*Atelier Rosemount" in Montreal*) shows 92% energy reduction in the social housing project.

As the indoor environment should not be worse than the outdoor, the lesson from SARS-CoV-2 leads us to a variable rate of over-pressurized ventilation in all rooms except for a selected bedroom. Overpressure of indoor air requires a fundamental change of the humidity-control strategy and the development of new moisture-buffer technology.

4. Conclusions from the Work, Further Action Plan

In this article, the authors touched upon many important topics related to the energy efficiency of buildings., namely optimization of the HVAC and implementation of new nearly zero-energy retrofitting technology. The authors also stress the need for improving the ventilation by using filtration with M13 device or designated outdoor air system (DOAS) with exterior filtration.

The currently used concept of a passive house includes many improvements but also uses many arbitrary criteria that restrict the applicability of this technology. Furthermore, when an occupant opens windows during inclement weather, he/she may destroy "energy efficiency". The history of building science from its beginnings almost 100 years ago up to the development of net-zero-energy buildings gave us an understanding that the next generation of buildings will be designed with the indoor environment as the starting point. If we satisfy the occupant's need for large windows, individual ventilation on demand, and hydronic heating/cooling systems built in walls or floors, we are making progress toward sustainable buildings. Furthermore, when our heating/cooling system operates at low temperature without noise or visible heaters or ventilators we are on a solid basis for the next generation of buildings.

This work was started about 12 years ago. Yet, while we agreed with the basis for a change in the approach, our previous attempts to synthesize the environmental aspects of building science were shallow. The indoor environment is more than thermal comfort. While we knew that electrical heat-pump technology will be a key in the next generation of buildings, we also realized that the focus of building science must be on renovation. The review showed that the next generation of technology must be active and involve use of air cavities. The most significant contribution to our research came from the NY test house [38] and Hungarian demonstration house [46], where a direct coupling between hydronic heating and a ground heat exchanger was used. Yet, as we will incorporate hybrid solar panels and water-sourced heat pumps in the next-generation technology, we will use a building's automatic control system instead of a direct connection.

The critical issue today is the necessity for rapid action. There are a few components of housing obsolescence that, combined with an urgent need to reduce climate change, provide us with the perfect opportunity to change the challenge into a win-win situation. Construction today is facing four crisis elements: (1) affordability, (2) lack of skilled trades, (3) productivity (no change for the last 10 years while the manufacturing sector in the U.S. increased productivity by 70%), and (4) the digitalization of industry (again less than 20% production in the U.S. is not on the building site; in Sweden, for instance, more than 80% is manufactured off the site). If we add the need for zero energy (zero carbon emissions) and health concerns highlighted by the spread of COVID-19, we get a situation calling.

Yet, until recently, all these pieces of knowledge did not have linkage to the occupant. The breakthrough came with the analysis of SARS-CoV-2 in the low-energy buildings. In the recovery bedroom, an occupant needs air pressure to be lower than in the rest of the indoor space and also a strongly variable ventilation rate. Yet the whole dwelling needs to have some air movement. This implies that living space itself must have air pressure gradients and effectively one must use much more carefully designed humidity control. In North America, we had air circulation imposed by the air-borne heating systems, but we did not appreciate its significance. Today we know that neither opening widows (Europe) nor having air conditioner in the window (U.S.) make economic sense. Today we can design buildings that are energy efficient, inexpensive, and produce more energy than they use. We can do in the harsh climates of Canada or humid climates like Florida. The design principle is the same, but the details are different.

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 of how we deal with technology that makes the socio-economic impact. Overdoing the intellectual part of technology in 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 the administration policy, one aspect, e.g., energy efficiency, is stressed while others are neglected, the whole technology becomes simplified and unbalanced. Our current system of supporting applied research requires a visible fragmentation, while the 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; it does not fit into applied research because one cannot estimate the monetary savings of this approach. Of course, those who realize the significance of the continuum of data and control models for the optimization of the HVAC will continue doing this type of research, but the whole world of academia is excluded as they rely on the government support.

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 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 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) numbers, parameters such as subsidies, taxes, or standards. He contradicts *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.*"

To the sustainability research:

> "*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 [47] highlighted that a scientific revolution that comes with a small step in the socio-economic situation is close to the change. The authors claim that the change-of-thinking-paradigm needed for the next generation of building technology is just this last step and slowing or reversing climate change is *the transcending paradigm of our time*. Understanding this paradigm should motivate all involved in building science (physics) to mobilize the public and explain to politicians that the important approach in the post-COVID world is to invest in the renovation of our buildings. In effect, this review shows that it is not gas emission or energy saving, but an *emerging holistic vision* that must be communicated to the broad public. The only way to accelerate the green revolution is not through green materials but through broad public–private programs of education and demonstrations of the need for reinvesting in the next generation of retrofitted buildings.

Now, after repeated waves of pandemic, comes the realization that the next generation of new or renovated dwellings must provide an indoor space suitable for the quarantine 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. Therefore, the requirements for retrofitting must be broadened to include an adequate handling of DOAS ventilation with interior air circulation. In effect, one may summarize the above discussion as follows:

> *"The next generation of environmental quality management technology should have a dedicated, hybrid ventilation system with an adequate management of air humidity."*

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References

1. Flynn, J.E.; Segil, A.W. *Architectural Interior Systems: Lighting, Air Conditioning, Acoustics*; U.S. Department of Energy Office of Scientific and Technical Information: Oak Ridge, TN, USA, 1970.
2. Bomberg, M.; Brennan, T.; Henderson, H.; Stack, K.; Walburger, A.; Zhang, J. *High Environmental Performance (HEP)—Residential Housing for NY State*; New York State Energy Research and Development Authority: New York, NY, USA; National Center for Energy Management and Building Technologies: Alexandria, VA, USA, 2009.
3. Brennan, T.; Henderson, H.; Stack, K.; Bomberg, M. Quality Assurance and Commissioning Process in High Environmental Performance (HEP) House in NY State. Available online: https://www.semanticscholar.org/paper/QUALITY-ASSURANCE-AND-COMMISSIONING-PROCESS-IN-HIGH-Brennan-Bomberg/6093cda3698953a834b37a7b12ced95ad1ef9636 (accessed on 7 May 2022).
4. Walburger, A.; Brennan, T.; Bomberg, M.; Henderson, H. Energy Prediction and Monitoring in a High—Performance Syracuse House. 2010. Available online: http://thebestconference.org/BEST2 (accessed on 2 October 2019).
5. Aelenei, L.; Frattari, A.; Riscala, L.; Altan, H.; Hashemi, A.; Aoul, K.A.T.; Noguchi, M. Zero energy homes. In *ZEMCH: Toward the Delivery of Zero Energy Mass Custom Homes*; Noguchi, M., Ed.; Springer: Cham, Switzerland, 2016; pp. 275–309.
6. Bomberg, M.; Kisilewicz, T.; Mattock, C. *Methods of Building Physics*; Cracow University of Technology: Kraków, Poland, 2015.
7. Fedorczak-Cisak, M.; Bomberg, M. Dlaczego wielorodzinne budynki mieszkalne w Vancouver zużywały tyle samo energii w 2002 co w 1929 roku? *Mater. Bud.* **2022**, *1*, 58–60. [CrossRef]
8. Bomberg, M.; Onysko, D. Heat, Air and Moisture Control in Walls of Canadian Houses: A Review of the Historic Basis for Current Practices. *J. Build. Phys.* **2002**, *26*, 3–31. [CrossRef]
9. Radziszewska-Zielina, E.; Kania, E. Problems in Carrying Out Construction Projects in Large Urban Agglomerations on the Example of the Construction of the Axis and High5ive Office Buildings in Krakow. *MATEC Web Conf.* **2017**, *117*, 00144. [CrossRef]
10. Bielski, A.; Zielina, M.; Młyńska, A. Analysis of heavy metals leaching from internal pipe cement coating into potable water. *J. Clean. Prod.* **2020**, *265*, 121425. [CrossRef]
11. Młyńska, A.; Zielina, M.; Bielski, A. Contamination of drinking water soon after cement mortar lining renovation depending on the disinfectant doses. *SN Appl. Sci.* **2019**, *1*, 516. [CrossRef]
12. Piasecki, M.; Radziszewska-Zielina, E.; Czerski, P.; Fedorczak-Cisak, M.; Zielina, M.; Krzyściak, P.; Kwaśniewska-Sip, P.; Grześkowiak, W. Implementation of the Indoor Environmental Quality (IEQ) Model for the Assessment of a Retrofitted Historical Masonry Building. *Energies* **2020**, *13*, 6051. [CrossRef]
13. Fedorczak-Cisak, M.; Kowalska-Koczwara, A.; Pachla, F.; Radziszewska-Zielina, E.; Szewczyk, B.; Śladowski, G.; Tatara, T. Fuzzy Model for Selecting a Form of Use Alternative for a Historic Building to be Subjected to Adaptive Reuse. *Energies* **2020**, *13*, 2809. [CrossRef]

14. Dudzik, M. Towards characterization of indoor environment in smart buildings: Modelling PMV index using neural network with one hidden layer. *Sustainability* **2020**, *12*, 6749. [CrossRef]
15. Lstiburek, J.W.; Pressnail, K.; Timusk, J. Transient Interaction of Buildings with HVAC Systems—Updating the State of the Art. *J. Therm. Envel. Build. Sci.* **2016**, *24*, 111–131. [CrossRef]
16. Romanska-Zapala, A.; Bomberg, M.; Dechnik, M.; Fedorczak-Cisak, M.; Furtak, M. On Preheating of the Outdoor Ventilation Air. *Energies* **2019**, *13*, 15. [CrossRef]
17. Kisilewicz, T. Passive control of indoor climate conditions in low energy buildings. *Energy Procedia* **2015**, *78*, 49–54. [CrossRef]
18. Bomberg, M.; Kisilewicz, T.; Nowak, K. Is there an optimum range of airtightness for a building? *J. Build. Phys.* **2015**, *39*, 395–421. [CrossRef]
19. Bomberg, M.; Romanska-Zapala, A.; Yarbrough, D. Journey of American Building Physics: Steps Leading to the Current Scientific Revolution. *Energies* **2020**, *13*, 1027. [CrossRef]
20. The Saskatchewan Conservation House—Passive House Canada; Maison Passive Canada. Available online: https://www.passivehousecanada.com/policy-series-2-operating-efficiency-what-is-the-target/the-saskatchewan-conservation-house/?gclid=Cj0KCQjwsdiTBhD5ARIsAIpW8CIG5VAnKScXvx1ukIH26-VUe49Wy29QrP9lwPXvS0v54UIxF4RVGy0aAucoEALw_wcB (accessed on 7 May 2022).
21. Romanska-Zapala, A.; Bomberg, M.; Fedorczak-Cisak, M.; Furtak, M.; Yarbrough, D.; Dechnik, M. Buildings with environmental quality management (EQM), part 2: Integration of hydronic heating/cooling with thermal mass. *J. Build. Phys.* **2018**, *41*, 397–417. [CrossRef]
22. Lstiburek, J.; Pressnail, K.; Timusk, J. Evaluating the Air Pressure Response of Multizonal Buildings. *J. Therm. Envel. Build. Sci.* **2016**, *25*, 299–319. [CrossRef]
23. Yarbrough, D.W.; Bomberg, M.; Romanska-Zapala, A. Buildings with environmental quality management, part 3: From log houses to environmental quality management zero-energy buildings. *J. Build. Phys.* **2019**, *42*, 672–691. [CrossRef]
24. Fedorczak-Cisak, M.; Furtak, M.; Radziszewska-Zielina, E. Certification of "Nearly Zero-Energy Buildings" as a Part of Sustainability. In Proceedings of the International Scientific Conference "People, Buildings and Environment 2018 (PBE), Brno, Czech Republic, 17–19 October 2018; Volume 222.
25. Air Barrier Systems in Buildings; WBDG—Whole Building Design Guide. Available online: https://www.wbdg.org/resources/air-barrier-systems-buildings (accessed on 7 May 2022).
26. Perrault, J.C. *Air barrier systems: Construction applications. An Air Barrier for the Building Envelope*; National Research Council of Canada: Saskatoon, SK, Canada, January 1989.
27. Kisilewicz, T. Wpływ izolacji termicznej ścian na mikroklimat w budynkach w okresie letnim. *Mater. Bud.* **2015**, *1*, 112–115. [CrossRef]
28. Hu, X.; Shi, X.; Bomberg, M. Radiant heating/cooling on interior walls for thermal upgrade of existing residential buildings in China. In Proceedings of the In-Build Conference, Cracow TU, Cracow, Poland, 17 July 2013.
29. Fadejev, J.; Simson, R.; Kurnitski, J.; Bomberg, M. Thermal mass and energy recovery utilization for peak load reduction. *Energy Procedia* **2017**, *132*, 39–44. [CrossRef]
30. Bomberg, M.; Onysko, D. (Eds.) Energy Efficiency and Durability of Buildings at the Crossroads. Available online: http://thebestconference.org/BEST1 (accessed on 25 February 2022).
31. Less, B.D.; Walker, I.S.; Casquero-Modrego, N. *Emerging Pathways to Upgrade the US Housing Stock: A Review of the Home Energy Upgrade Literature*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2021.
32. Klingenberg, K.; Kernagis, M.; Knezovich, M. Zero energy and carbon buildings based on climate-specific passive building standards for North America. *J. Build. Phys.* **2016**, *39*, 503–521. [CrossRef]
33. Bomberg, M.; Pazera, M. Methods to check reliability of material characteristics for use of models in real time hygrothermal analysis. In Proceedings of the First Central European Symposium on Building Physics, Cracow–Lodz, Poland, 13–15 September 2010.
34. Bomberg, M.; Gibson, M.; Zhang, J. A concept of integrated environmental approach for building upgrades and new construction: Part 1—Setting the stage. *J. Build. Phys.* **2014**, *38*, 360–385. [CrossRef]
35. Yarbrough, D.W.; Bomberg, M.; Romanska-Zapala, A. On the next generation of low energy buildings. *Adv. Build. Energy Res.* **2021**, *15*, 223–230. [CrossRef]
36. Romanska-Zapala, A.; Furtak, M.; Fedorczak-Cisak, M.; Dechnik, M. Need for Automatic Bypass Control to Improve the Energy Efficiency of a Building Through the Cooperation of a Horizontal Ground Heat Exchanger with a Ventilation Unit during Transitional Seasons: A Case Study. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Polzunov Altai State Technical University, Barnaul, Russia, 27–28 June 2019; Volume 471.
37. Dudzik, M.; Romanska-Zapala, A.; Bomberg, M. A Neural Network for Monitoring and Characterization of Buildings with Environmental Quality Management, Part 1: Verification under Steady State Conditions. *Energies* **2020**, *13*, 3469. [CrossRef]
38. Bomberg, M. A concept of capillary active, dynamic insulation integrated with heating, cooling and ventilation, air cond. system. *Front. Archit. Civ. Eng. China* **2010**, *4*, 431–437. [CrossRef]
39. Wright, G.; Klingenberg, K. *Climate-Specific Passive Building Standards*; The National Renewable Energy Laboratory: Golden, CO, USA, July 2015.

40. Häupl, P.; Grunewald, J.; Fechner, H. Moisture behavior of a "Gründerzeit"—house by means of a capillary active int. insulation. In Proceedings of the 5th Building Physics Symposium in the Nordic Countries, Gothenburg, Sweden, 24–26 August 1999; pp. 225–232.
41. Fořt, J.; Kočí, J.; Pokorný, J.; Podolka, L.; Kraus, M.; Černý, R. Characterization of Responsive Plasters for Passive Moisture and Temperature Control. *Appl. Sci.* **2020**, *10*, 9116. [CrossRef]
42. Künzel, H.M. *Simultaneous Heat and Moisture Transport in Building Components, One- and Two- Dimensional Calculations Using Simple Parameters*; Fraunhofer Institute of Building Physics: Holzkirchen, Germany, 1995.
43. Vereecken, E.; Roels, S. Capillary active interior insulation: Do the advantages really offset potential disadvantages? *Mater. Struct. Constr.* **2015**, *48*, 3009–3021. [CrossRef]
44. Romanska-Zapala, A.; Dudek, P.; Górny, M.; Dudzik, M. Modular statistical system for an integrated environmental control. *E3S Web Conf.* **2020**, *172*, 19006. [CrossRef]
45. Krecké, E.D. Passive House Building Technology. Available online: http://www.isomax-terrasol.eu/fileadmin/_migrated/content_uploads/ISOMAX-TERRA-SOL-engl.pdf (accessed on 1 May 2022).
46. Kisilewicz, T.; Fedorczak-Cisak, M.; Barkanyi, T. Active thermal insulation as an element limiting heat loss through external walls. *Energy Build.* **2019**, *205*, 109541. [CrossRef]
47. Kuhn, J.; Ebert, H.P.; Arduini-Schuster, M.C.; Büttner, D.; Fricke, J. Thermal transport in polystyrene and polyurethane foam insulations. *Int. J. Heat Mass Transf.* **1992**, *35*, 1795–1801. [CrossRef]