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The Effect of Degradation on Cold Climate Building Energy Performance: A Comparison with Hot Climate Buildings

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Abstract: The issues of reducing energy consumption in buildings and their decarbonisation are currently among the most pressing. However, such an important aspect of the problem under discussion as the impact of unavoidable degradation processes on energy demand in buildings remains poorly understood. In addition, there are only a limited number of practical guidelines that can be used to take this factor into account at the design stage and during the further operation of buildings. The aim of this work was to assess the potential impact of component degradation and ageing on heating energy consumption in buildings, including insulated glass units, thermal insulation, airtightness, heat recovery of mechanical ventilation systems, and photovoltaic modules. The detached and apartment buildings were considered to be in a cold climate in the context of the Republic of Belarus. The study was based on simulation research using EnergyPlus. As a result, it was found that a possible increase in heating energy consumption might reach 17.6–61.2% over 25 years in detached houses and up to 23.6–89.8% in apartment buildings. These indicators turned out to be higher than the previously identified values for cooling energy consumption in a hot–humid climate. Based on the findings, recommendations for considering the degradation factor in cold climates in practice were developed, which were compared and integrated into the author's existing guidelines.

Keywords: ageing; component degradation; durability; cold climate; building energy performance; dynamic thermal simulation; case study; decarbonisation

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1. Introduction

Reasonable consumption of various types of energy resources and the reduction of greenhouse gases emissions are currently among the key issues on the global agenda. The buildings sector is given special consideration, as it accounts for approximately 30% of the global final energy consumption and about 27% of total energy sector emissions [1]. Approximately 6% of the global carbon dioxide emissions additionally account for the manufacturing of building materials (so-called "embodied carbon") [1]. If we consider the European space, then the operation of buildings in Europe accounts for 40% of energy consumption and 36% of CO_2 emissions. In addition, the volume of embodied carbon in some cases may already reach 10–50% of the total life cycle of buildings [2] (up to 90% according to [3]). Among the key measures that help to reduce the amount of energy consumed and have already found wide applications in the design and construction of buildings, the following can be identified: renewable energy sources, passive techniques in the design, changing thermostatic set points, highly efficient building services and their proper maintenance, efficient lighting and appliances, durable high-quality building materials, reuse and recycling of them, increased flexibility, the popularisation of reasonable energy consumption by residents, etc. Notably, despite all the measures taken, the global energy demand continues to grow. According to [4], in 2021, there was the most significant increase in energy consumption (by 4%) and operational CO_2 emissions (by 5%) over the last decade. Interestingly, according to experts [1], the average building's energy intensity should be reduced by 35% by 2030 in order to comply with the declared Net Zero Scenario.

As noted in [2], the EU will face the problems of an ageing building stock in the coming decades. Moreover, most existing buildings are not energy efficient enough to meet the stated goals of decarbonisation [5]. The main reason for the non-compliance of most buildings with the stated requirements is the fact that, at the time of their construction, there were no special requirements or standards for energy efficiency. In some studies [6], for example, the concept of "ageing residential buildings" was used, which was also explained by the outdated design standards and construction standards to which they were built. Some researchers have even established some relationships between the age of buildings and their energy performance. For instance, Aksoezen et al. [7], during an assessment of the energy consumption in buildings in Basel, revealed an interesting fact that the oldest group of buildings built before 1921 were characterised by the lowest energy demand compared to buildings built over the next six decades. In turn, Mohamed et al. [8], assessing energy consumption in UK schools, found that new school buildings tend to consume less energy for heating and more electricity than old buildings.

The processes of ageing and degradation themselves also play a significant role. As Feng et al. noted in [9], the worsening of energy performance indicators in buildings is due to the fact that buildings deteriorate with age. The uniqueness and complexity of such processes stem from the fact that, even under normal conditions, there are a large number of external and internal environmental factors affecting buildings, all of which are in complex relationships, and each of these factors is constantly changing by nature. Authors in [10] noted, for example, that it is difficult to assess the consequences of materials degradation for the operational energy needs of a building. However, it is obvious that ageing and degradation are unavoidable and affect, among other things, important building elements such as envelope components and building services. What is even more important is the fact that, as noted in [11], buildings start to degrade from the day they are put into service. Given the urgency of the issue of ageing and degradation, questions have been raised more and more recently about the need to consider the entire lifecycle of buildings in order to minimise the building materials used in them and the energy consumed [12,13]. Some experts, for example, point to the need for long-term decarbonisation plans and net zero pledges in order to comply with these principles [1].

In this work, the factor of degradation and ageing of buildings is investigated in terms of its impact on the increase in energy demand over time. As in the first part of this research [14], this study also attempts to give practical importance to the results, namely, to develop technical guidelines that will not only help to more clearly understand the essence and intensity of degradation processes in buildings, but also allow the application of specific measures to minimise such an impact on energy demand in buildings over the course of time. This will contribute to the fact that buildings can be designed from the very beginning in such a way as to reduce operational carbon dioxide emissions, and as noted in [2], "they will require no future renovation work to improve their performance." Therefore, the primary aim of this research was to study the impact of degradation on the energy performance of buildings in cold climates. The results obtained will enrich the previously developed and hot–humid climate-based set of guidelines, which allow specialists to assess the possible performance deterioration with time and adopt the necessary measures while understanding the difference between the trends in the impact of degradation in two radically different climatic conditions. This study examines a wide range of degrading components (insulated glass units, thermal insulation, airtightness, heat recovery systems, photovoltaic modules) and types of buildings, which provided a broad range of results and allowed for more extensive conclusions.

Based on the primary aim, the following main objectives can be identified:

- Evaluate the existing evidence on the performance degradation of various components of buildings in cold climates.

- Identify the effect of degradation on the energy performance of buildings in cold climates.
- Perform a comparative analysis of the results obtained in a cold climate with the previously obtained results in a hot–humid climate.
- Provide new recommendations as applied to cold climates and complement these with the existing guidance for hot–humid climates.

2. Literature Review

2.1. Existing Approaches to Assessing the Deterioration of Building Performance

To date, in the context of the intensive development of various aspects of sustainability, studies on the impact of ageing and degradation on building energy performance are becoming increasingly relevant. Thomas et al. [15], for example, noted that the wear of both building systems and components may considerably degrade the performance of buildings. This ultimately leads to an increase in maintenance and replacement requirements as well as an increase in energy consumption during their operation. As such, Litti et al. [16] introduced the so-called "yearly energy performance decay rate" parameter to adjust the actual energy demand in buildings, taking into account the windows' performance decay. Authors in [11], using deterministic and stochastic methods, proposed an approach for predicting possible changes in buildings' performance during their service lives, considering changes in physical properties due to deterioration of building systems and components, maintenance procedures, and changes in weather conditions.

Eleftheriadis & Hamdy [17] pointed out the need to consider the factor of performance degradation already in the early design stage. Analysing other sources, the authors concluded that degradation processes can lead to a 20–30% deterioration in building performance after 20 years of operation. The authors in [18] also proved (using energy modelling in the EnergyPlus V 5.0 software) that the use of degradation models for components such as XPS insulation, gas boilers, and air-source heat pumps leads to a significant increase in primary energy consumption in a single-family house over 20 years: by 18.4% with a high level of maintenance of heating components and by 47.1% with a low level of maintenance. The key importance of cooling and heating equipment in increasing energy demand during building ageing was also revealed in [19]. Thus, by modelling the energy consumption (using IDA ICE software) in the library building located in Turin, a possible increase in primary energy consumption of about 8% in 10 years and about 18% in 20 years was found, and a significant share of this increase was due to the degradation of the boiler and chiller. The study [20] examines the case of housing refurbishment and subsequent analysis of changes in the energy performance of buildings during the degradation of vacuum insulation panels (VIPs), glazing systems, ground source heat pumps (GSHP), and photovoltaics. The performance of these components was regulated by the "derating factor" of efficiency. As a result, it was found that due to the degradation, the global primary energy consumption in the building increased by 67.3% over 25 years. De Masi et al. [21] attempted to simulate changes in the energy performance of a dwelling using DesignBuilder V6.0 software when the thermal conductivity of VIPs on external walls changes. As a result, it was revealed that such deterioration can cause an increase in energy consumption of 3% over 15 years. During an experimental study of the deterioration of thermal performance of grey EPS and polyurethane insulation as part of the external thermal insulation composite system (ETICS) [22], a minimal change in their thermal conductivity was established. Subsequent thermal dynamic simulations of this deterioration in the DesignBuilder showed a corresponding, rather insignificant increase in energy consumption in a single-family house (by about 2% after 8 years). Stazi et al. [23] performed a dynamic thermal simulation of the energy performance of a residential building using EnergyPlus. As a result, it was found that with the revealed increase in thermal conductivity of insulating materials by 12% after 25 years, the increase in energy demand for heating was only 2%. Asphaug et al. [24] performed simulations in SIMIEN software to assess changes in energy consumption in buildings when the U-value of insulated glass units (IGU) changes. It was found that the growing demand for heating energy with a drop in the volume concentration of inert gas in IGUs from 92.7% to 0% was about 5–6% for an office building and 8–9% for a dwelling. A simulation of the energy performance of schools in Greece was performed in [25], also using EnergyPlus, while improving the properties of the deteriorated cool roof coatings. Cleaning the roof, in particular, allowed for a 18.8% declining cooling demand and a 72% decline with the application of the new cooling coating. There was also a negative effect of such improvements: an identified increase in the required energy for heating by approximately 4% and 22%, respectively. The effect of the four-year degradation of white and beige exterior wall finishes on the building's energy needs for cooling was also presented in a study by Paolini et al. [26]. Using WUFI Plus 3.0.3 software, it was found that for a building with a white facade, the increase in cooling energy demand due to such degradation was 5–11%.

It is often the case that newly constructed or renovated buildings do not meet the design requirements, as a result of which there is a clear excess of energy consumed already at the beginning of operation. In practice, the concept of the "energy performance gap" is used to describe such a discrepancy [27]. Among the main causes of this discrepancy are design errors, violations of technological processes during construction, substandard building materials, improper work of building services, the behaviour of residents, etc. At the same time, as noted in [28], the mechanism of this discrepancy is still not precisely understood. In this regard, for example, experts note the importance of updating SAP models using "as-built" information in order to clearly understand the alleged building's performance. In turn, Marshall et al. [29] pointed out that the discrepancy in the thermal performance of the building fabric is observed even if it was modelled based on what was actually built. It is noteworthy that in [27], an attempt was made to apply adjusting factors to the primary properties of the building envelope to reduce the magnitude of the performance discrepancies. As the authors noted, good design, detailing, and workmanship are the fundamental pillars in lowering the fabric thermal performance discrepancies. All these conditions are properly observed when creating so-called "passive houses." Notably, this technology has proven its efficiency in the long term. For instance, according to [30], during the monitoring of one of the first prototypes of a passive house, energy consumption in such a building remained extremely low and stable even after 25 years of operation. In general, it can be noted that the initial quality of the construction and the level of compliance with design requirements are important for assessing the deterioration of building performance over time.

The study of the variability of the energy performance of buildings under the influence of degradation and ageing is inextricably linked to predicted climate changes. Very often, this issue focuses on assessing the balance between the growing cooling demand and falling heating demand in buildings, which may additionally be exacerbated by their possible degradation. Waddicor et al. [19] discovered that possible building ageing increases the need for energy; however, while this can be compensated for in the winter season by savings on heating energy due to an increase in mean global temperatures, the degradation effect was exacerbated in the summer by an increase in cooling demand. The corresponding results of the influence of climate change on the electricity demand in buildings were obtained in [31], namely, that the effect of reducing the need for heating ultimately reduces the total electricity consumption in the countries of northern and central Europe, whereas in the southern countries, the increase in electricity demand for cooling due to global warming exceeds the possible reduction in electricity consumption for heating. The most complete assessment of the relationship between degradation processes and the variability of the energy performance of buildings is possible only with a simultaneous assessment of the economic benefits. For example, Smagulov et al. [32] conducted the techno-economic feasibility analysis of an on-grid photovoltaic solar system installed on the roof of an airport, taking into account its degradation, and found that a possible reduction in key financial indicators might range from 16.2 to 43.5% over 25 years.

One of the main issues in assessing the significance of the degradation factor is the limited amount of quantitative data on degradation as such [11]. In addition, even the available data should be appreciated on a qualitative level [17]. The issue of getting the right data throughout the life cycle of buildings in order to decarbonise the building materials sector was also noted in [4]. The first part of this work [14] presents an extensive analysis of the existing evidence on the deterioration of the initial properties of various components of buildings. The following are the established key patterns of degradation in different environmental conditions.

2.2. Features of Building Components' Degradation in Different Environmental Conditions

The reliability of the building envelope is especially important in extreme environmental conditions. As noted in [33], in the case of the disruption of building services, the building envelope is the first line of defence against facility failure. One of the main and most vulnerable components of the building shell that affect its performance are the windows. The main cause of insulated glass units' (IGU) degradation is the possible leakage of inert gas from the inner cavity between the glasses, as well as the resulting deterioration of the low-emission coatings, which is primarily caused by the ageing of the sealants used. For instance, Kralj et al. [34] noted that the durability of IGUs is largely determined by the proper use of polymeric seals, which in turn are highly susceptible to the negative influence of high ambient temperatures. The authors demonstrated the alleged relationships between the peak temperature of sealants and the primary IGU life expectancy. For instance, when the peak temperature reached up to 80 °C, the lowest estimated IGU life expectancy was for the conditions in Rome and the highest for Hamburg. Thereby, it is obvious that the hotter the climatic conditions, the shorter the expected lifetimes of IGUs.

Thermal insulation has traditionally been regarded as one of the most important energy-saving measures in conditions of high heating energy consumption [35,36]. At the same time, the use of insulating materials is also an effective solution to reduce the energy demand for cooling in hot climates [37–39]. The properties of thermal insulation under operating conditions may radically differ from those originally stated. Particular attention among specialists is paid to the ability of thermal insulation to absorb moisture as well as the dependence on the influence of temperature. For example, there is a linear relationship between temperature and thermal conductivity for most insulating materials, and the latter might increase by 20–30% within the temperature range from −10 °C to 50 °C [40]. At the same time, as indicated in [41], the elevated temperatures have only a minor effect after a longer period. However, as Berardi [42] noted, exposure to extremely high temperatures should be avoided, as this can lead to unrealistic ageing issues. For some insulating materials, namely PIR, a nonlinear relationship between temperature and thermal conductivity is observed [41,43], with a significant increase in the latter at cold temperatures. According to [35,36], insulating materials must be designed with the goal of outlasting the building, because replacing or repairing these materials is typically difficult due to the high labour intensity of such works. However, as indicated in [22], international research focuses mainly on assessing the initial effectiveness of thermal insulation without considering its ageing. The accelerated ageing of XPS and PIR insulation samples was performed in [41] when exposed to different temperatures, which corresponded to the climatic conditions of Canada. As a result, lower conditioning temperatures were discovered to slow the change in thermal conductivity over the ageing period. The authors in [43] also demonstrated the deterioration of the effective thermal conductivity during accelerated ageing of PIR and PUR insulation under the influence of high temperature, moisture, and freeze-thaw cycling. For example, it has been found that repeated freeze-thaw cycles lead to the degradation of foam polymers, allowing more of the insulating blowing agent to escape. At the same time, the authors noted that there are no hard and fast rules governing how insulating materials perform in various environmental conditions. It is important to note that the choice of thermal insulation is largely determined by weather conditions. An extensive analysis of the selection of suitable thermal insulation materials depending on climate is presented in [44]. In addition, a certain amount of knowledge has already been accumulated on the possible degradation of insulation materials in various climatic regions: an increase in the thermal conductivity of VIP insulation by 10.6% over 5 years in southern Italy [21], an increase in the thermal conductivity by 12% of glass wool insulation in masonry cavity walls in residential building after 25 years of operation in central Italy [23], a decrease in the thermal resistance of mineral wool in the flat roof of a school building by 7.4% after 5 years of operation in Hungary [45], and a deviation of the VIP properties of about 10% over 5 years in Canada [46]. Some studies have revealed the stability of the properties of thermal insulation [30,47] or even its improvement [48].

When considering the deterioration of the energy performance of buildings, researchers pay particular attention to airtightness, which is closely related to other indicators of the effective operation of buildings. As Bomberg et al. [49] noted, the airtightness of the building is essential to better control the intensity of air exchange, to reduce the amount of moisture carried by moist air and harmful particles carried from the outdoors or from building materials, to reduce the amount of heat/cold gain or loss, etc. It is worth noting that in many studies, scientists have concluded that the major deterioration of the airtightness is observed at the very beginning of the building's operation. Among the main causes of this phenomenon are the drying of wooden frames, shrinkage of mastic during the first time the building is heated, cracking at the joints due to structure movements and foundation settlement, deterioration of air sealant applied around windows and doors, a combination of incompatible materials, drilling holes when furnishing, etc. [50,51]. The authors in [52], after analysing other sources, noted that energy losses due to air leakage amount to about 13–50% under heating conditions and about 4–20% under cooling conditions worldwide. It is worth noting the ambiguity surrounding the effect of seasonal changes on building airtightness. For example, Moujalled et al. [50] did not detect any significant seasonal variation during the measurement of the air leakage rate in different seasons. Only in one case did the airtightness of the building under consideration seem a little better in the summer than in the winter. At the same time, Wahlgren [53] clearly revealed a lower airtightness of wooden frame dwellings in the winter season (by 8–10%) in the climatic conditions of Sweden. In turn, Feijó-Muñoz et al. [54] revealed some patterns in different climatic zones, in particular, the airtightness of buildings in a temperate climate with dry and hot summers had worse indicators than in a dry, hot desert climate.

Solar reflectance of the building envelope is an effective energy saving solution for regions with hot climates. As many authors noted, buildings have traditionally been painted white in countries with hot climates to make them cooler and more comfortable [55,56]. The use of such a solution in conditions of significant heating energy consumption is rather ambiguous. Shen et al. [57], for instance, found that an increase in the solar reflectance of a building's coatings reduced the indoor air temperature equally in both summer and winter. As a result, the authors concluded that such a measure in the conditions of Shanghai was likely to lead to a negative year-round effect due to an increase in heating energy demand. Dias et al. [58] discovered the possibility of complete abandonment of cooling in a building in Portugal due to the use of cool paints for the roof and façade. At the same time, the authors detected an increase in heating energy demand of about 30%. Ozel [59] also found that in the conditions of the continental climate of Turkey, when the solar absorptance of an external surface changes from 0 to 1, the growth in demand for cooling is faster compared with a decrease in heating energy demand.

In this part of the research, instead of considering the less effective solar reflectance of the building envelope in cold climates, the performance degradation of the mechanical ventilation heat recovery (MVHR) system was considered, which is one of the most effective energy saving measures in buildings in such conditions [60]. As Tommerup and Svendsen noted in [61], with appropriate thermal insulation and airtightness, up to 80–90% of ventilation losses can be recovered. As also mentioned in [62], the tendency towards more airtight homes leads to the fact that MVHR systems will become the dominant form of ventilation in new buildings. At the same time, according to [63], the actual performance of such (even completely new) systems is quite difficult to evaluate, especially given the large number of factors affecting them [64–66]. For example, authors in [67] found a decrease in heat recovery efficiency from 50–90% to 5–68% only due to infiltration. Researchers in [68], during the field tests of the performance of mechanical ventilation systems in residential buildings, have detected that the actual values of heat recovery efficiency in many cases of experimental observation were lower than the stated nominal values: for decentralised systems about 70% (with nominal 76–91%), for centralized systems about 65% (with nominal 88–94%). Interesting results were obtained in [64], where the average revealed efficiency of the heat recovery ventilation system in severe cold climates was 75%, in cold climates 65%, and in a climate with a hot summer and a cold winter only 50%. It has been rightly observed in [69] that the MVHR system does not belong to the fit-and-forget category, and therefore, its constant maintenance plays a key role in ensuring high efficiency. Investigating heat recovery in the mechanical ventilation systems of three residential facilities in the UK over a three-year period, it was found that the heat recovery performance was in the range of 85–90% most of the time (declared efficiency was 91%). It was also discovered that in cold weather, the efficiency might decrease by about 5%; in addition, contaminated filters could also cause a decrease in efficiency of another 15%. At the same time, an example of the stable operation of such systems was shown in [30], where all the elements of the MVHR system were in good condition and provided an initial recovery efficiency of 82% even after 25 years of operation, which allowed the authors to make an assumption about extending the service life of the most basic components up to 50 years. It is worth noting that researchers pay particular attention to the durability of various components of such systems. For instance, in [60], it was noted that, for example, flat-plate heat exchangers, due to the absence of moving parts (unlike rotary wheels), are characterised by high reliability for a long time. Furthermore, the authors emphasise the importance of research into measuring the long-term performance of membrane energy exchangers (MEE), taking into account the effects of membrane ageing and fouling. The importance of studying the mechanisms of influence of the properties of membrane materials to facilitate the evaluation of longevity and degradation was also noted in [70].

One of the key indicators of the degradation of photovoltaics is a decrease in their performance, which can be caused by harsh environmental conditions, complex internal stresses, etc. [71]. To assess this phenomenon, the so-called degradation rate (R_D) can be used [72]. Many studies distinguish two phases of PV technologies' degradation, namely the first, accelerated degradation within 1–3 years, in which there is a decrease in performance of 1–7%, and the second, linear degradation, in which deterioration occurs at a slower pace (0.5–1.0%) [73,74]. Climatic conditions are one of the most important factors in this issue. According to the authors of [75], citing other sources, degradation occurs primarily in temperate climates due to thermomechanical fatigue caused by the difference in ambient temperatures between winter and summer, and in tropical climates due to humidity combined with high temperatures. Halwachs et al. [76] also investigated the failures of photovoltaics in various climatic zones and found out that, for instance, heat damage and hot spots are the most frequent defects for the tropical and temperate zones; soiling and homogeneous dust for the arid zone; and physical damage and cracks for the continental zone. Faster degradation of photovoltaics in hot climates was presented in [77] (in the Indian context). In particular, it was found that the greatest degradation was observed in the hot and dry climatic zone, followed by the hot and humid zone, and the least in the cold zone. Authors in [78] conducted studies of the degradation of photovoltaic solar systems in the Mediterranean climate and established an estimated degradation rate of 1.48% per year. The annual degradation values recommended in [73] were 0.5% per year in temperate climates and 0.7% per year in high-temperature climates. It is also noted that a climate with a high temperature accelerates the initial stabilisation, whereas a moderate climate tends to prolong this stage and make it practically indistinguishable from long-term degradation. At the same time, according to the most extensive database on the PV degradation collected in [79] (the average value of $R_D \approx 0.5$–1.0% per year), it was found that, on the one hand, the so-called climatic trend seems to be traceable, especially in a desert climate, but in general, there was no significant difference by climate. As a result, the authors concluded that hotter climates and mounting configurations may lead to a higher rate of deterioration in some products.

2.3. Literature Appraisal

According to the literature review, building ageing and degradation appear to be important in the deterioration of their energy performance over time. Existing research in this direction concerns a wide range of aspects, including the degradation of individual components of buildings, the dynamic modelling of the likely deterioration of the energy performance of buildings using a broad range of different software, the gap between the expected and actual energy performance, climate change, economic benefits, etc. One of the least studied issues (owing mainly to the complexity of collecting data on degradation processes and their proper assessment) is the elaboration of specific guidelines for taking into account the impact of degradation of various components of buildings already at the design stage. In addition, the analysis of various guidelines and international reports indicates that consideration of the whole life cycle of buildings is gradually becoming important in the decarbonisation policy of the building sector. Even in such global guidelines, however, there is a scarcity of data on the ageing and degradation processes, as well as of measures to mitigate their impact. It is important to take into consideration that the existence of a large number of inefficient buildings is due not only to the fact that these buildings were built in accordance with outdated codes and standards, but also to the natural processes of ageing and degradation that constantly occur in them. Based on the above, the major research question can be established, first identified in [14], on how to take into account the dependence of energy demand in buildings on the unavoidable degradation processes already at the design stage in order to reduce their negative effect in the long run. Accordingly, one of the main objectives of this study was to create practical recommendations for cold climate conditions that will allow specialists in various fields to assess the possible risks of increasing energy consumption over the course of time and apply relevant steps. In addition, it is important to consider the variety of climatic conditions in which buildings are subject to degradation. As the literature review has shown, environmental weathering affects the properties of building components in different ways. For example, very often the effects of humidity and high temperatures are mentioned as key factors in the deterioration of various components of buildings. At the same time, it may appear that low temperatures slow down the ageing process. However, when exposed to cold temperatures, in particular with frequent freeze–thaw cycles, irreversible structural changes also occur, causing a significant deterioration in the properties of materials. In this way, this study of the effect of degradation on cold climate building energy performance will also allow a comparative analysis of previously identified patterns of operational behaviour of buildings in a hot–humid climate [14].

3. The Case Studies

3.1. The Climate

A continental climate without a dry season and with a warm summer (the Dfb climatic zone according to the Köppen–Geiger classification [80]) was selected for case studies in this research, considered in the context of the Republic of Belarus (Figure 1). The prototypes of the case study buildings were in two cities: Dzyarzhynsk, located in the central part of the country, and Brest, located in the southwestern part.

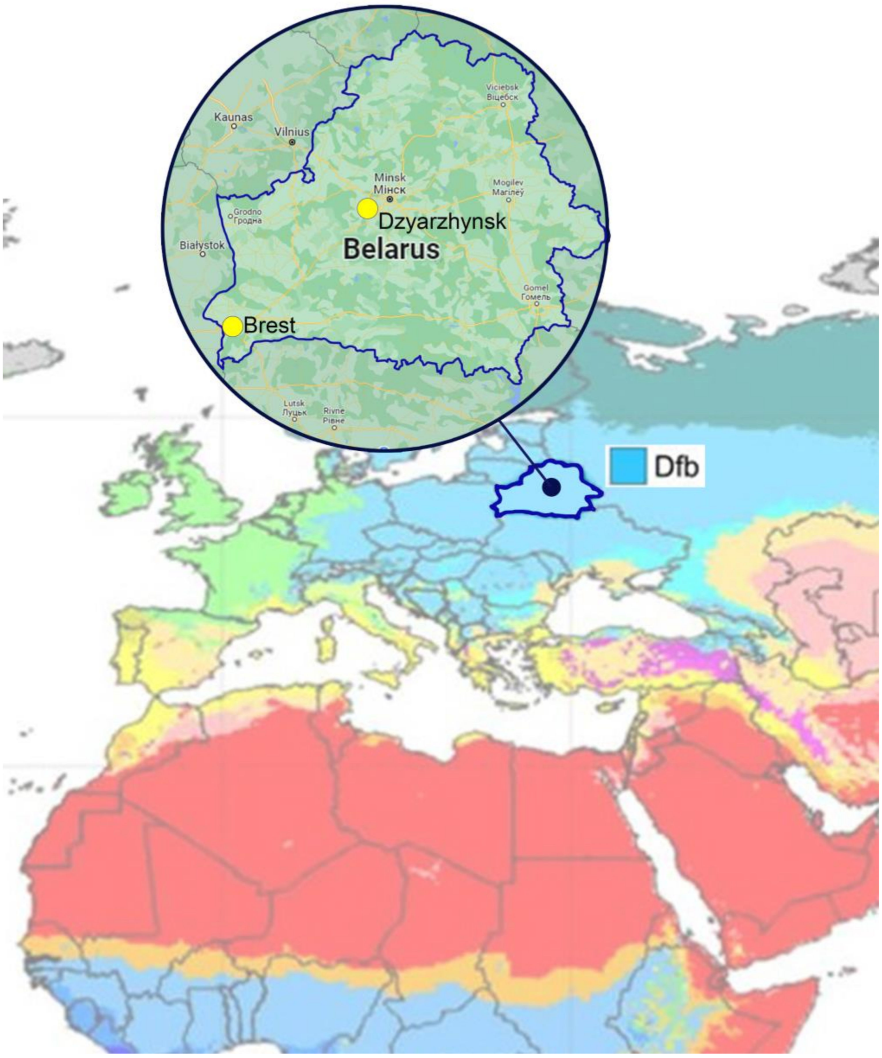

Figure 1. Location of the climatic region of the case study buildings (according to the Köppen–Geiger classification [80]).

Belarus has a temperate continental climate with distinct seasons, including cold winters, warm summers, and variable springs and autumns. The territory of Belarus belongs to a region with an estimated value of heating degree days (HDD) equal to approximately 3500–4500, and with an insignificant indicator of cooling degree days (CDD) [81]. In this way, the climate under consideration is characterised by a high demand for heating during a considerable part of the year (on average from October to April) and insignificant cooling needs. Belarus is characterised by positive average annual air temperatures, which gradually increase in the south and south-west directions [82]. The average annual temperature is 4.5 °C in the north-east and 7 °C in the south-west. In July, the average temperature is 17.8 °C; in January, it is −6.7 °C. The highest temperature over the years of observations was +34 ... +38 °C, and the lowest was −34 ... −42 °C. The average annual precipitation is about 650 mm, most of which (about 70%) falls from April to October. Winter winds are south-westerly, while summer winds are north-westerly. The average annual wind speed in open areas is 4 m/s; in lowlands, it is about 3 m/s. Snow falls annually, and the thickness of the snow cover reaches 15–22 cm [83]. The duration of sunshine in Belarus is about 1730–1950 h per year. The annual average relative humidity varies from 65% to 90%.

3.2. Description of Buildings

According to the projected Net Zero Scenario [1], carbon dioxide emissions caused by the operation of buildings should be reduced by approximately 2.5 times, while the share of emissions from the residential sector will even increase, i.e., housing will further enhance its importance in the energy saving issue. It is also noteworthy that the increasing global population will cause the global floor space to grow. According to experts [2], the currently existing building area will double by 2060, while it is obvious that a significant part of this increase will relate to housing. Given the above, this research was based on the analysis of the energy performance of residential buildings. The energy consumed by the residential sector in Belarus is about 28.3% of the total [84]. According to [85], about 64% of families in Belarus live in apartments, and 30% in detached houses (Figure 2). Most of the apartment buildings are in cities (approx. 77.7%), while most of the detached houses are in rural areas (approx. 70.8%). The average area of apartments is 59.7 m^2, and the average area of single-family houses is 156.8 m^2. As such, the two most representative types of housing in Belarus (detached and apartment buildings) were selected for case studies (Figure 3).

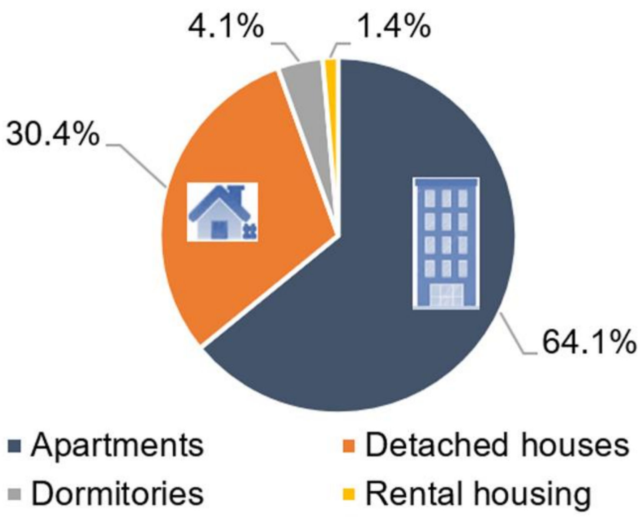

Figure 2. The main types of housing in Belarus [85].

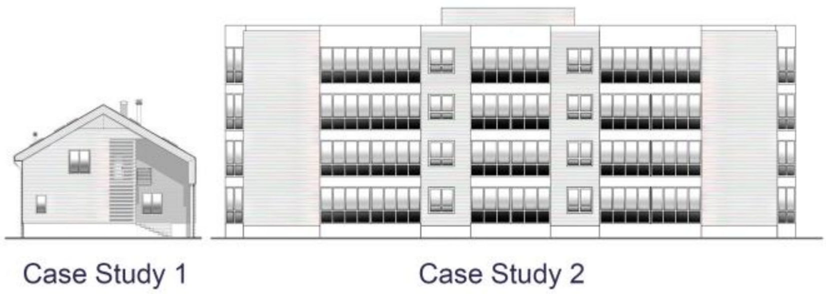

Figure 3. Selected prototypes of buildings in Belarus for case studies. Derived from images/info in [86,87].

Case study 1. The so-called First Multicomfort House was built in Dzyarzhynsk in 2013 [86]. As indicated in the project, the estimated energy consumption for heating is 29.49 kWh/m^2 (this is 69% lower than the standard value). The structural system is a timber frame made of wooden I-beams, with mineral wool insulation. Among the main passive design measures are an effective building orientation, large windows on the south side to receive passive solar heat in winter, roof windows to improve natural lighting, a ZIP exterior shade system on the windows that protects from excess solar heat in summer, and a dark floor in the living room to accumulate solar heat during the daytime in winter. The building has an MVHR system with a heat recovery efficiency of 90% [88]. The building also provides for the use of photovoltaic modules. The floor plans are shown in Figure 4.

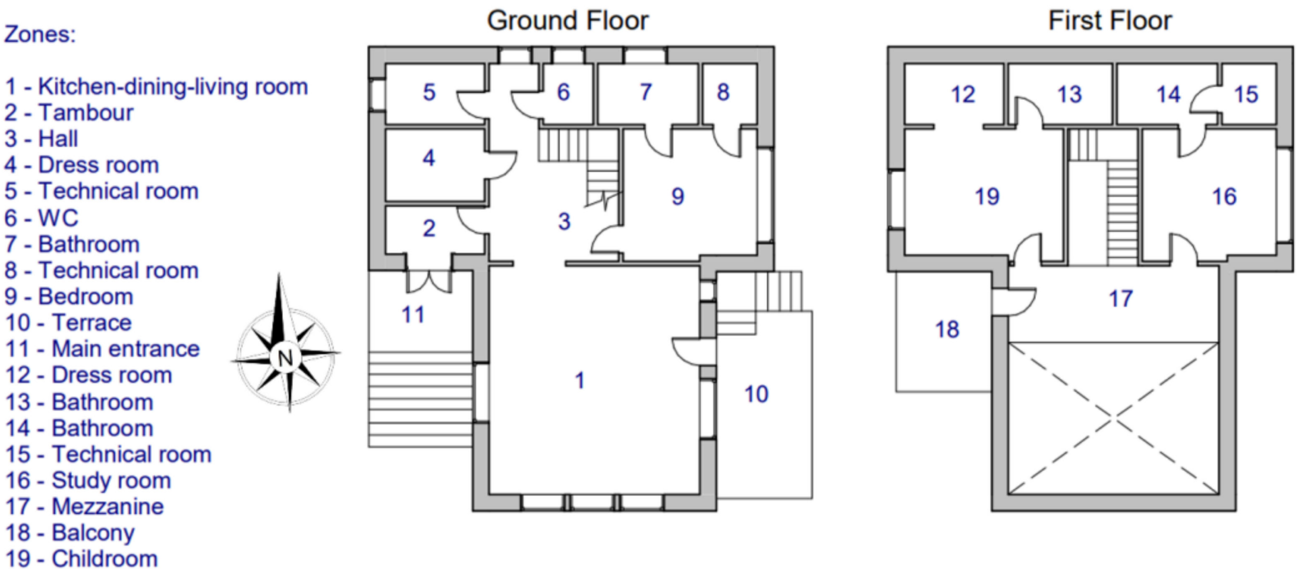

Figure 4. Floor plans of the Detached house in a cold climate (Case Study 1) [86].

Case study 2. A multi-apartment residential building, which included 36 apartments, was built in Brest in 2019. This building is one of the examples of energy-efficient buildings in Belarus [87]. The constructive system is a bearing-wall system made of precast three-layer reinforced concrete panels with an inner layer of polystyrene foam insulation. The envelope of the building is characterised by a high level of airtightness and thermal insulation. The heat recovery unit is installed in each apartment on the balcony. At cold outdoor air temperatures, the supply air can be "warmed up" by an electric air heater built into the heat recovery unit. The typical floor plan is shown in Figure 5.

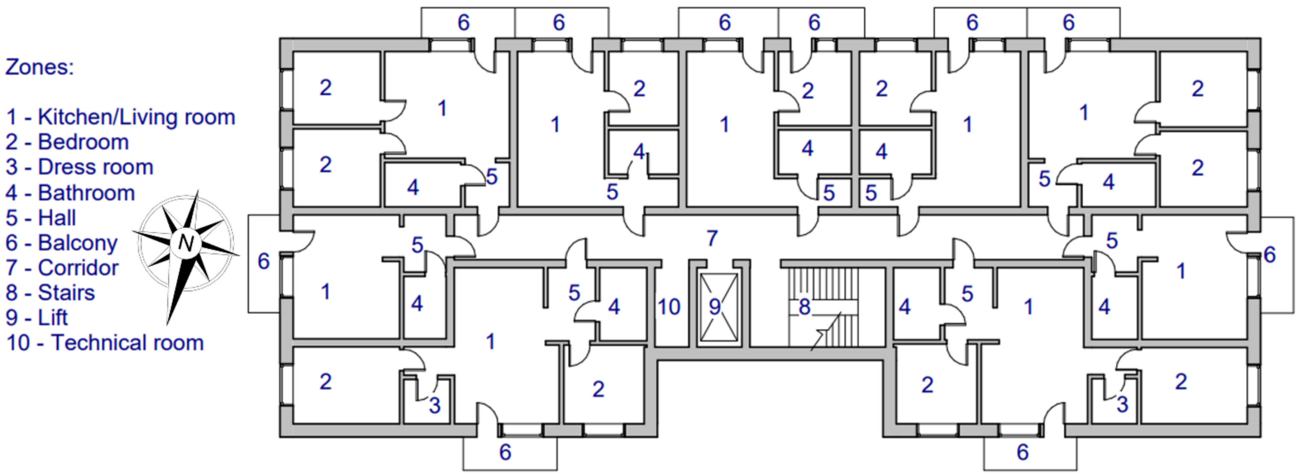

Figure 5. Typical floor plan of the Apartment building in a cold climate (Case Study 2) [87].

Table 1 shows the main building characteristics for both case studies. It should be mentioned that two types of buildings were studied by the level of airtightness and insulation (more or less airtight and insulated buildings) in each of the case studies. It is worth noting that the difference in U-value and airtightness between the two types of buildings was approximately two times greater (a similar gradation was adopted in the work [14] in a hot–humid climate).

Table 1. Main characteristics of case study buildings [86–88].

	Case Study 1		**Case Study 2**	
Location	Dzyarzhynsk (Belarus)		Brest (Belarus)	
Type	Detached house		Apartment building	
Latitude Longitude	LAT 53°41′ N LONG 27°08′ E		LAT 52°08′ N LONG 23°40 E	
Shape	Square		Rectangle	
Building length, m	13.9		37.78	
Building width, m	12.5		15.28	
Number of stories	2		4 and a basement	
Occupied floor area, m^2	188.5		1861.6	
Occupied volume, m^3	773.0		5383.5	
Unoccupied floor area, m^2	–		665.7	
Unoccupied volume, m^3	–		1624.0	
U-value, W/m^2K	More airtight and insulated	Less airtight and insulated	More airtight and insulated	Less airtight and insulated
Walls	0.078	0.155	0.145	0.29
Roof	0.077	0.155	0.136	0.276
Ground floor	0.086	0.173	0.252	0.509
$Windows_{wall}$	0.96	0.96	0.96	0.96
$Windows_{roof}$	0.83	0.83	–	–
External door	0.93	1.475	1.475	2.95
Airtightness, h^{-1}	0.5	1.0	0.4	0.8
Gross Window-Wall Ratio (WWR), %	9.74–Window-Wall Ratio 5.6–Skylight-Roof Ratio	8.2	27.35	
Power density, W/m^2	Kitchen-dining-living room–30.28, bedroom-dress room-study room–3.58, bathroom–1.67, domestic circulation–1.57–2.16, WC–1.61			
Occupancy schedule	by default			
Setpoint Temperatures:				
Living/Dining	H–21 °C HS–12 °C		H–21 °C, HS–12 °C C–25 °C, CS–28 °C	
Domestic circulation, Bathroom/WC	H–20 °C		H–20 °C, HS–12 °C	
Bedroom, Dress room, Study room, Kitchen	HS–12 °C		C–25 °C, CS–28 °C	
Common circulation areas Technical room/Storage	H–18 °C HS–12 °C		H–18 °C, HS–12 °C C–25 °C, CS–28 °C	
Lighting	LED with linear control			
Heating	Underfloor heating Ground Source Heat pump (CoP = 3.5)		Underfloor heating (CoP = 1.0)	
Cooling	–		Cooling system (CoP = 4.5)	
Heating/Cooling season	September-May		October-April	
Domestic Hot Water (DHW)	The same as heating		Instantaneous hot water system–CoP = 1.0	
Ventilation	Mechanical with heat recovery (Ventilation rate–1.0 ac/h)		Mechanical with heat recovery (Ventilation rate–1.0 ac/h)	
PV modules (ASE 300-DFG/50)	250W–15 units S = 36.44 m^2		–	

H—heating; HS—heating setback; C—cooling; CS—cooling setback.

4. Methodology

4.1. Research Methods

The methodology of this study was selected similarly to that used in [14]. Its milestones are shown in Figure 6.

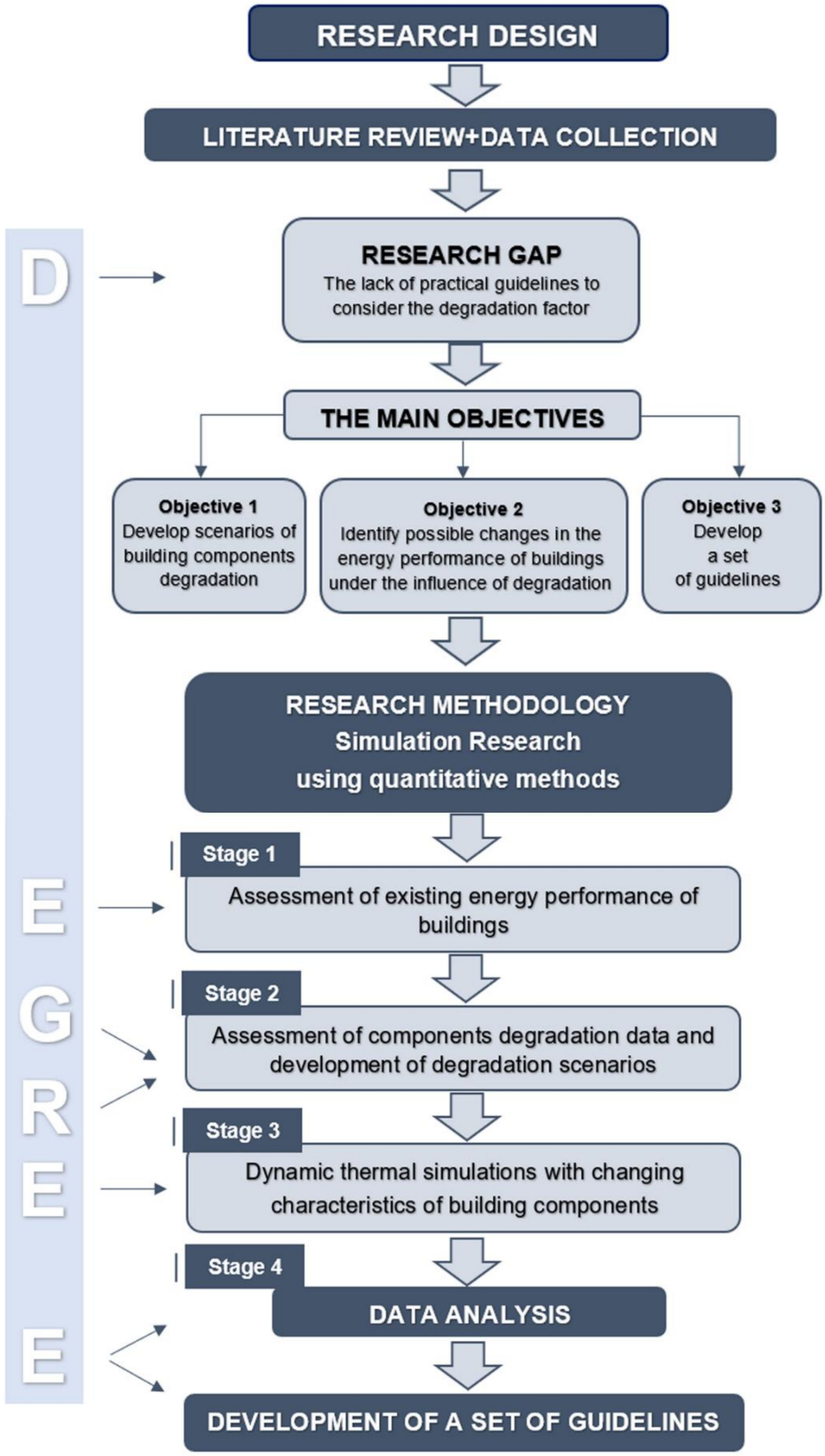

Figure 6. The research design [14].

The assumption identified during the literature review was that ageing and degradation processes contribute to the deterioration of energy performance of buildings over time. It is important to note that the currently existing approaches to modelling possible energy demand in buildings are based on the use of various indicators of the properties of building components, which are included as input data in the most commonly used thermal dynamic simulation software. Therefore, if we identify possible options for deterioration of these property indicators over the years and conduct a series of sequential dynamic simulations with these degraded values, then we will be able to obtain patterns of a corresponding increase in energy demand in buildings.

The main stages of the selected methodology of the DEGREE simulation research [89] can be described as follows. The literature review made it possible to determine the research gap and the specifics of the study. The development of dynamic models of case study buildings and the initial thermal dynamic simulations of their energy performance allowed the establishment of basic indicators of energy efficiency, namely the required energy for heating. Further, after analysing the collected information about the established facts of degradation and ageing of various components of buildings over time, the most likely scenarios of their performance deterioration were elaborated. The application of the degrading characteristics of various building components in dynamic models has provided the main patterns of changes in the energy performance of buildings, namely heating energy consumption. As dynamic simulations were performed, a comparative assessment of the results obtained was carried out, and certain conclusions were drawn, on the basis of which a set of guidelines with recommendations for specialists were developed to take the degradation factor into account in practice. It is worth noting that a quantitative method was used in this simulation research, since most of the work was related to the evaluation of quantitative data on the properties of building components as well as the resulting indicators of energy consumption in buildings.

4.2. Elaboration of Probable Degradation Scenarios

Table 2 depicts probable scenarios of building component performance deterioration, which were based on the analysis of the data described in [14], as well as those additionally presented in this paper, taking into account the specifics of the climatic region under consideration and the corresponding energy-saving solutions: the decrease in the volume concentration of inert gas, as well as the deterioration of the quality of the low-emission coatings for insulated glass units; an increase in thermal conductivity under the influence of environmental conditions for thermal insulation; a gradual increase in air permeability when sealants wear out and cracks appear as a result of structure movements and foundation settlement for airtightness; inevitable contamination of filters, as well as installation errors for the heat recovery system; and performance degradation owing to environmental and internal stresses for photovoltaics. This study also included an additional scenario 3.4 with a more significant (by 30%) deterioration of the airtightness after one year of operation for Case Study 1 (to take into account the possible deterioration of airtightness due to the behaviour of the wooden frame of the building). As a result, for each type of building component in this work, a wide range of possible degradation has been established, namely cases of minimal degradation (which in practice is the result of high production quality, reliable construction materials, and favourable environmental conditions) and maximum degradation (due to low component reliability, unfavourable operating conditions, and so on). It is important to note that the selected scenarios reflect only the average and estimated rates of deterioration of the performance indicators of the considered building components.

Table 2. Possible scenarios of building component performance degradation over 25 years in cold climates (based on [14]).

Building Component	Type of Degradation	№ of Scenario	Description
Insulated Glass Units (IGU)	reduction of filling with inert gas	1.1	from 90% to 65%
		1.2	from 90% to 85%
		1.3	from 90% to 0%
	reduction of filling with inert gas+Low-E coating degradation	1.4	from 90% to 65%, ↑SHGC
Thermal insulation	an increase in thermal conductivity	2.1	for walls and roof by 12.5%
		2.2	for walls and roof by 50%
		2.3	only for walls by 12.5%
		2.4	only for roof by 12.5%
Airtightness	an increase in air permeability	3.4	by 37.5% (the case for a detached house with a timber frame in a cold climate)
		3.1	by 27.5%
		3.2	by 17.5%
	a decrease in air permeability	3.3	by 17.5%
PV modules (only for case study 1)	performance deterioration	5.1	by 27.5%
		5.2	by 40%
Heat recovery of MVHR system	reduction of heat recovery efficiency	6.1	by 15%
		6.2	to 0% (in case of complete shutdown of the system)

↑—increase.

4.3. Dynamic Thermal Simulations

The DesignBuilder software (version 6.1.8.021) based on the EnergyPlus simulation engine was chosen for the simulation study [90,91]. Dynamic thermal simulations were carried out on the dynamic models of buildings (Figure 7), which have geometric parameters as well as the main characteristics of the properties of materials and structures, as close as possible to the selected prototypes of buildings. Case Study 1 also includes another object adjacent to the building in question that may affect its performance—a building located 10.7 m from the southern facade of the main building. Based on the created dynamic models, thermal dynamic simulations were carried out, as a result of which the initial energy indicators of existing buildings were obtained, which are given in Table 3. These initial characteristics of the energy demand formed the basis for further research; in particular, the results of dynamic thermal simulations obtained subsequently were compared with these initial values.

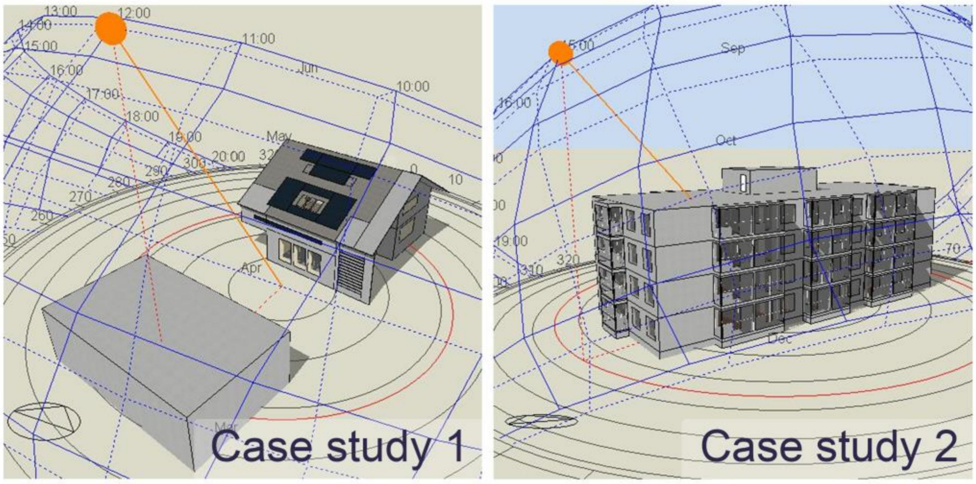

Figure 7. Dynamic building models of case studies.

Table 3. Energy performance indicators of the prototypes of selected buildings in cold climates.

	Case Study 1		**Case Study 2**	
	1 *	**2 ***	**1 ***	**2 ***
Total Energy consumption, kWh/m^2, including:	55.17	92.95	95.33	130.21
Room Electricity	18.49	21.62	37.44	37.12
Lighting	5.97	6.76	14.06	13.95
Heating	25.29	59.55	25.93	64.184
Cooling	–	–	0.35	0.25
DHW	5.42	5.02	17.55	17.41
Energy from PV modules, kWh/m^2	14.99	15.59	–	–
CO_2 emissions, kg/m^2	24.35	46.88	57.77	80.55
Operative temperature, °C	December–20.03 °C July–26.64 °C	December–19.75 °C July–23.65 °C	January–18.58 °C July–26.13 °C	January–17.03 °C July–25.40 °C
Solar gains, kWh/m^2	43.56	45.28	16.07	15.64
Heat losses, kWh/m^2 Windows Walls Roof External infiltration	 −28.47 −13.73 −7.85 −72.56	 −28.00 −25.67 −15.32 −169.44	 −15.50 −7.13 −4.39 −50.10	 −13.23 −11.89 −7.51 −89.34
Heat recovery sensible heating (% from the total zone heating)	77.3%	43.1%	34.3%	16.7%

* 1—More Airtight and Insulated Building; 2—Less Airtight and Insulated Building.

Initially, the dynamic modelling of building energy performance was performed under the impact of degradation on each of the components individually (a total of 268 dynamic simulations), after which certain combinations of the combined degradation effect of all components were selected (a total of 32 dynamic simulations). Consideration of the possible simultaneous degradation of various components of buildings was carried out according to two possible scenarios: the best-case scenario (which reflected the lowest level of possible degradation) and the worst-case scenario (reflected the highest level of possible degradation). Both scenarios are presented in more detail in Tables 4 and 5. In this research, a similar breakdown of the 25-year period under consideration into stages was used, as in [14]: “as designed”, “as built”, “1 year”, “5 years”, “10 years”, “15 years”, "20 years", and "25 years". Figure 8 shows a scenario tree for a cold climate (similar to the one presented in [14]), which reflects the division of dynamic simulations performed depending on the degradation level under consideration.

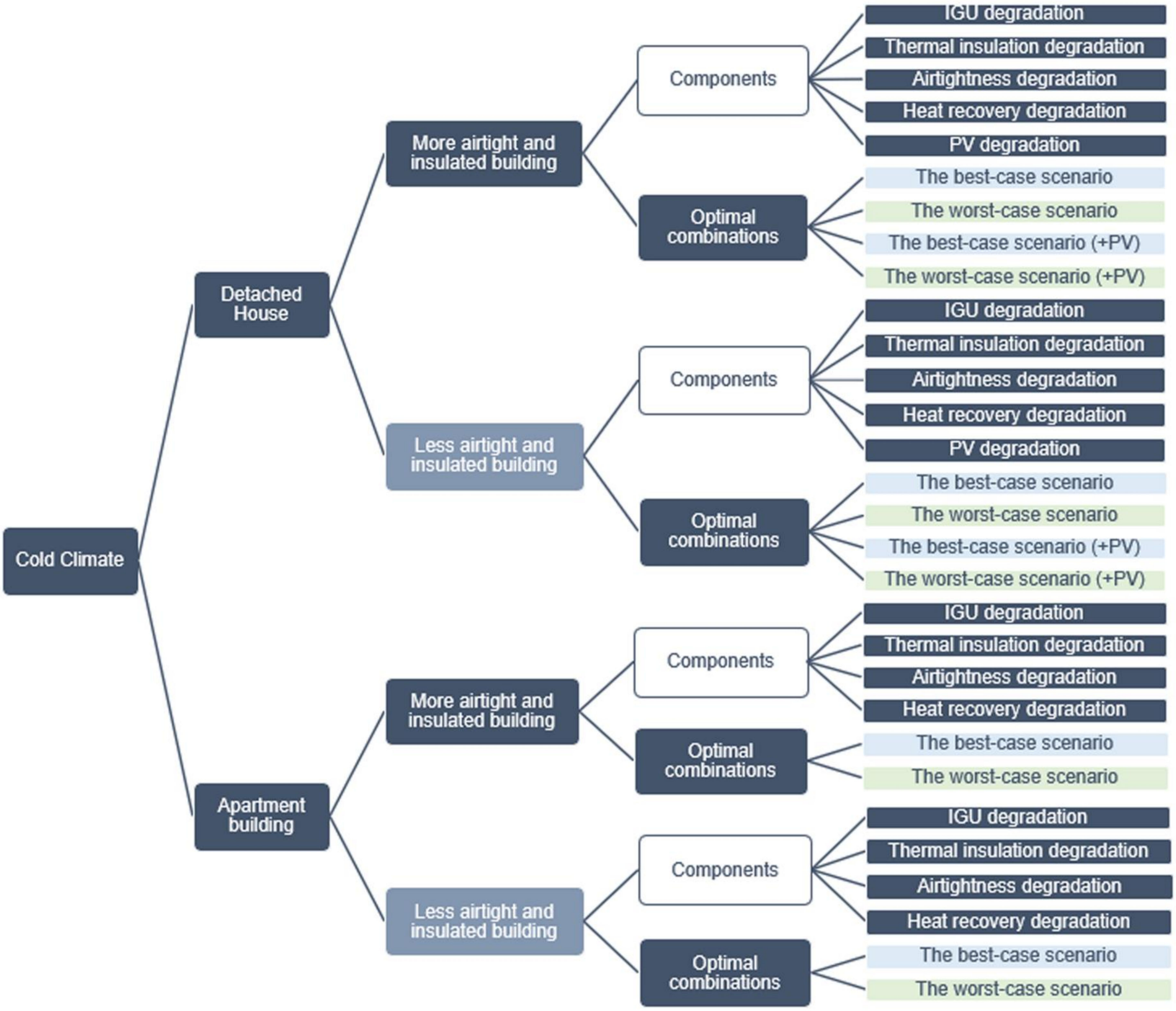

Figure 8. An execution tree of dynamic thermal simulations in the conditions of cold climates (based on [14]).

Table 4. Stages of building components' degradation (the best-case scenario) (based on [14]).

The Operational Stage	Windows (↓Filling with Inert Gas)	Insulation (↑Thermal Conductivity)	Air Permeability (↑)	MVHR (↓Heat Recovery Performance)		PV Modules (↓Performance)
	Scenario 1.2	Scenario 2.1	Scenario 3.2	Scenario 6.1 (Detached)	Scenario 6.1 (Apartments)	Scenario 5.1
As design	100	100	100	90	65	100
As built	90	100	100	90	65	90
1 year	89.8	100.5	110	90	65	85

Table 4. *Cont.*

The Operational Stage	Windows (↓Filling with Inert Gas)	Insulation (↑Thermal Conductivity)	Air Permeability (↑)	MVHR (↓Heat Recovery Performance)		PV Modules (↓Performance)
	Scenario 1.2	Scenario 2.1	Scenario 3.2	Scenario 6.1 (Detached)	Scenario 6.1 (Apartments)	Scenario 5.1
5 years	89	102.5	110	75	50	82.5
10 years	88	105	110	75	50	80
15 years	87	107.5	112.5	75	50	77.5
20 years	86	110	115	75	50	75
25 years	85	112.5	117.5	75	50	72.5

↑—increase; ↓—decline.

Table 5. Stages of building components' degradation (the worst-case scenario) (based on [14]).

The Operational Stage	Windows (↓Filling with Inert Gas)	Insulation (↑Thermal Conductivity)	Air Permeability (↑)		MVHR (↓Heat Recovery Performance)		PV Modules (↓Performance)
	Scenario 1.3	Scenario 2.2	Scenario 3.4	Scenario 3.1	Scenario 6.2 (Detached)	Scenario 6.2 (Apartments)	Scenario 5.2
As design	100	100	100	100	90	65	100
As built	90	100	100	100	90	65	90
1 year	89	102	130	120	50	50	85
5 years	85	110	130	120	0	0	80
10 years	80	120	130	120	0	0	75
15 years	70	130	132.5	122.5	0	0	70
20 years	50	140	135	125	0	0	65
25 years	0	150	137.5	127.5	0	0	60

↑—increase; ↓—decline.

5. Results and Discussion

5.1. The Relationship between IGU's Degradation and Building's Performance Deterioration

The following main conclusions can be identified regarding the buildings in cold climates (Figure 9):

1. The increase in energy consumption for heating due to IGU degradation in the more airtight and insulated detached house occurred more quickly (by 0.68–4.54% over 25 years) compared to the less airtight and insulated building (by 0.32–2.13%). It is noteworthy that according to scenario 1.4, energy consumption for heating is even slightly reduced (by less than 1%) due to the minor predominance of incoming solar gains over heat losses with this type of degradation.
2. A similar situation was also observed in apartment buildings. In particular, the increase in energy consumption for heating due to the deterioration of window performance can reach 0.3–8.32% over 25 years in the more airtight and insulated apartment building and up to 0.51–3.35% in the less airtight and insulated building. In this way, it is quite clear that a more airtight and insulated shell of a building contributes to a faster response to the deterioration of the properties of its constituent elements: in this case, windows.
3. It was also found that changes in the energy consumption of apartment buildings occurred faster than in detached houses (approximately 1.8 times in more airtight and insulated buildings and 1.6 times in less airtight and insulated buildings).

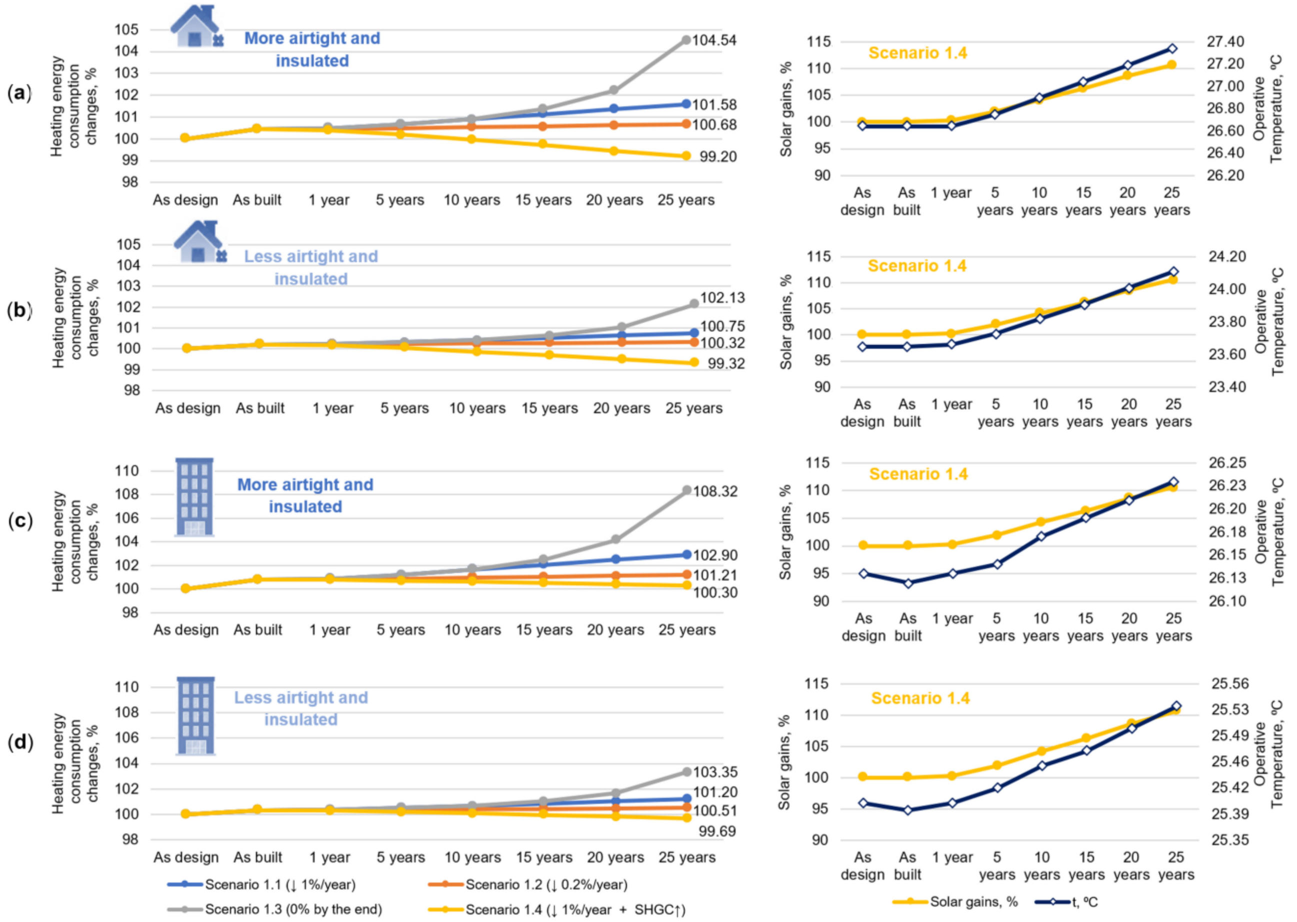

Figure 9. The effect of IGU performance degradation on energy consumption in buildings in cold climates: (**a**,**b**) detached houses; (**c**,**d**) apartment buildings.

Comparing these results with the conclusions obtained in [14], it can be noted that in a hot–humid climate there was an inverse pattern when in apartment buildings, the change in energy consumption during the degradation of IGU occurred slower than in detached houses. It is worth noting that this fact requires further investigation, since there was a significant difference between the window–wall ratio (WWR) indicator in the buildings under consideration in a cold climate (8.2% in the detached house and 27.35% in the apartment building), while in the buildings under consideration in a hot–humid climate, the WWR in both cases was 29%. At the same time, it should be pointed out that a similar effect was revealed, where more airtight and insulated buildings were more vulnerable to degradation than less airtight and insulated buildings in both climatic conditions. However, in a cold climate, the difference between these indicators was much greater. For instance, according to scenario 1.3, this difference was 2.1 times in a cold climate and 1.4 times in a hot–humid climate for detached houses. In turn, for apartment buildings, these values were 2.5 times and 1.5 times, respectively.

5.2. The Relationship between Thermal Insulation Degradation and Building's Performance Deterioration

The following main conclusions can be identified regarding the buildings in cold climates (Figure 10):

1. It was found that more airtight and insulated buildings are more vulnerable to the degradation of thermal insulation than less airtight and insulated buildings. In particular, the possible increase in heating energy consumption might reach up to 8.1% in the more airtight and insulated detached house, and up to 6.76% in the less

airtight and insulated detached house. In apartment buildings, these values were equal to 13.48% and 9.43%, respectively.

2. The changes in heating energy consumption in apartment buildings occurred faster than in detached houses: approximately 1.7 times for more airtight and insulated buildings, and 1.4 times for less airtight and insulated buildings.

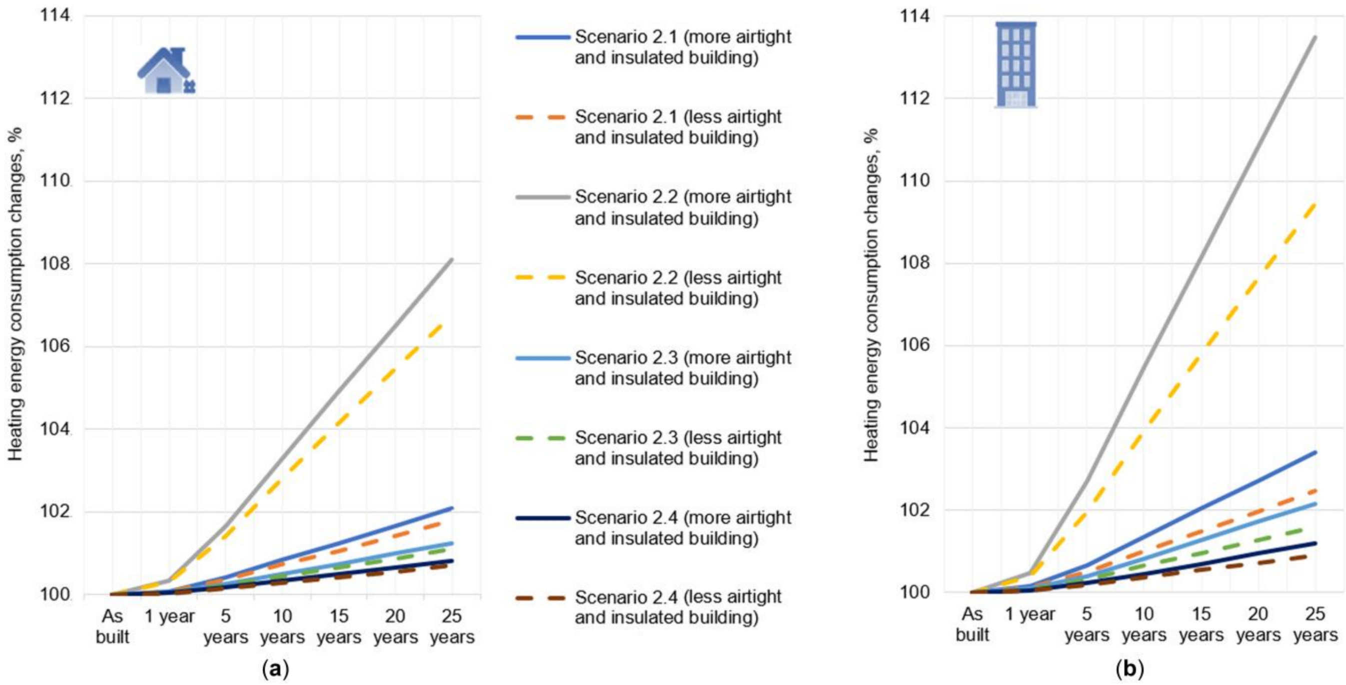

Figure 10. The effect of deterioration of the properties of insulation materials on the heating demand in buildings in cold climates: (**a**) detached houses; (**b**) apartment buildings.

When the obtained results of the effect of thermal insulation degradation are compared to the findings in [14], it is possible to see a significantly faster change in the heating energy consumed in a cold climate compared to the cooling energy consumed in a hot–humid climate. For a cold climate, the range of possible increases in heating energy demand for all types of buildings, according to the worst–case scenario 2.2, varied from 6.76 to 13.48%, while in a hot–humid climate, it was within the range of 1.02–2.36%. Therefore, it is obvious that the influence of possible degradation of thermal insulation has a more significant impact on the change in the energy performance of buildings in conditions of predominant energy consumption for heating than in conditions of prevailing demand for cooling energy. At the same time, it is important to note that, as in the case of IGU's degradation, in the considered situation of possible degradation of thermal insulation, there was an ambiguous relationship between buildings of different types. In particular, detached houses were more vulnerable in hot–humid climates, while apartment buildings turned out to be more vulnerable in cold climates. It can also be noted that in cold climates, a similarly greater influence of an increase in the thermal conductivity of wall insulation on the change in energy consumption in buildings was revealed (compared with the roof insulation) (Figure 11). The possible gap in these indicators for detached houses in cold climates was $(+1.25\%_{\text{wall}})/(+0.82\%_{\text{roof}}) \approx 1.52$ (in hot–humid climates ≈ 1.78). In apartment buildings, the same pattern was observed. This difference was $(+2.15\%_{\text{wall}})/(+1.19\%_{\text{roof}}) \approx$ 1.81 times greater in cold climates (and $\approx$1.54 in hot–humid climates).

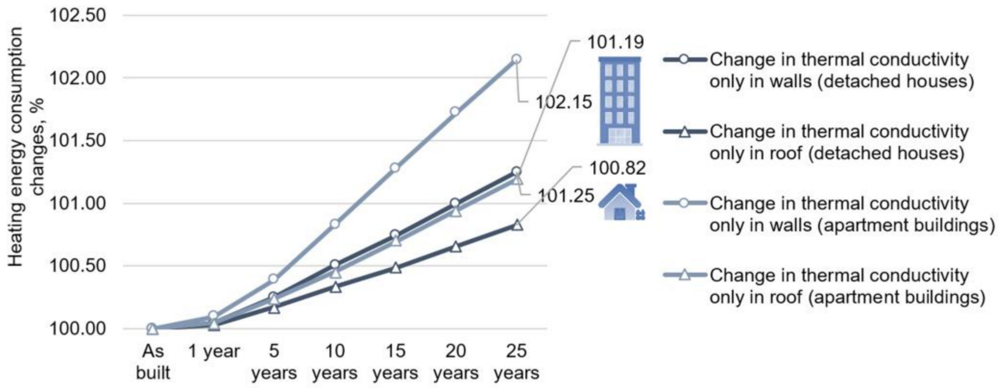

Figure 11. The effect of degradation of thermal insulation in walls and roofs (separately) on energy consumption in cold-climate buildings.

5.3. The Relationship between Airtightness Degradation and Building's Performance Deterioration

The following main conclusions can be identified regarding the buildings in cold climates (Figure 12):

1. The increase in energy consumption for heating associated with an increase in air permeability occurred more slowly in the more airtight and insulated detached house (by 12.29–19.35% (26.46%) over 25 years) than in the less airtight and insulated building (by 13.57–21.36% (29.16%)). It is likely that the lower initial value of uncontrolled air flows in more airtight and insulated buildings contributes to a lesser impact of the degradation of airtightness on energy consumption. Moreover, a more insulated shell in this case also makes a positive contribution to curbing energy demand.
2. In apartment buildings, on the other hand, the increase in energy consumption for heating occurred faster in the more airtight and insulated buildings (by 19.85–31.34% over 25 years) than in the less airtight and insulated buildings (by 16.77–26.33%). As such, this result was the opposite of the one obtained for the detached houses.
3. If we consider the difference between detached and apartment buildings, then it was found that in apartment buildings, the change in energy consumption occurred faster than in detached houses (approximately 1.6 times for more airtight and insulated buildings and 1.2 times for less airtight and insulated buildings).

If we compare these results in cold climate conditions with the previously obtained results in a hot–humid climate [14], it is possible to note the following: similar trends were observed in both climatic conditions, in which less airtight and insulated detached houses were more vulnerable to changes in energy performance under the influence of degradation of airtightness. Furthermore, in a cold climate, the potential increase in energy demand occurred faster than in a hot–humid climate. As for the apartment buildings, there was a similar tendency for less airtight and insulated apartment buildings to be more vulnerable in a hot–humid climate, whereas in a cold climate, more airtight and insulated apartment buildings were more susceptible to degradation. Most likely, this discrepancy needs to be clarified for a larger number of buildings under consideration.

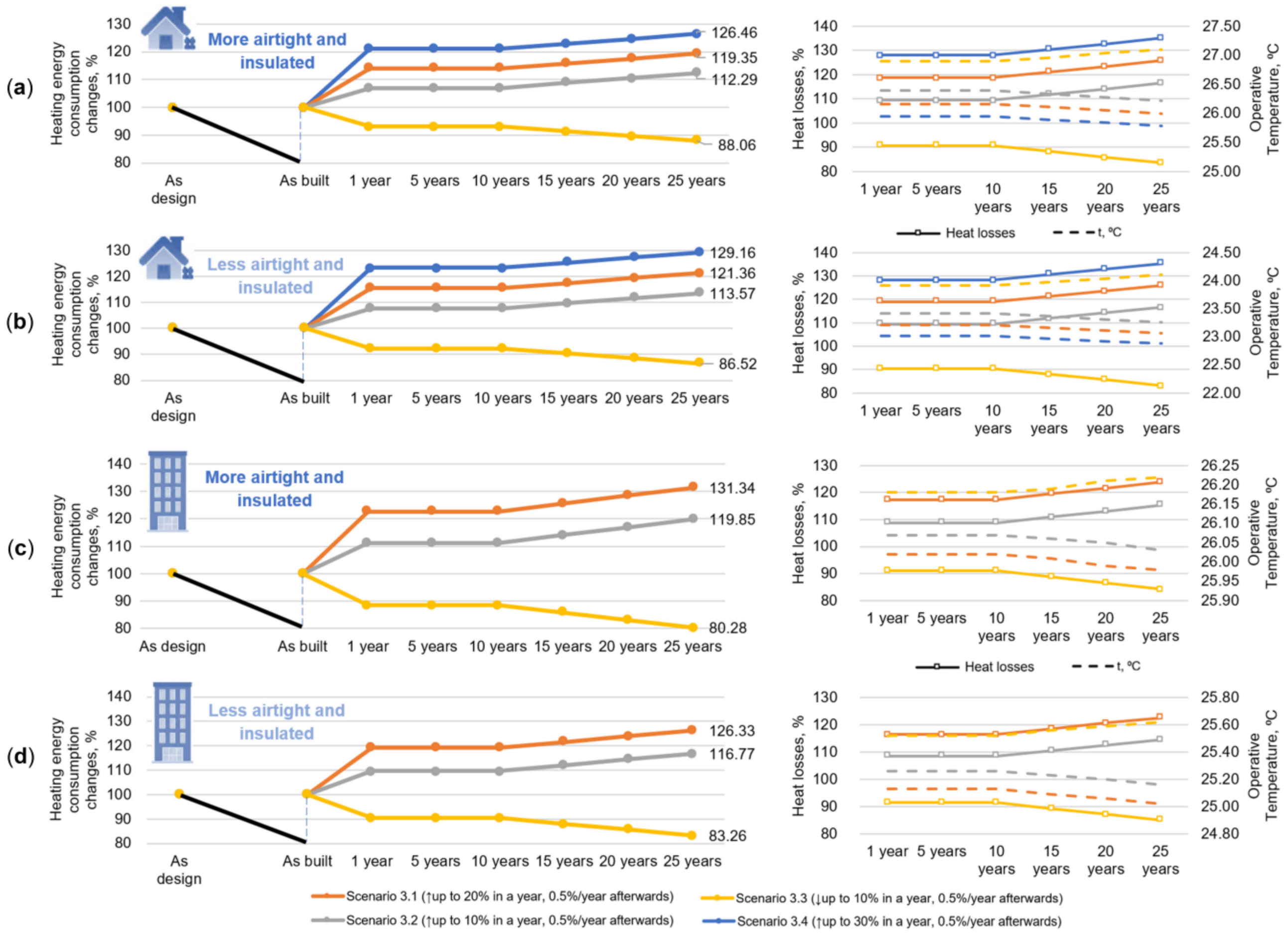

Figure 12. The effect of airtightness performance degradation on energy consumption in cold-climate buildings: (**a**,**b**) detached houses; (**c**,**d**) apartment buildings.

5.4. The Relationship between Mechanical Ventilation Heat Recovery Degradation and Building's Performance Deterioration

Figure 13 shows graphs of changes in the energy consumed for heating according to the selected scenarios for reducing the efficiency of heat recovery by the mechanical ventilation system. It can be noted that the apartment buildings in question turned out to be more vulnerable to changes in energy consumption (changes range from 3.8% to 34%) compared to the detached houses (from 1.8% to 20.5%). These figures also show the vulnerability of such systems in buildings with different levels of airtightness, i.e., the efficiency of heat recovery decreased 1.8 times faster in the more airtight and insulated detached house, and 2.1 times faster in the more airtight and insulated apartment building than in the less airtight and insulated buildings. Figure 14 presents data on the effect of degradation of components such as IGU, thermal insulation, and airtightness on the efficiency of heat recovery. As it can be seen, the greatest impact on the efficiency of the heat recovery of the MVHR system was a deterioration in airtightness; the next most important factor was thermal insulation; and the least impact was the degradation of IGU.

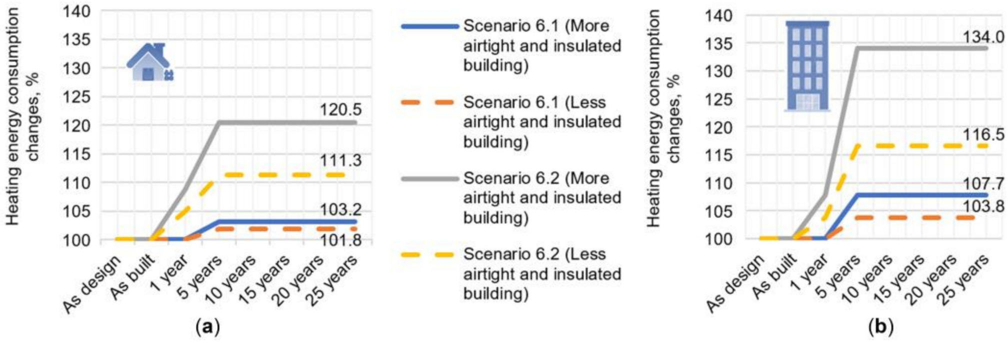

Figure 13. Changes in the heating energy consumption in buildings according to various scenarios of the performance degradation of the MVHR system: (**a**) detached houses; (**b**) apartment buildings.

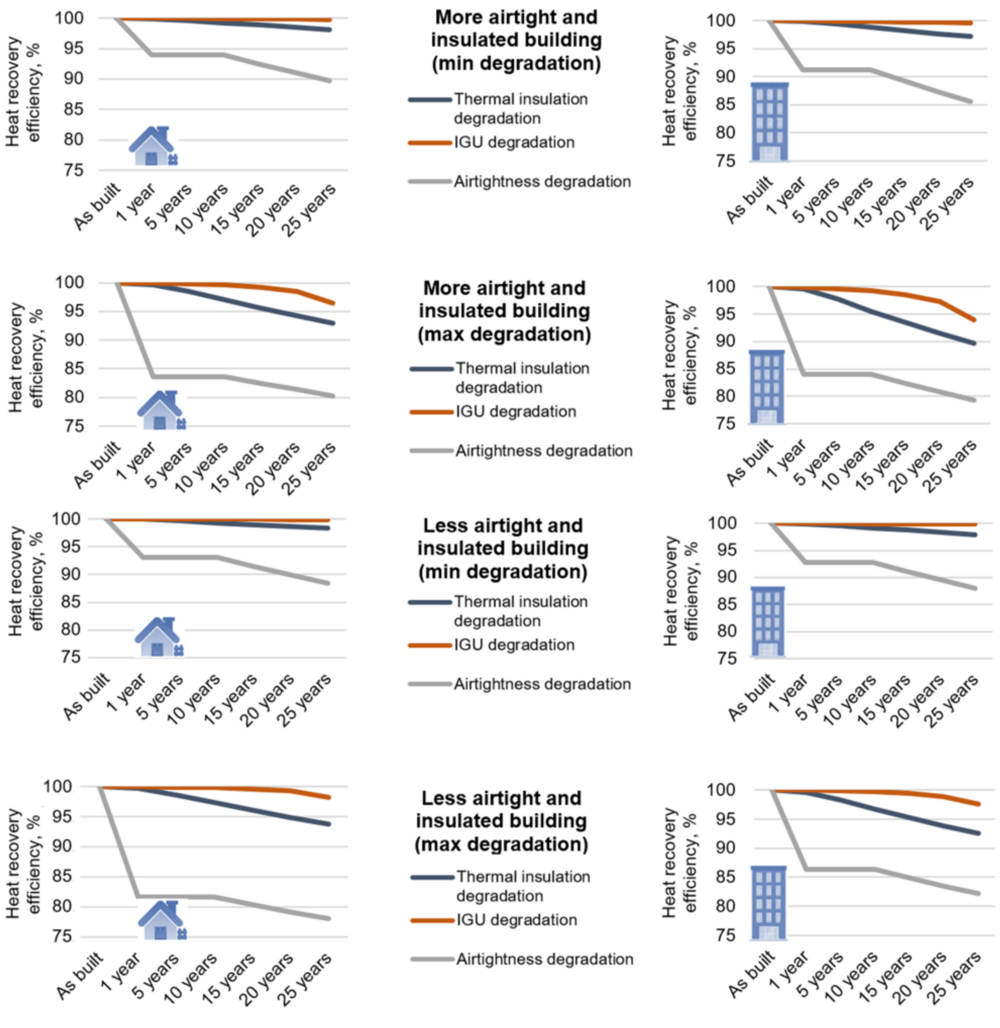

Figure 14. The influence of degradation of thermal insulation, IGU, and airtightness on the change in the performance of the MVHR system (cases of minimum and maximum degradation).

5.5. The Relationship between PV Module Degradation and Building's Performance Deterioration

The effect of performance degradation of PV modules was estimated based on an increase in energy demand from the power grid and operational carbon dioxide emissions. In this paper, the possible degradation of photovoltaics was considered only for the detached house (Case Study 1), for which the following results were obtained (Figure 15). As can be seen, the potential increase in energy demand from the power grid and the amount of CO_2 emissions was within 10–15% over a 25-year period. Therefore, it can be concluded that in a cold climate, the decrease in the energy generated as a result of the degradation of photovoltaic modules occurs more slowly compared to a hot–humid climate [14]. It is also important to note that the initial energy generated by photovoltaics in a cold climate was approximately two times less than in a hot–humid climate.

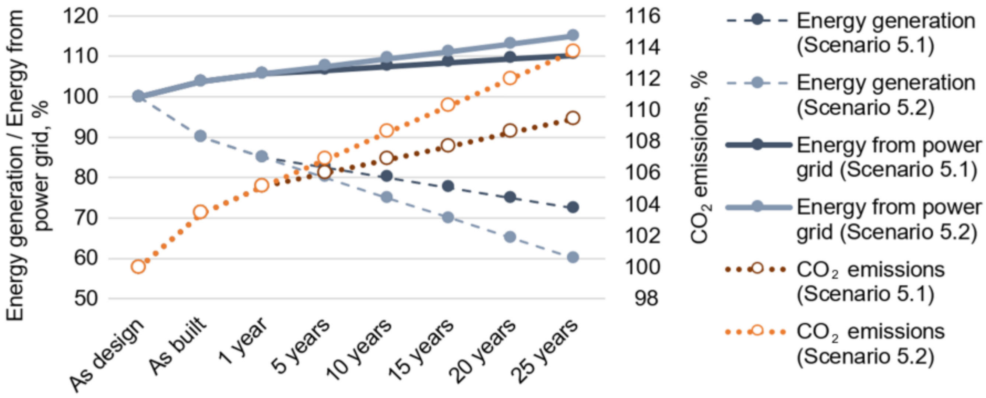

Figure 15. The effect of PV module performance degradation on increased energy demand from the power grid and operational CO_2 emissions (based on the Case Study 1).

5.6. The Combined Impact of Degrading Building Components

Figure 16 shows a possible increase in energy demand in buildings in a cold climate with simultaneous deterioration of all the building components considered. As can be seen, the potential heating demand growth in detached houses might reach 18.4–61.2% over 25 years for more airtight and insulated buildings and 17.6–49.8% for less airtight and insulated buildings. For apartment buildings, this increase was even greater: 32.6–89.8% and 23.6–56.3%, respectively. If we compare the obtained values with the previously established results in [14], two distinctive features can be noted. Firstly, the possible increase in the prevailing heating energy consumed in a cold climate was significantly higher than similar values for cooling in a hot–humid climate. This difference was 1.6–1.9 times for more airtight and insulated detached houses and approximately 1.4 times for less airtight and insulated detached houses. In turn, for apartment blocks, these indicators were 2.8–3.6 and 1.9–2.1 times, respectively. Secondly, in a cold climate, there was a reverse trend: the apartment buildings turned out to be more vulnerable to degradation compared to the detached houses.

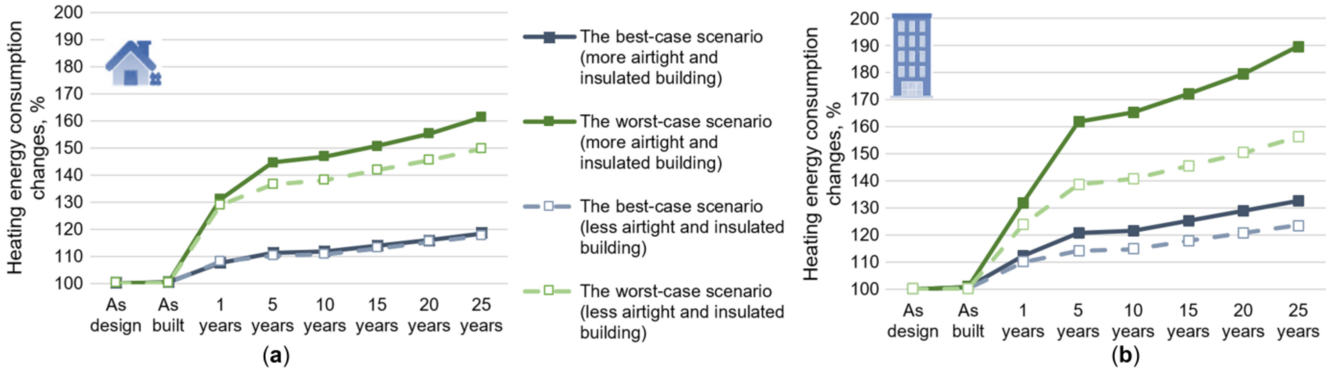

Figure 16. Probable growth in the energy demand in buildings over time due to degradation: (**a**) detached houses; (**b**) apartment buildings.

Interestingly, the more airtight and insulated buildings have shown greater vulnerability to degradation than less airtight and insulated buildings. Meanwhile, the initial demand for energy in more airtight and insulated buildings was significantly lower. In particular, for such a detached house, the revealed expected increase in energy consumption by 61.2% was equivalent to a change in the energy consumed for heating from 25.29 to 40.76 kWh/m^2. The revealed lower percentage estimated growth in energy consumption of 49.76% for the less airtight and insulated detached house was equivalent to a significantly greater increase in actual energy from 59.55 to 89.18 kWh/m^2. It is worth noting that this trend in a cold climate was more unambiguous than the revealed patterns in a hot–humid climate, where the greater vulnerability of more airtight and insulated buildings was obvious only after 10 years of operation.

It is also worth noting that the biggest jump in the increasing demand for energy is observed at the very beginning of the building's operation (Figure 17). In the cold climate, this indicator had significantly higher values than those obtained in [14]. Thus, if in a cold climate, the maximum increment of energy consumption reached 30.7% for detached houses and 31.3% for apartment buildings; then, in a hot–humid climate these indicators were 12.9% and 12.7%, respectively.

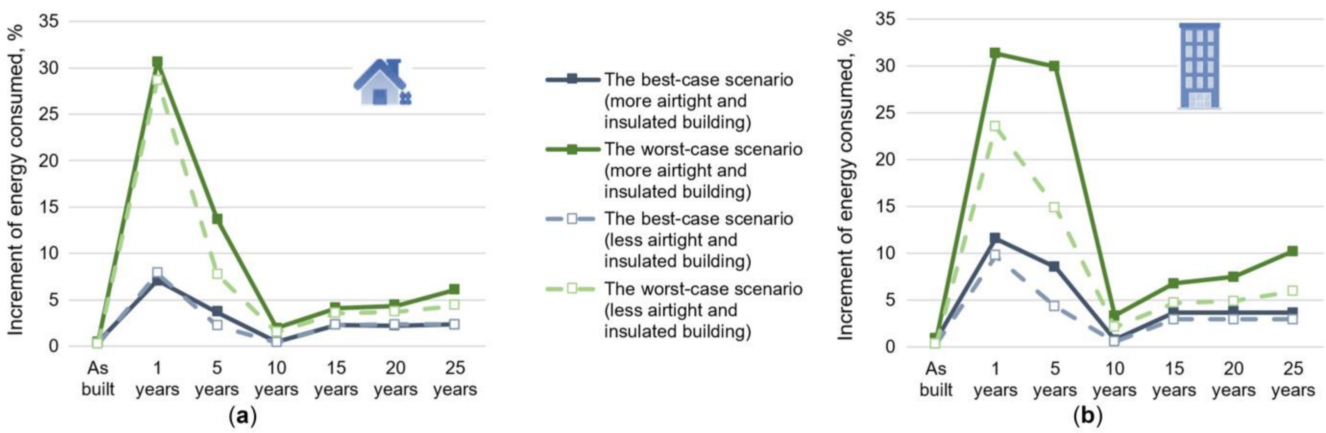

Figure 17. Possible increments in heating energy consumed in buildings over time under the influence of degradation: (**a**) detached houses; (**b**) apartment buildings.

The increase in heating energy consumption from the power grid in detached houses is shown in Figure 18. Among other things, an interesting fact can be noted, namely, that an increase in energy demand from the power grid (in the presence of photovoltaics) occurs much faster than in their absence. For example, in the more airtight and insulated detached house without PV modules, the possible increase was 61.2% (from 25.29 to 40.76 kWh/m^2), whereas in the detached house with PV modules, it was 208.3% (from 10.3 to 31.76 kWh/m^2). Noteworthy, the resulting maximum change in energy consumption from the power grid (in percentage terms) due to the degradation of PV modules in a cold climate was lower than that established in a hot–humid climate [14]. The use of photovoltaics necessitates a high level of reliability and quality in its components, as any deterioration in their performance results in a significant demand for energy from the power grid in both climatic conditions.

In addition to the graphs presented above, pie charts were also developed in this study to more clearly show the impact of the degradation of each of the components on the energy performance of buildings during their operation. Figures 19 and 20 show data without photovoltaic modules, while Figures 21 and 22 show data with PV modules.

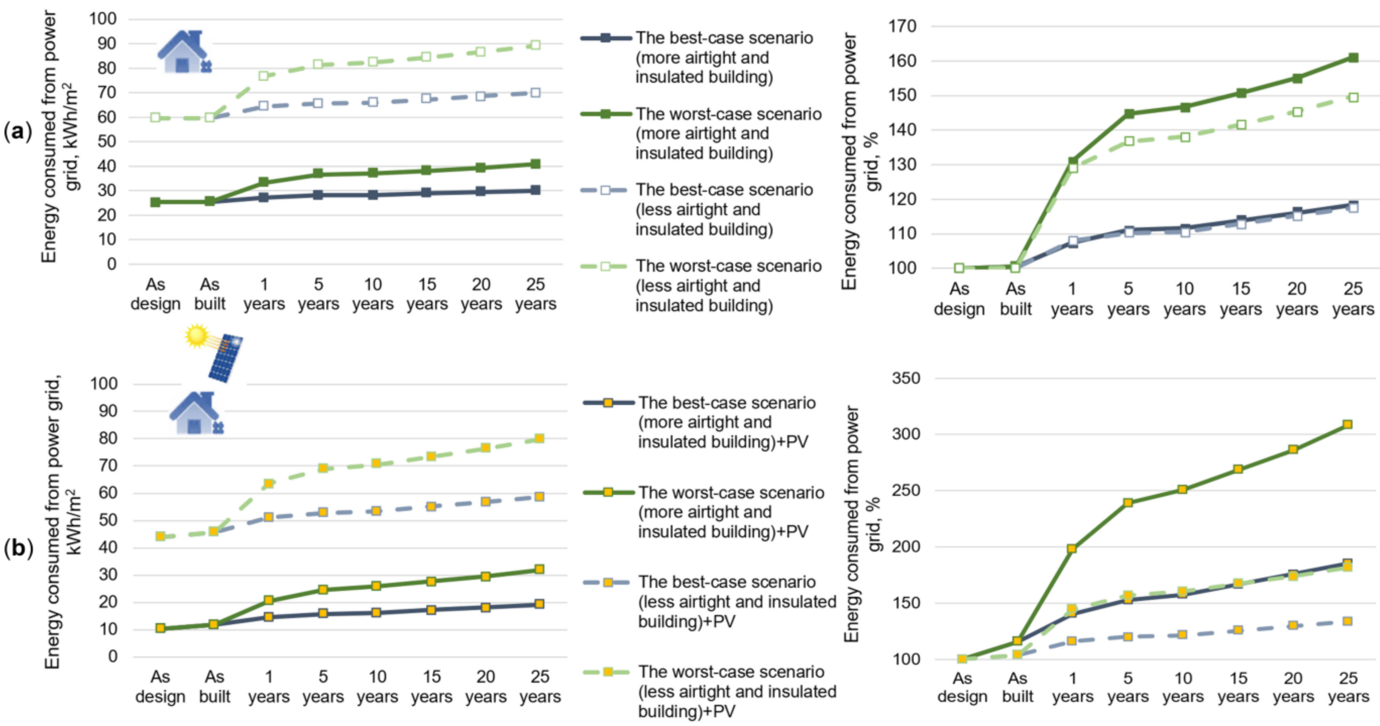

Figure 18. Probable changes in the heating energy demand from the power grid in the detached house under the influence of degradation: (**a**) without photovoltaic modules; (**b**) with photovoltaic modules.

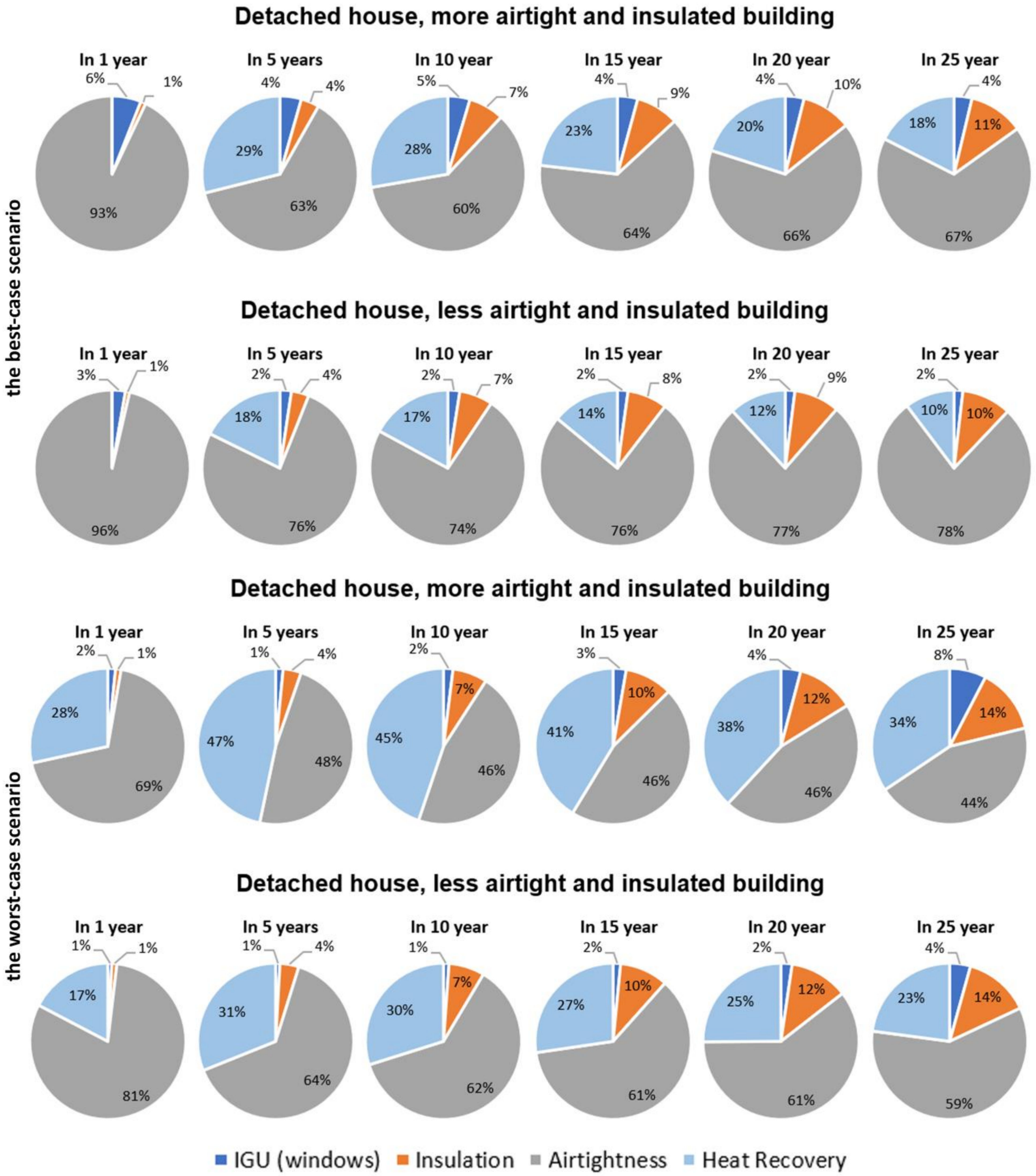

Figure 19. The contribution of each degrading component to the building's performance deterioration with time (detached houses).

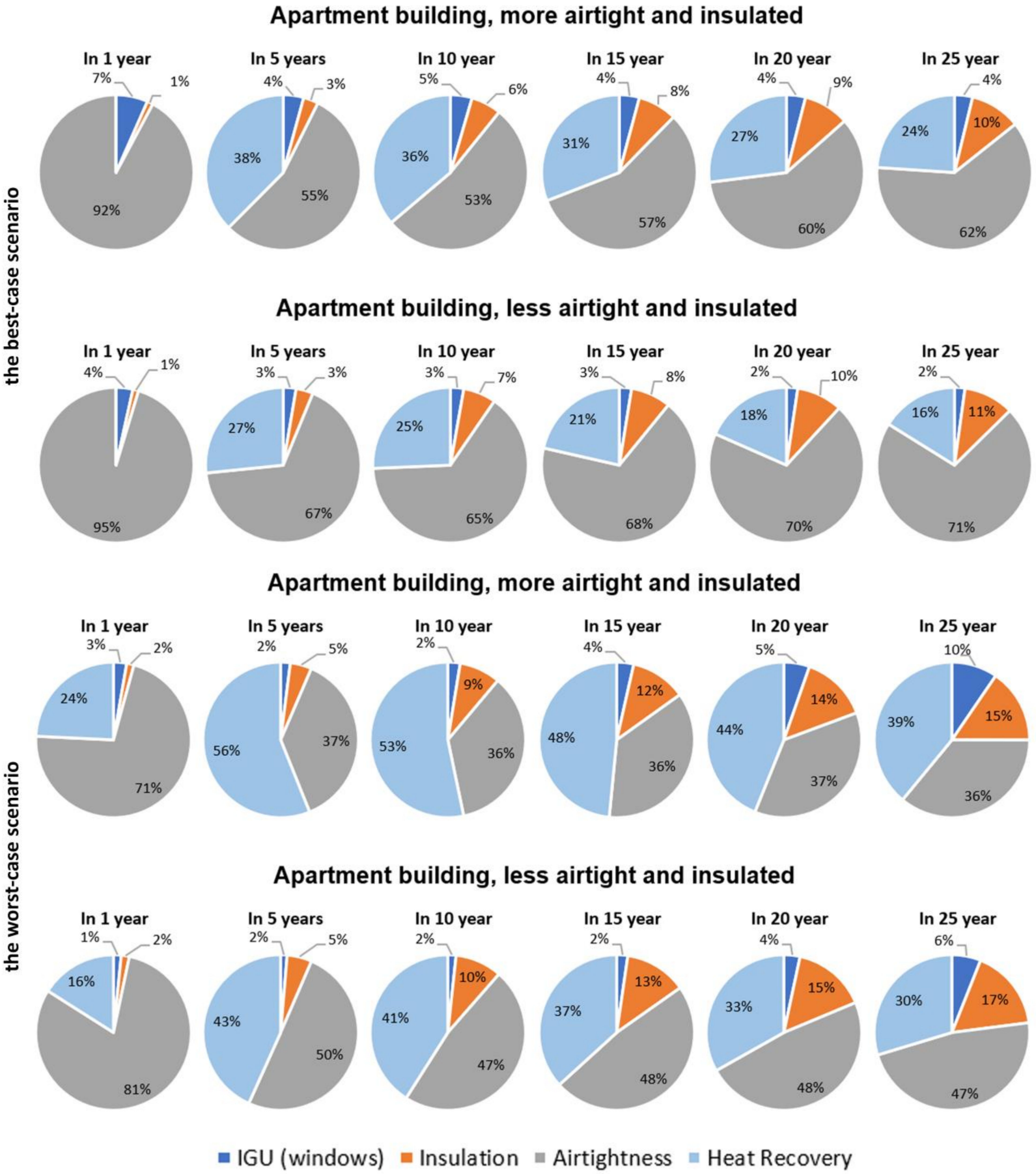

Figure 20. The contribution of each degrading component to the building's performance deterioration with time (apartment buildings).

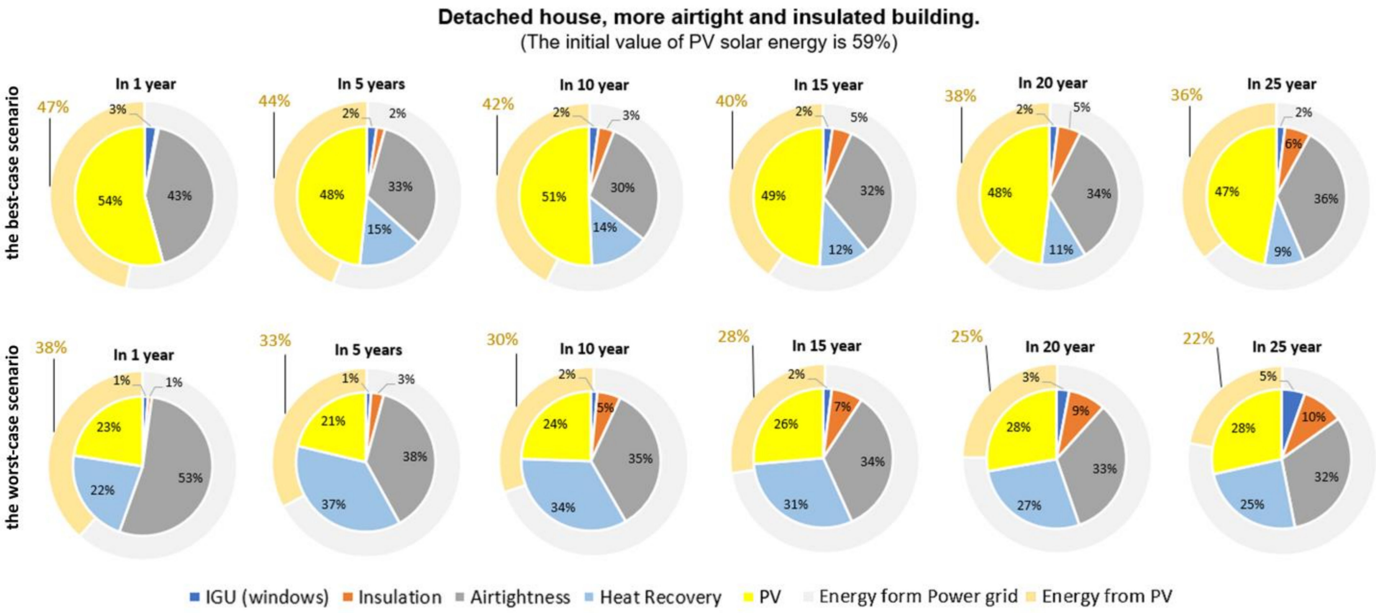

Figure 21. The contribution of each degrading component to the building's performance deterioration over time (more airtight and insulated detached houses with photovoltaics).

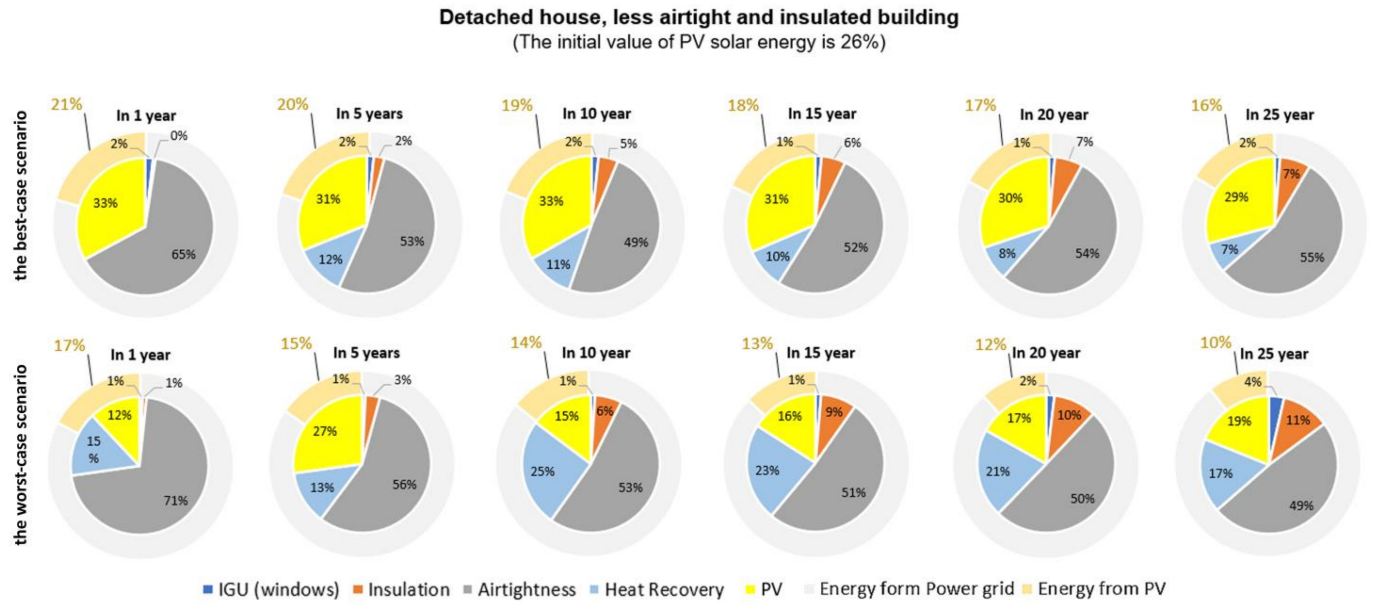

Figure 22. The contribution of each degrading component to the building's performance deterioration over time (less airtight and insulated detached houses with photovoltaics).

6. A Set of Guidelines

The results of this simulation research made it possible to identify key patterns of changes in the energy performance of buildings under the influence of ageing and degradation processes in a cold climate. The results obtained were given an applied character by making them into a set of practical recommendations.

Taking into account the main patterns of changes in energy consumption in buildings identified in this study under the influence of degradation in a cold climate, as well as a comparative analysis of the results obtained with key conclusions for hot–humid climate conditions [14], the following is a general set of guidelines for both climatic conditions. In this way, this set of guidelines is applicable for the following conditions: at least for the climates of Belarus and the UAE and, at most, for regions of cold and hot–humid climate conditions, which according to the Köppen climate classification system, corresponds to the climatic zones Dfb and BWh, respectively. Further, it considers buildings of two different types (detached and apartment buildings) with two levels of airtightness and insulation.

6.1. Recommendations for the Entire Building

1. The energy performance of buildings in a cold climate is more vulnerable to degradation than in a hot–humid climate. Therefore, the aspect of the climatic region where the building is located is important when considering possible changes in its energy consumption under the influence of the degradation of various building components. In particular, the following indicators of a faster increase in energy demand in a cold climate compared to a hot–humid climate can be distinguished (how many times):
    - for more airtight and insulated detached houses: 1.6–1.9
    - for less airtight and insulated detached houses: 1.4
    - for more airtight and insulated apartment buildings: 2.8–3.6
    - for less airtight and insulated apartment buildings: 1.9–2.1
2. More airtight and insulated buildings are more vulnerable to the degradation of various building components, compared to less airtight and insulated buildings. This is evidenced by the fact that the increase in energy demand over time in the first case occurs faster than in the second. In this regard, it is obvious that the importance of the quality and reliability of the building materials and structures used will increase with the increase in the level of airtightness and insulation of the projected building. The following indicators of a faster increase in energy consumption in more airtight and insulated buildings can be distinguished (how many times):
    - for detached houses in a cold climate: 1.05–1.2
    - for apartment buildings in a cold climate: 1.4–1.6
    - for detached houses in a hot–humid climate: 1.1
    - for apartment buildings in a hot–humid climate: 1.1
3. The greatest deterioration in energy performance of buildings due to degradation occurs within the first years of their operation. In addition, such an initial increase in energy consumption in a cold climate has significantly higher values than in a hot–humid climate.

6.2. Recommendations Concerning Possible Insulated Glass Unit's Degradation

1. With the degradation of IGU, the increase in energy consumption occurs at a faster rate in more airtight and insulated buildings. This conclusion is valid for both cold and hot climates. This means that the requirements for the quality of the windows used increase in direct proportion to the level of airtightness and insulation in buildings. As indicative quantitative indicators of this pattern, it is possible to refer to the established dependencies in Figure 9 in this study and in [14].
2. It is important to note that most likely, the change in energy consumption during IGU degradation occurs more slowly in apartment buildings than in detached buildings (with an average WWR indicator in a building of about 27–30%).
3. In addition, as indicated in [14], in hot and humid climates, special attention should be paid to the reliability of low-emission coatings on IGU since their degradation leads to a significant growth in cooling energy demand.

6.3. Recommendations Concerning Possible Thermal Insulation Degradation

1. It should be borne in mind that the consequences of degradation of thermal insulation in a cold climate are more significant than in a hot–humid climate, which requires a more cautious choice of building insulation materials in the first case. This recommendation is based on the established fact that with the degradation of thermal insulation, the increase in heating demand in cold climates occurs more rapidly than the increase in cooling demand in hot–humid climates. The estimated quantitative indicators of this dependence can be seen in Figure 10 in this study and in [14].
2. The deterioration of the performance of the thermal insulation of walls has more significant negative consequences for the energy performance of buildings compared with the deterioration of the thermal insulation of the roof. This pattern is observed in both climatic regions. It is possible to distinguish the following gap between the influence of thermal insulation of walls and roofs (how many times): for the detached house in a cold climate: 1.5; for the apartment building in a cold climate: 1.8; for the detached house in a hot–humid climate: 1.8; for the apartment building in a hot–humid climate: 1.5.

6.4. Recommendations Concerning Possible Airtightness Degradation

More airtight and insulated buildings have shown less vulnerability to deterioration of airtightness; therefore, when designing buildings, it is advisable to minimise the likelihood of excessive uncontrolled air flows in the building. To do this, it is necessary to choose high-quality and durable sealants, control the formation of cracks, be more careful when drilling new holes during the furnishing, etc. The dependences given in Figure 12 (in this study and in [14]) allow the estimation of the difference in the effect of airtightness deterioration on energy demand in a building, depending on its type and climatic conditions.

6.5. Recommendations Concerning Possible Degradation of Solar Reflectance of the Building Envelope

Ref. [14] presents the main recommendations for taking into account the degradation of solar reflectance of the building envelope. It is only worth noting that in climatic regions where there is a significant demand for heating energy in buildings all year, the level of solar reflectance of building envelope coatings should be carefully chosen, with accurate modelling of building energy performance, assessment of the energy balance, and economic benefits from simultaneous minimisation of energy demand for cooling and possible increases in heating energy consumption.

6.6. Recommendations Concerning Possible Performance Degradation of the MVHR System

1. The efficiency of the MVHR system in more airtight and insulated buildings is higher than in less airtight and insulated buildings.
2. The design of the MVHR system should be carried out in close relationship with the main indicators of the airtightness and insulation of the building envelope, primarily airtightness. The effect of the degradation of various elements of the building envelope on the efficiency of the heat recovery system can be seen in Figure 14. The following coefficients can be distinguished to reflect a possible decrease in the performance of heat recovery: with degradation of IGU: 0.94–0.99; with degradation of thermal insulation: 0.9–0.99; with degradation of airtightness: 0.78–0.9.
3. The performance of the heat recovery of typical mechanical ventilation systems installed in apartment blocks is more susceptible to the effects of degradation compared to those in detached houses, i.e., the increase in heating demand during the degradation of this system in the first case occurs faster.

6.7. Recommendations Concerning Possible PV Module Degradation

When introducing PV modules into a building's energy network, it should be borne in mind that the reduction of energy generated during their degradation occurs more intensively in hot climates compared to cold climates. It is also critical to pay close attention to the reliability and durability of photovoltaic modules in both climatic conditions when selecting them.

6.8. Application of Graphic Material

On the example of a more airtight and insulated detached house in a cold climate (in the worst-case scenario of degradation), the principle of using the developed pie charts (Figures 19–22) to assess how much a particular component of a building has an impact on the overall deterioration of its performance over the course of time is shown below. The greatest contribution to the increase in energy consumption in such a building after a year of operation is made by the deterioration of airtightness (Figure 19). This indicator reduces the level of its influence from 69% to 44% over 25 years. The second most important factor is the degradation of the heat recovery system, which also gradually reduces its impact from 47% to 34%. It is also possible to trace a gradual increase in the importance of the degradation of thermal insulation and IGUs. When using PV modules (Figure 21), it is clear that airtightness continues to have the greatest impact on the increase in energy consumption, while by the end of the period, the wear out of photovoltaic modules as well as the degradation of heat recovery and airtightness have approximately the same effect (≈25–30%).

Similar graphic materials for hot–humid climate conditions were also presented in Figures 19–22 in [14].

7. Output and Impacts

The findings of this study contributed to a better understanding of the effect of degradation and ageing processes on the deterioration of the energy performance of buildings over time in a cold climate. A special contribution was made by comparing the results obtained with the conclusions in a hot–humid climate. Among the key findings, the following main provisions can be distinguished:

1. The degradation of building components such as IGUs, thermal insulation, airtightness, heat recovery units of MVHR systems, and PV modules greatly affected the increase in heating demand in cold climates.
2. Taking the degradation factor into account, it was possible to identify the following main patterns: (1) Degradation processes had a more significant influence on the deterioration of the performance indicators of buildings in a cold climate compared to a hot–humid climate; (2) The greatest influence on the increase in energy consumption in a hot–humid climate was exerted by such indicators as the deterioration of low-emission coatings on windows, as well as airtightness degradation; in turn, in a cold climate, the deterioration of airtightness and heat recovery performance were of key importance; (3) The most substantial growth in energy demand is observed at the very beginning of building operation, and the sharpest jump in the deterioration of energy performance also occurs in cold climates; (4) It was revealed that the higher the level of airtightness and insulation of the building, the more vulnerable it is to degradation and ageing processes; (5) The constancy of the thermal insulation properties of the walls is more important than the thermal insulation of the roof in ensuring the stability of energy consumption in buildings in the long run; (6) As for building services, it was found that the greatest impact of the decrease in the performance of heat recovery in the mechanical ventilation system was a deterioration in the airtightness of buildings; (7) The degradation of PV modules in a cold climate also led (albeit to a lesser extent than in hot–humid climates) to a significant increase in energy consumption from the power grid.

3. It is also possible to note some interesting relationships established between the results obtained and the features of degradation of various components of buildings identified during the literature review. For instance, the fact noted by some scientists that in hotter conditions, under the influence of high temperatures affecting the sealants, the service life of IGUs is significantly lower than in colder conditions, which can be to some extent consistent with the results obtained, according to which a possible increase in cooling demand due to the degradation of a low-emission coating in a hot–humid climate was much higher than the values obtained in this study in a cold climate. Interesting results were obtained regarding the effect of thermal insulation in both climatic conditions. Therefore, despite the fact that scientific research generally confirms the linear relationship between thermal conductivity and temperature, the results obtained show the high importance of the degradation of thermal insulation in cold climates. In this way, it can be argued that heat transfer in a cold climate is more dynamic, and thermal insulation is rightfully considered one of the key measures to increase energy efficiency according to the world's leading guidelines. The established fact that uncontrolled air flows cause significantly greater global energy losses during heating than during cooling is also consistent with the results obtained in this work of a faster increase in energy demand in buildings due to the deterioration of airtightness in a cold climate compared with a hot–humid climate. The close relationship revealed in this study between the performance of the mechanical ventilation system's heat recovery and the airtightness also confirms the identified statements about the efficiency of the heat recovery system precisely in conditions of high building envelope performance.
4. The set of guidelines developed on the basis of the revealed patterns of behaviour of buildings in the ageing process embodies one aspect of the novelty of this study. In particular, in addition to enriching the general knowledge on this topic, the identified dependencies made it possible to quantify and correlate various factors that aggravate or, conversely, weaken the effect of degradation on increasing energy demand. In this way, the formulated recommendations will allow specialists in various fields at various stages of the life cycle of buildings to mitigate the effect of unavoidable degradation.

8. Conclusions and Recommendations

This research has contributed to the development and enrichment of scientific knowledge on the impact of the degradation and ageing of various components of buildings on their energy performance over time. At the same time, the main result of this work and its novelty is the development of practical recommendations for taking into account this factor of degradation at various stages of the life cycle of buildings.

The methodology chosen in this study made it possible to achieve the primary aim, namely, to study the impact of degradation on changes in energy consumption in buildings in cold climates. The results obtained, including a comparative analysis with previously published findings [14], allowed us to approach the solution of the research issue of taking the degradation factor into account in practice, by creating a set of guidelines for different climates, contexts, and building typologies. Among the main stages of the study, it is possible to note the assessment of the initial energy performance indicators of selected buildings, the development of the most likely scenarios for the degradation of the building components considered, the dynamic thermal modelling of the energy performance of buildings with changing characteristics of components, and the analysis and formulation of the results in the form of a set of guidelines. It is worth noting that the key importance of the chosen methodology was the assessment of quantitative indicators of both the deterioration of the performance characteristics of individual components and the resulting values of the changing energy demand of buildings under the influence of degradation. In this way, it was the evaluation of numerical indicators that made it possible to conduct a comparative analysis and formulate the recommendations that can be used in practice.

Therefore, in the expanded set of guidelines presented in this paper, the features of two climatic conditions (hot–humid and cold) for detached and apartment buildings, with two levels of airtightness and insulation, are considered. This set of guidelines is applicable for the following conditions: at least for the climates of Belarus and the UAE and, at most, for regions of cold and hot–humid climate conditions, which according to the Köppen–Geiger classification, correspond to the climatic zones Dfb and BWh, respectively.

In general, the results of thermal dynamic simulations showed that a possible increase in energy consumption for heating under the influence of degradation in a cold climate might reach over 25 years: for detached houses, up to 18.4–61.2% for more airtight and insulated buildings and 17.6–49.8% for less airtight and insulated ones; for apartment buildings, up to 32.6–89.8% and 23.6–56.3%, respectively. This was much more than the possible increase in cooling energy consumption detected under the influence of degradation in a hot–humid climate (approximately 1.4–1.9 times for detached houses and 1.9–3.6 times for apartment buildings). Moreover, the growth in demand for energy in buildings at the beginning of operation in cold climates was much higher than the same indicator in hot–humid climates. Overall, the study conducted in cold climates also proved that more airtight and insulated buildings were more vulnerable to degradation. It should be taken into account that the initial energy demand in such buildings is much lower, which makes them an effective technology even in conditions of possible degradation.

As a whole, it can be concluded that this study aimed to investigate the impact of degradation on changes in the performance of buildings, and one of the key objectives, the implementation of which enhanced the novelty of this study, was to create a set of guidelines that can be used in practice to take into account the factor of degradation in order to minimise this impact over time. This work had some limitations, including the nature of the ageing processes under consideration, which cannot guarantee obtaining any unambiguous outputs, especially given the limited amount of data. Additionally, the conclusions obtained are based only on the selected buildings' studies. However, the basis created in this work can be further improved in the course of future research. In particular, it is necessary to consider other climatic conditions, to cover more buildings, and to include in the study possible options for the refurbishment of buildings.

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References

1. International Energy Agency. Buildings. Available online: https://www.iea.org/reports/buildings (accessed on 10 January 2023).
2. World Green Building Council. EU Policy Whole Life Carbon Roadmap #BuildingLife. 2022. Available online: https://worldgbc.org/article/eu-policy-whole-life-carbon-roadmap-for-buildings (accessed on 10 January 2023).
3. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings–The hidden challenge for effective climate change mitigation. *Appl. Energy* **2020**, *258*, 114107. [CrossRef]
4. United Nations Environment Programme. Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. 2022. Available online: https://wedocs.unep.org/handle/20.500.11822/41133 (accessed on 11 January 2023).

5. European Commission. In Focus: Energy Efficiency in Buildings. Available online: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en#:~:text=Energy%20efficient%20buildings%20will%20result,air%20quality%20and%20improved%20health (accessed on 11 January 2023).
6. Li, L.; Wang, Y.; Wang, M.; Hu, W.; Sun, Y. Impacts of multiple factors on energy consumption of aging residential buildings based on a system dynamics model–Taking Northwest China as an example. *J. Build. Eng.* **2021**, *44*, 102595. [CrossRef]
7. Aksoezen, M.; Daniel, M.; Hassler, U.; Kohler, N. Building age as an indicator for energy consumption. *Energy Build.* **2015**, *87*, 74–86. [CrossRef]
8. Mohamed, S.; Smith, R.; Rodrigues, L.; Omer, S.; Calautit, J. The correlation of energy performance and building age in UK schools. *J. Build. Eng.* **2021**, *43*, 103141. [CrossRef]
9. Feng, H.; Liyanage, D.R.; Karunathilake, H.; Sadiq, R.; Hewage, K. BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. *J. Clean. Prod.* **2020**, *250*, 119543. [CrossRef]
10. Thomas, A.; Menassa, C.C.; Kamat, V.R. System dynamics framework to study the effect of material performance on a building's lifecycle energy requirements. *J. Comput. Civ. Eng.* **2016**, *30*, 04016034. [CrossRef]
11. De Wilde, P.; Tian, W.; Augenbroe, G. Longitudinal prediction of the operational energy use of buildings. *Build. Environ.* **2011**, *46*, 1670–1680. [CrossRef]
12. #BuildingToCOP. Built Environment Highlights from COP26. Available online: https://buildingtocop.org (accessed on 20 October 2022).
13. World Business Council for Sustainable Development. Net Zero Buildings: What does It Mean? (COP27). Available online: https://events.wbcsd.org/virtual-meetings/project/net-zero-buildings-what-does-it-mean (accessed on 11 January 2023).
14. Taki, A.; Zakharanka, A. The Impact of Degradation on a Building's Energy Performance in Hot-Humid Climates. *Sustainability* **2023**, *15*, 1145. [CrossRef]
15. Thomas, A.; Menassa, C.C.; Kamat, V.R. A Framework to Understand Effect of Building Systems Deterioration on Life Cycle Energy. *Procedia Eng.* **2015**, *118*, 507–514. [CrossRef]
16. Litti, G.; Audenaert, A.; Lavagna, M. Life cycle operating energy saving from windows retrofitting in heritage buildings accounting for technical performance decay. *J. Build. Eng.* **2018**, *17*, 135–153. [CrossRef]
17. Eleftheriadis, G.; Hamdy, M. Impact of building envelope and mechanical component degradation on the whole building performance: A review paper. *Energy Procedia* **2017**, *132*, 321–326. [CrossRef]
18. Eleftheriadis, G.; Hamdy, M. The Impact of Insulation and HVAC Degradation on Overall Building Energy Performance: A Case Study. *Buildings* **2018**, *8*, 23. [CrossRef]
19. Waddicor, D.A.; Fuentes, E.; Sisó, L.; Salom, J.; Favre, B.; Jiménez, C.; Azar, M. Climate change and building ageing impact on building energy performance and mitigation measures application: A case study in Turin, northern Italy. *Build. Environ.* **2016**, *102*, 13–25. [CrossRef]
20. Danza, L.; Belussi, L.; Guazzi, G.; Meroni, I.; Salamone, F. Durability of technologies in the keeping of ZEB's performances. *Energy Procedia* **2018**, *148*, 138–145. [CrossRef]
21. De Masi, R.F.; Ruggiero, S.; Vanoli, G.P. Multi-layered wall with vacuum insulation panels: Results of 5-years in-field monitoring and numerical analysis of aging effect on building consumptions. *Appl. Energy* **2020**, *278*, 115605. [CrossRef]
22. D'Agostino, D.; Landolfi, R.; Nicolella, M.; Minichiello, F. Experimental Study on the Performance Decay of Thermal Insulation and Related Influence on Heating Energy Consumption in Buildings. *Sustainability* **2022**, *14*, 2947. [CrossRef]
23. Stazi, F.; Tittarelli, F.; Politi, G.; Di Perna, C.; Munafò, P. Assessment of the actual hygrothermal performance of glass mineral wool insulation applied 25 years ago in masonry cavity walls. *Energy Build.* **2014**, *68*, 292–304. [CrossRef]
24. Asphaug, S.K.; Jelle, B.P.; Gullbrekken, L.; Uvsløkk, S. Accelerated ageing and durability of double-glazed sealed insulating window panes and impact on heating demand in buildings. *Energy Build.* **2016**, *116*, 395–402. [CrossRef]
25. Mastrapostoli, E.; Santamouris, M.; Kolokotsa, D.; Vassilis, P.; Venieri, D.; Gompakis, K. On the ageing of cool roofs: Measure of the optical degradation, chemical and biological analysis and assessment of the energy impact. *Energy Build.* **2016**, *114*, 191–199. [CrossRef]
26. Paolini, R.; Zani, A.; Poli, T.; Antretter, F.; Zinzi, M. Natural aging of cool walls: Impact on solar reflectance, sensitivity to thermal shocks and building energy needs. *Energy Build.* **2017**, *153*, 287–296. [CrossRef]
27. Gupta, R.; Kotopouleas, A. Magnitude and extent of building fabric thermal performance gap in UK low energy housing. *Appl. Energy* **2018**, *222*, 673–686. [CrossRef]
28. Gupta, R.; Kapsali, M.; Howard, A. Evaluating the influence of building fabric, services and occupant related factors on the actual performance of low energy social housing dwellings in UK. *Energy Build.* **2018**, *174*, 548–562. [CrossRef]
29. Marshall, A.; Fitton, R.; Swan, W.; Farmer, D.; Johnston, D.; Benjaber, M.; Ji, Y. Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance. *Energy Build.* **2017**, *150*, 307–317. [CrossRef]
30. Feist, W.; Pfluger, R.; Hasper, W. Durability of building fabric components and ventilation systems in passive houses. *Energy Effic.* **2020**, *13*, 1543–1559. [CrossRef]
31. Pilli-Sihvola, K.; Aatola, P.; Ollikainen, M.; Tuomenvirta, H. Climate change and electricity consumption—Witnessing increasing or decreasing use and costs? *Energy Policy* **2010**, *38*, 2409–2419. [CrossRef]

32. Smagulov, Z.; Anapiya, A.; Dikhanbayeva, D.; Rojas-Solorzano, L. Impact of Module Degradation on the Viability of On-Grid Photovoltaic Systems in Mediterranean Climate: The Case of Shymkent Airport. *Int. J. Renew. Energy Dev.* **2021**, *10*, 139–147. [CrossRef]
33. Axelarris, L.; Cooke, A.; Fredeen, C.; Garber-Slaght, R.; Leffel, E.; Ricketts, L.; Rose, W.; Zarling, J.P.; Zhivov, A. Building Envelope Characteristics in Cold Climates. *ASHRAE Trans.* **2021**, *127*, 583.
34. Kralj, A.; Drev, M.; Žnidaršič, M.; Hafner, J.; Černe, B. Multipane Glazing Durability: Report. Available online: https://www.researchgate.net/publication/327467400_Multipane_glazing_durability (accessed on 10 January 2023).
35. Insulation Manufacturers Association. Insulation for Sustainability: A Guide. 2020. Available online: https://xco2.com/insulation-for-sustainability-a-guide (accessed on 20 January 2023).
36. XCO2. Insulation for Sustainability: A Guide. 2020. Available online: https://highperformanceinsulation.eu/wp-content/uploads/2016/08/sustainability_a_guide.pdf (accessed on 20 January 2023).
37. Taleb, H.M. Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings. *Front. Archit. Res.* **2014**, *3*, 154–165. [CrossRef]
38. Ihm, P.; Krarti, M. Design optimization of energy efficient residential buildings in Tunisia. *Build. Environ.* **2012**, *58*, 81–90. [CrossRef]
39. Schnieders, J.; Feist, W.; Rongen, L. Passive Houses for different climate zones. *Energy Build.* **2015**, *105*, 71–87. [CrossRef]
40. Pásztory, Z. An overview of factors influencing thermal conductivity of building insulation materials. *J. Build. Eng.* **2021**, *44*, 102604. [CrossRef]
41. Molleti, S.; Van Reenen, D. Effect of Temperature on Long-Term Thermal Conductivity of Closed-Cell Insulation Materials. *Buildings* **2022**, *12*, 425. [CrossRef]
42. Berardi, U. The impact of aging and environmental conditions on the effective thermal conductivity of several foam materials. *Energy* **2019**, *182*, 777–794. [CrossRef]
43. Belanger, D.; Berardi, U. The impact of aging on the effective thermal conductivity of foam insulation: A simulation investigation using laboratory characterization data. In Proceedings of the 10th conference of IBPSA-Canada, Montreal, QC, Canada, 9–10 May 2018.
44. Dong, Y.; Kong, J.; Mousavi, S.; Rismanchi, B.; Yap, P.S. Wall Insulation Materials in Different Climate Zones: A Review on Challenges and Opportunities of Available Alternatives. *Thermo* **2023**, *3*, 38–65. [CrossRef]
45. Nagy, B.; Simon, T.K.; Nemes, R. Effect of built-in mineral wool insulations durability on its thermal and mechanical performance. *J. Therm. Anal. Calorim.* **2020**, *139*, 169–181. [CrossRef]
46. Molleti, S.; Lefebvre, D.; van Reenen, D. Long-term in-situ assessment of vacuum insulation panels for integration into roofing systems: Five years of field-performance. *Energy Build.* **2018**, *168*, 97–105. [CrossRef]
47. Johansson, P.; Adl-Zarrabi, B.; Kalagasidis, A.S. Evaluation of 5 years' performance of VIPs in a retrofitted building façade. *Energy Build.* **2016**, *130*, 488–494. [CrossRef]
48. Stazi, F.; Di Perna, C.; Munafò, P. Durability of 20-year-old external insulation and assessment of various types of retrofitting to meet new energy regulations. *Energy Build.* **2009**, *41*, 721–731. [CrossRef]
49. Bomberg, M.; Kisilewicz, T.; Nowak, K. Is there an optimum range of airtightness for a building? *J. Build. Phys.* **2016**, *39*, 395–421. [CrossRef]
50. Moujalled, B.; Leprince, V.; Berthault, S.; Litvak, A.; Hurel, N. Mid-term and long-term changes in building airtightness: A field study on low-energy houses. *Energy Build.* **2021**, *250*, 111257. [CrossRef]
51. Sherman, M.; Chan, W.; Walker, I. Durable Airtightness in Single-Family Dwellings: Field Measurements and Analysis. *Int. J. Vent.* **2015**, *14*, 27–38. [CrossRef]
52. Zheng, H.; Long, E.; Cheng, Z.; Yang, Z.; Jia, Y. Experimental exploration on airtightness performance of residential buildings in the hot summer and cold winter zone in China. *Build. Environ.* **2022**, *214*, 108848. [CrossRef]
53. Wahlgren, P. Seasonal variation in airtightness. In Proceedings of the 35th AIVC Conference "Ventilation and Airtightness in Transforming the Building Stock to High Performance", Poznań, Poland, 24–25 September 2014.
54. Feijó-Muñoz, J.; Pardal, C.; Echarri, V.; Fernández-Agüera, J.; Assiego de Larriva, R.; Montesdeoca Calderín, M.; Poza-Casado, I.; Padilla-Marcos, M.Á.; Meiss, A. Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary islands. *Energy Build.* **2019**, *188*, 226–238. [CrossRef]
55. Boixo, S.; Diaz-Vicente, M.; Colmenar, A.; Castro, M.A. Potential energy savings from cool roofs in Spain and Andalusia. *Energy* **2012**, *38*, 425–438. [CrossRef]
56. Pal, R.K.; Goyal, P.; Sehgal, S. Thermal performance of buildings with light colored exterior materials. *Mater. Today Proc.* **2020**, *28*, 1307–1313. [CrossRef]
57. Shen, H.; Tan, H.; Tzempelikos, A. The effect of reflective coatings on building surface temperatures, indoor environment and energy consumption—An experimental study. *Energy Build.* **2011**, *43*, 573–580. [CrossRef]
58. Dias, D.; Machado, J.; Leal, V.; Mendes, A. Impact of using cool paints on energy demand and thermal comfort of a residential building. *Appl. Therm. Eng.* **2014**, *65*, 273–281. [CrossRef]
59. Ozel, M. The influence of exterior surface solar absorptivity on thermal characteristics and optimum insulation thickness. *Renew. Energy* **2012**, *39*, 347–355. [CrossRef]

60. Bai, H.Y.; Liu, P.; Alonso, M.J.; Mathisen, H.M. A review of heat recovery technologies and their frost control for residential building ventilation in cold climate regions. *Renew. Sustain. Energy Rev.* **2022**, *162*, 112417. [CrossRef]
61. Tommerup, H.; Svendsen, S. Energy savings in Danish residential building stock. *Energy Build.* **2006**, *38*, 618–626. [CrossRef]
62. Cutland, N. Lessons from Germany's Passivhaus Experience. NHBC 2012. Available online: https://www.nhbcfoundation.org/publication/lessons-from-germanys-passivhaus-experience/ (accessed on 1 February 2023).
63. Ploskić, A.; Wang, Q. Evaluating the potential of reducing peak heating load of a multi-family house using novel heat recovery system. *Appl. Therm. Eng.* **2018**, *130*, 1182–1190. [CrossRef]
64. Zhao, L.; Liu, J. Physical environmental and behavioral drivers of heat recovery ventilation system feasibility in various climate zones. *Energy Convers. Manag.* **2022**, *259*, 115586. [CrossRef]
65. El Fouih, Y.; Stabat, P.; Rivière, P.; Hoang, P.; Archambault, V. Adequacy of air-to-air heat recovery ventilation system applied in low energy buildings. *Energy Build.* **2012**, *54*, 29–39. [CrossRef]
66. Juodis, E. Extracted ventilation air heat recovery efficiency as a function of a building's thermal properties. *Energy Build.* **2006**, *38*, 568–573. [CrossRef]
67. Roulet, C.A.; Heidt, F.D.; Foradini, F.; Pibiri, M.C. Real heat recovery with air handling units. *Energy Build.* **2001**, *33*, 495–502. [CrossRef]
68. Merzkirch, A.; Maas, S.; Scholzen, F.; Waldmann, D. Field tests of centralized and decentralized ventilation units in residential buildings—Specific fan power, heat recovery efficiency, shortcuts and volume flow unbalances. *Energy Build.* **2016**, *116*, 376–383. [CrossRef]
69. Sharpe, T.; McGill, G.; Gupta, R.; Gregg, M.; Mawditt, I. Characteristics and performance of MVHR systems A meta study of MVHR systems used in the Innovate UK Building Performance Evaluation Programme. 2016. Available online: https://radar.gsa.ac.uk/4073/1/MVHR%20Meta%20Study%20Report%20March%202016%20FINAL%20PUBLISHED.pdf (accessed on 13 February 2023).
70. Li, J.; Shao, S.; Wang, Z.; Xie, G.; Wang, Q.; Xu, Z.; Han, L.; Gou, X. A review of air-to-air membrane energy recovery technology for building ventilation. *Energy Build.* **2022**, *265*, 112097. [CrossRef]
71. Omazic, A.; Oreski, G.; Halwachs, M.; Eder, G.C.; Hirschl, C.; Neumaier, L.; Pinter, G.; Erceg, M. Relation between degradation of polymeric components in crystalline silicon PV module and climatic conditions: A literature review. *Sol. Energy Mater. Sol. Cells* **2019**, *192*, 123–133. [CrossRef]
72. Osterwald, C.R.; Adelstein, J.; del Cueto, J.A.; Kroposki, B.; Trudell, D.; Moriarty, T. Comparison of Degradation Rates of Individual Modules Held at Maximum Power. In Proceedings of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conference, Waikoloa, HI, USA, 7–12 May 2006; pp. 2085–2088. [CrossRef]
73. Strevel, N.; Trippel, L.; Gloeckler, M. Performance characterization and superior energy yield of First Solar PV power plants in high-temperature conditions. *Photovolt. Int.* **2012**, *17*, 7.
74. Vazquez, M.; Rey-Stolle, I. Photovoltaic module reliability based on field degradation studies. *Prog. Photovolt. Res. Appl.* **2008**, *16*, 419–433. [CrossRef]
75. Ye, J.Y.; Reindl, T.; Aberle, A.G.; Walsh, T.M. Performance degradation of various PV module technologies in tropical Singapore. *IEEE J. Photovolt.* **2014**, *4*, 1288–1294. [CrossRef]
76. Halwachs, M.; Berger, K.; Maul, L.; Neumaier, L.; Voronko, Y.; Mihaljevic, A.; Hirschl, C. Descriptive statistics on the climate related performance and reliability issues from global PV installations. In Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands, 25–29 September 2017; pp. 1–3.
77. Dubey, R.; Chattopadhyay, S.; Kuthanazhi, V.; John, J.J.; Vasi, J.; Kottantharayil, A.; Arora, B.M.; Narsimhan, K.L.; Kuber, V.; Solanki, C.S.; et al. Performance degradation in field-aged crystalline silicon PV modules in different indian climatic conditions. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, USA, 8–13 June 2014; pp. 3182–3187. [CrossRef]
78. Malvoni, M.; Leggieri, A.; Maggiotto, G.; Congedo, P.M.; De Giorgi, M.G. Long term performance, losses and efficiency analysis of a 960kWP photovoltaic system in the Mediterranean climate. *Energy Convers. Manag.* **2017**, *145*, 169–181. [CrossRef]
79. Jordan, D.; Kurtz, S.; VanSant, K.; Newmiller, J. Compendium of photovoltaic degradation rates. *Prog. Photovolt. Res. Appl.* **2016**, *24*, 978–989. [CrossRef]
80. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 1–12. [CrossRef] [PubMed]
81. Mourshed, M. Climatic parameters for building energy applications: A temporal-geospatial assessment of temperature indicators. *Renew. Energy* **2016**, *94*, 55–71. [CrossRef]
82. Bertosh, E. Vulnerability and Adaptation to Climate Change in Belarus: National Report. Eastern Countries Forum on Climate Change, Minsk. 2014. Available online: https://www.minpriroda.gov.by/uploads/files/Otsenka-ujazvimosti-Belarusi-Rus.pdf (accessed on 10 February 2023).
83. Leonovich, I.I. The Climate of Republic of Belarus; Minsk, BNTU. 2012. Available online: https://rep.bntu.by/handle/data/3501 (accessed on 13 February 2023).
84. BelStat. Final Consumption of Fuel and Energy Resources by Consumption Sectors. Available online: https://www.belstat.gov.by/ofitsialnaya-statistika/realny-sector-ekonomiki/energeticheskaya-statistika/anual-dannye/konechnoe-potreblenie-energii-/ (accessed on 28 October 2022).

85. BelStat. Housing Construction in the Republic of Belarus: Statistical Compendium. Minsk: Statistical Committee of the Republic of Belarus. 2014. Available online: https://www.belstat.gov.by/ofitsialnaya-statistika/publications/izdania/public_compilation/index_3486 (accessed on 10 February 2023).
86. Kucheravy, A. The First Multicomfort House. Available online: http://kucheravy.archi/1-j-multikomfortnyj-dom-v-belarusi (accessed on 21 August 2022).
87. Soroka, M. Underfloor Heating and No Radiators. Take a Look at What the First Energy-Efficient Class A+ Building in Belarus Looks Like. Available online: https://realt.by/brest-region/news/article/26256 (accessed on 21 August 2022).
88. Krasovskaya, O. The Owner of the Most Energy-Efficient Detached House in the Country. Available online: https://realt.onliner.by/2015/12/07/energo-6 (accessed on 22 August 2022).
89. Rossetti, M.D. *Simulation Modeling and Arena*, 2nd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2016; pp. 8–15.
90. DesignBuilder. Designbuilder Software Features, Simulation Made Easy. 2022. Available online: https://designbuilder.co.uk (accessed on 3 January 2023).
91. EnergyPlus. EnergyPlus Software Features. 2022. Available online: https://energyplus.net (accessed on 3 January 2023).