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Review

Sustainable Construction—Technological Aspects of Ecological Wooden Buildings

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Abstract: Wooden construction constitutes a specific branch of the building industry that focuses on high-quality materials, a developed sense of aesthetics connected with comfort and functionality, and concern for ecology and durability. This type of construction has a positive effect on human quality of life. This article focuses on modular frame construction and technological aspects of wooden houses built according to Canadian or Scandinavian technologies. Taking weather conditions of Scandinavian countries into consideration, timber is a popular building material, which, when preserving certain parameters such as density of rings, may provide durability of a modular wooden building even up to 200–300 years. This article is a review and presents the possibility of producing frame buildings in Europe (Poland) in accordance with the applicable standards, including a heat transfer coefficient U = 2 [W/(m^2·K]. In Poland, wooden frame buildings can be traced back to the 14th century. Wooden frame buildings and modular wooden frame buildings were produced even earlier in Norway. Wooden construction continued in the mid-1800s in various forms (with wooden filling and/or panels). In the mid-1900s (1941), certain dimensioning became regulated by law, which then applied to different types of insulation fillings. Prefabricated modular wood frame houses were common in the 1960s.

Keywords: construction; wood materials; timber; chipboard; building materials

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1. Introduction

21st century is characterized by an accumulation of regulations and guidelines aiming to improve the quality of the environment and life from an ecological point of view while simultaneously addressing economic considerations. The events of recent months, such as material deficits ranging from electronics to clothing, delays or shortages in the delivery of building materials (thermal insulation materials, construction materials, and rapidly growing prices of materials such as wood and steel), the effects of the COVID-19 pandemic, geopolitical conflicts, difficulties in obtaining energy resources such as clean fuels or electricity, and (in most of the Western countries) the highest inflation observed in 20–40 years, have motivated scientists and engineers all over the world to rethink old technologies and seek rational solutions both in terms of energy and economics [1–3].

In addition, there is a lot of concern about the energy crisis and dwindling resources to produce building materials, which has caused their cost to grow each month. Therefore, solutions are being sought and aimed at limiting negative environmental changes caused by broadly understood industrial activity, which is one of the sources of air pollution (415 ppm CO_2 in the atmosphere in May 2019 [4,5]). This information is part of the subject of economics and sustainable development, which combines aesthetic, ecological, economic, and industrial values since a clean environment is a necessary factor for maintaining health and wellbeing. In Europe, main environmental health problems are related to indoor and outdoor air pollution, poor water quality, deficient sanitation, and hazardous chemicals penetrating soil. Rapid development of the construction sector and popularity of concrete-based houses, while having numerous benefits, has several negative features. Poor quality of components, impurities present in the mixture and lower durability of the final material often contribute to respiratory diseases [6,7]. Contact of human skin with concrete, which on occasion may be rich in chromium compounds, can cause irritation [8]. Wood and stone are one of the oldest materials used in the building industry [9,10]. The oldest wooden buildings in Poland were constructed in 14th and 15th century and are mostly sacral buildings (churches, temples, and chapels) [11]. Popularity of timber as a building material was linked to its accessibility and thus low cost of acquisition and processing technology. Along with the appearance of other construction materials, e.g., pottery, concrete, reinforced concrete, or steel, popularity of timber decreased. These types of materials are currently common in highly developed metropolis areas or in areas with high population density, where it is necessary to build high and rather narrow constructions. It was only in the 1970s and 1980s that the topic of ecology and sustainable construction returned and the environmental costs of artificial materials and their impact on health and the environment were realized. Wood began to regain its position on the list of valued building materials. Wood is characterized by a favorable thermal insulation coefficient (the thermal conductivity coefficient for wood U [W/(m K)]: 0.16–0.3 for pine and spruce and 0.22–0.4 for oak [12]) as well as resistance to chemical corrosion. While timber architecture in Europe and Poland has historically been rich, wooden construction is not very popular in Europe at the present time.

Taking into consideration all the reasons outlined above, this paper reviews ecological wooden construction as a contender for achieving environmental and economic balance. Moreover, recently, due to the high inflation, economic instability, and difficulties in obtaining loans for long-term projects such as construction of a brick house, investors have been putting additional time constraints on the construction of single-family houses. Often, one of the conditions for obtaining a viable financing source for new construction is the time of completion. Brick or concrete-based houses, depending on the financial capabilities of the investor, can take up to several years to finalize. Conversely, wooden frame houses can be built within few weeks, and the entire construction process can be closed within a few months (3–6). For these reasons, the construction cost is about 15–30% lower than that of a traditional house, and it does not compromise applicable construction and environmental (the heat transfer coefficient: U) standards [12,13].

This article describes the characteristics of American wood construction executed according to Canadian and Scandinavian technologies that perform well under challenging weather conditions, i.e. cold and long winters. In addition, in some of the regions that are susceptible to the seismic shocks, this type of construction is advantageous because a lightweight structure is better at withstanding seismic waves. Moreover, in crisis situation (damage to a house, fire, or earthquake), such a house can be dismantled faster and rebuilt in a shorter time. This type of construction is also slowly becoming more popular in European countries such as Poland. The climate in Poland is like that of Canada or Scandinavia, although the winters in Poland are considered milder. An example of similar wood-based facility built in Poland is presented in terms of the applicable so-called WT standards (Technical Standards 2021), which are specific to the requirements imposed by the country. In Poland, special attention is currently paid to the heat transfer coefficient (U) and EP indicator (Primary Energy index of the building) for both brick and wooden buildings and is currently set at: 0.2 $W/(m^2 \cdot K)$ for external construction walls (*WT 2021 Standard* [14]). Heat transfer coefficients of partitions (U) are expressed in $[W/(m^2\ K)]$.

The energy efficiency of the house depends to a large extent on the thermal insulation of the building's external partitions, i.e., the foundations, external walls, and roof. To determine the insulation performance, the U heat transfer coefficient is used, and based on this coefficient, the appropriate thickness of the insulation material as well as its quality and type are selected (which also affects the prices and ultimately depends on the opinion and decision of the investor). The level of energy efficiency of buildings (EP), which is usually described by their energy standard and is expressed in kWh/(m^2 year), is the maximum rate of primary energy consumption by buildings per m^2 of usable area (which is determined on an annual basis) [12,13,15–17].

The new WT 2021 is the result of the pro-ecological attitude of the European Parliament, which, since 2010, has been introducing directives to minimize the need to use primary energy, meaning that buildings in the EU should meet established requirements for low energy consumption. The WT 2021 standards are now the basis for sustainable green construction and assume energy consumption for:

(a) individual buildings and multi-family residential buildings at the level of: EP = 65 kWh/m^2·year;
(b) collective flat buildings at the level of: EP = 75 kWh/m^2·year;
(c) public buildings at the level of: EP = 45 kWh/m^2·year.

The amendment reduces the EP for a single-family building from 95 kWh/m^2·year to 70 kWh/m^2·year [12,14]. These requirements and arrangements relate to the country, climate, production capacity, shipping, and economic possibilities for a given country [18].

The aim of this article is to review solutions for timber construction and disseminate information on frame structures and the possibility of their construction in different climates depending on the environmental conditions. Timber frame construction is very popular in North America in all types of climate zones as well as in Scandinavia. In recent years, more buildings of this type have been built in Poland using horizontally stacked logs or timber frames, which employ large framework akin to skeleton.

The subject of this article tries to emphasize the fundamental relationship between timber, sustainable construction, and 'green construction', and it attempts to define the benefits of the timber-oriented construction technology. Sustainable construction assumes the need to reduce the use of natural aggregates, which are commonly used in concrete-based construction, and which cause environmental changes, hence affecting the composition of earth's crust and climate. The use of quartz sand is widespread throughout the world. Natural sand and gravel aggregates are minerals that react quickly to market demands, and the level of their extraction can be treated as an indicator that reflects the overall economic situation of the country (Figure 1). An important criterion to ensure ecological wellbeing is inhibition of climate change and reduction of CO_2 emissions, which are highly related to industrial production and processing of substrates (including cement, sands, and aggregates) in the construction sector.

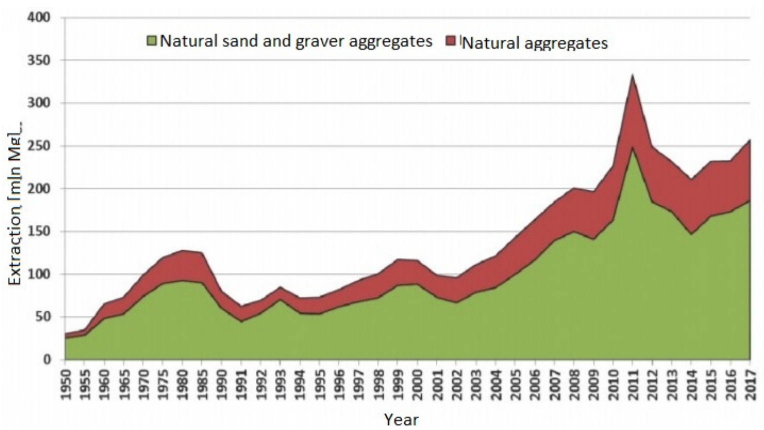


Figure 1. Sand consumption in Poland between 1950 and 2017 [19].

The European Association of the Cement Industry (CEMBUREAU) confirmed in its report that the cement industry has declared its contribution to the implementation of the so-called Green Deal by achieving the climate neutrality objective of the cement and concrete sector throughout the entire supply chain by 2050. To achieve this, CEMBUREAU will review the goals of the *Roadmap for a low-carbon economy in 2050* [20–22].

Therefore, this topic is important because many building materials contain quartz sand. The first alarming indicator of the sand crisis reached scholars from Vietnam when their Ministry of Public Construction was commissioned to study the availability of sand used for construction purposes. The results of this past study predicted an unfavorable scenario that by 2020, the country's raw material may be lacking. Since this raw material is renewed very slowly and is subjected to heavy industrial use (e.g., in construction) its consumption is currently the highest in the history. Further studies conducted by other researchers confirmed the findings of scientists from Vietnam (article and information from 2017) [23]. In 2017, the extraction of sand and gravel was even higher than that of the fossil fuels or biomass, because sand is a key raw material used in the production of concrete, glass, and electronics. In addition, it was considered that sand is also used as an aid in natural disasters to build protective shafts. In 2010, 11 billion tons of sand were mined only for the use in construction, and in 2016, the mining industry of this raw material was worth USD 8.9 billion [23,24]. During following years (until 2019), further increase in the demand in this segment was observed, and SiO_2 production increased by 24%. So far, no country in the world has introduced regulations aimed at more responsible and optimal extraction and use of sand. A sand deficit can significantly affect the entire construction industry, and single-fraction desert sand is completely useless for construction purposes [25,26]. Sand is undoubtedly an important asset. In Arab countries, sand needs to be imported from Australia. Singapore has expanded its area by 150 km^2 in 5 years, leading directly to the sand crisis in Indonesia [27]. Germany has recently exported 3 million tons of sand, and between 2011–2015, China used more sand aggregate (and cement) than the USA in the entire 20th century [28,29].

Frame construction works well in virtually every climate (Figures 2–7). The differences in construction mainly depend on the amount and type of insulation material constituting the filling of the skeleton, which also depends on the construction standards imposed by each country. As mentioned above, timber frame buildings not only perfectly meet thermal standards and work well in challenging climates where negative temperatures prevail (Canada, arctic and continental climates), but they are also an excellent solution in ocean-subtropical and Mediterranean climates (California) [30–32]. For example, in Toronto (Figures 2 and 3), summers are comfortable, winters are freezing, snowy, and windy, and it is partly cloudy all year round. Over the course of the year, the temperature typically varies from −8 °C to 25 °C and is rarely below −17 °C or above 29 °C.

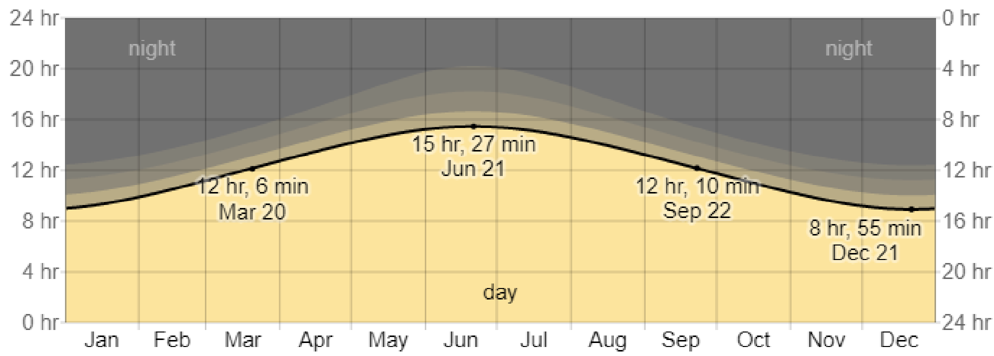


Figure 2. Hours of daylight and twilight in Toronto, Canada [33].

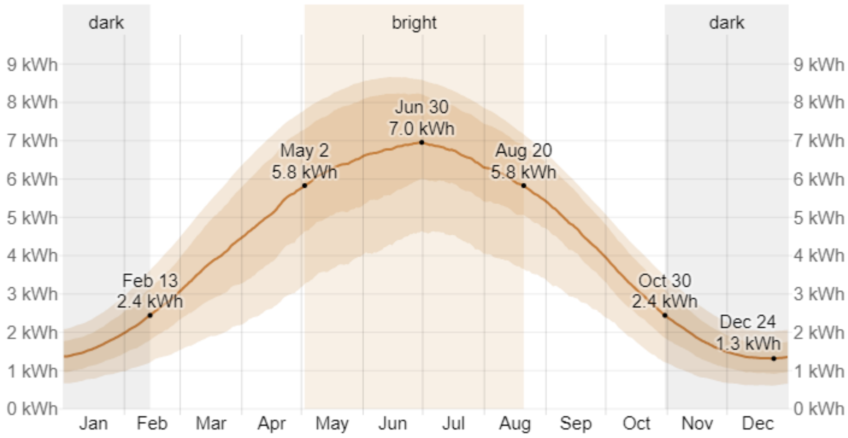


Figure 3. Average daily incident shortwave solar energy in Toronto, Canada [33].

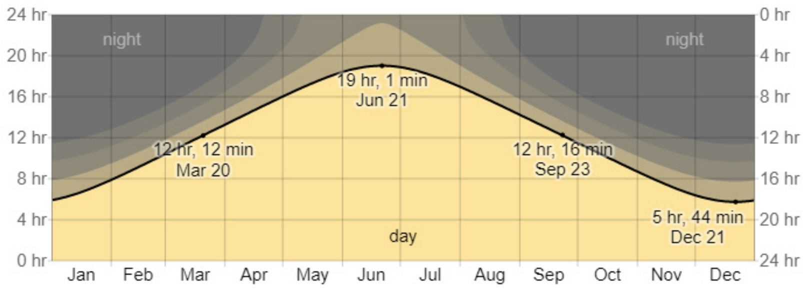


Figure 4. Hours of daylight and twilight in Bergen, Norway [34].

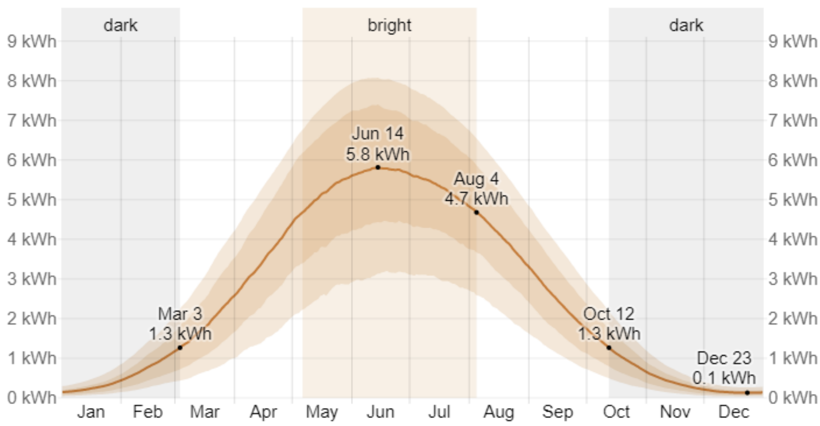


Figure 5. Average daily incident shortwave solar energy in Bergen, Norway [34].

In Bergen (Norway, Figures 4 and 5), summers are cool and mostly cloudy, winters are long, cold, and windy, and it is rainy all year round. Over the course of the year, the temperature typically varies from −2 °C to18 °C and is rarely below −8 °C or above 23 °F [34].

In addition, frame construction works very well in seismic areas such as California, because the skeleton and the individual elements that make up the body of the object cooperate with each other during earthquakes. Therefore, it seems beneficial to approach wooden construction in accordance with the principles of sustainable development and ecological construction. Wood used in construction is implemented following principles established by the FSC (Forest Stewardship Council—FSC Principles and Criteria for Forest Management) [35]. The FSC defines the rules of using forest resources so that forest management is carried out in an environmentally responsible manner, in a socially beneficial way, and in a way that is economically profitable over the long term. One of the first activities of the FSC was to develop a set of principles defining the best forest management practices. There are ten FSC principles that must be followed by forest owners and managers to obtain a Forest Stewardship Certificate. These principles range from addressing issues related to the environmental impact, to community relations and workers' rights, as well as monitoring and evaluation issues. The FSC has also defined several criteria for each principle to provide practical means of verifying compliance with them. The FSC principles have been designed to be applied worldwide and consider different types of forest areas as well as cultural, political, and legal conditions [35].

In Los Angeles, California (Figures 6 and 7), summers are hot, arid, and clear, while winters are cool, wet, and partly cloudy. Over the course of the year, temperature typically varies from 9 °C to 29 °C and is rarely below 6 °C or above 34 °C [36].

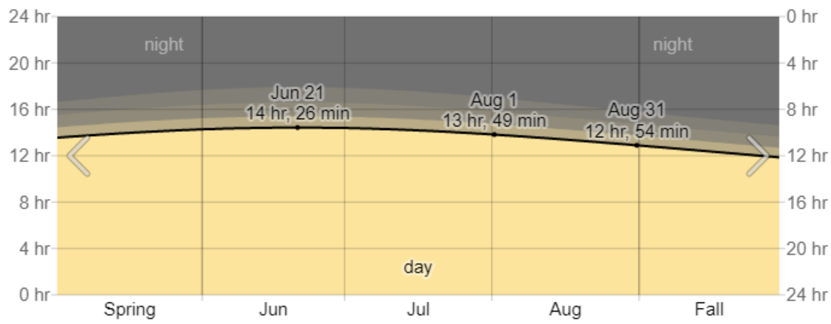


Figure 6. Hours of daylight and twilight in the in Los Angeles, California [36].

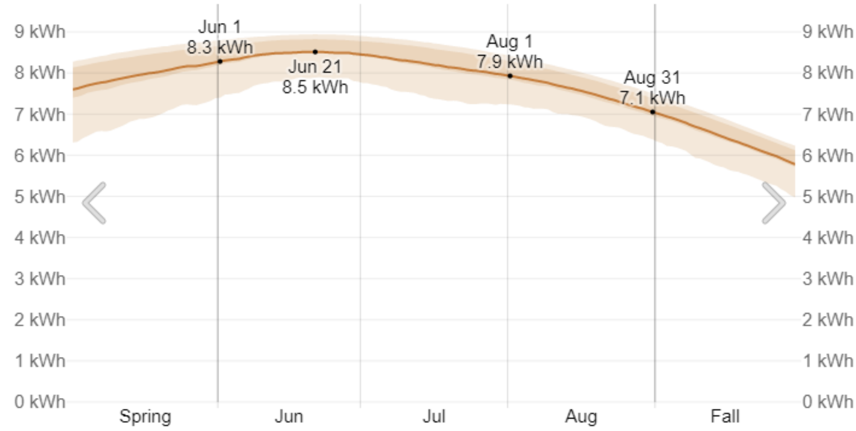


Figure 7. Average daily incident shortwave solar energy in Los Angeles, California [36].

Below are scanning electron microscope (SEM) images showing microstructures of sand-based (Figure 8) and wood-based (Figure 9) construction materials. Construction materials, including both artificial (bricks or concrete) and natural materials such as wood are influenced by climate change. This is especially true for those with large number of pores (i.e., voids). The material most susceptible to temperature changes is artificial stone, i.e., sand-based materials. SEM photos are presented below to illustrate structure of the two construction materials.

The images of bricks (Figure 8) and wood (Figure 9) show the differences in the microstructure of these two materials. Due to the dissimilarity in pore structure the flow of moisture in the materials is different. Bricks and concrete (i.e., artificially produced construction materials) periodically change their functional properties because of changes in their microstructure (the amorphic C-S-H phase crystallizes, i.e., reduces its surface area, which creates free spaces in the material and thus forms pores into which water penetrates). The appearance of the C-S-H phase proves the proper course of the hydration process in the presence of SiO_2 sand (permanent bonds in silicate materials are formed during the storage of the mixture in reactors for about 4 h and later over the course of the autoclaving process (8 h)). Elevated temperatures facilitate transformation of amorphous C-S-H phases into crystalline tobermorite [37]. In the case of wood, there is no suchreaction. Wood is also still considered one of the most natural materials in the history of construction [38]. The scale of the consumption of raw materials in concrete-based construction creates significant problems because excessive production and use of natural resources lead to global warming and melting of glaciers. In addition, scientists from Ohio State University and Lawrence Berkeley National Laboratory have also shown the emergence of new viruses and bacteria previously unknown to science linked to the changes in our ecosystems [36–41]. Researchers form the University of California in Los Angeles (UCLA) are also actively studying the reduction of environmental changes caused by the construction sector and the possibility of CO_2 absorption in concrete. They have been working on so-called "CO_2 Concrete", focusing on the CO_2 mineralization and carbonation of portlandite, which can ensure CO_2 uptake and cementation at optimal production prices thus creating paths for zero-emission cementation [40–46]. This is possible due to the microstructure and properties of these building materials associated with the solids that are formed during the hydration process between the binder and water. By knowing the composition of building materials and thermodynamic relationships and by having information on the microstructure of materials and the resulting properties, one can properly optimize their composition and production processes in accordance with environmental protection standards. Until then, however, the environment and the construction sector need to be fully integrated. Not all types of construction require the use of 'artificial stone'. Consequently, it is often necessary to use other solutions and construction technologies, especially in case of single-family housing [10,19,20]. This article focuses mainly on detached buildings. Construction materials for their walls mainly comprise of ceramic bricks, sand-lime bricks, light autoclaved aerated concrete, or natural wood. Because of its ideal properties, such as durability and resistance to weather conditions (excluding fire resistance) [47], ease of processing, thermic insulation, and aesthetic values, wooden frame construction has been recently growing in popularity. Different woods have different natural resistance to attack from destructive organisms (fungi and wood-destroying insects such as woodworms). Sapwood in the wood is not resistant to biological attack, and the natural resistance of the heartwood varies from poor to very good. This becomes apparent over time when the wood is exposed to moisture. Wood maintains its durability through proper transport of moisture (Figure 9, image of the internal microstructure of wood), while artificial stone (bricks and concrete) can saturate with water only up to a certain percentage (e.g. 16% for autoclaved bricks, Figure 8, photo of the microstructure and pores). Heartwood comprises of inactive wood cells. The openings between the fibers that occur in sapwood that should allow for water transport are closed, and heartwood tends to be quite resistant to water transport. Thus, the classification of inherent durability is generally based on the resistance of heartwood to wood-destroying fungi in contact with the substrate (standard SS-EN 350). Wood ordered as heartwood must not contain sapwood in order to meet required standards. When talking about wood with high natural resistance in contact with the ground, this usually refers to heartwood from imported wood species such as teak, iroko, cumaru, false acacia (*Robinia pseudoacacia*), and western red cedar. Currently Swedish woods, i.e., oak heartwood has the best natural durability. Moisture content is specifically defined as the ratio of the weight of the water in the wet material to the weight of dried wood after drying at it 103 °C. The moisture content affects gluing and surface treatment as well as properties of wood such as dimensions, strength, and resistance to degradation (durability) [47–49]. Wood exposed to light and UV radiation generally shows changes in appearance due to color change (photo-yellowing) of the wood surfaces. Currently, research is being carried out to enhance the resistance of wood to sunlight by using, for example, chemical modification (e.g., the use of isopropenyl acetate in the presence of anhydrous aluminum chloride as a catalyst under solvent-free conditions) [50]. Wood-oriented construction technology is particularly advanced in Scandinavian and Canadian regions [11,51–60]. Additionally, research conducted by scientists from the University of Manitoba in Canada showed a link between habitation in concrete buildings and development of asthma. In recent times, when society had to face the coronavirus pandemic, boosting human health and immunity became even more important [55,56].

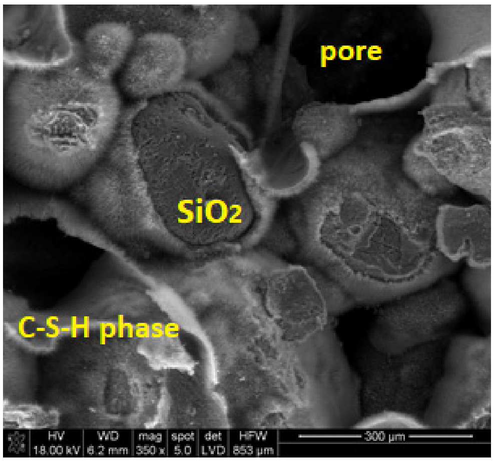


Figure 8. SEM image showing microstructure of 'artificial stone', i.e., brick/mortar, which was made of natural quartz sand SiO_2 (90% by weight), lime CaO (7% by weight), and water H_2O (about 3% by weight); magnification 350×.

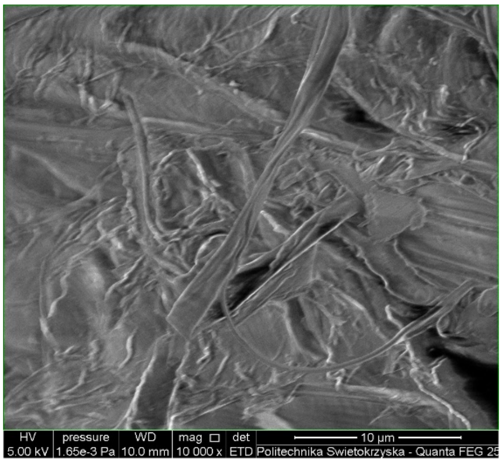


Figure 9. SEM image showing microstructure of a tree used in timber frame construction; magnification 10^4×.

2. Technology of Wooden Frame Houses

The quality of material in wooden frame construction has a significant impact on the use of the structure (the life cycle of a building object with proper operation). Every beam has a stamp indicating its resistance class. It is recommended to use lumber of the C27 class and with a bending resistance of a minimum of 27 MPa.

Timber should have dense grains, and wood material, before being used in construction, should be dried to the level of the final moisture content established in the wood's final application and according to standards imposed by a given country. For example, according to Norwegian regulations, humidity cannot exceed 12%. Moreover, any trace of mold, fungi, or insects leads to rejection of the material. The key to maintaining high quality is linked to the dryness of wood; when it is dry, it is stable in its size and may deform only to a negligible extent. Methods of wood drying may be classified into two main categories: natural drying (seasoning) or kiln drying (Table 1 and Figure 6).

Table 1. Cost of the individual materials used for manufacturing external/internal walls in Polish zlotys.

Material	Price [zł]	Price per m^2 [zł]
Plasterboard A13 1200 × 2600 × 12.5 mm	27.99	8.97
Gypsum plasterboard HA13 1200 × 2600 × 12.5 mm	38.87	12.46
Ursa Mineral Wool Standard 50 mm 16.8 m^2	151.03	8.99
Polmar Styrofoam plate Roof/Floor 040 50 mm	95.99	16.00
Masterplast Grid Fiberglass Masternet A-145	105.00	2.10
Atlas Mineral plaster 25 kg	47.48	5.32
Ceresit CT 48 Silicone Paint 15 l	363.10	7.26
Atlas Grawis S styrofoam adhesive 25 kg	21.99	4.40
Adhesive for expanded polystyrene and mesh Atlas Grawis U, 25 kg	29.99	5.99
Koelner connector for styrofoam, long: 120 mm (250 pcs.)	75.00	-
Cekol Smoothing coat GS 200 20 kg	37.80	5.67
OSB 3 plate, dim. 12 mm × 1250 mm × 2500 mm	109.31	34.97
Universal acrylic primer Magnolia 10 l	19.99	-
Color of nature—113 Paint, 5 l	79.00	1.13
Façade board PHASE thickness: 1.9 × width: 14 × length: 300 cm	33.95	33.95
PINE paneling thickness: 1.2 × width: 9.7 × length: 240 cm	49.88	49.88

Frame walls consist of the following construction elements: ground beam, columns, caps, snaps, and rafters (Figure 7). Assembly of the frame of wooden house should begin with wooden ground beams (wooden foundations) under the upper floor, ceiling, or walls. Direct contact with concrete or attack of insects may lead to rotting. For this reason, the ground beam should be placed under conditions of higher pressure, which will protect it from the abovementioned threat. If the ground beam is not secured under pressure, one should separate it from the fundaments with a polyurethane tape or a double layer of bituminous tar paper with the addition of polyurethane foil so that it provides required dump insulation. The ground beam should be anchored in fundaments using steel anchors, for example, 12 in spacing of a maximum of 180 cm. The anchors should be located approximately 30 cm from the ground beam ends (foundation) and in the joints from the inner edges [61–65].

Characteristics of Construction of Wooden Frame House Technology

Timber framing technology is recognized as the foundation of Canadian wood frame houses. Originally, it was a wooden skeleton with large cross sections. Timber framing with large cross sections was a starting point for the development of Canadian frame houses with characteristic features of wooden frames divided into large sections. The associated difficulty of linking materials was the reason why this type of construction required many qualified people [61,62]. In the USA, we can still observe the oldest examples of these buildings, which date back to the first half of the 17th century [63]. Contrary to popular belief, the homeland of this technology was not North America. It arrived there when Europeans settled on the new continent and subsequently flourished there. The current technology used in wooden houses is largely based on Canadian (Figures 10–12) and Scandinavian designs [58]. Originally, British, German, and Dutch settlers brought this method of construction called timber frame to the new continent, which has been mastered by Americans throughout the years (Figure 11).

Frame houses in Canada have a modular prefabricated form or are assembled at the construction site. In the Canadian skeleton system, 38 mm thick elements form the structure of the walls, ceiling, and roof. The outer walls are made of solid wood, are 140 mm wide, and are filled with insulation, which is usually glass wool [64,65].

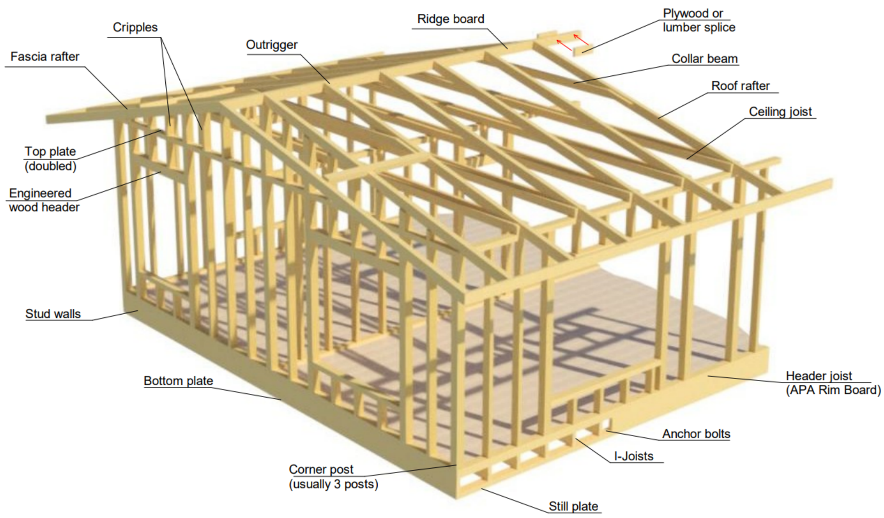


Figure 10. Components of a frame wall.

(**a**) (**b**)

Figure 11. An example of a timber frame during the construction of a multi-family building (Los Angeles, California): (**a**) an example of a wooden skeleton.; (**b**) upholstery of the skeleton with fiber boards and further technological layers.

(**a**) (**b**)

Figure 12. An example of a wooden building according to Canadian technology: (**a**) wooden houses in Canada; (**b**) The Gamble House (Pasedena, California), one of the oldest wooden houses in the USA. Built in 1908, it is currently a house of historical and cultural importance.

Americans eventually realized that the frame could be constructed from beams of smaller sections without affecting its stability, hence reducing the need for highly skilled workers. In this way, the timber frame method morphed into the wood frame method, which is distinguished by thinner beams of higher density. This also reduced the amount of work needed to construct such a house. In the 18th century, a method called balloon frame was introduced by George Washington Snow. In 1832, during the construction of a warehouse, he applied a method of using walls that began on the ground beam and reached the top plate where rafters were based. Unlike the previous methods, where the walls were dealt into parts for the ground floor and first floor, this method allowed using poles of even smaller sections and weight [66]. Wood needed for the bottom and top plate was eliminated, which lowered the costs of construction and transport, thus enabling delivery to inaccessible areas. All these factors shortened construction time. It was wrongly believed that wind would blow such constructions into the air like a balloon, which is where the name of this method originates from. Along with the rapid development of frame building technology in North America, in 1927, a regulation called "building codes" was introduced, which governed standards related to the construction industry, fire protection, electrical wiring, and hydraulic systems. Substantial contributions to the development of the wood frame methods were made by the Swedish. In 1820, an architect named Frederick Blom designed a prototype of a prefabricated frame house [58,59,67–70].

In the middle of the 20th century, balloon technology began to recede in favor of platform framing, where floors can be constructed separately. This period may be recognized as the beginning of light wooden frame building. The platform framing method is still widely used in the USA, Canada, and Scandinavian countries (90% of houses are constructed using this method) [61,71]. Scandinavian houses built in Norway are mostly manufactured at the construction site and prefabricated elements are limited to roofing as trusses. Systems of layers of external walls can also differ [16].

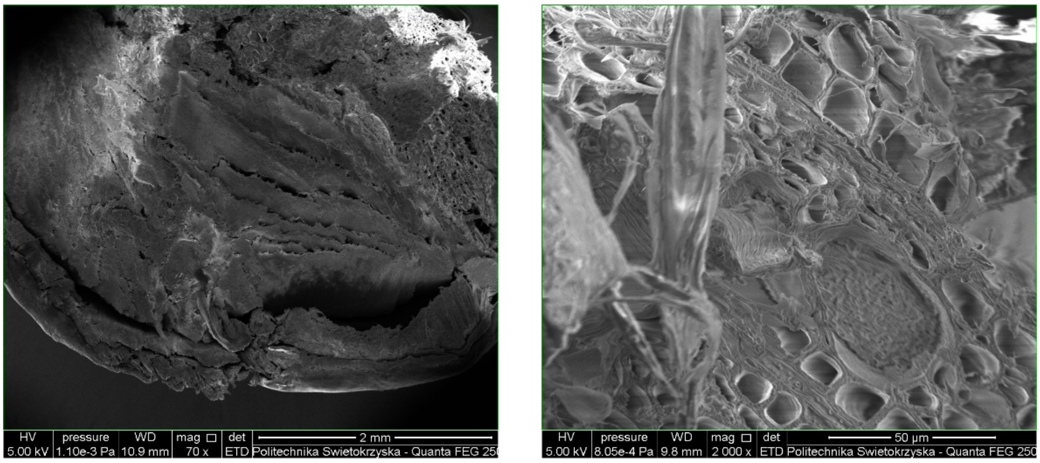
Chipboards are used in the production in which the shavings are dispersed. Boards have homogeneous structure, are resistant to deformation and are easier to cut, without fraying the edges. The density of the chipboard increases with the contact surface area of the chips. These types of panels have very good insulation and strength parameters (resistant to impacts, cracks, fractures, and discoloration) [72].

3. Materials and an Example of the Construction of a Building Based on a Wooden Frame

Wood and stone are the main materials used in wooden frame buildings, i.e., stone foundations, wooden walls, steep roofs covered with wood chips or reed, stone floors, stairs, etc. [70]. Wood used for the construction of frame houses is an ecologically friendly renewable material, and its harvesting is not harmful to the natural environment if it is carried out carefully and in accordance with the codes guarded by the FSC (Forest Stewardship Council). A feature of wood that requires special attention is its moisture content [47–51]. Lumber obtained from freshly cut trees has excessively high moisture, which is preventing it from effectively being used in the construction process. Therefore, it needs to be subjected to drying processes. There are two methods of wood drying: (a) the natural method, i.e., drying in the open air, and (b) the artificial method, which is drying in chamber dryers with forced air circulation and at elevated temperature. As a standard, the wood should be dried to a humidity level of 30%, and during drying, free water which normally fills the pores of the wood should be removed. This state is called the 'fiber saturation state', and in this condition, wood does not change its properties or dimensions. Due to the anisotropic structure of wood, this material undergoes shrinkage processes when under the influence of variable exploitation conditions, which involves further reduction of the moisture content (from 30% to even 0%). The shrinkage value depends on the type of wood and its cross-section characteristics. Therefore, it accounts for:

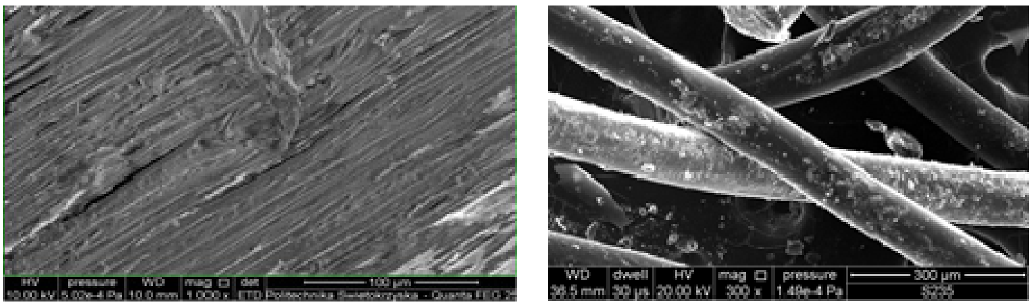
(a) 6–13%—shrinkage for the tangential direction (cut tangent to the rings);
(b) 3–5%—shrinkage for the radial direction (cutting in the plane perpendicular to the jars);
(c) 0.1–0.8%—cutting along the fibers [73].

In contrast to shrinkage, wood may also be subjected to a process known as swelling, which is associated with the absorption of water vapor from the air. Both processes have reversible effects on the wood and are characterized by displaying a change in linear dimensions [62,73]. SEM image showing the internal structure of timber with visible layers, fibers, and pores is presented below (Figures 13 and 14). These images have been included to illustrate the internal structure of wood which is influencing the flow of moisture (and related properties in the wood.



(**a**) (**b**)

Figure 13. Scanning electron microscope (SEM) images of wood: (**a**) wet wood, horizontal cross section, magnification 70×; and (**b**) wet wood, vertical section, magnification 2×10^3.



(**a**) (**b**)

Figure 14. Scanning electron microscope (SEM) images of wood: (**a**) dry wood, vertical section, magnification $10^3\times$; and (**b**) natural plant fibers, magnification $3 \times 10^2\times$. Image acquired on the scanning electron microscope Quanta 250 FEG (FEI Company).

Wooden houses are usually built on traditional foundation walls supported by reinforced concrete footings, i.e., similarly to brick houses. When building a timber frame, dimensional modules must be used. In accordance with the modules, wall columns should be spaced every 40 or 60 cm, ceiling beams every 40 cm, and roof rafters every 60 cm. The width of the oriented strand board (OSB) and drywall or gypsum fiber boards, which encase the timber frame, fits these modules. This makes their assembly much easier because the contacts of the plates fall exactly on the structural element to which they need to be attached [57,74,75].

Basic elements used in wooden houses include damp screens applied from the inside and wind insulation foil placed from the outside. Spacing between construction poles is filled with mineral wool of different thicknesses that depends on the size of the partition.

When examining the technology of construction of frame houses in Scandinavia, weather conditions must be taken into consideration (Figures 15 and 16). In certain regions of a country, some methods used for construction may differ, which is clearly seen in Scandinavian countries, where the climate in the north is harsher than in the south. Furthermore, although they have many things in common, there are also many differences between Canadian, Swedish, and Norwegian buildings. These differences are related to the method of construction of load-bearing walls and roofing as well as their sizing. To give an example, when the basic width of the wooden beam used in the structure of external walls is described as "two-by-four" inches, this translates to the 36 mm × 148 mm size in Norway and to the 38 mm × 140 mm size in Canada. The bigger the increase in the thickness of partitions, the more visible the differences in sizing become. In North American countries, the work is mainly performed at the construction site, where the material is delivered and elements are cut into desirable sizes and then connected, which often creates a complicated system of external walls. In Scandinavian countries, mainly in Sweden, a very simple design is preferred, where the building is usually set on fundaments in the shape of a square. Most of the construction elements, such as external and interior walls or roofing are manufactured in the factories and later brought to the construction site as ready-to-use prefabricated elements. The advantage of this method comes not only from its simplicity but also from its preservation of accuracy. Construction beams of modular objects are characterized by greater thickness (45 mm) and width (min. 230 mm) compared with their handmade equivalents. When implementing such a material, the amount of wood used for lintels and caps is limited. Any potential issues are noticeable only when additional insulation and outside stiffening beams are applied. With this method of installing thermal insulation, it is easier to eliminate thermal bridges that could occur in the building's external partitions. Thermal insulation from the inside is usually arranged only when it cannot be done from the outside (especially in countries where most months are described as cool, i.e., Scandinavia, Canada, and Western, Central, and Eastern Europe). One of the arguments for such a solution is, for example, the fact that the house is subject to conservation protection laws and its elevation cannot be changed [69,74]. Structural walls in half-timbered houses are insulated throughout the entire thickness of the frame. Insulation improves thermal efficiency of the building, but it also adds weight to it. Canadians use chipboard or plywood of increased damp resistance then apply a layer of thermal insulation such as mineral wool or polystyrene. When using the latter, they often forget to leave a ventilation gap to protect the building from dampness [16,57,59]. In Scandinavia, wood-based panels, the so-called "asfaltplate", or plasterboard are used as sheathing plates. A vertical wooden grate is then installed with a spacing of 60 cm to provide a ventilation gap on top of which elevation is installed. Norwegians currently use an additional insulation layer from the internal side of the house, i.e., screen foil and wooden strips, which are installed with a spacing of 60 cm vertically and horizontally, and which are filled with a 5 cm thick mineral wool layer. In this additional compartment, the building's installation can be safely placed without any damage to the screen foil, thus protecting the frame of the building from any harm caused by moisture. Another difference in construction of houses built according to Scandinavian technology is the method of finishing the facade of the wooden frame. In Canada, the exterior cladding is covered with materials such as clinker, vinyl siding, or thin coat plaster. Inside the building, plasterboard plates are the most common. In Scandinavian countries, however, environmentally friendly materials dominate, such as traditional plasterwork, cladding brick, or a clapboard siding. The latter is also often used for finishing the interior of the building, including ceilings, by installing it directly onto the construction of external and internal walls or attaching it to the wooden lattice under the ceiling. There are also differences in materials used for roofing in the frame house. In America, very cost-effective asphalt shingles are popular and ceramic elements are rarely observed, whereas in northern Europe, traditional materials such as metal, ceramic, or cement are used for roofing [69,70].

(**a**) (**b**)

Figure 15. An example of a wooden building produced using Scandinavian technology: (**a**) blown up and then leveled rock yard prepared for the construction of a wooden frame house in Norway; (**b**) frame construction of a wooden house according to Scandinavian technology manufactured at the construction site.

(**a**) (**b**)

Figure 16. An example of a wooden building produced using Scandinavian technology: (**a**) frame construction of Scandinavian house; (**b**) construction of a wooden frame house with vapor barrier and thermal insulation.

4. Development of Wooden Technology in European Countries According to Ecological Aspects

Ecology in the context of this article refers to the reduction of heat loss in the building due to the use of thermal insulation materials and hence reduction of need for excessive heating of the building, especially in winter (and subsequently the reduction of fuelconsumption). Timber frame construction has become popular in an increasing number of countries, not only in America and Scandinavia but also in other parts of Europe. Many examples of wooden frame houses can be found in Poland, for example. Due to the cold climate, particular attention is paid to the standard requirements for the heat transfer coefficient U. In Warsaw (Figures 17 and 18), summers are usually comfortable and partly cloudy, but winters are long, cold, cloudy, windy, snowy, and with temperatures often falling below 0 °C. Over the course of the year, the temperature typically varies from −4 °C to 24 °C and is rarely below −14 °C or above 30 °C [74]. For these reasons, the climate in Poland is also favorable to timber construction since weather conditions are like those in Canada but with warmer winters.

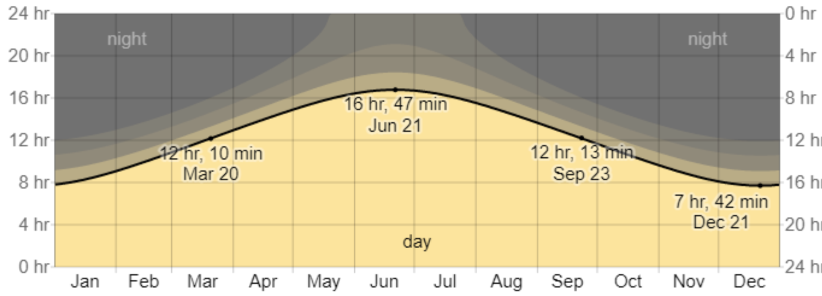


Figure 17. Hours of daylight and twilight in Warsaw, Poland [76].

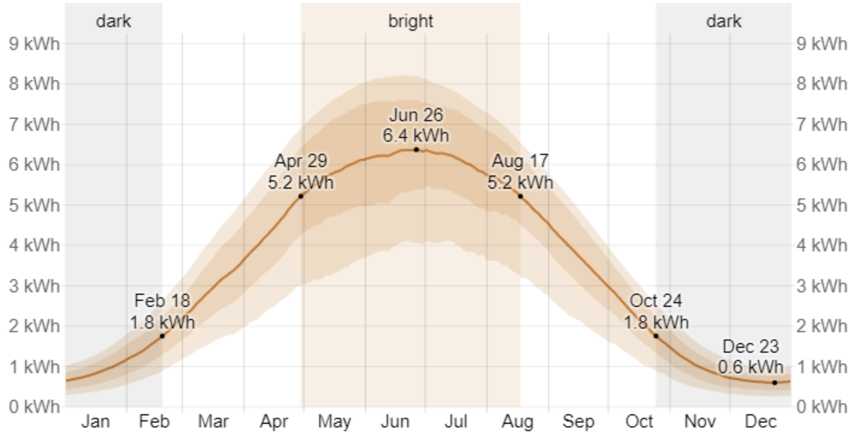


Figure 18. Average daily incident shortwave solar energy in Warsaw, Poland [76].

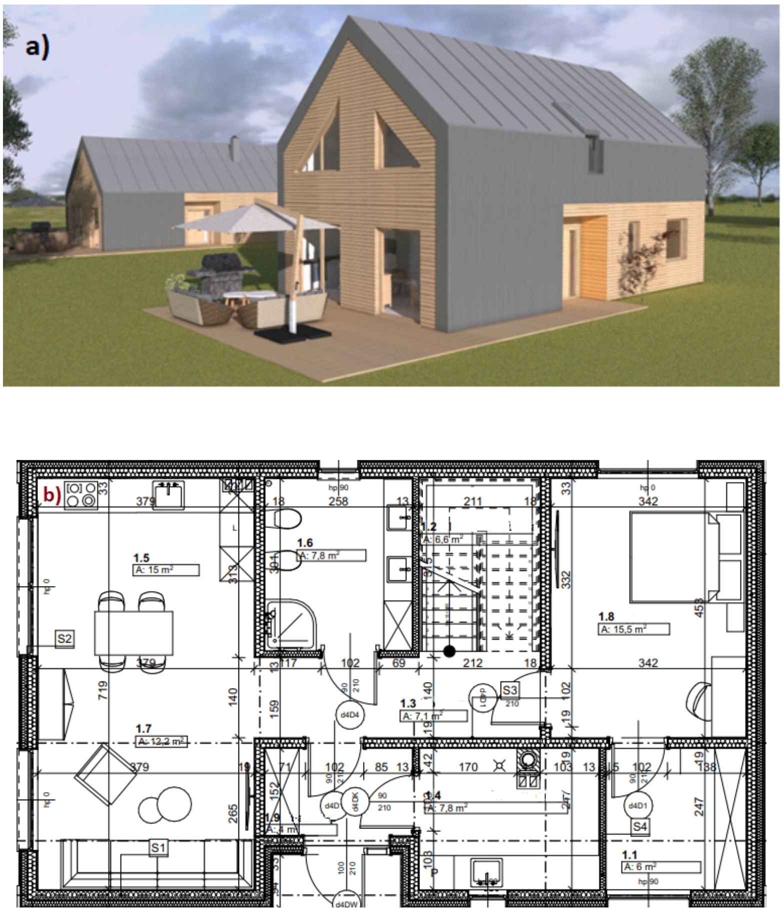
Consumers, when deciding on the choice of materials for building a house, especially single-family houses, must now comply with standard building codes, especially regarding the proper thermal insulation of buildings (U [W/m^{2}K]). In addition, the quick completion of the backbone of the proposed facility (6–12 weeks from the time of obtaining the building permit) is one of the easiest ways to obtain a loan [75,77].

One of the documents that defines the conditions for new and modernized buildings, where one of the main assumptions is the use of ecological solutions and renewable energy sources, is the *WT 2021 Standard*. The *WT 2021 Standard* specifies issues related to the significant tightening of legislators' recommendations regarding the energy efficiency of buildings. Currently, every investor planning construction must choose pro-ecological and pro-economic solutions and technologies that can successfully blend in with passive construction [14,18,78,79]. In the case of WT 2021, the heat transfer coefficient is also important and should account for a maximum of [80]:

⇒ 0.2 W/m^2·K—external wall;
⇒ 0.15 W/m^2·K—roof, flat roof;
⇒ 0.3 W/m^2·K—floor on the ground;
⇒ 0.9 W/m^2·K—vertical windows;
⇒ W/m^2·K— roof windows;
⇒ W/m^2·K—exterior doors.

This type of building can be designed and manufactured in agreement with the following energy standards (Figures 19 and 20):

⇒ E2—all-year house (U = 0.19 W/m^2·K);
⇒ E3—energy-saving house (U = 0.15 W/m^2·K);
⇒ E4—a perfectly insulated house (U = 0.10 W/m^2·K).



1.1—room/wardrobe (6.0 m²);
1.2—staircase (6.6 m²);
1.3—hall (7.1 m²);
1.4—utility room/boiler room (1.55 m²);
1.5—kitchen (15 m²);
1.6—toilet (7.8 m²);
1.7—living room (12.2. m²);
1.8—room (15.5 m²).

Figure 19. An example of a timber frame building (DomyExpert); (**a**) elevations and view; (**b**) ground floor plan.

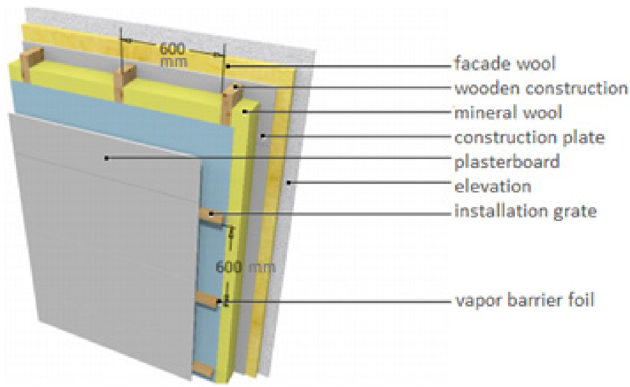


Figure 20. Wall cross section of an energy-saving house E2 (E2—a minimum basic standard that meets the requirements of the European Union).

Below is an example of a timber frame building designed for Polish conditions (Figure 19) that has an area of up to 100 m^2 and meets the WT 2021 standards (Figures 21–26).

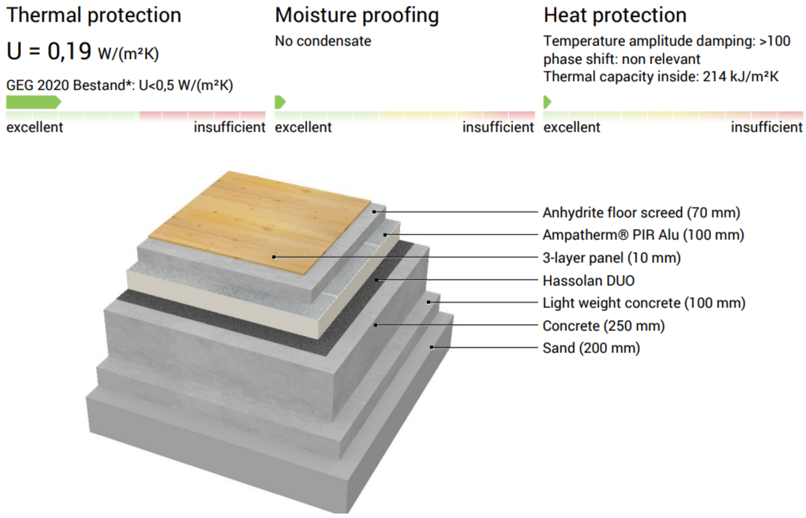


Figure 21. Cross section through the layers of the floor in a wooden frame building according to the applicable building codes regulating the heat transfer coefficient (U) in warm, transitional, and continental climates.

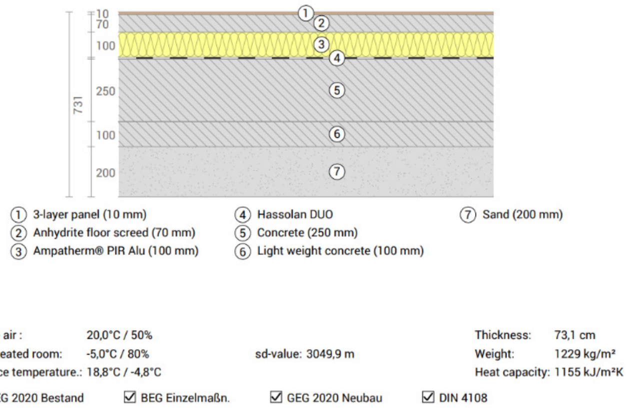


Figure 22. Cross section through the floor layers in a frame building.

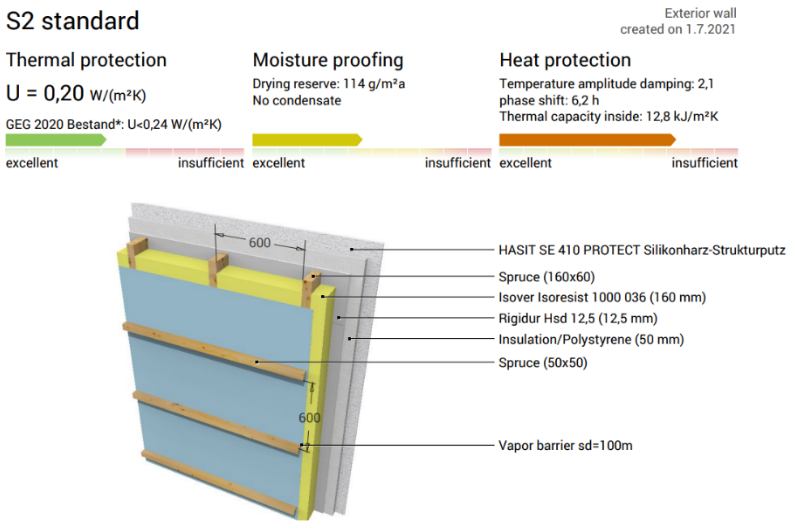


Figure 23. A section through a wall in a standard frame building.

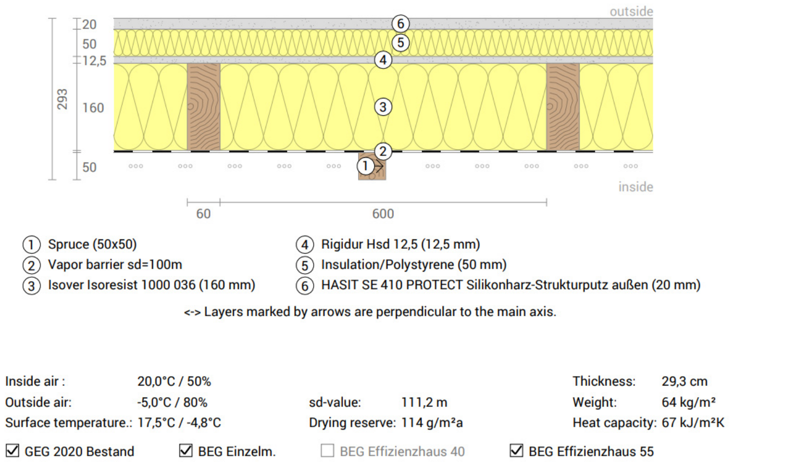


Figure 24. A section showing the wall layers in a frame building.

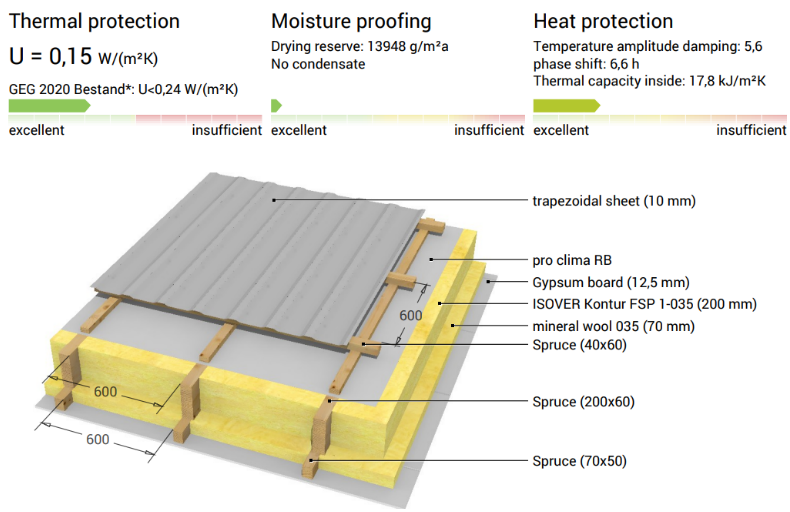


Figure 25. Cross section of a roof structure in a frame building.

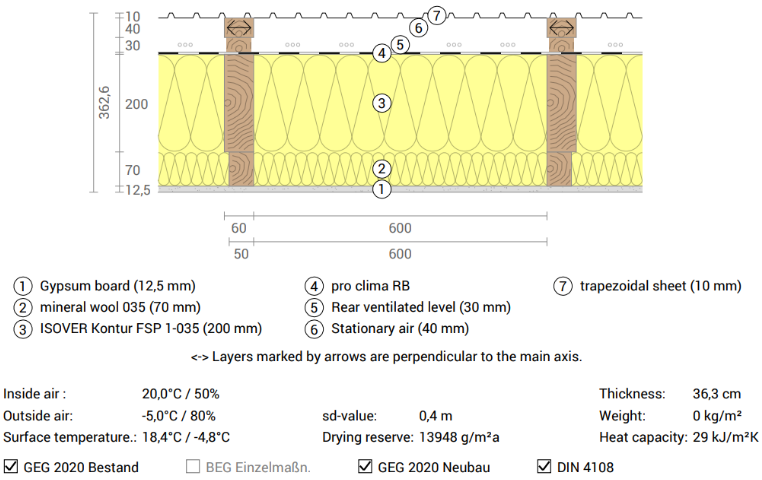


Figure 26. Cross section through the roof layers in a frame building.

The project was made by the DomyExpert company [13]. E2 is currently the minimum basic standard that meets the requirements of European guidelines (and we adopt this standard for example and financial optimization).

These standards can be modified and adjusted to meet the needs and costs of the investor. Basic solutions for the construction of floors and external walls according to the basic variant are presented below (Figure 21).

$$(\text{U coefficient} = 0.2\ \text{W}/(\text{m}^2\cdot\text{K}))$$

The article presents examples of materials that are used by DomyExpert [13] to meet the basic energy efficiency standards (E2), but the customer can choose other solutions.

Alternative materials to polystyrene or mineral wool that exhibit ecologically safe properties and that exhibit thermal insulation properties include:

- wood, the basis of the frame construction;
- earth (popular 'mud-huts' and buildings made in the ground; the ground is a natural thermal isolator);
- straw (the heat transfer coefficient of pressed straw is similar to that of polystyrene and mineral wool, i.e., approx. 0.04 [W/(m^2·K)];
- insulation made of cellulose and cotton fibers; 80% of insulation is made of recycled materials. Cellulose fibers consist of newsprint with the addition of boron salts.

Wood remains the best building material in terms of ecologically safe building materials and is the only building material with a negative CO_2 footprint [38,72]. Good options for eco-friendly insulation include stone mineral wool insulation, cellulose, fiberglass, hemp, cotton (denim), and straw bales [81,82].

5. Economic Aspects of Traditional Timber Construction According to the Most Popular Skeleton Technology

Two types of external walls that exhibit different cross sections and thicknesses and that are composed of different material solutions were compared in terms of cost. For each of the proposed technologies, technical and economic analyses (including analysis of labor costs) were performed (Tables 1–3) to assess the cost of finishing load-bearing walls of a surface area of 100 m^2 from the outside and 95 m^2 from the inside. When comparing skeleton houses based on Scandinavian and Canadian technologies (Figures 14–16), very few differences were noticed, although it should be kept in mind that they can significantly affect the durability of such an object. The conducted technical and economic analyses showed that the costs of finishing the building while maintaining similar heat transfer coefficients and almost identical thermal insulation thicknesses is improved when executing Canadian design, which can be distinguished by a load-bearing wall of a smaller thickness. Taking this into consideration, the question that follows is why Scandinavian technology is still preferred over the technology that originated in North America. The answer can be found in the wall-making technology developed by the inhabitants of Northern Europe. Namely, the gap between the façade and the structure provides an air supply, which allows the wood to breathe and wicks away moisture. The layer of polystyrene, which is impermeable to moisture and attached directly to the OSB board, adversely affects the durability of wood because it causes rotting of structural elements. In addition, the wooden grate used inside, which is filled with an additional layer of mineral wool, allows for the installation within it. It does not damage the vapor barrier and prevents moisture from entering the wooden structural pillars. The characteristic wooden facing from the outside and paneling used from the inside also provide a much faster way to finish projects while simultaneously ensuring the use of ecological materials and the possibility of reconstruction of the building without damage to the permanent elements. These factors therefore speak for the implementation of the designs according to Scandinavian technology and environmentally beneficial wooden construction in general. Economic comparison of the material costs (including the labor) for finishing load-bearing walls of a surface area of 100 m^2 from the outside and 95 m^2 from the inside by a given technology are shown in Tables 1–3 and in Figure 27. The analysis was performed in relation to the actual Polish conditions, as this system has become popular in Central and Eastern Europe (for comparison 1 USD currently translates to 4.45 PLN).

Table 2. The cost of finishing external walls using Canadian technology according to the Polish prices in zlotych (PLN).

Layers of the External Wall	The Amount of Material	Cost of Material [zl]	Labor/Assembly Cost [zl]
Silicone paint	100 m^2	726.20	7500
Mineral plaster	280 kg	569.76	
Adhesive for the grid	500 kg	599.80	
Net	100 m^2	210.00	
Styrofoam 50 mm	100 m^2	1600.00	
Styrofoam adhesive	500 kg	439.80	
Pegs/dowels	240 pcs	75.00	
OSB board12 mm	100 m^2	3497.92	4275
G-K board 12.5 mm	95 m^2	852.15	6650
Filling + cleaning	95 m^2	1077.30	3325
Priming	2 × 95 m^2	39.98	950
Painting	2 × 95 m^2	316.00	2660
The total cost of material and work:		35,363.91	

Table 3. The cost of finishing external walls using Scandinavian technology presented in Polish currency (zloty, PLN).

Layers of the External Wall	The Amount of Material [m^2]	Cost of Material [zl]	Labor/Assembly Cost [zl]
Wooden facing	100	3395.00	35,600
Strips 40 × 60	168	924.00	
Waterproof G-K board 12.5 mm	100	1246.00	
50 mm mineral wool	50	764.15	
Vertical and horizontal distances every 60 cm	346.5	1836.45	
Wooden paneling	95	4738.60	
The total cost of material and work:		48,004.20	

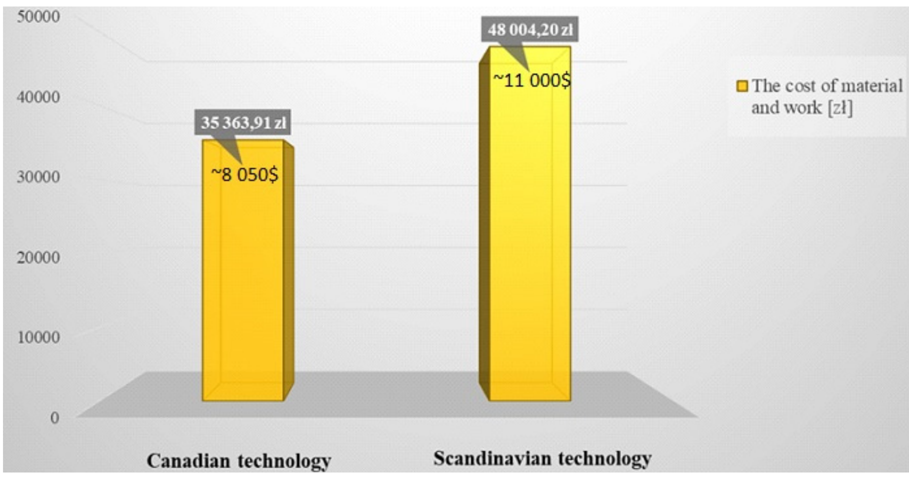


Figure 27. Comparison of the costs of finishing the exterior wall of a skeletal house using to the specified technology.

The displayed prices are estimated and given as of 2021, when, after the pandemic and a temporary stagnation in production, prices of building materials began to rise sharply. It was especially visible on the American market. On 15 April 2021, future prices for deliveries scheduled for May reached 1260.70 USD per 1000 feet of boards (1 mbf = approx. 2.36 m^3) with demand still high. The data show that until 2018, the contract prices of construction timber in the US never exceeded 500 USD/mbf, and a year earlier, they were around 225 USD/mbf. According to the National Association of Home Builders, an association of companies involved in building houses, the increase in wood prices has thus far translated into an average increase in the price of a new home by an average of 24,000 USD (Figure 28, [82]).

Figure 28. Increase in construction timber prices on the US contract market [USD/mbf], photo CME Group [82].

6. Discussion and Conclusions

Wood is a popular material that potentially enable development of ecologically sustainable and cost-effective construction solutions. As the analysis presented in this work shows, it is also a safe material and is preferred in seismic regions, as it is capable of withstanding minor shocks or soil subsidence without cracking the walls. Timber frame buildings are perfect for a versatile climate such as the cool climate observed in North American or Scandinavian countries (providing users with comfortable warm conditions for living, working, and relaxing) as well as in a Mediterranean and subtropical oceanic climate. The presented material was based on Polish standards and prices in PLN (Polish zloty which currently translates to 0.22 USD) and is only an example comparison. Polish construction is trying to adapt Canadian and/or Scandinavian systems especially in the areas subjected to seismic impacts which are linked to mining. Technical report provided by the Institute of Wood Technology titled *Wooden construction as a stimulus for housing development in Poland* states that there are currently 532 companies on the market capable of building wooden houses according to the skeleton system. In addition, 60–80 of these manufacturers can fully prefabricate, and 258 of them build log houses. According to the Central Statistical Office, 905 wooden buildings (940 apartments) were built in Poland last year, which accounts for 1% of the total construction industry [82]. Unlike artificially manufactured products, such as concrete, wood poses no health risks in terms of respiratory illnesses or exposure to the trace elements [83]. Wooden construction is durable, healthy, environmentally friendly, and is an excellent alternative to traditional brick construction. In addition, it is characterized by the high speed of implementation, which is important from a technological and economic point of view, especially now, when the speed of life and transactions is much faster than even ten years ago. Some wooden buildings can last for centuries, which will ensure a perfect symbiosis with nature and society as well as an appropriate quality of life. For this purpose, it is critical to ensure that wood is properly impregnated to maintain its excellent strength properties, pest protection, and aesthetic values. The aim of this article was to present the characteristics of wooden construction and to disseminate information about the possibility of building wooden houses in Europe, using Poland as an example. With the current lifestyle, numerous health, and epidemiological threats, as well as environmental and natural crises in which people are often exposed to stress, wooden construction seems to be a solution beneficial from a technological, ecological, and health point of view. Moreover, it can easily meet the construction standards defined and required by individual countries.

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References

1. Desilver, D. Inflation has risen around the world, but the U.S. has seen one of the biggest increases. *Pew Research Center*. 24 November 2021. Available online: https://www.pewresearch.org/fact-tank/2021/11/24/inflation-has-risen-around-the-world-but-the-u-s-has-seen-one-of-the-biggest-increases/ (accessed on 2 October 2022).
2. Available online: https://forsal.pl/gospodarka/inflacja/artykuly/8493084,inflacja-panstwa-swiat.html (accessed on 2 October 2022).
3. Available online: https://worldpopulationreview.com/country-rankings/inflation-rate-by-country (accessed on 2 October 2022).
4. Stepien, A.; Piotrowski, J.Z. Thermal insulation of autoclaved materials. *J. Phys. Conf. Ser.* **2021**, *2069*, 012037. [CrossRef]
5. Available online: https://www.theweathernetwork.com/ca/news/article/carbon-dioxide-now-at-highest-level-in-human-history (accessed on 11 May 2022).
6. Stefanidou, M.; Kamperidou, V.; Konstandinidis, A.; Koltsou, P.; Papadopoulos, P. 24-Rheological properties of biofibers in cementitious composite matrix. In *Advances in Bio-Based Fiber*; Moving towards a Green Society, The Textile Institute Book Series; Woodhead Publishing: Sawston, UK, 2022; pp. 553–573. [CrossRef]
7. Available online: https://www.eea.europa.eu/pl/themes/human/about-environment-and-health (accessed on 2 October 2022).
8. Neville, A.M.; Brooks, J.J. *Concrete Technology*; Pearson Education: London, UK, 2006; ISBN1 8131705366. ISBN2 9788131705360.
9. Available online: http://www.understandconstruction.com/wood.html (accessed on 3 May 2022).
10. Available online: https://www.britannica.com/science/wood-plant-tissue/Bark-and-bark-products (accessed on 2 October 2021).
11. Szałygin, J. Dziedzictwo drewnianej architektury w Polsce. *Ochrona Zabytków* **2013**, *1–4*, 281–298. Available online: https://ochronazabytkow.nid.pl/wp-content/uploads/2019/08/OZ_1-4_2013_17_Szalygin.pdf (accessed on 16 September 2022).
12. Available online: https://www.muratorplus.pl/technika/izolacje/wspolczynnik-przewodzenia-ciepla-od-czego-zalezy-przewodnictwo-cieplne-materialow-aa-ft7i-XYum-5Wij.html (accessed on 10 October 2021).
13. Available online: https://www.domyexpert.com/ (accessed on 5 May 2022).
14. Available online: https://www.mwconstruction.group/en/blog/new-technical-conditions-WT-2021-check-what-is-changing (accessed on 1 October 2022).
15. Available online: http://cieplej.pl/index_artykuly.php5?dzial=2&kat=8&art=168 (accessed on 5 November 2022).
16. *PN-EN ISO 6946*; Polish and European Standards. Komponenty Budowlane i Elementy Budynku/Components and Emelents of Buildings. Opór Cieplny i Współczynnik Przenikania Ciepła. /Thermal Resistance and Heat Transfer Coefficient/. 2008. Available online: https://www.iso.org/standard/65708.html (accessed on 16 September 2022).
17. Available online: https://receptynadom.pl/lepiej-ocieplac-sciany-zewnatrz-niz-wewnatrz/ (accessed on 3 October 2022).
18. Department of Building and Safety. Wood Frame Prescriptive Provisions one Story Residential Construction Only. Information Bulletin/Public–Building Code Reference No.: LARC, Document No. P/BC 2020-004, Previously Issued As: P/BC 2017-004. Available online: https://www.ladbs.org/docs/default-source/publications/information-bulletins/building-code/wood-frame-prescriptive-provisions-one-story-residential-construction-only-ib-p-bc2011-004.pdf?sfvrsn=9798eb53_48 (accessed on 1 October 2022).

19. Kozioł, W.; Baic, I. *Kruszywa Naturalne w Polsce–Aktualny Stan i Przyszłość/Natural Aggregates in Poland—Current State and Future*; Association of Mining Engineers and Technicians: Katowice, Poland, 2018; Volume 74, pp. 1–8. Available online: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-c90be74b-16a0-4e69-949c-44dc21ec40b1 (accessed on 26 October 2022).
20. Available online: https://cembureau.eu/ (accessed on 3 July 2022).
21. Available online: https://www.bta-czasopismo.pl/wydarzenia/uwolnic-budownictwo-z-kajdan-kongres-urbi (accessed on 3 October 2021).
22. Available online: https://www.stambet-bud.pl/blog/czy-piasek-sie-kiedys-skonczy (accessed on 13 April 2022).
23. Available online: https://wgospodarce.pl/informacje/40559-piasek-na-wyczerpaniu (accessed on 13 April 2022).
24. Available online: https://www.polsatnews.pl/wiadomosc/2021-06-04/na-swiecie-moze-zabraknac-piasku-zniknely-juz-24-wyspy/ (accessed on 13 April 2022).
25. Available online: https://www.rp.pl/biznes/art10117381-surowce-ziemi-zabraknie-piasku (accessed on 2 October 2022).
26. Available online: https://businessinsider.com.pl/technologie/nauka/na-swiecie-konczy-sie-piasekwyczerpuja-sie-zasoby-naturalne/l989njv (accessed on 3 October 2021).
27. Available online: https://www.rp.pl/polityka/art1250151-singapur-sie-powieksza-wiec-malezja-nie-sprzeda-mu-piasku (accessed on 3 October 2021).
28. Available online: https://www.kieruneksurowce.pl/artykul,56090,czy-na-ziemi-zabraknie-piasku.html (accessed on 3 October 2021).
29. Available online: https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/ (accessed on 2 July 2021).
30. Singh, S.; Singh, P.; Rangabhashiyam, S.; Srivastava, K.K. *Global Climate Change*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2021; ISBN1 9780128230978. ISBN2 9780128229286.
31. Available online: https://weatherspark.com/countries/CA (accessed on 26 September 2022).
32. Available online: https://www.coastal.ca.gov/coastalvoices/resources/Biodiversity_Atlas_Climate_and_Topography.pdf (accessed on 16 September 2022).
33. Available online: https://weatherspark.com/y/19863/Average-Weather-in-Toronto-Canada-Year-Round (accessed on 26 September 2022).
34. Available online: https://weatherspark.com/y/52849/Average-Weather-in-Bergen-Norway-Year-Round (accessed on 26 September 2022).
35. Available online: https://weatherspark.com/y/1705/Average-Weather-in-Los-Angeles-California-United-States-Year-Round (accessed on 26 September 2022).
36. Available online: https://pl.fsc.org/pl-pl/certyfikacja-gospodarki-lesnej-fm (accessed on 2 October 2022).
37. Stepien, A.; Potrzeszcz-Sut, B.; Prentice, D.P.; Oey, T.; Balonis, M. The Role of Glass Compounds in Autoclaved Bricks. *Buildings* **2020**, *10*, 41. [CrossRef]
38. Available online: https://domolubni.pl/ekologiczne-materialy-budowlane/ (accessed on 9 November 2022).
39. Available online: https://dzienniknaukowy.pl/planeta/w-tybetanskim-lodowcu-odkryto-nieznane-nauce-wirusy-sprzed-15-tys-lat (accessed on 2 July 2021).
40. Domínguez-Martín, M.A.; Sauer, P.V.; Kirst, H.; Sutter, M.; Bína, D.; Greber, B.J.; Nogales, E.; Polívka, T.; Kerfeld, C.A. Structures of a phycobilisome in light-harvesting and photoprotected states. *Nature* **2022**, *609*, 835–845. Available online: https://www.nature.com/articles/s41586-022-05156-4 (accessed on 22 September 2022). [CrossRef] [PubMed]
41. Sant, G.; Rajabipour, F.; Weiss, J. The influence of temperature on electrical conductivity measurements and maturity predictions in cementitious materials during hydration. *Indian Concr. J.* **2008**, *82*, 7–16.
42. Wang, B.; Krishnan, N.M.A.; Yu, Y.; Wang, M.; Le Pape, Y.; Sant, G.; Bauchy, M. Rradiation-induced topological transition in SiO_2: Structural signature of networks' rigidity. *J. Non-Cryst. Solids* **2017**, *463*, 25–30. [CrossRef]
43. Vance, K.; Falzone, G.; Pignatelli, I.; Bauchy, M.; Balonis, M.; Sant, G. Direct Carbonation of $Ca(OH)_2$ Using Liquid and Supercritical CO_2: Implications for Carbon-Neutral Cementation. *Ind. Eng. Chem. Res.* **2015**, *54*, 8908–8918. [CrossRef]
44. Wei, Z.; Falzone, G.; Wang, B.; Thiele, A.; Puerta-Falla, G.; Pilon, L.; Neithalath, N. The durability of cementitious composites containing microencapsulated phase change materials. *Cem. Concr. Compos.* **2017**, *81*, 66–76. [CrossRef]
45. Oey, T.; Timmons, J.; Stutzman, P.; Bullard, J.W.; Balonis, M.; Bauchy, M.; Sant, G. An improved basis for characterizing suitability of fly ash as a cement replacement agent. *J. Am. Ceram. Soc.* **2017**, *100*, 4785–4800. [CrossRef]
46. Krishnan, N.M.A.; Wang, B.; Le Pape, Y.; Sant, G.; Bauchy, M. Irradiation- vs. vitrification-induced disordering: The case of α-quartz and glassy silica. *J. Chem. Phys.* **2017**, *146*, 204502. [CrossRef]
47. Available online: https://www.swedishwood.com/wood-facts/about-wood/from-log-to-plank/durability-and-resistance (accessed on 2 October 2022).
48. Standard SS-EN 350-2016; Durability of Wood and Wood-Based Products–Testing and Classification of the Durability to Biological Agents of Wood and Wood-Based Materials. 2016. Available online: https://standards.iteh.ai/catalog/standards/cen/b02d18a7-87ce-4a20-84c7-c0de641a2780/en-350-2016 (accessed on 2 October 2022).
49. Available online: https://www.swedishwood.com/wood-facts/about-wood/wood-and-moisture/ (accessed on 3 October 2022).

50. Nagarajappa, G.B.; Pandey, K.K. UV resistance and dimensional stability of wood modified with isopropenyl acetate. *J Photochem. Photobiol B* **2016**, *155*, 20–27. [CrossRef]
51. Żenczykowski, W. *Budownictwo Ogólne. T.1. Materiały i Wyroby Budowlane*; Arkady: Warszawa, Poland, 1976.
52. Żenczykowski, W. *Budownictwo Ogólne–Tom 1–Materiały i Wyroby Budowlane*; Arkady: Warszawa, Poland, 2005; ISBN 978-83-213-4334-1.
53. Żenczykowski, W. *Budownictwo Ogólne–Tom 3–Elementy Budynków, Podstawy Projektowania*; Arkady: Warszawa, Poland, 2008; ISBN 978-83-213-4557-4.
54. *PN-EN Standards: 338*; Drewno Konstrukcyjne-Klasy Wytrzymałości. /Wood Constructions-Wood Grades/. 2004. Available online: https://mann.eu.com/dane/cms/klasy_drewna_pn-en.pdf (accessed on 3 October 2022).
55. Polyzois, D.; Kell, J.A. Repair and rehabilitation of wood utility poles with fibre-reinforced polymers. *Can. J. Civ. Eng.* **2011**, *34*. [CrossRef]
56. Miller, D.J.; Jiang, D.; Ruest, K.L.; Dales, R.E. The impact of wood heating in houses on airborne endotoxin and sustainable heating in rural forested areas. In Proceedings of the 12th International Conference on Indoor Air Quality and Climate, Austin, TX, USA, 5–10 June 2011.
57. Available online: https://muratordom.pl/budowa/domy-drewniane/domy-drewniane-zdrowe-i-szybkie-w-budowie-domy-z-drewna-aa-dPHc-F7BX-gKxM.html (accessed on 27 February 2022).
58. Available online: https://www.drewhome.com.pl/technologia-historia (accessed on 26 February 2022).
59. Matyskiewicz, J. *Konstrukcja Budynków w Szkielecie Drewnianym*; Amerykańsko-Polski Instytut Budownictwa/American-Polish Building Institute: Gdańsk, Poland, 1995.
60. Available online: https://fachowydekarz.pl/analiza-porownawcza-przyporzadkowania-klas-wytrzymalosciowych-drewna-konstrukcyjnego-klasom-wizualnym-dawniej-i-dzis (accessed on 9 October 2022).
61. Cmhc—Home To Canadians. Available online: https://chbanl.ca/wp-content/uploads/CMHC-Canadian-Wood-Frame-House-Construction.pdf (accessed on 2 October 2022).
62. Available online: https://www.nrcan.gc.ca/our-natural-resources/forests/industry-and-trade/forest-products-applications/mass-timber-construction-canada/23428 (accessed on 2 October 2022).
63. Available online: https://www.geni.com/people/George-W-Snow-inventor-balloon-frame-construction/6000000004957932184 (accessed on 27 February 2022).
64. Available online: https://www.mgprojekt.com.pl/blog/dom-szkieletowy/ (accessed on 2 May 2022).
65. Available online: https://legacyusa.com/blog/truss-roof-vs-rafters/ (accessed on 2 October 2022).
66. Available online: https://www.glessnerhouse.org/story-of-a-house/tag/George+Washington+Snow (accessed on 5 December 2021).
67. Available online: http://domykanadyjskie.com/historia-technologii/ (accessed on 9 August 2021).
68. Available online: http://www.drevohaus.pl/?drev=technologia_produkcji (accessed on 5 September 2022).
69. *PN-B-02361*; Polish and European Standards. Pochylenia Połaci Dachowych./Roof Pitch/. 2010. Available online: https://sklep.pkn.pl/pn-b-02361-2010p.html (accessed on 16 September 2022).
70. Piróg, M.; Chądzyński, A. Development Prospects for Traditional Construction Wooden/Perspektywy Rozwoju Tradycyjnego Budownictwa Drewnianego. *Teka Kom. Arch. Urb. Stud. Krajobr.-OL PAN* **2010**, *6*, 73–78. Available online: http://old-panol.ipan.lublin.pl/wydawnictwa/TArch6/Pirog.pdf (accessed on 16 September 2022).
71. Available online: https://ratajewski.com/www/dom_szkieletowy_po_szwedzku_czy_kanadyjsku/ (accessed on 5 December 2021).
72. Available online: https://www.domoweklimaty.pl/czytelnia/plyty-pilsniowe-i-wiorowe-wady-i-zalety-rodzaje-plyt-budowlanych-wielowarstwowych (accessed on 10 November 2022).
73. Available online: http://www.tyble.pl/index.php/porady/192-wilgotnosc-drewna-1.html (accessed on 4 May 2022).
74. Available online: https://www.finehomebuilding.com/project-guides/framing/laying-out-and-detailing-wall-plates (accessed on 2 October 2022).
75. Available online: https://www.engineersedge.com/thermodynamics/overall_heat_transfer-table.htm (accessed on 3 October 2022).
76. Available online: https://weatherspark.com/y/87583/Average-Weather-in-Warsaw-Poland-Year-Round (accessed on 3 October 2022).
77. Soteris, A. Kalogirou Solar Energy Engineering. *Process. Syst.* **2009**, 121–217. [CrossRef]
78. Available online: https://www.instalacjebudowlane.pl/10838-33-68-standard-wt-2021--wymagania-warunki-techniczne.html (accessed on 8 September 2022).
79. Available online: https://www.drewno.pl/artykuly/12103,domy-drewniane-moga-w-przyszlosci-stanowic-w-polsce-nawet-jedna-piata-budynkow.html (accessed on 9 October 2022).
80. Available online: https://ozeprojekt.pl/standard-wt-2021-wymagania/ (accessed on 8 September 2022).
81. Available online: https://www.leafscore.com/eco-friendly-living-products/the-best-materials-for-eco-friendly-insulation/ (accessed on 10 November 2022).
82. Dominik Jabłoński Wood Industry Increase in the Price of Saw Blades in the USA Causes Difficult Deliveries in Poland. Drewno.pl. Available online: https://www.drewno.pl/artykuly/12061,wzrost-cen-tarcicy-w-usa-powoduje-trudnosci-z-dostawami-w-polsce.html (accessed on 8 September 2022).
83. Krechowicz, M.; Piotrowski, J.Z. Comprehensive Risk Management in Passive Buildings Projects. *Energies* **2021**, *14*, 6830. [CrossRef]