Potential Advancement in Energy Efficient and Passive Buildings under Different Climate Conditions – a Comprehensive Analysis of Dominant Parameters

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Abstract

Energy consumption in the building sector has been on the rise recently. In addition, buildings are considered a major contributor to greenhouse gas emissions. To ensure sustainability, building energy efficiency is crucial. Passive house standard is a voluntary standard for major energy saving potential in buildings. This potential can be generally realized through building envelope insulation and more efficient mechanical systems. However, energy efficiency and indoor air quality for occupants can not always be concurrently fulfilled. The current paper presents a comprehensive review of energy saving and indoor air quality studies in passive buildings under different climates. It highlights the main operating parameters that ensure the feasibility of occupant comfort in energy efficient passive buildings. It also highlights the challenges and the limitations that need to be considered. The paper aims to provide guidance for the optimum conditions to achieve comfortable passive buildings worldwide.

1. Introduction and literature review

Buildings consume more than a third of the annual energy consumption worldwide [1-2]. People spend a large portion of their day indoors. This makes the occupant comfort crucial in different building applications [3-4]. This will not be guaranteed except with efficient heating and cooling systems that can contribute up to 70% of building energy consumption [5].

There has been a lot of focus in the recent years towards building energy efficiency [6]. The two main motives are to reduce the running cost and to ensure a better environmental impact [7]. The active technologies to achieve this were mainly directed to mechanical systems of heating and cooling, and electrical systems as well [8-10]. The passive technologies include the internal gains control [11-12]. Both categories have shown a promising potential to achieve energy efficiency.

Passive houses have been considered in efficient buildings research for the past few decades [13]. European countries have been leading in the passive house technology [14]. It has been shown that passive house was able to achieve up to 80% reduction in heating energy consumption and 50% less overall energy consumption [15]. For a house to be considered passive, the following criteria need to be met [16]:

- Space heating yearly energy demand is less than 15 kWhr/m^2.

- Air tightness is less than 0.6 ACH at 50 Pascals.
- Indoor temperature does not exceed 25 ºC for more than 10% of the year.

In 1990, the first passive house was constructed in Darmstadt, Germany [17]. After six years, the passive house institute was also founded in Germany to help with the widespread integration of passive houses technology. The number of passive houses started to grow since then. The latest number published by the international passive house institute is 47400 passive houses worldwide [18].

Passive house standard requirements are considered aggressive compared to the traditional building code. Figure 1 shows a comparison between energy use and yearly greenhouse gas emissions in traditional building, low energy building and the passive house [18]. As shown from the figure there is a significant decrease in energy use and emissions between the traditional building and the passive house. Passive house is considered also superior to a low energy building. It has less than 20% of low energy building energy use. It also offers a noticeable reduction in greenhouse gas emissions.

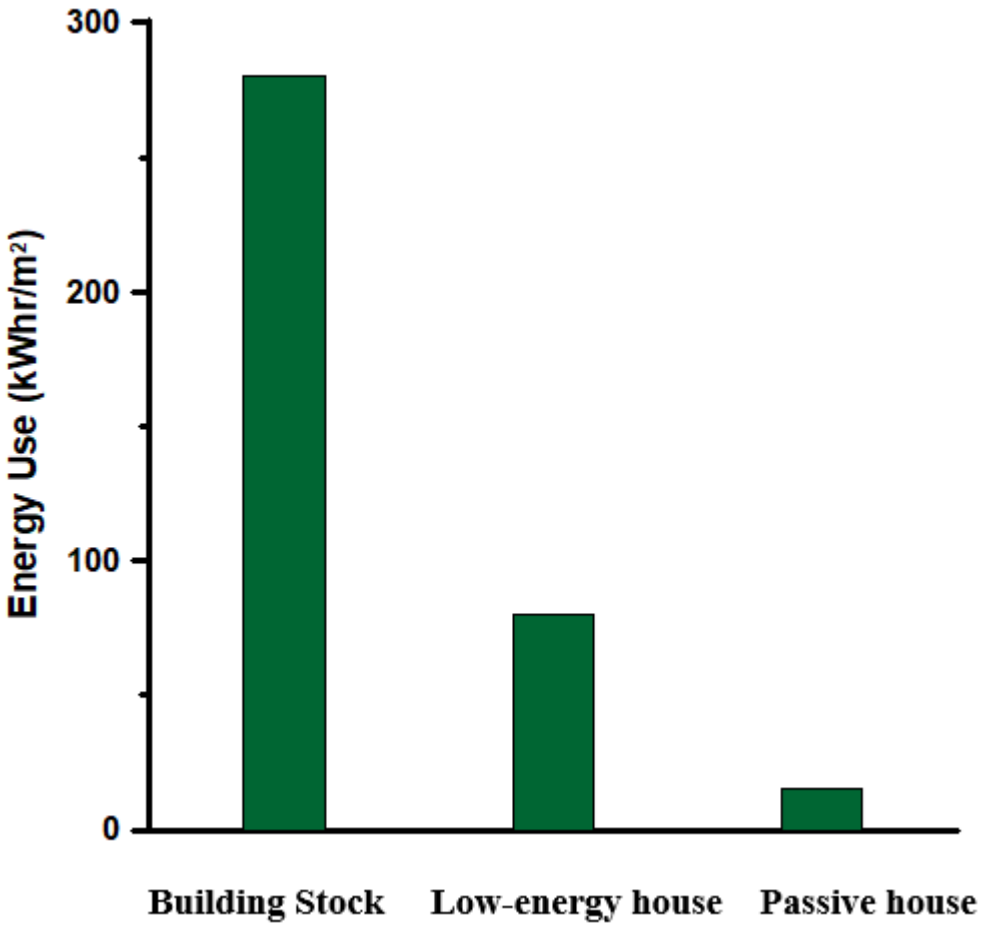

Figure 1: Comparison of energy use and greenhouse gas emissions of traditional buildings, low energy buildings and passive houses [18].

Several research has focused on the required efficiency for mechanical systems to achieve the passive house requirements. Dodoo et al. [19] investigated the effect of ventilation heat recovery integration in passive buildings in Swedish climate. They found that the district heating system with biomass has 30% less energy use compared to electric heating. This highlights the importance of efficient mechanical system for low energy use. In addition, life cycle analysis has shown its better environmental impact. The ventilation heat recovery system integration has provided additional reduction to the energy use as well.

Passive house requirements were also applied to a rehabilitated office building in Europe [20]. It was done by integration of ground heat exchanger and night time ventilation. The phase change materials were integrated to the walls and the ceiling of the building. As they have a relatively higher storage capacity, they were able to maintain a uniform indoor comfort temperature. The thermal comfort was monitored during the summer months to ensure that overheating is not significant. 10.6% of the hours of the year had an indoor temperature that is greater than 26 ^{o}C.

In cold climates, Georges et al. [21] investigated numerically the air heating of passive houses. They focused on the impact of internal gains, temperature differences between the rooms and thermal losses. Four cold climate zones were considered in the analysis. Their results have shown the limitations associated with centralized air heating system integration. They provided valuable recommendation for consistent air heating in cold climates.

Other research has focused on achieving indoor comfort conditions in passive buildings. P. Rohdin et al. [22] performed a post occupancy evaluation of the indoor air quality in nine passive homes. They shed the light on the significant energy saving in passive buildings. However, under some conditions, passive buildings can have higher indoor temperature than traditional buildings. In the nine buildings considered in the analysis, the average indoor temperature was maintained at 24 ^{o}C. Mlakar and Strancar [23] reported that indoor comfort conditions were maintained the majority of time in Slovenia. However, when the weather is very hot during the summertime, the indoor air temperature can increase to be as as high as 27 ^{o}C.

There has been numerous research work reported on different energy saving measures in passive houses [24]. A lot of research has been also done on the indoor air quality in passive buildings [25]. However, very scarce research has been reported on the coupling of energy efficiency and indoor air quality in passive buildings. The current paper will provide a detailed review on the topic. Such analysis methodology has not been reported before. A comprehensive parametric analysis will be presented in the following sections for the effect of building envelope design and orientation, occupant behavior, mechanical system operation on energy efficiency and indoor air quality in passive buildings.

2. Dominant parameters affecting passive house performance under different climatic conditions

2.1. Building envelope and orientation effect on passive house performance

Building envelope is the main shield between the building and the surrounding. A typical building envelope structure is shown in figure 2. It consists of exterior cladding, different control layers and

the structure. The perfect envelope need to have a good control of air, heat, rain and moisture [26-27]. The envelope needs to be airtight as air leakage is considered a major energy loss. The heat transfer needs to be mitigated specially in harsh climates. Rain and moisture have an adverse effect on the structural integrity of the building envelope. Numerous research work has been directed to innovative technologies that make the envelope more robust under different climate conditions [28-29]. From the prospective of passive ultralow energy building, a tight well insulated building envelope is of utmost importance. The highly efficient design of the building envelope can greatly simplify the needed heating system for building and hence can achieve up to 80% reduction in space heating demand and 50% reduction in primary energy consumption [30].

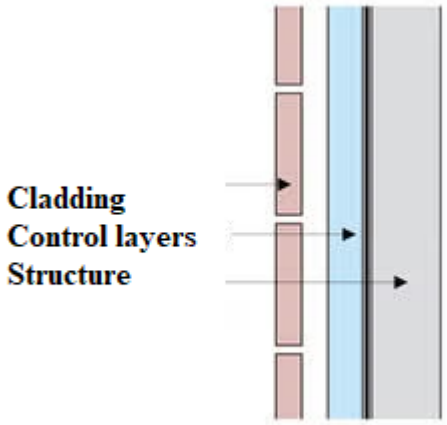

Figure 2: A typical building wall structure.

Mlakar and Strancar [23] analyzed the overheating problem that can happen in single family homes in Solvenian climate. They found out that the problem can happen frequently during the hot summer months. They performed a thorough data analysis that has shown the energy reduction potential in passive house. It also highlighted the main contributors to the increase of overall temperature. Among them, building envelope parameters seem to be dominant. Opening windows at night appeared to be effective in reducing overheating. In addition, the application of shading to the southern and western windows allowed for better indoor comfort temperature.

Katunský and Lopušniak [31] proposed a numerical solution to solve the overheating problem in a low energy passive house. The solution method included two complementing approaches. The first includes optimization technique for the shading using visualization tools. The second includes a detailed tracking for the sun path to optimize the shading design. They found out that building orientation and construction material are the most effective parameters to overcome the overheating problem. Wolfgang et al. [32] has shown different thermal imaging for a traditional building and a low energy passive building. The passive building thermal imaging has shown a lot more uniform temperature profile. In their study, they highlighted that the main trouble points that can cause problems in a passive house are the glazing and thermal insulation.

Figueiredo et al. [33] used EnergyPlus to model passive house performance in Portugal climate. They found a potential heat load reduction of 62%. They have investigated several parameters to overcome overheating. The light steel framing and shading were found to be effective in reducing

overheating by 4.4%. Figueiredo et al. [34] presented a multiobjective optimization technique to relate energy saving potential to thermal comfort in passive house in Portugal. They were able to achieve up to 42% reduction in consumption while complying with passive house indoor comfort standard.

Vettorazzi et al. [35] simulated three single family buildings in three climate zones in Brazil. They found out that the glazing percent and proper shading are the keys to ensure indoor thermal comfort in all buildings. They were able to get a heating load reduction of up to 91% when glazing percent was 39%. This ensures that proper building envelope design is the key for efficient passive house performance. Teixeira et al. [36] provided a comprehensive literature review on smart modern glazing systems. They considered different climates in their analysis. They emphasized that the traditional glazing can have thermal losses that are major sources of building energy inefficiency. They reported that electrochromic and thermochromic glazing are the most energy efficient. They are well suited to ensure the indoor thermal comfort in the passive house. Guo et al. [37] performed optimization analysis on maintaining thermal comfort in passive house in the Chinese climate. They found out that by limiting the window opening area throughout different times of the day can stabilize the indoor temperature to be around 18 ^{o}C which makes occupants comfortable in the building.

In India climate, Chanda and Biswas [38] investigated the impact of building envelope material on energy saving potential in passive house. They used Design Builder and Energy Plus in their simulations. They were able to attain comfort conditions within 1% of ASHRAE threshold. Obrecht et al. [39] investigated the optimum glazing percent in passive houses in European climate. Under wide climate conditions a percent between 38% and 42% resulted in the best energy saving potential while maintaining the indoor thermal comfort conditions. Menard and Souviron [40] investigated the potential of passive solar heating with glazing. They emphasized that although it is beneficial in cold weather, it is an additional load in summer. The architectural design needs to be taken into account with careful consideration. In addition, adjustable shades can offer a better way of managing thermal loads. Cao et al. [41] have concluded that BIM modelling is very efficient in preventing overheating. Under Chinese climate, the optimization of building envelope can limit the maximum indoor temperature to 25 ^{o}C at noon in the summer solstice.

Amoruso and Schuetze [42] used passive house planning package to asses the potential of timber in three passive buildings in Korea climate. They found that timber offers good reduction in greenhouse gas emissions. However, they pointed out that achieving carbon neutrality is more difficult in multiresidential buildings compared to single family homes due to the higher envelope heat losses. Norouzi et al. [43] assessed the great potential of timber in United Kingdom climate through life cycle analysis. They found out that there can be up to 51% reduction in whole lifecycle carbon relative to using traditional material.

The majority of studies were focused on temperature analysis in passive house. Scarce research was reported on humidity levels. Pukhkal et al. [44] conducted this analysis in Serbia Climate. They found that the risk of condensation increases as outdoor temperature is below -6 ^{o}C. An additional gypsum layer added to inner side of room reduces the risk of condensation.

There has been numerous studies on energy efficient buildings and advanced techniques to promote energy savings [45-46]. One technique that was found to be promising is the integration of phase change materials [47-49]. Phase change materials (PCMs) are different substances that store heat and release it through phase change process. The phase change latent heat is very high compared to sensible heat. This offers the compact storage advantage [47]. In addition, phase change happens at a constant temperature which offers system temperature modulation. PCMs can be: organics, inorganics and composites. Organics were found to be the most suitable for building applications. They are subcategorized to paraffin and fatty acids [47]. They have numerous good features as being non corrosive and have stability under several charging and discharging cycles. Figure 3 shows the main applications of phase change materials in buildings. Due to their high latent heat, they are considered to be a great thermal energy storage for the envelope. The additional PCM layer adds proper insulation to the building. It is also used in passive heating and cooling applications due to the efficiency in charging and discharging heat through the PCM. As they are of set phase change temperature, this aids in temperature regulation within the building to ensure it is within the thermal comfort recommendations. In addition, they are very effective when integrated to solar panels due to their promising storage potential.

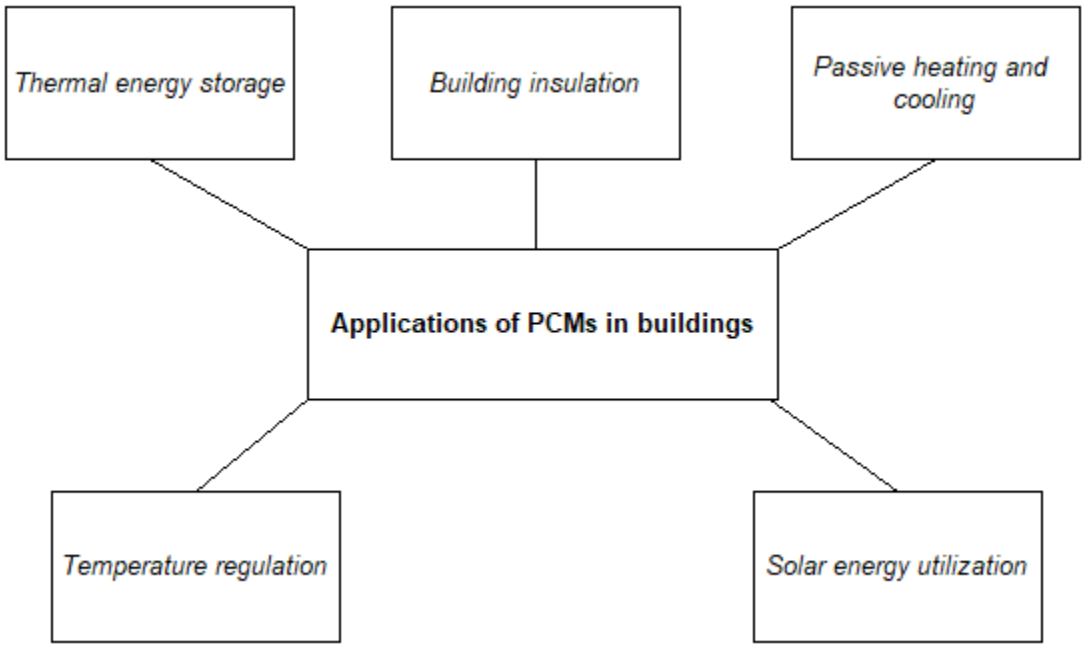

Figure 3: Applications of PCMs in buildings.

Abass and Muthulingam [50] provided a comprehensive review of PCM integration in building applications. The integration to building envelope has shown promising potential in energy saving and carbon reduction in different climates. However, they pointed out that life cycle cost needs to be carefully considered. Zhang et al. [51] provided a detailed review of different modes of PCM integration to building like layer addition, Trombe wall and its integration to photovoltaic. They found a promising reduction of energy consumption of up to 32% in different climates. They also reported higher degree of thermal comfort. Leibnitz et al. [52] found a promising potential of

composite wood phase change material to maintain comfort temperature in passive buildings. They found that it dampens temperature variation around the phase change temperature. They also reported the high potential of greenhouse gas emissions mitigation using this technology.

Li et al. [53] analyzed the feasibility of PCM layer integration in rural passive houses in China. They considered the varying outdoor conditions in different climate zones. They found that the optimal PCM melt temperature was higher when the average outdoor temperature was higher. PCM yielded the highest benefit in colder climate zones. It was able to maintain the comfort temperature up to 90% of the time. Khayyaminejad and Fartaj [54] investigated the potential of adding n-Henicosane layer to walls of a residential building located in Windsor, Ontario. Despite the cold weather, they found that the PCM addition contributed to a daily saving of 3.5% of building energy. Persson and Westermark [55] investigated the potential of PCM utilization as cool storage. They used real climate files for a Swedish passive house. The house experienced excessive overheating during summer. The addition of PCM was simulated in MATLAB. PCM reduced the overheating hours significantly which enhanced occupant comfort.

Photovoltaic integration has also shown a great potential for energy efficient buildings [56-57]. It provides energy savings and GHG reduction potential. However, the cost needs to be taken into careful consideration. Nkado et al. [58] investigated the potential of adding photovoltaic panels to passive house to reduce the carbon footprint. They highlighted that although there is a great potential, there are still significant hurdles that need to be taken into account. They include: the high installation cost, the variability between as built and design conditions and also the climate specific challenges. The feasibility is very dependant on the location.

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2.2. Occupant behavior effect on passive house performance

Passive house performance is strongly impacted by the occupant load. Different occupancy density and profiles affect the comfort in passive buildings. Mach et al. [59] performed a comparison of performance of single family house and a multiunit residential building. The potential of energy saving in the multiunit residential building was a lot higher compared to the single family home. This is due to the higher occupant density in multiunit residential building.

Wang et al. [60] presented an analysis for the indoor air quality and energy performance in an efficient school building. The performed their analysis numerically by considering six design points and two scenarios. They found out through optimization the dominant parameters on building performance. The parameters are occupancy, indoor set point and heat recovery rate.

Ridley et al. [61] compared the performance of two adjacent passive homes located in the Welsh climate. Their net greenhouse gas emission percent was 13% and 33%. The occupants' decision on operating electrical appliances had a noticeable effect on the emissions saving potential. In addition, the glazing area and installation of photovoltaic panels were very effective in reducing energy consumption and GHG emissions.

Blight and Coley [62] presented a regression analysis method to correlate energy consumption in 100 passive houses to internal loads. They used realistic semi-empirical profiles to account for

lights, equipment and occupancy loads. They implemented multiple regression methods to enhance the results accuracy.

Foster et al. [63] investigated the problems that face the Scottish passive houses. They found that behavioral variables can lead to overheating in the summer months. They studied the major influencers on energy consumption. They found that the unbalanced mechanical ventilation has attributed to 80% of the problems.

Sameni et al. [64] investigated the overheating risk in social housing in England. Their study considers 25 flats indoor temperature analysis in three cooling seasons in Coventry, UK. They found that two third of the flats experienced overheating. The analysis emphasized that this was more related to occupant behaviour than the building construction. Rawi and Al-Anbuky [65] developed a sensor network model to assess how occupant behaviour affect thermal comfort in a living space. They considered the environment to be the static node and occupants to be the dynamic nodes. They correlated the predicted mean vote to the occupant activity and environmental conditions. Predicted mean vote has values ranging from -3 to 3 [66]. A value of Zero is considered the optimum. Predicted mean vote ranging from -0.5 to 0.5 is considered to be comfortable for occupants.

Karimipanah et al. [67] investigated the thermal comfort in a two floor school. They varied the ventilation methods and investigated how it affected thermal comfort in the classroom through 56 CFD cases. They found the CFD results to be in agreement with the experimental data. Noh et al. [68] investigated the thermal comfort in a lecture room with 4-way cassette air-conditioner. They performed an analysis of predicted mean vote to ensure comfort. They found that increasing the discharge angle has an adverse effect on the indoor thermal comfort. Cwf and Kim [69] reviewed the different standards that focused on energy efficiency and indoor air quality. They reported that building research establishment environmental assessment method (BREEAM) has its core focus on the building energy efficiency. On the other hand, LEED focuses more on indoor environmental quality in sustainable buildings. Proper air conditioning and occupant activities are critical in achieving energy efficiency and indoor air quality in sustainable buildings especially in tropical climates [70].

2.3. Building mechanical system effect on passive house performance

Mechanical system has an important role in ensuring the indoor air quality in different passive buildings. Ventilation is considered the most crucial. Without adequate ventilation, vulnerable occupants in particular are at higher risk. The studies included both traditional methods and innovative methods that can be integrated into the building systems [71]. There are also different simulation packages that can be used to assess the energy saving from the HVAC systems. One of them is the computational fluid dynamics (CFD) that is able to assess the temporal and spatial variations of the temperature and indoor air quality parameters. Those link directly to the quantification of energy saving [72].

Liu et al. [73] investigated the turbulent transport of indoor air pollutants in a residential room. They found that the indoor comfort is significantly enhanced by increasing the fresh air percent and the incoming air filtration efficiency. The best outcome can be theoretically achieved by

having 100% fresh air. However, the economic aspect needs to be taken into account. Achieving a predicted percentage dissatisfied index less than 20% is considered satisfactory [74]. This means that less than 1 in five occupants in a certain space might feel not comfortable. Steiger et al. [75] studied the carbon dioxide distribution in naturally ventilated high occupancy room. They found that the buoyancy effect was able to diminish the carbon dioxide concentration away from the source towards the ceiling. The proper simulation of air flow patterns can ensure the thermal comfort within the room. Wang et al. [76] investigated the thermal comfort conditions in a passive building of a public school located in south Germany. They found that the heat recovery unit addition to the air conditioning system can enhance thermal comfort. They found an effective energy saving measure was to use the heat recovery system to precool the building during the night. The design of an effective control system is the most powerful way to guarantee indoor comfort [77]. The passive building includes a lot lower heat losses compared to the traditional building which includes much higher heat losses compared to the passive building. Building automation systems need to be integrated to ensure that individual spaces within large buildings are receiving the adequate amount of ventilation. Continuous monitoring of temporal variations in temperatures and humidity can be used to program alarm systems with corrective actions to the HVAC system operation [78]. The dynamic interaction between the internal load and efficient HVAC system must be considered for long term energy efficient operation.

Rohdin et al. [79] performed post occupancy evaluation of passive houses located in Sweden. They included 39 newly built terrace homes in their analysis, nine of them were built according to the passive house standards. They collected onsite data and performed CFD simulations in their analysis. They found that the passive homes were likely to experience cooler floors relative to the traditional homes. They also found that the passive homes experience higher indoor temperature during the summer months. This dictates a more efficient design for the ventilation system to reduce the overheating extent. Schnieders [80] provided a comprehensive analysis for 14 passive houses with 221 dwelling units built across Europe according to passive house standard. They reported the great potential of energy efficient passive buildings in having 80% less energy consumption compared to traditional buildings. This was mainly attributed to the more efficient HVAC operation. An average indoor temperature of 21.4 ^{o}C was maintained the majority of time. There was rare overheating days during the hot summer season.

Schnieders and Hermelink [81] presented the analysis of 11 passive houses with 100 dwelling units. They found that the passive house heating demand to be 15%-20% of the conventional buildings. The primary energy consumption was 50% less than conventional building. The incurred extra cost was only 10% for integrating the energy efficient measures. Dodoo et al. [82] investigated the effectiveness of ventilation heat recovery integration to residential buildings in Sweden. Although it increases the electric energy consumption, it reduces space heating energy use. The effect is more pronounced when the ventilation heat recovery is added to resistance heated buildings compared to those that are district heated. Fouih et al. [83] found similar results for integrating the heat recovery to the dwellings in France. This is considered of special importance as the energy consumption in dwellings is 40% of the total building consumption. Fux et al. [84] reported the effectiveness of model predictive control to model passive house performance in Switzerland. They found that the weather effect and lumped representation of different building

systems were able to produce robust results. The temperature predictions in the model were within 1 ^{o}C for two days period and within 3 ^{o}C for four days period.

Puteh et al. [85] surveyed the thermal comfort in schools located in warm and humid climate. They found that higher temperature can be prevalent in naturally ventilated buildings in such climate. This necessitates better control for the HVAC system operation in such high internal heat load buildings. Wang et al. [86] presented an analysis for energy efficiency and thermal comfort in school buildings located in Germany. They assessed the feasibility of the integration of heat recovery heat pump and displacement ventilation system. They performed an analytical model and presented correlations for the results. They found out that with proper operation, energy efficiency and thermal comfort aligning with the standards [87] can be guaranteed. Krüger and Givoni [88] performed an analysis for a passive two storey dorm building of a university located in Israel. They did a separate analysis for the indoor temperature during the summer and the winter seasons. They developed correlations to link the indoor temperature to the outdoor variation in temperature. They validated the data with field measurements. The models have shown a very good agreement with the measured data. Chel and Tiwari [89] performed an analysis of ecofriendly passive house located in India climate. There was a great potential of energy saving in heating and cooling of about 1481 kWh/year and 1813 kWh/year respectively. The reduction of carbon dioxide emissions was found to be 5.2 metric tons/year.

The measure of CO_2 concentration is an important metric to ensure that indoor air quality is met [90]. A concentration of more than 1400 ppm is threatening for the occupant comfort [91]. Recent research has reported that 74% of the houses that are built according to the passive house standard never experienced a CO_2 concentration of higher than 1200 ppm [92]. The use of mechanical ventilation with the heat recovery system is effective in bringing CO_2 concentration down. Bedrooms are typically the areas of highest CO_2 concentration. The peak concentration ranges from 800-1500 ppm at night. The high concentration is usually attributed to high density of occupants in those areas [93]. Total volatile organic compounds concentration was also found to be a lot lower when comparing passive houses to conventional homes (300 µg/m3 in and 560 µg/m3 in conventional homes respectively [94].

3. Summary of research findings

This section summarizes the research outcomes discussed in the previous sections. Passive houses have shown a great potential for energy saving compared to traditional buildings. However, thermal comfort need to be considered as overheating problems were reported in numerous research work. To guarantee energy saving and thermal comfort, three major parameters need to be considered. They are: building envelope specifications, occupant behaviour and mechanical system efficiency. Table 1 highlights the main findings of research that concentrated on building envelope parameters. As seen from the table, the high resistance of walls is very effective in better passive house indoor comfort conditions. Phase change materials are effective in increasing the envelope thermal mass which translates to better indoor comfort. In addition, glazing is considered very important. There needs to be careful optimization for its parameters in different climates.

Table 2 summarizes the effect of occupant behaviour on thermal comfort in passive houses. It seems that occupant decision regarding the electrical equipment operation has a noticeable effect on indoor comfort. In addition, opening windows and doors in random manner can adversely impact the thermal comfort. Table 3 includes the research related to the mechanical systems efficiency. It is evident that adequate ventilation is crucial to maintain thermal comfort in different climates. Heat recovery ventilators are very efficient energy saving measures. Special consideration need to be taken into account when modelling buildings with high internal loads like schools. In those buildings, the passive building performance is highly sensitive to the ventilation pattern. Building management systems are the most efficient way to guarantee thermal comfort in buildings.

Table 1: Research considering the building envelope parameters effect on passive house performance

Study	Location	Methodology	Main findings
Mlakar and Strancar [23]	Solvenia	Thorough data analysis	- Proper glazing is effective in reducing overheating. - Shading to the southern and western windows allowed for better indoor comfort temperature
Katunský and Lopušniak [31]	Slovakia	Optimization technique for the shading using visualization tools.	- Building orientation and construction material are the most effective parameters to overcome the overheating problem.
Wolfgang et al. [32]	Germany	Thermal imaging	- Main trouble points that can cause problems in a passive house are the glazing and thermal insulation.
Figueiredo et al. [33]	Portugal	EnergyPlus modelling	- The light steel framing and shading were found to be effective in reducing overheating by 4.4%.
Figueiredo et al. [34]	Portugal	Multiobjective optimization	- Proper envelope parameters can guarantee up to 42% reduction in energy consumption.
Vettorazzi et al. [35]	Brazil	Numerical model	- Space heating load reduction of up to 91% can be achieved when glazing percent was 39%.
Teixeira et al. [36]	Different climates	Comprehensive review	- Electrochromic and thermochromic glazing are well suited to ensure the indoor thermal comfort in the passive house.
Guo et al. [37]	China	Optimization analysis	- Limiting the window opening area throughout different times of the day

			can stabilize the indoor temperature to be around 18 ^{o}C.
Chanda and Biswas [38]	India	Design Builder and Energy Plus	- Proper envelope material can retain comfort conditions within 1% of ASHRAE threshold.
Obrecht et al. [39]	European climate	Optimization analysis	- Under wide climate conditions a percent between 38% and 42% resulted in the best energy saving potential while maintaining the indoor thermal comfort conditions.
Menard and Souviron [40]	European climate	Numerical model	- Adjustable shades can offer a proper way of managing thermal loads and avoiding overheating.
Cao et al. [41]	China	BIM modelling	- The optimization of building envelope can limit the maximum indoor temperature to 25 ^{o}C at noon in the summer solstice.
Amoruso and Schuetze [42]	Korea	Passive house planning package model	- They found that timber offers good reduction in greenhouse gas emissions. - Achieving carbon neutrality is more difficult in multiresidential buildings compared to single family homes due to the higher envelope heat losses.
Norouzi et al. [43]	United Kingdom	Life cycle analysis	- They found out that there can be up to 51% reduction in whole lifecycle carbon relative to using traditional material.
Pukhkal et al. [44]	Serbia Climate	Numerical model	- They found that the risk of condensation increases as outdoor temperature is below -6 ^{o}C. - An additional gypsum layer added to inner side of room reduces the risk of condensation. -
Abass and Muthulingam [50]	Different climates	Review	- The integration of PCMs to building envelope has shown promising potential in energy saving and carbon reduction in different climates. - Life cycle cost needs to be carefully considered.

Zhang et al. [51]	Different climates	Review	- Promising reduction of energy consumption of up to 32% can be achieved in different climates.
Leibnitz et al. [52]	Switzerland	Experimental	- Promising potential of composite wood phase change material to maintain comfort temperature in passive buildings.
Li et al. [53]	China	Numerical model	- PCM yielded the highest benefit in colder climate zones. It was able to maintain the comfort temperature up to 90% of the time.
Khayyaminejad and Fartaj [54]	Windsor, Ontario	Numerical model	- Despite the cold weather, they found that the PCM addition contributed to a daily saving of 3.5% of building energy.
Persson and Westermark [55]	Sweden	MATLAB numerical model	- PCM reduced the overheating hours significantly which enhanced occupant comfort.

Table 2: Research considering the occupant behaviour parameters effect on passive house performance

Study	location	Methodology	Main findings
Mach et al. [59]	Ontario, Canada	Numerical	- The potential of energy saving in the multiunit residential building was a lot higher compared to the single family home. This is due to the higher occupant density in multiunit residential building.
Wang et al. [60]	Germany	Numerical	- They found out through optimization the dominant parameters on building performance. The parameters are occupancy, indoor set point and heat recovery rate.
Ridley et al. [61]	Wales, UK	Data logging and Monitoring	- The net greenhouse gas emission percent was up to 33%. - The occupants' decision on operating electrical appliances had a noticeable effect on the emissions saving potential.

Foster et al. [63]	Scotland	Data logging and analysis	- Unbalanced mechanical ventilation has attributed to 80% of the overheating problems.
Sameni et al. [64]	Coventry, UK	Data logging and analysis	- Two third of the flats experienced overheating due to occupant behaviour.
Noh et al. [68]	Korea	CFD numerical analysis	- Increasing the discharge angle of 4-way cassette air-conditioner has an adverse effect on the indoor thermal comfort.

Table 3: Research considering the mechanical equipment parameters effect on passive house performance

Study	Location	Methodology	Main findings
Liu et al. [73]	China	Modelling turbulent transport equations	- Indoor comfort is significantly enhanced by increasing the fresh air percent and the incoming air filtration efficiency.
Steiger et al. [75]	Denmark	Modelling carbon monoxide distribution	- Buoyancy effect was able to diminish the carbon dioxide concentration away from the source towards the ceiling. - The proper simulation of air flow patterns can ensure the thermal comfort within the room.
Wang et al. [76]	Germany	Data logging and analysis	- An effective energy saving measure was to use the heat recovery system to precool the building during the night.
Rohdin et al. [79]	Sweden	CFD numerical modelling	- Passive homes experience cooler floors relative to the traditional homes. They also experience higher indoor temperature during the summer months. - A more efficient design for the ventilation system reduces the overheating extent.

Schnieders [80]	Europe	Data analysis	- Passive buildings have 80% less energy consumption compared to traditional buildings. - Efficient HVAC operation maintains average indoor temperature of 21.4 ^{o}C the majority of time.
Schnieders and Hermelink [81]	Germany	Data analysis	- Primary energy consumption of passive building was 50% less than conventional building. - The incurred extra cost was only 10% for integrating the energy efficient measures.
Dodoo et al. [82]	Sweden	Numerical	- Ventilation heat recovery was found more effective when added to resistance heated buildings compared to those that are district heated.
Puteh et al. [85]	warm and humid climate	Data analysis	- Better control for the HVAC system operation is needed in high internal heat load buildings.
Wang et al. [86]	Germany	Analytical model	- Heat recovery heat pump and displacement ventilation system are effective for thermal comfort in school buildings.
Chel and Tiwari [89]	India	Numerical model	- Energy saving in heating and cooling were about 1481 kWh/year and 1813 kWh/year respectively in passive building. - The reduction of carbon dioxide emissions was found to be 5.2 metric tons/year.

Due to the complexity of the optimization problem of passive house energy efficiency and thermal comfort, few research work was reported on it. Ylmen et al. [95] investigated the effect of building insulation on life cost analysis of building and global warming mitigation potential. The results shows that the algorithm architecture and considered system boundaries have major influence on optimization findings. Omitting those secondary effects can result in unreliable results. Balali and Valipour [96] investigated the priority passive parameters and the construction and operation of passive healthcare facilities. They investigated the thermal, light and acoustic comfort in the considered buildings. They found that optimizing window design, using a naturally ventilated envelope and using sun shading devices were found to be the most influential. Balali et al. [97] focused on optimization study of passive parameters of Iranian traditional and historical buildings.

They found that increasing building thermal mass through sunspaces and tightening building envelope are the most effective for energy efficient thermally comfortable building. Wang and Zhao [98] ranked the priority parameters for passive buildings in China. They found that the U values for the building envelope is the most important followed by the glazing percent and properties.

The majority of the work that has been done on new buildings to comply with the passive house standard. However, retrofitting the existing buildings was reported to be challenging [99]. The main reason behind it is the associated cost. Building officials need to prioritize energy saving and environmental impact over the added expenses. Vargas and Hamui [100] pointed out that the building envelope changes to comply with the passive house standard is the most significant hurdle. It can result in a payback period that can be higher than 10 years which is discouraging for homeowners. Asaee et al. [101] reported that the retrofits of the building envelope need to be complemented by the integration of renewable technologies especially in cold climates like Europe and Canada. The financial burden is a lot higher due to the high space heating needs of buildings in such harsh conditions. Figure 4 summarizes the main hurdles for retrofitting existing envelopes to the passive house standard. The obstacles lie mainly in the antiquated codes are older buildings did not have to comply with stringent energy efficiency measures. Aesthetic requirements present a challenge in that aspect as well. The financial burden is considered to be high and needs justification for building owners. In addition, the requirements of passive house standard are really strict when compared to the existing conditions of the code compliant buildings.

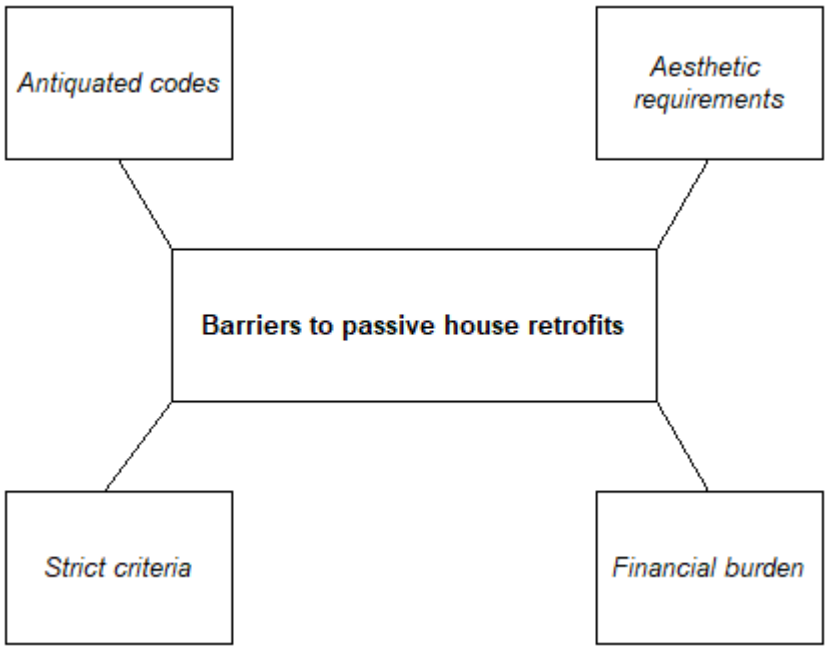

Figure 4: Main hurdles for retrofitting existing buildings to the passive house standard.

4. Conclusions and recommendations

Building energy efficiency has been considered extensively in the current state of the art. Reducing energy consumption and mitigating greenhouse gas emissions are crucial to meet the global sustainability goals. The passive house concept has been studied in different scholarly works in the past decades. A passive house is an ecofriendly ultra low consumption house. It has shown its promising potential in different climates. The majority of research on passive houses was performed in Europe. The current review paper provided a comprehensive analysis of the most recent work on the topic. The main findings are as follows:

- The majority of research on passive houses concentrated on the energy saving potential.
- Thermal comfort need to be addressed in passive houses as during the summer it can experience overheating.
- Different research work either considered energy saving or thermal comfort analysis in passive buildings. Few research has reported an analysis of both topics.
- The major parameters affecting passive house performance are related to: building envelope, occupant behavior and HVAC systems.
- The building envelope needs to be very well insulated to reduce the heat transfer between the passive house and the surrounding.
- Phase change materials integration to building envelope was found to be very effective due to the stable phase change temperature.
- The glazing percent needs to be optimized as passive houses tend to overheat during the summertime. A percent up to 40% can provide substantial energy saving.
- Electrochromic and thermochromic glazing were found to be the most energy efficient.
- Automatic shading system can guarantee a great potential of heating and cooling energy saving.
- Occupant behavior affect the passive house heating and cooling loads significantly. Careful energy analysis need to be included in case of high internal load buildings as schools.
- Ventilation is crucial to maintain indoor thermal comfort. Adequate ventilation can reduce overheating during the summer.
- Heat recovery system has a large potential of energy saving specially in high internal load buildings.
- Night time ventilation is an effective mean of passive cooling. It can reduce the extent of overheating and save energy of HVAC system throughout the day.
- In transitional seasons, when outdoor temperature approaches the desired indoor set point, native ventilation is effective. It enhances the occupant comfort and also provides considerable amount of energy savings.
- A CO_2 concentration of more than 1400 ppm is threatening for the occupant comfort. Recent research has reported that 74% of the houses that are built according to the

passive house standard never experienced a peak CO_2 concentration of higher than 1200 ppm.

- Total volatile organic compounds concentration was also found to be a lot lower when comparing passive houses to conventional homes (300 µg/m3 in and 560 µg/m3 in conventional homes respectively.

The current review paper has highlighted that there needs to be more focus on passive houses outside Europe. In addition, energy saving studies have been reported on long term basis unlike the thermal comfort analysis. There needs to be better standardization for the comfort conditions in passive buildings. Furthermore, the possibility of retrofitting existing buildings to the passive house standard needs to be investigated. Those recommendations need to be explored in the context of life cycle cost financial analysis.

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