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Review

A Review on Numerical Approach to Achieve Building Energy Efficiency for Energy, Economy and Environment (3E) Benefit

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Abstract: Increasing energy demand in buildings with a 40% global share and 30% greenhouse gas emissions has accounted for climate change and a consequent crisis encouraging improvement of building energy efficiency to achieve the combined benefit of energy, economy, and environment. For an efficient system, the optimization of different design control strategies such as building space load, occupancy, lighting, and HVAC becomes inevitable. Therefore, interdisciplinary teamwork of developers, designers, architects, and consumers to deliver a high-performance building becomes essential. This review aims to endorse the importance of Building Performance Simulation in the pre-design phase along with the challenges faced during its adaptation to implementation. A morphology chart is structured to showcase the improvement in Building Energy Efficiency by implementing Building Performance Simulation for different building energy systems and by implementing various energy efficiency strategies to achieve the 3E benefit. As a developing nation, India still lacks mass application of Building Performance Simulation tools for improving Building Energy Efficiency due to improper channelizing or implementation; thus, this framework will enable the designers, architects, researchers to contemplate variable building energy optimization scenarios.

Keywords: building energy efficiency; simulation; energy; environment; economy; building performance simulation

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1. Introduction

Global climate change has adversely affected flora and fauna in form of catastrophe and pandemics [1]. The direct relation between human comfort and rising energy demand indicates the increase in heat-trapping gases as a clear consequence of fossil burning. To this, the building sector accounts for about 40% of total global energy consumption [2] which is predicted to increase up to 50% by 2050. Majorly, space conditioning, ventilation, and occupant comfort account for this consumption with 29% CO_2 emissions inferred just for space conditioning of residential buildings [3–9]. This continuous consumption of fossil fuels has raised concerns about energy efficiency strategies for a sustainable future [4,10,11]. Moreover, the beginning of the 21st century has shown the importance of 3E inter-relation in a global economic scenario. Thus, to improve energy efficiency strategies several types of research have been proposed concerning passive strategies [12] that include thermal insulation, natural ventilation, shading, shape optimization [13], and active strategies by capture, conversion, and use of renewable energy [14–16]. Hence, many global initiatives have been taken like subsidies for fossil fuel removal, carbon pricing, and auctions to lower the cost of renewable energy [17].

Considering that, for a 2 °C decrease in global temperature by 2050 in response to the Paris agreement, it required a shift from high to low carbon emitting source of energy. As stated in Equation (1), the logarithmic change in atmospheric CO_2 has a proportional relation with the increasing temperature,

$$C(t) = \delta T(c) = 1.44\varepsilon \log_e(C/C_0) \quad (1)$$

where the equilibrium climate sensitivity ε exhibits a value between 1.5 and 4.5 [18]. For this required change of reduced emission, EPBD indicated "almost zero energy buildings" that operate at minimal power to provide efficient space conditioning, domestic hot water, and general building operations [19]. Noticeably, the journey of minimum energy building to zero energy building to positive zero energy building is to minimize the energy consumption and produce on-site renewable energy sources that enable emissions reduction [20]. Furthermore, it requires rigorous experimental and analytical studies to achieve BEE by assembling several parameters, such as optimal thermal comfort, proper ventilation, good indoor air quality, and occupant comfort [4–7]. Thus, there emerged a need to model the energy system at an initial stage of designing which can further help to optimize the system from consumption to production, making it less susceptible to failure [21].

Hereby, it becomes highly significant to imbibe the lessons of the Integrated Design Process (IDP) from Europe and North America to achieve efficient teamwork for a rapid pace implication of energy-efficient buildings on the ground [22–24]. There exist various design assumptions and energy simulation needs to implement IDP, which can be accomplished by the evolution of innovative solutions, such as BPS [25]. The evolution and implementation of a successful design by simulation and modeling face substantial challenges, i.e., from adaptation to implementation [26,27]. By overcoming these challenges and indulging in smart solutions aid to cogenerate a simultaneous benefit in energy consumption and demand with cost-effective solutions by keeping the environment's betterment in view. This collaborative entailment of 3E will help to generate clean energy with reduced GHG emissions by adopting IDP for a reduced LCC and overall cost [27].

This review article evaluates the energy, economic, and environmental benefits by acquiring optimization techniques to achieve BEE by analyzing different authoritative sources for instance research articles, reviews, conference papers, thesis, and books. The motivation acquired for providing this study includes:

- nZEB is a well-evolved concept amongst many developed nations in contrary to the developing nations which are still at their naive stage [28].
- The concept of nZEB is welcomed eminently but still lacks in mass application to date or acceptance due to improper channelizing or implementation [29].
- The skepticism maintained among the developers and users towards the performance of renewable source energy production and huge capital costs take back their initiatives [30].
- Lack of research and study in this field along with a shortage of manpower with expertise in simulation and modeling to make nZEB optimized and cost-effective design [2,30,31].
- Smaller building projects with lower budgets make it less likely to consider building energy analysis while designing.

This paper aims to review the importance of modeling and simulation techniques along with the challenges faced during the evolution of BPS, in achieving a well-performing cost-effective low energy building. The contribution followed by this review work is as follows:

- The importance of the BPS tool with 3E's evaluation to achieve building energy efficiency.

- An insight into the challenges involved while implementing a BPS tool thereby, looking to the possible solutions.
- The significance of cost-effective energy optimization strategies that significantly equips for the improvement in the environment by a reduction in GHG emissions.
- A recommendation for the Indian scenario is based on the analyzed study.

2. Methodology

To design an energy-efficient building, it is pertinent to keep track of the quantum of energy and carbon emission. In this prospect, a morphology chart is prepared (Figure 1) interpreting the correlation between the objective of improving building energy efficiency to achieve the entailment between 3E's. This paper aims to review the numerical approach utilizing the BPS tool to strategize various alternative solutions to achieve building energy efficiency to balance different aspects of BES (building space load, HVAC, lighting, and occupant comfort).

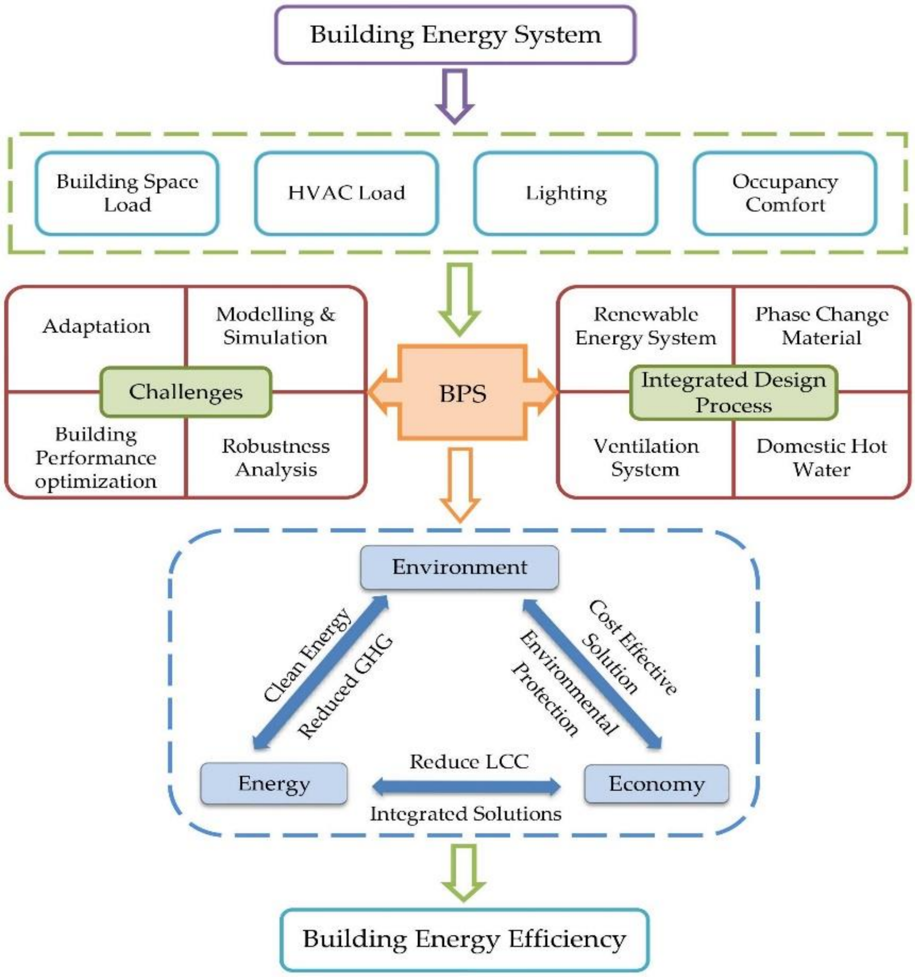

Figure 1. A Morphology Chart.

Successful implementation of the BPS tool requires overcoming certain challenges, i.e., challenges during adaptation of a BPS tool, conducting modeling and simulation, building performance optimization, or robustness analysis. After the successful adaptation of a BPS tool, it is implemented to optimize various passive and active design strategies. The inclusion of such a BPS tool for designing an energy-efficient building becomes significantly useful in the evolution of the integrated design process approach towards attaining 3E. The coexistence of 3E leads to an integrated solution providing clean energy and reduced GHG emission, and thereby reducing total LCC and capital cost. Further, this paper is structured as follows, Section 3 describes the need for coexistence of 3E considering different global scenarios along with an onlook to the current Indian perspective, which leads to the importance of using a BPS tool as described in Section 4 along with the challenges involved during different phases, Section 5 reviews 27 case studies for the application of BPS tool into different energy efficiency strategies (RES, Passive) with its 3E evaluation. Section 6 gives discussion and hypothesis, and Section 7, conclusion and future recommendations.

3. The Need for the Coexistence of 3E's

The coexistence of energy, economy, and environment is a prerequisite that ensures healthy, stable, and sustainable development. The overall performance of a building is classified based on energy, economic and environmental performance, where energy savings depend on optimized innovative design strategies, the environmental impact depends on GHG and CO_2 emissions, and economic performance requires reduced LCC and overall cost [32–34].

The developed nations can refine their resources in response to the rising energy demand and thereby encouraging the developing nations for similar adaptations. An analytical result on 74 metropolitical cities based on utilizing 100% wind, water, and solar (WWS) gave, increased non-mortality impacts by 2050, decreased air pollution and global warming costs by $2600 billion/year and $3500 billion/year, respectively, energy and health savings of $1500/person/year, climate cost savings of about $6700/person/year, respectively [35]. Another study in China based on the techno-economic feasibility of 100% renewable energy for a residential household with its lifecycle analysis suggested a hybrid power system for the environment, energy, and economic benefit [36]. In the context of RES solar thermal collectors and PV contributes to reducing thermal demand thereby, reducing electricity demand on power grids during peak hours, refs. [37,38] significantly contributing to the coexistence of 3E. Luong et al. analyzed the implementation of solar panels on the vertical facades of the building for its lifecycle cost and thus its input in cost minimization of the project to achieve optimal energy efficiency along with environmental performance [39].

The cost-effective sustainable development has turned up the concerns towards the need of considering LCC, thermal comfort, heat demand, and infiltration while building up a structure. For a cost-optimal nZEB, a detailed and prior analysis should be done based on LCC and available resources as the selection of resources is often region-based depending on its availability and returns in terms of GHG emissions [40,41]. A study based on energy and analysis for a house located in Poland attributed to the wooden structure instead of brick that excelled in terms of LCC, and GHG emission but eventually showed degradation in terms of thermal comfort. Results showed the importance of photovoltaic (PV) and a biomass boiler for electricity that eventually reduces GHG emissions [37].

Rogoza et al., in a case study, found that solutions for energy, expenses, and pollution are different when analyzed individually and, therefore, suggested for multi-criteria 3E optimization. It was found that 3E optimization is suitable to express the interest of the state or community rather than an individual consumer [42]. Further, a study was done to optimize the insulation thickness of the external wall based on 3E evaluation. The individual results based on energy, economy, and environment analysis gave 8 cm thick polyurethane, 7 cm thick Rockwool, and 20 cm thick Expanded PolyStyrene as optimum insulation material, respectively, whereas, the combined 3E criteria suggested for 11 cm mineral wool insulation [43].

Hence, from the above analysis, it is clear that the coexistence of 3E gives a combined community benefit in terms of the improvement of BEE. However, for this combined benefit, an efficient analytical tool is required that can optimize different design strategies to achieve clean and affordable energy to accomplish sustainable cities and societies.

Indian Perspective

In terms of emission targets, India is supposed to decrease CO_2 emissions per gross domestic product development from 2005 levels by one-fourth time with the help of renewable energy resource utilization and by stepping into clean energy like CNG, PNG, solar, etc. In India, 30–40% of energy consumption is from buildings with a continual increase of 12% per annum which is twice the economical electricity growth [44,45]. Though the per capita emission is accounted for 2.7 tons of carbon equivalent the alarming increase in the population triggers the major consent for the need for a strategic intervention of innovative technology as an alternative to bring a paradigm shift. India has significant opportunities to improve energy efficiency where it can prioritize efficiency gains while strengthening its economy and making decarbonization more affordable [29,46]. Looking for the fact that the existing initiative of a combination of renewable energy and energy efficiency measures to improve building energy efficiency is yet to be scaled up [45]. Hence, it is subjected to the increased need for government initiatives to develop clean energy resources with the use of solar, wind, hydropower, GSHP.

The Indian economy is currently operating at a high level of inefficiency even after establishing the Bureau of Energy Efficiency in 2002, which periodically mandates regulatory standards and formulates promotional schemes to improve energy efficiency. India at present operates at a low-efficiency level, thereby suggesting, that huge benefits could be secured by expanding energy efficiency programs. However, to achieve these expansion improvements in energy efficiency, there needs to be a substantial investment in strategies in the pre-design control phase [47]. To shift current extensive economic growth in response to higher energy consumption and increase technical innovation inputs requires investment in R&D for efficient design strategies focusing on the introduction, conversion, and utilization of advanced technologies to promote energy efficiency, reduce environmental pollution and promote economic growth [44]. Furthermore, there is a requirement to establish a perfect environment legislation system and environmental standard system, to strengthen the enforcement of environmental laws. All of these will be expected to continuously improve environmental quality and sustainability of economic development fulfilling the required energy demand [30].

To develop these energy-efficient systems and strategies, utilizing building performance simulations at an initial stage is a step forward, as optimization of the system from consumption to production makes it less susceptible to failure. The proposed system control depends upon different energy and performance-based simulations, for which an effective and reliable simulation procedure is required. Therefore, the use of the BPS tool becomes significant with changing physical phenomena of building to reach its energy demand with reduced economic cost and increased environmental value.

4. Cognizance to Building Performance Simulation

Computational modeling and simulation is the process of analyzing mathematical models to predict different physical characteristics and operational behavior for an energy-efficient built environment. The amalgamation of various theories underlying different disciplines attributes both power and complexity to BPS. The most relevant performance metric prioritized while using a BPS tool constitutes a BES which is anything responsible for the consumption of energy within a building and can be classified as building space load, HVAC, lighting, occupancy, and comfort [48,49].

4.1. Building Space Load

It is the rate at which heat loss or gain occurs from a space that relies on factors like outside temperature, relative humidity, indoor occupancy, and heat flow having a direct influence over HVAC. Therefore, the building space load needs to be rectified first to ensure the intact comfort condition of the building. On a mathematical note, space load can be denoted as in Equation (2) [50]:

$$Q_{BSL} = Q_{LOSS} - Q_{GAIN} \quad (2)$$

where, Q_{BSL} = Building space load, Q_{LOSS} = total rate of heat loss, Q_{GAIN} = excluding HVAC summation of all heat gains.

4.2. HVAC System

It is not only responsible for 40–60% net energy consumption in the building but also hooks up for the occupant comfort conditions, thus becoming a challenge in itself to optimize the heating/cooling status for better conditioning without compromising the comfort state. HVAC is a technology to provide thermal and indoor air quality. Building energy consumption can be significantly altered by improving the HVAC system, such as with an additional insulating layer that might give a small thermal transmittance value or by switching from non-renewables to renewables [51,52]. Since each building is unique, to get an appropriate HVAC, the parameters usually differ, i.e., from the material used to the buildings existing weather condition.

4.3. Lighting System

Lighting systems have a specific share of energy consumption within a building consequently they also act as space load for their property to relieve heat during their operation. Even though, such heat dissipation can aid as a source of heat for the cold climatic condition within buildings. It can be mathematically be evaluated as in Equation (3) [50]:

$$E_T = P_L \times T_u \quad (3)$$

where, E_T = total energy consumed by lighting, P_L = installed lighting load, T_U = total usage time

4.4. Occupancy and Comfort

Indoor air quality is an important factor to determine the occupant's comfort within the building. This is the most uncertain element during a design control phase as it varies very abruptly. Hence the inclusion of BPS into this zone undergoes optimization and robustness checks to assist a real functional design [53].

BES not only increases the cost of operation but also indirectly impacts the environmental conditions hence correct decision at a pre-design phase and a good design process becomes an important factor for assessment of building energy performance which depends on several factors like construction material, design system, orientation, etc. At the cost of real-time simulation, many problems are awaited by the researchers like costlier experimentation, longstanding experimental work, and techniques with the least possibility of simulating all the alterative parameters at a provided condition in a peculiar environment [54]. The extra edge given by interpolation and iterative methods has proved to be a cost-saving alternative for the vast experimentation conducted [55]. Many other factors hampering real-time experimentation are the absence of a proper laboratory, costly equipment, the need for a rigorous experimental procedure, or time constraints. Simulation, on the other hand, seems to be quicker, more transient, accurate, and less vulnerable to any of the external factors, such as human error, outside weather, instrumental error. Mathematical and numerical validation of the simulation software improves the rate of efficiency of the predicted results [56,57]. It is possible to synthesize the weather data in simulation software in prospects of future or possible changes required. Simulation procedures can cope with uncertainties such as ambient temperature or relative humidity or even occupant behavior which becomes a real challenge during laboratory experimentation [58,59]. Merits of simulation and modeling [60–63]:

- Instantaneous results with cost-effectiveness and least time-consuming.
- Able to deal with rarest environmental conditions
- The scope of prototype building is reduced constituting towards non–damaging testing.
- Many critical and complex matters can be diagnosed effectively.
- The optimization is much approachable, as parametric modulations can be easily made.
- At times it suggests alternatives that suit the requirement.
- Has the capability to put forth an entire report analysis based upon economy, efficiency, payback period, life cycle assessment, marketing performance, etc.

Though the process of using simulation tools has found global importance, the credibility within the developed or existing tools underlies several challenges faced while adapting them. The following section will briefly describe the interlinked challenges faced while adaptation, simulation, and optimization of a BPS tool.

4.5. Challenges during BPS

4.5.1. Adaptation

Amongst the architecture and engineer community the usability of the BPS tool depends upon various aspects, underlying are the four I's (i.e., Interest, Information, Investment, and Integration) identified as gaps and barriers in concise of a wide range of adaptability of BPS [64,65].

- *Interest*: Increased use of BPS tools requires interest amongst the developers as well as consumers relating to advances in BES modeling.
- *Information:* It is required to provide the simulation tool with a vital range of information regarding various building properties and types of material that are readily available on an online database.
- *Investment:* It becomes a high time need to considerably invest into the planners, designers, and engineers to enrich in the BPS field for substantially increasing the rate of capacity building.
- *Integration*: A multi-disciplinary integrated teamwork aspires within a system to bring forth an excellent enumeration of knowledge and data where the researchers can share their input and data to the practicing professionals to increase the adaptability and implementation of low-cost energy-efficient buildings.

These challenges can be looked at by conjugation of four I's between governance, education system, developers, planners, and designers.

4.5.2. Modeling and Simulation

After the successful adaptations of the simulation tool, the next challenge occurs during modeling and simulation to effectively select a BPS tool, the concept building of BPS to its efficient model construction which is further headed by the quality assurance. Further, it faces uncertainty challenges during and after the implementation of the BPS tool which significantly affects the overall performance of the building. The following are the challenges faced during modeling and simulation [66–68].

- *Concept building:* Mathematical model is set up for the simulation to analyze the primary prerequisite inputs from the field with the least range of error considering the possible scenario. Hence, it is a two-way process, i.e., for a variation in the process either the conceptual part of the modeling is to be addressed or on contrary, a new suitable mathematical model needs to be evaluated.
- *Model construction:* Building model is created using a Graphical User Interface (GUI) in a Geometrical Model Environment (GME) to stipulate a precise solid analysis within a simulation environment. Essentially mathematical model setup is discretized spatially and temporally with certain algorithms assigned to it. The main challenge is to keep in view the capability of the particular BPS tool.

- *Quality assurance:* The user should constitute a deep knowledge of the simulation and be aware of the uncertainties, with proper verification of the conceptual model into the BPS program. To assure the quality of the model an excellent endeavor in input variables uncertainty is required for estimating the aspired simulation result.
- *Weather data:* A significant boundary condition to be given as an input variable is the major source of uncertainty for the fact that some regime's particular database might not be available or one that is available might be outdated, i.e., the climate change impacts with the proceeding years need to be considered while designing. The possible solution given up by the researchers is Generating Regional Climate Model (RCM) from Global Climate Model (GCM) with some boundary conditions, or by morphing, which includes stretching, combining, or both along with the application of transformational algorithms to derive a typical database from the monthly variation of GCM, lastly by stochastically generating weather data using computer algorithms derived from GCM hourly resolution. All of these computational methods require a high end of expertise to calibrate the result and make the desired input.
- *Occupant behavior:* It is a kind of aleatory uncertainty hooked up with the unavailability of quality data regarding occupant behavior. Challenge is to develop a realistic model to predict the behavior, applicability, and implementation of a good action model and finally integrating this model with occupant presence. The solution lies within setting up a model platform that could define the behavior of the occupant, thereby establishing a simulation methodology for the same to analyze the influence of occupant behavior.
- *Software coupling:* The challenge lies within the entailment of multiple tools that can be easy, time-bound, and effective to engulf the interaction and necessary feedback for increased efficiency to calibrate a synergetic evolution of the system like that of a combination of HVAC and RES.
- *BPS + BIM:* Building information modeling (BIM) along with Building energy modeling (BEM) helps to make the process efficient and fast during the early phase of design with an improved LCC analysis. The major challenge is the required expert knowledge to map different aspects of a building such as HVAC and RES into the BIM platform. Furthermore, it requires a properly analyzed boundary condition with a reliable system model along with a flexible user interface to substitute it with additional information.
- *Communication skills* To ensure a wide range of applicability it becomes a real challenge to convey the output in a less complex manner which particularly requires either high expertise or a kind of output that can be understood and accessed by the non-experts.
- *Suitable BPS tool selection*: Though the BPS tool comes along with a wide range of applicability the selection of the tool is categorized based on its capability to assess all basic issues regarding energy and cost-efficient building with a good technological mix based on the desired outputs. The selection criteria for a suitable BPS tool can be categorized based on the [69] usability and information management, knowledge for qualitative and quantitative decisions to analyze and optimize a complex design, accuracy, and ability to contemplate different design strategies, interoperability of the simulation tool with other tools.

One such illustration of the selection of a BPS tool is shown in Table 1 based on the different parametric abilities of BPS tools such as Trnsys, ESP-r, EnergyPlus where CI is denoting completely implemented, PI as partially implemented, OI as optionally implemented, and NI as not implemented. Considering the BPS tools used in the studies, it is possible to state that Trnsys and EnergyPlus are the most employed thermophysical tools [67].

Table 1. Software comparison based on different parameters applicability [50,68–73].

Parameters	Trnsys	ESP-r	Energy Plus
Simulation solution	CI	CI	CI
Multi-zone simulation	CI	CI	CI
Incorporating other tools (MATLAB, CFD, EES)	OI	NI	CI
Open-source code	NI	CI	CI
Ability to add mathematical submodel	CI	NI	NI
Thermal load calculation	CI	CI	CI
Natural ventilation	CI	NI	CI
Wind energy	OI	NI	CI
Dynamic variable in the transient solution	CI	PI	NI
Modeling carbon dioxide	OI	NI	CI
Simultaneous selection of building and users	CI	CI	NI
PCM	OI	NI	OI
Solar gains/shading and sky consideration	CI	PI	PI
EIA	CI	PI	CI

4.5.3. Building Performance Optimization

BPO is an automated simulation-based optimization tool instead of a conventional solution to find a cost-optimal model by repetitively calibrating with variable inputs to find an optimized solution. BPO is the means to operate different options for design such as dealing with an optimized LCC, total capital cost, and thermal comfort in perspective of nZEB. BPO with the type of implementation can be classified as single-objective or multi-objective optimization. Multi-objective optimization can be a solution for the need for an integrated solution that can successfully satisfy individual objectives. Optimization is assigned to a trade-off curve which resembles a graph of solution plotted in the form of a curve known as Pareto Frontier [74,75]. In this type of curve there exist one element that is better than other elements for one objective simultaneously, it doesn't lack behind any element with any particular objective. Optimization in itself becomes a tedious task to conjoin the distinct, non-uniform, and highly controlled characteristics of a building with challenges faced as irrelevant physical results, missing of the optimum solution, and it becomes a technically difficult task to enable a time-efficient simultaneous optimization [76]. Attia et al. based on their extensive literature survey and interviews of optimization experts identified several challenges faced during an optimization process [77].

- *Appreciation*: The low value of return and the lack of required appreciation amongst the architecture, engineering, and construction industry.
- *Approach*: It requires a systematic and standard approach as mostly the researchers endorse diverse and ad-hoc methods without a proper format or differentiation of usage
- *Ability*: Highly calculative and analytical ability is hoped amongst the user for interpreting the set value.
- *Awareness*: The methodology utilized to approach optimization is a rarely conceived matter, though many kinds of research have been initiated but still lacks wide practical applicability.
- *Availability*: Lack of design tools in the public domain that can easily be accessed with a better GUI and proper object-oriented process with capable visualization tools.
- *Uncertainty*: BPO is subjected to more amount of uncertainty making a huge obligation amongst researchers and software developers. Such as the detailed modeling can degrade the simulation-based optimization effectiveness thus failing to serve the purpose.
- *Time and information*: Designers require a reliable and object-oriented informative design tool that can significantly save time and effort at the early phase of design.
- *Interoperability and flexibility*: The interoperation characteristic of the optimization tool to flexibly interact with different design, simulation, and cost analysis tools is highly variable.

Thus, there exist several research-based solutions in this prospect like that of MOBO, MAOS that can successfully take care of many of these uncertainties. MAOS is a high-speed analysis tool along with the feature of avoiding uncertain repeated analysis which takes into account a holistic approach [78]. MOBO can deal with multi and single-objective optimization by automatic handling of constraints that can handle both continuous and discrete variables. It significantly lowers the computational time by parallel running the simulation. The available GUI makes it easy for coupling of MOBO along with the presence of different types of algorithms, i.e., deterministic, hybrid, exhaustive, and random [79].

4.5.4. Robustness Analysis

After performing all the BPS and BPO the assurance that the ultimate design need will be fulfilled or attained is surrounded by several uncertainties such as changing climate, occupant behavior, economic aspects which are rarely considered at the initial phase of design. Therefore, it creates a visible gap between realistic and designed models, robust assessment can reduce sensitivity to such changes [80]. Such an analytical model considering all the max-min, worst and best case helps to retain the aspired design model thus making it less sensitive to uncertainties. It can be assessed either by probabilistic or non-probabilistic analysis. Three steps involved in robustness analysis are: Obtain results from BPS analysis, secondly Single or multi-criteria method to ensure robustness, and finally, Multi-criteria decision making [81,82]. Challenges faced during adopting robustness analysis are, complex analysis when dealing with multiple criteria decision making, a requirement of expert advice for prioritizing the results obtained, and for cases having huge design variation the repetitive need for robust analysis will be challenging. As a solution to this Homaei and Hamdy studied and analyzed the integration of robustness assessment into the decision-making process by using multi-target key performance indicator, which takes multiple performances into account and differentiates between feasible and non-feasible solutions [83].

During the phase of implementation of a BPS tool into the building design process, the challenges faced from the stage of its adaptation to implementation are summarized in Table 2 into different stages, i.e., initial, mid, and final stage. The initial stage deals with the challenges of the inclusion of different analysis processes, furthering the mid-stage deals by carrying forward the design process perfections which requires especial accuracy, uncertainty analysis, etc. and at the final stage it is about the integration of all the acquired process with expertise to understand the output and results obtained and transform it into useful data for the implementation of the strategies on the ground.

Table 2. Different stages of challenges in BPS.

Reference	Challenges in	Initial Stage	Mid-Stage	Final Stage
[64,65]	Adaptation	Interest among developers, architects, and engineers	Information of the building properties on an online database. Investment in engineers and planners to enrich the BPS field	Integration of working professionals and researchers for wide-field applicability.
[53–55]	Modelling and simulation	Concept building and Model construction BPS tool quality assurance Weather data and Occupant behavior for their uncertainties	Software coupling, BPO, BPS+ BIM to deal with IDP, trade-off amongst numerous desirable results and eventually to deal with different uncertainty	Communication skills and Suitable BPS tool selection
[61–63]	BPO	Appreciation, Approach, Ability, Awareness to acquire an optimization tool	Availability and Uncertainty requires the need of an expert	Interoperability and flexibility of the BPO tool with another simulation environment.
[66–69]	Robustness analysis	To fulfill multiple criteria of design analysis	Increased expert advice	Huge design variation and need lead to a repetitive need for analysis.

5. 3E's Evaluation for Optimized Energy Efficiency Strategies

Optimization of a building is a promising technique to design energy-efficient strategies in respect to the key objective function related to energy (RE generation, savings), economy (LCC, payback, overall cost), and environment (CO_2 emissions). The use of renewable energy onsite [84,85], thermal insulation [86], or ventilation and heat recovery strategies [87] can cohesively work to achieve the building energy efficiency goal. The following section presents the state of art report for 27 case studies of distributed optimization variables as RES and passive strategies (PCM, ventilation), and multi-objective optimization. The studies identify the importance of the incorporation of an efficient BPS tool for an efficient design. Further, the analysis reflected the importance of climate-based studies on different optimization strategies, i.e., the value of the obtained results varies in accordance to different climatic conditions even within the same country location. The piecemeal way of using such strategies might give a less problem-oriented solution rather, approaching IDP can give a dignified solution. For optimization of such integrated solutions, it requires software coupling or BPO+BPS tools that can combine its individual optimization property for a reliable solution. The studies considered illustrate the importance of optimization in RE system, PCM, ventilation strategies to achieve 3E benefit.

5.1. Renewable Energy System

A simulation study based on [88] economic, environmental, and energy benefits around the different arena of the globe (Canada, Europe, America, Pakistan, Australia) for the establishment of zero energy homes in sub-zero temperature climates using on-site renewable energy sources (solar and wind) gave a reduction in energy demand by 50% than a conventional system. A whole year-long simulation performed predicted a good scope of nZEB with excellent performance under the inference of renewable sources of energy onsite. According to the study, the minimum electricity produced was 680 W in Barcelona and a maximum of 1400 W in Sydney.

For a warm temperate climate zone in upstate [6] New York a 1600 m^2 cleanroom set up is simulated for economic and environmental benefits by including energy efficiency strategies such as the heat recovery system from exhaust air, solar thermal preheating for a desiccant dehumidifier, improved lightning, and on-demand filtration control. Simulation results predicted to save 9 TJ, 862 tonnes of CO_2, and $164 k annually by implementing recommended strategies.

Two solar PV-driven conditioning systems, centralized electric heat pump + PV (reference) and centralized GSHP+PV (proposed), were compared using Trnsys 17 for energy and environment-based performance with five different solar trackings for high performance of PV plant in Italy. PV system provides electricity to both heat pumps from which deficit/surplus is taken/given from/to the power grid. From the proposed system results were primary energy savings of 101.67% in summer and 28.10% in winter, and CO_2 reduction reaching a maximum value of 45.86%. Solar tracking leads to better exploitation of solar radiation thus helping in exporting excess electricity to the power grid [89].

For a Greek hospital, solar air conditioning models were simulated as an environment-friendly method with zero emissions to reduce energy consumption [90]. Four different scenarios with variable parameters were analyzed during the study, which concluded that the fourth scenario proved to be efficient. It consisted of 74.23% solar cooling fraction and 70.78% solar heating fraction with 179 solar collectors to cover 500 m^2 surface. The configuration obtained a total CO_2 savings of 45.35 tons and overall energy savings of 113.58 MWh. The payback time for the investment cost without funding subsidies was computed to be 11.5 years which can reach up to 6.9 years by providing subsidies.

A solar-powered HVAC system was analyzed in Pakistan in terms of energy, economy, and environment (3E) [91]. A comparative analysis in Trnsys TRNBuild for vapor compression cycle (VCC) and solar-driven vapor absorption chiller (ACS) based cooling system has given the following results: annual primary energy consumption (kWh) of 2.23×10^6 and 5.74×10^5, annualized capital investment cost (Rs.) of 1.07×10^7 and 3.31×10^7, monthly running cost (Rs.) of 1,612,186 and 393,269, and annual CO_2 emissions (tons) of 346.78 and 108.58, respectively. Hence, the 3E's evaluation suggested that the ACS system was more environment-friendly, economical, and energy-efficient than the VCC system apart from the initial investment cost. It also suggested that changing the tilt of the collector will contribute 5% more solar irradiance/m^2 monthly.

The study observed variations during hourly simulation of cooling load in central Queensland subtropical climate Australia for three distinct zones with climatic variation (Emerald, Gladstone, Rockhampton) with a solar-assisted air conditioning system. For these three zones the energy savings obtained for a collector area of 50 m^2 and storage tank volume of 0.3 m^3 were 61%, 60%, and 60%, respectively, further it was observed that energy savings increased by changing storage tank volume to 1.8 m^3 as 88%, 82% and 80%, respectively [92].

A study based on the performance of domestic water heating for two model houses in Canada with drain water recovery gave annual energy and GHG savings which varied with the type of solar collector [93]. The simulation results showed that Model A set up with a gas boiler and flat plate solar collector gave annual energy savings of 1831 kWh and Model B with an electric tank and evacuated tube collector gave 1771 kWh savings. The simulation model was validated on basis of experimental data and extended a similar approach to commercial buildings for analysis into the other conventional system for different cities of Canada (Halifax, Montreal, Toronto, Edmonton, and Vancouver). The combo system was found useful for Edmonton by saving GHG emissions (per kg equivalent CO_2) of 685.06 kg for house A and 1565.36 kg for house B.

A numerical model was built to simulate solar thermal assisted space heating and summer electricity production, thermal energy storage, and electric chillers to capture waste heat for a desert climate (arid zone) in New Mexico [94]. Solar collector array equipped with flat plate collector of 124 m^2 area and vacuum tube with 108 m^2 arranged in series. Simulation results found that about 90% of heating requirements can be fulfilled by adopting certain energy conservation measures and total external cooling load can be reduced by 33% to 43% by solar cooling.

Air conditioning driven by mini wind turbine and GSHP for two Italian cities, Naples and Cagliari, simulated for an optimum design that works with efficiency along with other analysis based on energy, GHG reduction [95]. Primary energy savings for Naples ranged between 6.95 MWh and 10.4 MWh whereas, for Cagliari, it ranged between 12.2 MWh and 21.7 MWh, reduction in GHG emissions ranged between 1275 kg CO_2 and 2140 kg CO_2 for Naples.

The building energy demand was calculated for space heating and domestic hot water production with their financial interventions by simulating 1204 m^2 of building space [96]. The study analyzed energy optimization by replacing the conventional boiler with a Combined Heat Power and heat pump (CHP+ HP) for maximum utilization of renewable energy. The system observed an annual energy cost savings of $3730 per year with a reasonable payback time of 15.4 years. The study aimed to influence users to adopt technical interventions to reduce consumptions by energy optimization thus, creating a phenomenon that might involve both financial and environmental aspects.

Using the transient nature of Trnsys variable building load and the cooling tendency were simulated for nine typical cold areas in China to acquire an optimum solar heating and cooling system design for each area. For example, in Beijing for which the study optimized the tank volume by 1.16 m^3 and the fraction of collector to the volume of the tank by 0.04 m^3/m^2 [97].

Different alternative solutions were simulated for two different climates (Montreal and Los Angeles) for producing domestic hot water to approach nZEB along with the economic analysis. The results suggested the use of a thermal solar collector with electric backup provided by PV panels or a grid. The economic analysis also gave a system configuration of 4.5 m^2 collector area with 2.06 m^2 PV array with a payback of 11 years for Los Angeles whereas, it was 12 m^2 collector area 5.2 m^2 PV array and 29 years payback for Montreal which shows that the nZEB hot water production is not that much cost-effective in Montreal but can significantly contribute for the environmental benefit [98].

3E Evaluation

To optimize the RES, and energy-efficient technologies for space conditioning, electricity, and heating application under varying climatic conditions requires the need for modeling and simulation for proper design accomplishment as analyzed in Table 3. Among all the renewable energy sources sun is the most abundant and readily available source of energy. The application of solar energy as PV, thermal collectors along GSHP, and wind turbines is being well recognized. Solar-powered HVAC, AC has significantly reduced the annual operating cost, environmental impact, and increased fossils energy savings. The huge initial capital cost or payback time makes the application undeniably questionable which can be overlooked by the environmental savings achieved. Furthermore, the subsidies introduced by the government can significantly bring down the concern of initial investment cost for an optimized system with increased efficiency. The climatic variations observed in the case studies are sub-zero temperature, warm and temperate, Mediterranean, hot and dry, subtropical, arid, and cold. With each varying climatic condition, the observed system had a specific configuration and output component, these deviations can be well interpolated with the help of a simulation design model.

Table 3. 3E evaluation of RES/energy-efficient strategies.

Reference	Climate	Application	3E Evaluation
[88]	Sub-zero temperature	PV Wind turbine	50% demand reduction than a conventional system PV generated electricity Min: 680 W and Max: 1400 W
[6]	Warm and temperate	Controlled filtration, heat recovery system for exhaust air, improved lighting control	Saved 9 TJ, 862 tonnes CO_2, $164 k annually
[89]	Mediterranean	GSHP + PV	101.67% energy savings in summer and 28.10% in winter, 45.86% Reduced CO_2 emission Excess energy to grid
[90]	Temperate	Solar air conditioning	113.58 MWh overall energy savings CO_2 savings: 45.35 tons payback time: 11.5-year (without subsidies) 6-year (with subsidies)
[91]	Hot and dry	Solar-powered HVAC	ACS initial investment 3.1 more than VCC ACS running cost 4.1 times less than VCC ACS CO_2 emission 3.19 times less than VCC
[92]	Subtropical	Solar AC in Emerald, Gladstone, Rockhampton	Energy savings with (0.3 m^3 storage tank): 61%, 60%, 60% (1.8 m^3 storage tank): 88%, 82% 80%
[93]	Cold zone	Solar domestic water heating with Evacuated tube Flat plate collector	1771 kWh and 1831 kWh annual savings, respectively CO_2 savings of 685.06 kg and 1565.36 kg, respectively
[94]	Arid zone	Solar space conditioning	Reduced external energy requirement by 33–43% cooling and 90% for heating
[95]	Hot summer Mediterranean	Wind + GSHP	54.8% more energy reduction in Cagliari than Naples CO_2 reduction ranged between 1275 kg and 2140 kg

Table 3. *Cont.*

Reference	Climate	Application	3E Evaluation
[96]	Mediterranean	The exploitation of renewable energy, CHP+ HP model	$3730 per year savings 15.4 year payback time
[97]	Cold region	Optimal design of solar energy heating and cooling system, and calculating optimization parameters	Decrease in energy consumption of buildings thus reduced pollutant emissions.
[98]	Warm temperate	Solar thermal with PV electric backup	11-year payback for Los Angeles and 29-year payback for Montreal

5.2. Passive Design Strategies

Stritih et al. [99] performed an experimental study on a 2 × 2 m^2 composite wall with 0.12 m thickness, where the first layer is concrete mix and the second layer is microencapsulated PCM with concrete. A new wall with PCM was added to the Trnsys database (Type 101) for simulation of a composite wall with different types (wool and polyurethane) and the percentage of PCM. The difference observed between wool and polyurethane insulated wall cooling was 12.09 kWh/day. The average room temperature was 30 °C for a wall type with 0% PCM and 23 °C for the wall type with RT20 100% PCM. Essentially the selection of PCM is to be based upon the meteorological data, concerning the fact that PCM must cool down at night which can only happen if the ambient temperature is below the PCM melting point.

A simulation study was conducted for reduced energy consumption during space conditioning by using increased thermal capacitance and thermal storage management (ITC/TSM). The study also looks into tank volume reduction by inducing PCM into storage tanks by taking three tank locations outdoor, indoor, and buried [100]. ITC/TSM with zero percent PCM had 35% energy savings with 50-gallon tank volume, and ITC/TSM with 100% PCM had 35.2% energy savings with 5-gallon tank volume. The thermal losses for the indoor five-gallon tank are 99.58% less than the outdoor 50-gallon tank, and 99.54% less than the buried 50-gallon tank.

A PCM encapsulated latent heat thermal energy storage (LHTES) for cooling, fresh, and recirculated indoor air is simulated to check the efficiency of heavyweight and lightweight low enthalpy building. The results obtained suggested a reduction in the size of the mechanical ventilation system for better thermal comfort with PCM incorporation into building material such as concrete, plasterboard for thermal improvement. The simulation study aimed to evaluate the influence of walls/ceiling/floor with PCM for an overall energy balance of the building. A 3 °C decrease is observed by including PCM in-ceiling and west wall thereby, enabling the temperature range between 25 °C and 27.5 °C [101].

To study the thermal behavior of external walls with PCM a new type 260 was introduced into TRNSYS which was further validated by the experimental data obtained from the literature. A 0.50 m internal dimension cubical was used with a 2 mm layer of aluminum on the active face and the rest painted black. Type 260 is connected to type 56 to model the MICROBAT test cell. The maximum temperature range decrease was 10%. A maximum difference of 1.1 °C and a mean difference of 0.2 °C was obtained between numerical and experimental modeling [102].

Type 332 using FORTRAN was proposed to model heat transfer of PCM floor coupled with solar water heating system (PFCSS) which was then compared with experimental data using two mathematical models Mean Relative Error (MRE) of 0.6%, and Bland- Altman giving analysis with 95.1% confidence level. The study results show that if the temperature is maintained at 20 °C an experimental building obtains 5.87% energy savings with the incorporation of PCM than the control building without PCM [103].

The major share of residential energy consumption is attributed to the ventilation system in a dwelling [104]. A model in Trnsys was created for the dwelling which includes flow rates, envelope transmittance, and ventilation strategies for countries like the United States of America, Germany, France, UK, Spain, thereby comparing further their requirements with Passivhaus construction strategies that is an example of nZEB given by European Union. The results suggested revised strategies of ventilation system compared to Passivhaus standard as per heating and cooling demand by implementing heat recovery ventilation except for some warm climate regime of USA and Spain. Heat balance for each thermal zone is considered by Trnsys and energy balance is governed by equation [104]:

$$U_{air} = Q_{heat} - Q_{cool} + Q_{inf} + Q_{vent} + Q_{coup} + Q_{trans} + Q_{gint} + Q_{sol} + Q_{solar}\ [kJ/L] \quad (4)$$

where, U_{air} = internal energy changes, Q_{trans} = transmission into the surface, Q_{heat} = heating power, Q_{gint} = internal gain, Q_{cool} = cooling power, Q_{sol} = absorbed solar gains on all inside surface, Q_{inf} = gains during infiltration, Q_{solar} = convective energy gain of the zone due to radiation transmitted through windows, Q_{vent} = ventilation gains, Q_{coup} = coupling gains.

The researchers continued to study [11] different settings of comfort and demand for energy under warm climates for a range of temperatures and air humidity with Trnsys to calibrate the impact on each city, where they essentially analyzed the impact of change in comfort parameters settings on residential and traditional dwellings for air conditioning during summer and winter. With an average 1 °C change in temperature set value, the percentage of energy consumption reduces drastically. The study recommended the development of new control algorithms to optimize the set temperature of the different warm-climate regions for energy savings.

A UK-based building was modeled [105] with Trnsys and TRNFlow to obtain and improve the energy demand in terms of ACR and ventilation by using window operation data. Four house models were analyzed, where the first model studied the building infiltration rate without heat gains which were then carried off by the second model for calibration of constant air change rate conjoined by the rest two models. The coefficient of variation of the root mean square error ranged below 10% for all models and the average ACR was simulated as 0.7 h^{-1} which was well above the under-ventilated house (0.5 h^{-1}). Thus, proving the efficiency of Trnsys in energy-based assessments. This approach has been analyzed as an effective way to calibrate different behavior of householders thereby, providing a better way to attain decreased energy demand and health conditions by implying effective natural ventilation strategies.

A comparative simulation between Trnsys and other commercial software based on Italian standard UNITS 11,300 (static model) was done by Evangelisti et al. [58] for the influence of thermal inertia to assess building energy performance. Three walls with different stratigraphy of massive elements and insulating layers were analyzed using a 5 m × 5 m cubic test cell south facing to analyze the temperature for its internal and external walls. The simulation results showed that externally placed insulation of Extruded polystyrene (XPS) gave the least amount of annual cooling and heating demand than when it is being centrally or internally placed.

3E Evaluation

Advancements in passive strategies and thermal insulation materials besides RES for building applications are under continuous improvement and progress. By increasing thermal insulation with PCM, it decreases the energy consumption by reduced thermal load thereby saving CO_2 emissions and huge capital investments on technologies for incorporating thermal comfort. The calibrations done for PCM encapsulation are basically on the amount of energy savings with variant climatic conditions. PCM of various types, percentages, and materials is incorporated into a different part of the building (ceiling, floor, sidewalls, storage tanks) that consequently reduces energy consumption, CO_2 production, and cost associated with energy consumption. Another advancement in energy-efficient strategies is taken up by the correct estimation of ventilation strategies that are to be revised based on varying climatic conditions or the correct estimation of ACR to obtain natural ventilation. A single-degree decrease in the setpoint temperature gave a drastic reduction in the value of energy consumptions. For all these calculations a simulation tool used during the pre, during, and post-design phase can contribute to an energy-efficient design with decreased energy consumption thereby, with improved economic and environmental impact. Table 4 showcases the 3E evaluations for the aforementioned passive strategies.

Table 4. 3E evaluations of Passive strategies.

Reference	Climate	Strategy	Outcomes	3E Evaluation
[99]	Mediterranean climate	1st layer concrete mix and 2nd layer microencapsulated PCM with wool and polyurethane as wall material	The average decrease in temperature by 7 °C.	Decrease in annual energy demand thus reduced CO_2 emissions.
[100]	Humid subtropical	Solar thermal panels + 95% PCM encapsulated thermal storage	90% reduction in thermal storage tank volume with increased storage tank efficiency.	35% energy savings with average heating reduction by 48% and cooling reduction by 3%.
[101]	Continental climate	PCM in west wall, ceiling and floor	3 °C decrease in temperature	Economical optimization of PCM use depending on climate vulnerability.
[102]	Intermediate zone	PCM to increase thermal inertia of the building	Maximum temperature range decrease by 10%	Increased thermal comfort and reduced energy consumption
[103]	Temperate monsoon	PCM floor + Solar water heating	Decrease in indoor temperature by 2 °C–3 °C	Energy savings: 5.87%
[104]	Comparison between semi-arid, temperate, intermediate, and continental climate zone	To acquire heat recovery through ventilation	Revised ventilation strategies based on varying climatic zone in comparison to Passivhaus standard.	For colder climates, significant heat recovery can induce a huge amount of energy savings.
[11]	Warm climate	Impact of comfort parameters on air conditioning energy demand	With an average 1^0C change in set heat value, the percentage energy consumption reduces drastically	Energy savings between 30 and 46% for nZEB by optimizing the set temperature
[105]	Temperate	Calibrating air change rate energy demand and ventilation rate	Average ACR simulated as 0.7 h^{-1}, i.e., well above under-ventilated house ACR, i.e., 0.5 h^{-1}.	Better use of ventilation strategies to reduce energy demand
[58]	Mediterranean	Wall stratigraphy XPS installed internally, centrally, and externally	Externally placed XPS gave the least annual cooling and heating demand	Thermal insulation by adding XPS for increased thermal comfort to increase energy savings for space conditioning

5.3. Multi-Objective Optimization for Integrated Solutions

To find a combined optimized value of the required variables like onsite energy generation, HVAC system, or building envelope a BPS tool requires numerous amounts tests runs which require the multi-objective-based optimization. With multi-objective optimization criteria, dozens of potential design is revealed with a wide range of trade-offs between the aspired set of values. A different set of optimization tools are looked at in the following case studies as described in Table 5, a combination of ANN and GA [5] can save a significant amount of computational time, GenOpt [106] a generic optimization tool suitable to be coupled with any text-based simulation program, MATLAB [107] provides a variety of algorithms to solve constrained, unconstrained continuous, and discrete problems by performing trade-off analysis. EES is a powerful mathematical program that has a large database of thermophysical and mathematical properties [108].

Table 5. Software coupling for integrated solutions.

Citation	Software	Description	Remarks
[5]	Trnsys + GA + ANN	Three steps optimization, model created and validated in Trnsys, a database for ANN validation, finally GA was run using ANN for potential solutions	Simulation results were in good agreement with measured data, with relative errors of 3.7%, 3.4%, and 7.3% for heating, cooling, and fan monthly energy consumptions, respectively.
[106]	Trnsys + MATLAB co-simulator	The use of TRNSYS-MATLAB co-simulator as a relevant tool to evaluate the performance of solar desiccant cooling for hot and humid region where, MATLAB is used for the simulation of a process and TRNSYS is used for improving the energy efficiency of a system.	The combination of both helps in better predictive control of a more economical model. The co-simulator helps in evaluating efficiency of solar collector, temperature control of strong and weak desiccant, and flow rate control of desiccant and air.
[107]	Trnsys + MATLAB	Adsorption desalination system powered by solar for the arid region. 2 adsorbent beds with 13.5 kg of silica gel.	Specific daily water production = 10.5 m^3/ton COP = 0.5 Specific cooling power = 134 W/Kg
[109]	ESP-r + Trnsys	1424 ft^2 single family C-RISE house @ Carleton university. ESP-r and TRNSYS continue their iterative solution individually. Harmonizer to check global convergence between the two.	Able to evaluate the potential contribution of a seasonal thermal system.
[110]	GenOpt + Trnsys +Ecotect	8 m × 7.5 m × 3 m room with 27 people occupancy and 3.5 ACR ventilation rate. Set point temp = 20 °C and 26 °C GenOpt with Particle swarm optimization set parameters and constraints then fed into Trnsys Primary energy eq. calibrated: $PE_{tot} = PE_{heat} + PE_{cool} + PE_{light}$ $= Q_{heat} + \frac{Qcool}{3} \times 2.18$ Daylight analysis by Ecotect	27% reduction in objective function with respect to highest evaluated design. Discomfort index (DI) = 45% close to design value (43%) Daylight factor (DF) = 3.96% and good daylight distribution
[108]	EES + Trnsys	Solar absorption AC model is simulated using Trnsys Absorption cycle using water and lithium bromide solution is modeled using EES.	Increased initial cost. Reduced electricity on national grid hence CFC elimination. Minimized fossil fuel consumption.

6. Discussion and Hypothesis

The review gives insight into work done in the field of improving building energy efficiency by adopting optimization strategies. The key points of the analysis are:

6.1. The Need for Building Energy Efficiency

Building efficiency is a considerable factor to improve the functioning of a composite system designed to deliver occupants with high comfort, a harmless, alluring living, and work environment, which significantly requires efficient engineering designs, quality construction practices, and intelligent operation of the structures. Further, shifting current extensive economic growth in response to higher energy consumption and increase technical innovation inputs requires investment in R&D for efficient design strategies while focusing on the introduction, conversion, and utilization of advanced optimization tools.

6.2. 3E as an Important Factor to Achieve Building Energy Efficiency

As energy usage is interlinked with environmental harms, climate change, and economic developments, it is important to look up the integration of 3E's to obtain clean energy usage with reduced GHG emissions, LCC, and overall cost savings. The 3E optimization is suitable to express the interest of the state or community rather than an individual consumer. Individual aspects might give less problem-oriented solutions. However, for a sustainable energy-efficient future, collaboration of energy, economy, and environment becomes inevitable.

6.3. The Importance of BPS in This 3E Achievement

Energy-efficient building hooks with the optimization of BES (building space load, HVAC, lighting, occupant comfort) thus, the designers assess different solutions, i.e., either based on experimental evaluation which is a time-consuming process with many uncertainties and limitations, or dynamic simulations that is rather fast and reliable in a pre-construction phase. The implementation of a BPS tool during the design phase ensures a configuration of building with low consumption with the correct design of RES that will take care of these consumptions. Moreover, by implementing BPS it analyses the multi-energy efficiency solutions available combining both passive and active measures. Amongst the obtained results a BPS tool can analyze the conflicting impacts (negative and positive) on the building. The goal of the designers to reach minimal cost, maximum energy savings with maximum occupant comfort can be conflicting hence, it requires better decision-making optimization tools.

6.4. Challenges Faced during Implementation of a BPS Tool

Although the implementation of BPS tools is widely anticipated, several challenges are faced from its adaptation to implementation phase. Challenges while adapting the BPS tool are of interest among developers and designers with a substantial investment in them, information regarding various building properties, and finally, integration of multi-disciplinary teamwork for better results. After adaptation during modeling and simulation, the initial stage of challenges is conceptual building, a suitable construction model with its quality assurance and the uncertainties obtained in weather and occupant behavior. Further for an improvised development of IDP in a synergetic context, the evolution of software coupling, optimization tool introduction, or robustness analysis makes the use of simulation tool rather more typical and accurate. These aspects clearly demand the increased number of experts in this field. Building optimization is assigned to a trade-off curve which resembles a graph of solution plotted in the form of a curve known as Pareto Frontier. The challenges faced during BPO are that sometimes it gives irrelevant physical results though the mathematical solution might be correct. Several research-based tools are procured in this prospect like MOBO which can deal with multi and single-objective optimization by automatic handling of constraints, and MAOS, a high-speed analysis tool owing to the feature of avoiding uncertain repeated analysis which takes into account a holistic approach. Robustness analysis which helps in reducing the sensitivity to the changing environment on to the building model becomes more complex with extensive analytical requirements. The integration of robustness assessment enhances the decision-making process by using multi-target key performance indicators, which take multiple performances into account and differentiates between feasible and non-feasible solutions.

6.5. Application of BPS Tool to Achieve Optimized Energy-Efficient Strategies

The adaptation of the BPS tool into the design process can significantly reduce the cost and time along with variable evaluation of optimization and design strategies that in turn will be able to increase building energy efficiency. The importance of the BPS tool in the initial phase of design was observed in a study where 15% energy savings was achieved by modeling the building [57]. Simulation and modeling techniques with their correct execution can help in integrating energy, economic, and environmental concepts to obtain building energy efficiency.

For the above-analyzed case studies, the inclusion of RES with solar PV and its combination with GSHP and wind to achieve nZEB is well explored. The analysis done with the help of a BPS tool evaluates the effects of implementing these strategies to accomplish the energy efficiency goal. The studies [88,89,95,98] reflect the huge energy savings obtained with a significant reduction in CO_2 emissions. Along with the fact that these applications include huge initial investment costs but the overall yearly cost savings are spectacular in comparison to the conventional system. Solar HVAC/space conditioning has proved to be a better solution for temperate, hot and dry, subtropical, arid climatic zones [90–92,94]. Solar DHW [93] with a different type of tube arrangements at variable climate gave different outputs in energy savings and CO_2 emissions. Other energy-efficient technologies [6,96] work collaboratively to give the 3E benefit. The studies featuring passive strategies including PCM [99–103], wall stratigraphy [58], and ventilation [11,104,105] gave piecemeal or aggregated solutions at instants, as they can significantly bring down the thermal load of the building thus reducing the dependency on external factors to improve occupant comfort. The use of a BPS tool helps to evaluate the optimum value of these strategies at different climatic ranges as the solutions vary with varying climatic conditions.

6.6. The Significance of Multi-Objective Optimization to Achieve an Integrated Solution

Designers need to integrate huge series of measures, i.e., RES, passive and active strategies, to obtain the goal of combined 3E benefit. Hence, obtaining this multi-objective optimization goal requires the integration of BPS with BPO tools or software coupling [5,106–110]. This solution is an aid for the conventional method of running the simulation multiple times with a huge number of possible solutions by performing a trade-off analysis for the variable set of solutions obtained.

6.7. The Current Need for Building Energy Efficiency in India

As a developing nation with increasing development strategies, is estimated that the floor space will increase in India by 35 billion m^2 by 2050. This growth will consequently lead to increased energy usage within the built space. An illustration based on the need for BEE to attain SDGs is shown in Figure 2. It is estimated that in the duration of 30 to 40 years, the increase in buildings stock with a lack of energy efficiency measures will lead to increased energy demand and thereby higer power generation. This contionous rise can be looked on as an opportunity to establish a growth with proper planning. The UN's 2030 agenda is closely linked to India as many of the developmental factors are directly linked to SDGs (Affordable and Clean Energy, Industry Innovation and Infrastructure, Sustainable Cities And Society, Responsible Consumption And Production, Climate Action) [111].

This paper illustrates the state-of-the-art of optimization techniques to achieve building energy efficiency, comparing the main features of RES and passive strategies, the almost fifteen years of experience of technicians in this field, and provides beginners and non-insiders with a guide on this topic. From the above analysis, it is clear that to achieve building energy efficiency a successful integration of a BPS tool by overcoming the challenges faced during its adaptation and implementation based on 3E optimization helps to constitute a successful method for a sustainable city and society. The method of 3E based evaluation helps to develop an integrated design process which thereby, enumerates the benefit of a cost-optimal, energy-efficient, environment-friendly solution.

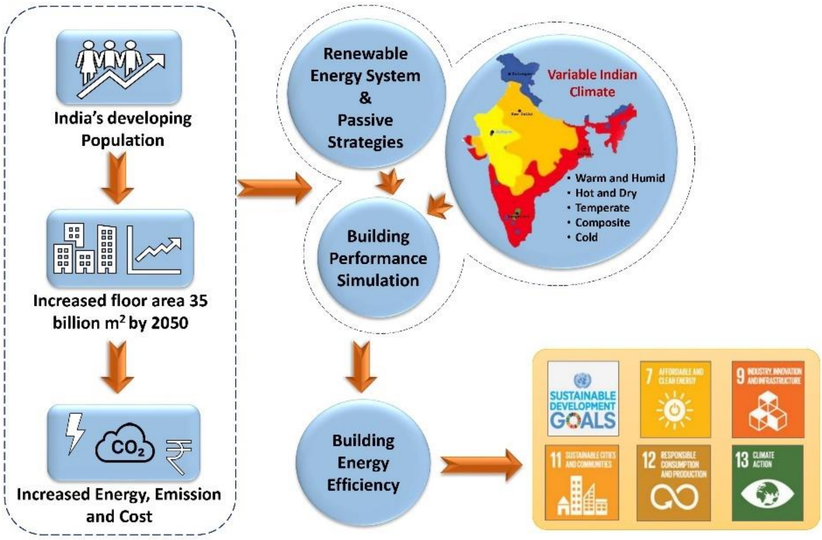

Figure 2. Need for building energy efficiency in India to attain SDG.

7. Conclusions and Future Recommendation

Amidst increased GHG emissions with rising building energy emissions and increased climate change the need for an energy-efficient building is highly obliged. Researchers are sequentially working in this regard, and the evolution of nZEB becomes notable. As this energy usage is interlinked with economical (LCC, overall cost), and environmental (CO_2) aspects, it requires a combined 3E based analysis. Therefore, robustness within the design model to achieve a sustainable, reliable, and long-lasting design essentially requires a proper performance-based validation that works at a greater level during predesign phase. Hence, for an efficient system, the optimization of different design control strategies becomes evident, this can be easily achieved by adopting BPS for a building design procedure. Though the BPS tool is being widely used across the globe by researchers but its practical application is restricted due to several challenges it engulfs from adoption to conduction of modeling and simulation until the optimization and robustness analysis to accommodate energy efficiency within a building. Further, the study reviewed the application of the BPS tool into energy-efficient strategies such as RES, passive strategies (PCM, ventilation) to achieve an optimum design giving maximum benefit in energy, economy, and environment. Further to evaluate the combined benefit of the required objective multi-objective optimization is a step ahead to evaluate the non-linearity of the problem with automated simulation-based optimization search techniques. These evaluation and optimization techniques can be better complimented with the help of legal requirements and constraints. As a developing nation, India still lacks in mass application of BPS tools for improving BEE due to improper channelizing. Implementing this framework will enable the designers, architects, researchers to contemplate variable building energy optimization scenarios.

Onlook to Future Recommendations Based on the Above Analysis for the Indian Scenario

Based on the five climatic zones of India, i.e., hot-dry, warm-humid, temperate, cold, and composite, this review analysis can be utilized to encompass various possible interventions based on subjective models observed under that peculiar climate. In terms of renewable energy at an individual or community level with proper analysis of the economy, energy and environment should be acquired by the Indian market to attain the goal of sustainability. To bring a paradigm shift altogether requires understanding the need for optimization and therefore, the motivation to bring in a change that can help in sustainable alternatives which can be easily adopted, implemented with reasonable cost, and payback time to easily peep into the common man's perspective. Thus, exists a serious need for the development of the concept and process of nearly zero energy buildings in India.

- For the achievement of building energy efficiency the important substituent, i.e., renewable sources like solar, geothermal, wind, are least deployed though available in ample amount due to lack of awareness and knowledge to the common public.
- Central and state-level policies with a proper advertisement of the importance of nZEB must be initiated.
- A proper code just for nearly zero energy buildings based on climatic conditions must exist.
- A further motivation-based approach by giving certifications for such buildings can improve its market value.
- Numerical approach importance is well discussed in this review, its advent can negotiate several structural, architectural, and design problems beforehand with minimal efforts. Therefore, a channel of expertise group needs to come into the picture for taking this goal to a next level.
- Monitoring mechanisms need to be incorporated for the time-to-time analysis of the implemented technologies.
- There must be one existing head who could properly chart and implant the nZEB concept into the country to bring it to a new normal.

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Abbreviation

3E	Energy, Economy and Environment
ACR	Air Change Rate
ACS	Absorption Cooling System
ANN	Artificial Neural Network
BEE	Building Energy Efficiency
BEM	Building Energy Modelling
BES	Building Energy System
BIM	Building Information Modelling
BPO	Building Performance Optimization
BPS	Building Performance Simulation
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
DHW	Domestic Hot Water
ECBC	Energy Conservation Building Code
EES	Engineering Equation Solver
EIA	Environmental Impact Assesment
EPBD	Energy Performance of Building Directive
EU	European Union
GA	Genetic Algorithm
GCM	Global Climate Model
GHG	Green House Gas
GME	Geometric Model Environment
GSHP	Ground Source Heat Pump

GUI	Graphical User Interface
HP	Heat Pump
HVAC	Heating, Ventilation and Airconditioning
IDP	Integrated Design Process
ITC	Increased Thermal capacitance
LCC	Life Cycle Cost
LHTES	Latent Heat Thermal Energy storage
MAOS	Multi-Aid Optimization Scheme
MOBO	Multi-Objective Building performance Optimization
MRE	Mean relative Error
nZEB	nearly Zero Energy Building
PCM	Phase Change Material
PNG	Piped Natural Gas
PV	Photovoltaic
R & D	Research & Development
RCM	Regional Climate Model
RES	Renewable Energy System
RH	Relative Humidity
SDG	Sustainable Development Goal
TSM	Thermal Storage Management
VCC	Vapour Compression cycle
WWS	Wind, Water and Solar
XPS	Extruded Polystrene

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