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# A REVIEW OF LIMITATIONS AND FUTURE CHALLENGES IN OPTIMIZATION OF ENERGY IN SUSTAINABLE HIGH-RISE BUILDINGS

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Review Article

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**ABSTRACT:** Sustainability has been one of architecture's most significant trends over the last twenty years. Environmental consciousness of professionals has put sustainability at the heart of the architectural profession and has contributed to adopting and implementing sustainable designs on the scale of urban landscapes. Buildings consume 40% of global energy, in which high-rise buildings account for a significant proportion of the total energy used. Hence, present study reviews limitations and future challenges in optimization of energy in sustainable high-rise buildings. Results of this study show that budget limitations, managerial and organizational policies, legal issues, technical and scientific infrastructure, and cultural and geographical aspects are all affecting the widespread use from energy optimization in current high-rise buildings and need to be considered in future studies.

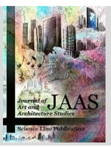
**KEYWORDS:** Energy, Sustainable Architecture, High-Rise Building.

## INTRODUCTION

Nowadays, energy crisis is among the most widespread discussions and numberless studies are being conducted throughout the world [1]. In the modern era, energy plays a key role in the socio-economic development of different countries. Therefore, management and optimization of energy consumption as one of the ways to ensure energy security is significantly considered by energy policymakers [2], The building sector has a considerable impact on the environment, since it accounts for one third of greenhouse gas emissions and 40% of the energy consumption worldwide [3], In a high-rise high-density city such as Hong Kong, buildings can even account for 60% of the carbon emissions and 90% of total electricity consumption [4]. As the residential building sector consumes approximately 30% of the total energy used worldwide, buildings account for approximately 36% of carbon dioxide (CO2) emissions the main causative pollutant for global warming [5-6] Futuristically, this percentage is expected to increase owing to the exponential growth in population and urban development. Consequently, cities expand vertically given the limited land space for accommodating the increasing population [7]. Moreover, the urban expansion will result in changes in energy use pattern, where further high demand in the building construction industry is a primary concern of governments, especially in developing countries, the availability of more modern housing in urban areas has helped significantly to meet the growing demand for housing from the huge number of people who move to fast-growing cities. Moreover, the urban expansion will result in changes in energy use pattern, which is further exacerbated by varying climate conditions [8-9]; thereby, evoking the need for urban sustainability. During the past decades, several studies are directed towards developing measures to promote building energy management, conservation and sustainability [10-11].

In general, five measures are identified to be impactful in reducing the ecological footprint of buildings: building insulation [12], equipment system [13], renewable resources [6], conserving behaviours [10] and control and management systems. Designing and implementing these measures based on climate data and characteristic features of the building will further augment the building performance [12]. Cao et al. [14] studied the effect of current climate trends on building heating and cooling loads and showed that the current trend has a more intense impact during winter than in summer. Heating loads were observed to decrease by 1%–4% while cooling loads increased by 0%–3% depending on location [14]. This result can offer insights into the design requirements for energy





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**1. Types of High-rise Buildings structural systems**

The followings are the conventional high-rise buildings addressed in relevant literature:

a. Braced frame structural system: Braced frames are cantilevered vertical trusses that resist lateral stresses, especially diagonal elements. The girders and columns serve as the "chords" and collectively they create the "web" of the vertical truss. Bracing components prevent beams and columns from bending. Braced frames have the excellent benefit of being repeatable up the height of the building with evident design and fabrication economy. It might, however, make it difficult to plan internally or choose where to put doors and windows. It must be integrated inside along with the walls and barriers, for this reason [16].

b. Rigid frame structural system: In a rigid frame construction, columns and beams are built as a single unit to endure moments brought on by loads. The bending stiffness of the columns, girders, and connectors in-plane determines the rigid frame's lateral stiffness. Buildings made with reinforced concrete can use it. It might also be employed in steel building, but the connections will be expensive. The chance of planning and installing windows due to the open rectangular arrangement is one of the benefits of rigid frames [17].

c. Wall-frame system (dual system): It is made up of a wall and a frame that work together horizontally to create a stronger and more rigid system. The walls can be found surrounding stairwells, elevator shafts, and/or at the outside of the structure. They are typically solid (not pierced by apertures). The walls may improve the frames' performance by, for example, preventing a soft story collapse. Wall-frame systems, which are superior to shear or rigid frame alone, are suited for buildings with a story count of between 40 and 60 stories. Steel rigid frames and braced frames both offer similar benefits of horizontal interaction [18].

d. Shear wall system: It is a continuous vertical wall made of masonry or reinforced concrete. Shear walls function as a thin, deep cantilever beam and can sustain both gravity and lateral stresses. It is ideally suited for bracing steel or reinforced concrete tall structures. This is due to the considerable in plane stiffness and strength of shear walls. Hotel and residential structures that have repeating floor-by-floor layout that enables the walls to be vertically continuous are good candidates for shear wall systems [19].

e. Core and outrigger structural system: By connecting the spine or core to the closely spaced outside columns, outriggers are rigid horizontal structures intended to increase the stiffness and strength of buildings during overturning. Shear walls or braced frames can be found at the core's center. By connecting two structural systems (a perimeter system and a core system), outrigger systems enable a structure to act almost like a composite cantilever. In reinforced concrete buildings, the outriggers take the shape of walls, whereas trusses are used in steel buildings. Up to five times as much moment resistance as a single outrigger system may be produced by multilevel outrigger systems [20].

**2. Technological advances modern high rise buildings**

Much of the “green” agenda focuses on reducing energy consumption. Buildings consume about 40% of the world’s energy, and elevators account for 2%–10% of a building’s energy consumption. During peak usage hours, elevators may utilize up to 40% of the building’s energy [21-22]. Glen Pederick, 2014, explains that everyday there are more than 7 billion elevator journeys taken in buildings all over the world; and as such, energy-saving elevators will reduce energy consumption significantly [23]. Fortunately, new technologies and best practices involving motors, regeneration converters, control software, optimization of counterweights and cabin lighting can yield significant savings [24]. Researcher Patrick Bass writes of recent examples of ThyssenKrupp technologies that provide energy savings of about 27% and space saving of about 30% [25].

Introduced in the mid-1990s, machine-room-less (MRL) technology was one of the biggest advances in elevator design since they went electric a century before. Manufacturers redesigned the motors and all other equipment normally housed in a machine room to fit into the hoistway, eliminating the need to build a machine room. Earlier, elevator equipment was so massive that a dedicated machine room (about 8 feet tall or greater) was required, usually placed above the hoistway atop a building’s roof. The machine room was costly because it needed to support heavy Today, MRL elevators are increasingly common [26]. The MRL system becomes even more energy efficient when it is combined with regenerative drives [27].

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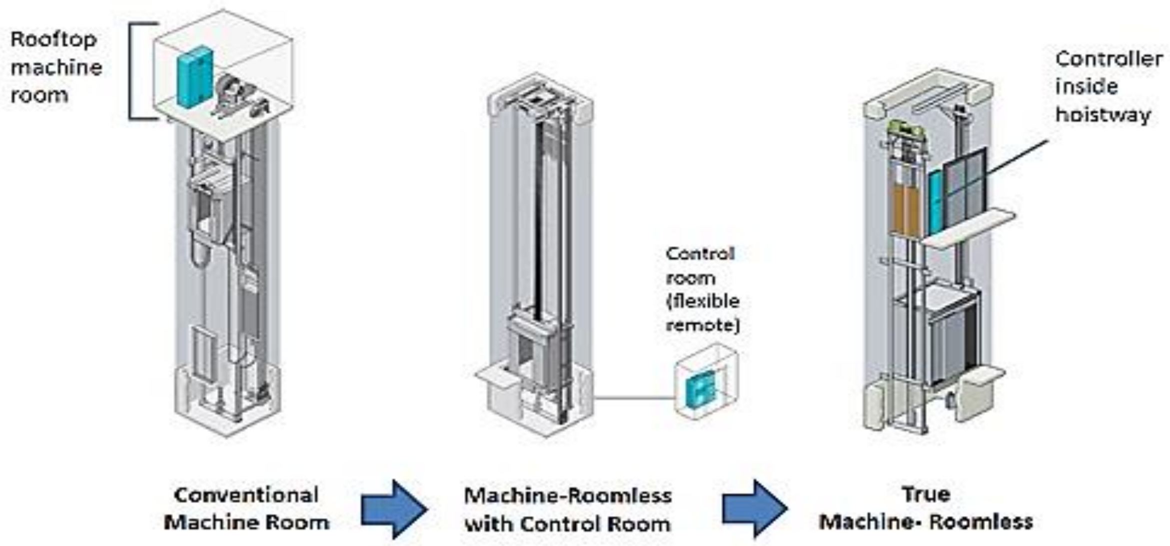


**Figure 2.** Gearless Machine-Roomless Revolution. Note space saving factor as technology advances. This increases usable spaces, which is crucially important in skyscrapers (Source: http://www.otisworldwide.com).

**a. Energy consumption in high-rise buildings**

Whilst the majority of tall buildings constructed today continue to demonstrate 'fourth generation' characteristics, meeting regulatory energy performance criteria, but not bettering these by any substantial amount, there is a growing number of high-rise designs and completed buildings that aim to go above and beyond the norm in terms of reducing primary energy consumption. In an age where climate change is arguably the greatest challenge to the modern world and bodies such as the IPCC are predicting a temperature increase of between 1.8°C and 4°C by the end of the century, this change cannot occur quickly enough. Arguably the first significant tall building reflecting these new environmentally conscious principles was the Commerzbank in Frankfurt (by Foster and Partners, 1997), although one could look to the bio-climatic skyscrapers of Dr Ken Yeang SOM's National Commercial Bank in Jeddah(1984), or even Frank Lloyd Wright's Price Tower in Oklahoma (1956) as earlier examples of 'sustainable' high-rise design. The Commerzbank, incorporates a high degree of primary energy-reducing design strategies and technologies that include:

- A full building height central atrium, providing natural lighting and ventilation to internal office spaces.
- The use of large, open sky gardens further to increase daylight penetration to office areas.
- A facade design that allows for natural ventilation for over half the year through operable windows (known as the Klimafacade). A water-based cooling system of chilled ceilings

in fact many qualities of the Commerzbank are typical of fifth-generation skyscrapers. In terms of form and shape, tall buildings of this category have high surface area to volume ratios — typically between 0.10 m2/m3 and 0.22 m2/m3— compared to around 0.09 m2/m3 for the more bulky fourth-generation buildings. This is achieved by utilising shallow floor plans (eg,. GSW Headquarters, Berlin, 1999) or by using large atria effectively to reduce the depth of deeper floorplates (eg, Deutsche Post Tower, Bonn, 2002); 'Swiss Re' Tower, London, 2004), allowing air and natural light to penetrate deep into office spaces. Although this increase in

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surface area to volume ratio would reduce artificial lighting loads and make natural ventilation a possibility, winter heating loads in these buildings would also rise as previously discussed. Artificial lighting requirements in these towers are further reduced by the use of photo- and motion-sensors that adjust over headlights, turning them down or off when natural lighting levels are sufficient, or when rooms are empty. For example, in the Bank of America Tower(New York, 2008) this technology will help to reduce the demand for electric lighting by 25%.

Energy consumption of the changes in tall-building characteristics across these five generations. Tall building envelope design in particular would benefit from such studies: determining whether future tall buildings may benefit from 'first and second generation' characteristics — such as increased opacity and thermal mass within the facade — in order to reduce their primary energy needs and assist in meeting the modern-day challenge of climate change.

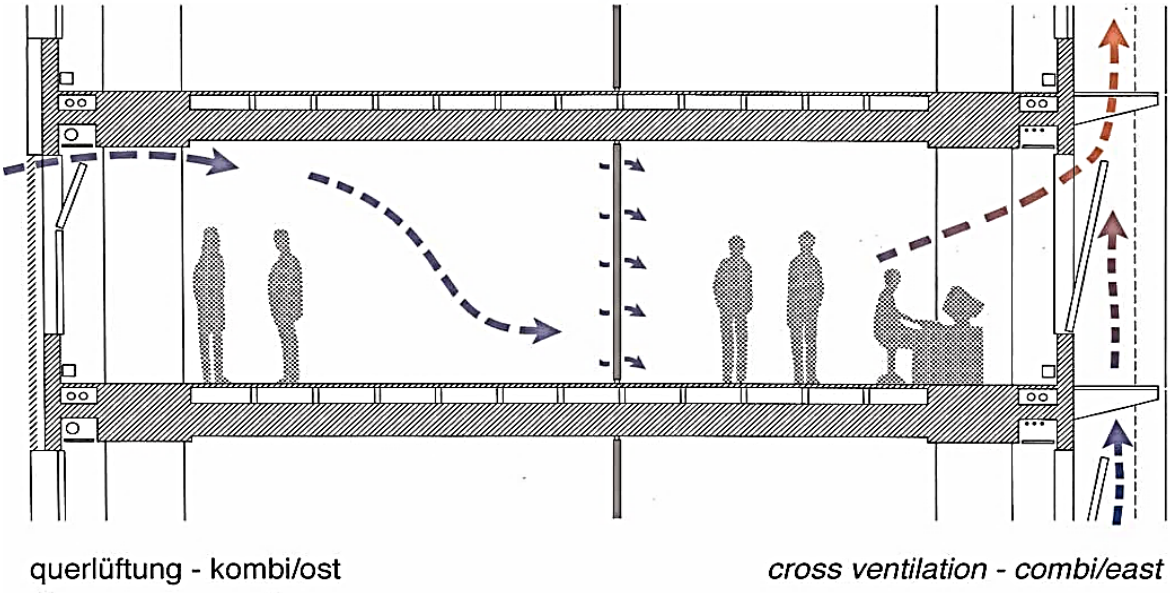


**Figure 3:** GSW Headquarters, Berlin, 1999. Part-section showing the natural ventilation strategy and double skin facade (to the right) [28].

## CONCLUSION

### Limitations

*Lack of data:* The lack of data on energy consumption and performance in high-rise buildings makes it difficult to optimize energy use.

Complex design: High-rise buildings have complex designs, making it challenging to optimize energy use.

*High cost:* The implementation of energy-efficient technologies and systems in high-rise buildings can be expensive, making it difficult for developers to invest in them.

Limited space: High-rise buildings have limited space for energy-efficient systems, making it challenging to implement them effectively.

*Technical expertise:* The optimization of energy in high-rise buildings requires technical expertise, which may not be readily available.

### Future challenges

*Rapid urbanization:* As more people move to cities, there will be an increased demand for high-rise buildings, which will require sustainable energy solutions.

*Climate change:* Climate change is a significant challenge that requires the optimization of energy in high-rise buildings to mitigate its effects.

*Advancements in technology:* As technology advances, there will be a need to incorporate new and emerging technologies into high-rise buildings to optimize energy use.

*Government policies:* Government policies and regulations play a significant role in promoting sustainable energy use in high-rise buildings. However, there is a need for more stringent policies to encourage developers to invest in sustainable energy solutions.

*Changing user behavior:* Changing user behavior is crucial in optimizing energy use in high-rise buildings. There is a need for education and awareness campaigns to promote sustainable energy use among building occupants.

*Aging infrastructure:* Many high-rise buildings are aging and require upgrades to their energy systems to improve efficiency.

*Integration of renewable energy:* The integration of renewable energy sources, such as solar and wind power, into high-rise buildings can be challenging due to limited space and complex designs.

*Resilience to natural disasters:* High-rise buildings need to be designed and built to withstand natural disasters such as earthquakes, hurricanes, and floods while maintaining energy efficiency.

*Equity and affordability:* Sustainable energy solutions in high-rise buildings should be accessible and affordable for all, including low-income residents, to promote social equity and reduce energy poverty.

*Smart building technology:* The integration of smart building technology, such as automated energy management systems and sensors, can help optimize energy use in high-rise buildings but requires significant investment and expertise.

*Energy storage:* High-rise buildings can benefit from energy storage systems to store excess energy generated from renewable sources or during off-peak hours for later use.

Energy consumption monitoring: To optimize energy use in high-rise buildings, it is essential to monitor energy consumption regularly to identify areas for improvement and track progress towards energy efficiency goals.

*Building codes and regulations:* Governments need to implement building codes and regulations that promote sustainable energy solutions in high-rise buildings and encourage developers to adopt green building practices.

*Public awareness and education:* Public awareness and education campaigns can help increase awareness of the benefits of sustainable energy solutions in high-rise buildings and encourage individuals to adopt energy-efficient behaviors.

*Renewable energy sources:* High-rise buildings can harness renewable energy sources such as solar, wind, or geothermal energy to reduce reliance on traditional fossil fuels.

*Energy-efficient lighting:* The use of energy-efficient lighting technologies such as LED lights can significantly reduce energy consumption in high-rise buildings.

*Water conservation:* High-rise buildings can implement water conservation measures such as low-flow fixtures, rainwater harvesting, and greywater recycling to reduce water consumption and wastewater.

*Life cycle analysis:* A life cycle analysis of high-rise buildings can help identify areas for improvement in terms of energy use, materials, and waste management throughout the building's lifespan.

Results of this study show that budget limitations, managerial and organizational policies, legal issues, technical and scientific infrastructure, and cultural and geographical aspects are all affecting the widespread use from energy optimization in current high-rise buildings and need to be considered in future studies.

## DECLARATIONS

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### Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

### Authors' contribution

Kadaei Samireh performed the research, data analysis, and manuscript writing.

### Competing interests

The author declares that there is no competing interest.

## REFERENCES

[1] Doraj, P., Aluclu, I., & Hossein Eskandani, O. (2021). The impact of architectural structures from past to present on developing tourism (example of the city of paris). International Journal of Scientific and Technological Research (JSTR), 7(9), 8-19. https://doi.org/10.7176/JSTR/7-09-02

[2] Moreira, A. C., Ribau, C. P., & Rodrigues, C. D. S. F. (2022). Green supply chain practices in the plastics industry in Portugal. The moderating effects of traceability, ecocentricity, environmental culture, environmental uncertainty, competitive pressure, and social responsibility. Cleaner Logistics and Supply Chain, 5, 100088. https://doi.org/10.1016/j.clscn.2022.100088

[3] Bartlett, E., & Howard, N. (2000). Informing the decision makers on the cost and value of green building. Building Research & Information, 28(5-6), 315-324. https://doi.org/10.1080/096132100418474

[4] Rahmani, A., Mashayekh, J., Aboojafari, R., & Naeini, A. B. (2023). Determinants of households' intention for investment in renewable energy projects. Renewable Energy, 205, 823-837. https://doi.org/10.1016/j.renene.2023.01.096

[5] Saleki, S., & Bahramani, S. K. (2018). Designing a Low-Carbon Building via LCB Method 3.0, Case Study: An Educational Building in Tehran. Journal of Construction in Developing Countries, 23(2), 129-150. https://doi.org/10.21315/jcdc2018.23.2.8

[6] Ascione, F., Bianco, N., Mauro, G. M., & Napolitano, D. F. (2021). Knowledge and energy retrofitting of neighborhoods and districts. A comprehensive approach coupling geographical information systems, building simulations and optimization engines. Energy Conversion and Management, 230, 113786. https://doi.org/10.1016/j.enconman.2020.113786

[7] Lima, I., Scalco, V., & Lamberts, R. (2019). Estimating the impact of urban densification on high-rise office building cooling loads in a hot and humid climate. Energy and Buildings, 182, 30-44. https://doi.org/10.1016/j.enbuild.2018.10.019

[8] Riahi, P., Mehrabani, SR., Safari Moradabadi, M. (2014). Investigating the effects of climate on the structure and body of architecture in cold and mountainous regions (case example: Palangan village), The first national conference on sustainable development in the sciences of geography and planning, architecture and urban planning, https://civilica.com/doc/336720

[9] Shen, P., Braham, W., & Yi, Y. (2019). The feasibility and importance of considering climate change impacts in building retrofit analysis. Applied energy, 233, 254-270. https://doi.org/10.1016/j.apenergy.2018.10.041

[10] Hong, Y., Deng, W., & Ezeh, C. I. (2019, May). Low-rise office retrofit: prerequisite for sustainable and green buildings in Shanghai. In IOP Conference Series: Earth and Environmental Science (Vol. 281, No. 1, p. 012025). IOP Publishing. https://doi.org/10.1088/1755-1315/281/1/012025

[11] Kadaei, S., Nezam, Z., González-Lezcano, R. A., Shokrpour, S., Mohammadtaheri, A., Doraj, P., & Akar, U. (2023). A new approach to determine the reverse logistics-related issues of smart buildings focusing on sustainable architecture. Frontiers in Environmental Science, 10, 2510. https://doi.org/10.3389/fenvs.2022.1079522

[12] Qian, D., Li, Y., Niu, F., & O'Neill, Z. (2019). Nationwide savings analysis of energy conservation measures in buildings. Energy Conversion and Management, 188, 1-18. https://doi.org/10.1016/j.enconman.2019.03.035

[13] Capellán-Pérez, I., Campos-Celador, Á., & Terés-Zubiaga, J. (2018). Renewable Energy Cooperatives as an instrument towards the energy transition in Spain. Energy Policy, 123, 215-229. https://doi.org/10.1016/j.enpol.2018.08.064

[14] Cao, J., Li, M., Wang, M., Xiong, M., & Meng, F. (2017). Effects of climate change on outdoor meteorological parameters for building energy-saving design in the different climate zones of China. Energy and buildings, 146, 65-72. https://doi.org/10.1016/j.enbuild.2017.04.045

[15] Gan, V. J., Wong, H. K., Tse, K. T., Cheng, J. C., Lo, I. M., & Chan, C. M. (2019). Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings. Journal of cleaner production, 231, 1375-1388. https://doi.org/10.1016/j.jclepro.2019.05.324

[16] Salman, K., Kim, D., Maher, A., & Latif, A. (2020). Optimal control on structural response using outrigger braced frame system under lateral loads. Journal of Structural Integrity and Maintenance, 5(1), 40-50. https://doi.org/10.1080/24705314.2019.1701799

[17] Senthilkumar, R., & Kumar, S. S. (2020). Seismic performance of semi-rigid steel-concrete composite frames. In Structures (Vol. 24, pp. 526-541). Elsevier. https://doi.org/10.1016/j.istruc.2020.01.046

[18] Gentile, R., Pampanin, S., Raffaele, D., & Uva, G. (2019). Analytical seismic assessment of RC dual wall/frame systems using SLaMA: Proposal and validation. Engineering structures, 188, 493-505. https://doi.org/10.1016/j.engstruct.2019.03.029

[19] Sun, J., Qiu, H., & Jiang, H. (2019). Experimental study and associated mechanism analysis of horizontal bolted connections involved in a precast concrete shear wall system. Structural Concrete, 20(1), 282-295. https://doi.org/10.1002/suco.201800113

[20] Patel, K., Patel, V., & Mevada, S. (2020). Design and Analysis of Core and Outrigger Structural System. https://d1wqtxts1xzle7.cloudfront.net/64634392/IRJET-V7I6567-libre.pdf

[21] Nemeth, B., & Place, H. (2011). Energy-efficient elevator machines. ThyssenKrupp Elevator: Frisco, TX, USA. https://doi.org/10.3390/buildings5031070

[22] Ziaee, S., Gholampour, Z., Soleymani, M., Doraj, P., Eskandani, O. H., & Kadaei, S. (2022). Optimization of energy in sustainable architecture and green roofs in construction: A review of challenges and advantages. Complexity, 2022. https://doi.org/10.1155/2022/8534810

[23] Al-Kodmany, K. M. (2021). Tall Buildings and Elevators: New sustainable Design. https://doi.org/10.1063/9780735424036_003.

[24] Kwatra, S., & Essig, C. (2014, May). The promise and potential of comprehensive commercial building retrofit programs. American Council for an Energy-Efficient Economy. https://www1.eere.energy.gov/wip/pdfs/53827-8.pdf

[25] Fakıoğlu Gedik, B., & Ay, B. Ö. (2023). The impact of service core reduction in supertall buildings: a study on structural design, embodied carbon, and leasable floor area. Architectural Science Review, 66(2), 144-153. https://doi.org/10.1080/00038628.2023.2182271

[26] Sachs, H., Misuriello, H., & Kwatra, S. (2015). Advancing elevator energy efficiency. Report A1501. https://unepccc.org/wp-content/uploads/sites/3/2016/03/a1501.pdf

[27] Makar, M., Pravica, L., & Kutija, M. (2022). Supercapacitor-based energy storage in elevators to improve energy efficiency of buildings. Applied Sciences, 12(14), 7184. https://doi.org/10.3390/app12147184

[28] Oldfield, P., Trabucco, D., & Wood, A. (2009). Five energy generations of tall buildings: an historical analysis of energy consumption in high-rise buildings. The Journal of Architecture, 14(5), 591-613. https://doi.org/10.1080/13602360903119405