Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
June 2023, Vol 12, No 2, 169-177
https://doi.org/10.21022/IJHRB.2023.12.2.169

Tall Buildings and Elevator Technologies: Improving Energy Efficiency

Kheir Al-Kodmany†

Department of Urban Planning and Policy, the University of Illinois at Chicago

†Corresponding author:
Kheir Al-Kodmany
E-mail: kheir@uic.edu

Abstract The massive increase in elevator usage and a severe demand for energy efficiency have prompted manufacturers to develop various innovative technologies, including AC and gearless motors, machine-room-less (MRL) technologies, regenerative drives, elevator ropes, and LED lighting. In addition, manufacturers are providing software solution systems such as destination dispatching systems, people flow solutions, standby mode, and predictive maintenance applications. Future technologies include electromagnetic levitation, circulating multi-car elevator systems, robotization, and drones. This article outlines elevators' technological advancements. It discusses how to harness new technologies and apply them to aging, modern, and future buildings.

Keywords Energy saving, Efficiency, Technologies, Hardware, Software, Apps

1. Introduction

Many cities are growing vertically. Building upward is primarily motivated by urban population growth (driven by natural population growth and significant rural-to-urban migration), rapid urban regeneration, skyrocketing land prices, active agglomeration, and globalization. The United Nations predicts that by 2050, 70% of the world's 9.7 billion population will reside in cities, up from 51 percent in 2010 (Walsh, 2022). As buildings proliferate and get increasingly taller to accommodate our growing population, we must start thinking about the best ways to cut consumption and the urban energy footprint. Buildings consume 40% of the world's energy. Cities trying to reduce their carbon footprints as the fight against climate change gains traction should prioritize buildings (Du et al., 2016).

The increasing verticality of the 21st-century city is placing a high demand on the elevator industry to improve quality and reduce energy consumption and carbon emissions (Hrabovsky et al., 2021). Indeed, several countries have passed energy efficiency laws to lessen the environmental impact of traditional energy sources. Reducing electrical energy use is essential to making national energy systems resilient enough to serve local and global economies. Elevator use affects building energy consumption, making it vital to sustainable development. More than seven billion elevator rides are taken daily in towering buildings worldwide. Elevators typically stay in a structure for long years and use considerable energy. As such, any elevator design and manufacturing improvement will have a significant economic and environmental impact (Yanbin et al., 2020).

This paper intends to inform architects, engineers, and developers about how to make the most of the potential of new elevator technologies. The conversation starts with a summary of some of the more notable improvements to energy efficiency. Then it quickly moves on to some of the more unique solutions. New elevator technologies can be divided into two groups: 1) energy-efficient hardware, like AC power, machine-room-less (MRL) technology, regenerative drives, elevator ropes, TWIN systems, double-deck elevators, and LED lighting; and 2) energy-efficient software, like destination dispatching systems, people flow solutions, and standby solutions.

2. Energy-Efficient Hardware

2.1. DC and AC Motors

One of the significant advances in elevator technology has been the replacement of conventional brushed DC (direct current) motors with more efficient AC (alternating current) motors. Before the 1990s, elevator systems relied on DC motors because it was easier to control elevator acceleration, deceleration, and stopping with this form of power. AC power was usually only used in freight elevators, where speed and comfort are less critical than in passenger elevators. By the late 1990s, however, more elevators had moved to AC machines because motor controller technology had advanced enough to regulate AC power, enabling smooth stopping, acceleration, and deceleration. DC motors were great when they first came out. Still, newer AC gearless motors are better in terms of performance, energy efficiency, and the ability to send extra power back into the building's electrical system (Kim, 2017; Al-Kodmany, 2014).

2.2. Geared and Gearless Motors

High-rise buildings typically employ geared or gearless traction elevators. Gearless elevator motors can be 50% smaller than geared ones because they don't have gears. The other parts would also become smaller because of the engine's reduction in size. In geared machines, the electric traction motor drives a reduction gearbox, the output from which turns a sheave over which the rope passes between the car and the counterweights. In contrast, the drive sheave is directly connected to the motor in gearless elevators, thereby eliminating gear-train energy losses. Therefore, a significant advantage of gearless motors is that they save about 25% more energy than geared motors. Gearless engines also run faster and enjoy greater longevity because they feature higher torque and run at lower rotations per minute (RPM). The major disadvantage of gearless elevators is the cost, materials, installation, and maintenance are generally more expensive than geared elevators. Despite the cost, more elevators today use AC, gearless motor machines because they are more efficient and last longer (Hamouche et al., 2017).

2.3. Machine-Room-Less (MRL) Technology

Elevator equipment used to be so big that it needed its own room, usually placed above the hoistway on the roof of a building and at least 8 feet tall. The machine room was costly because it was needed to support heavy machinery. Introduced in the mid-1990s, MRL technology was one of the enormous advances in elevator design since elevators became electric a century before. Elevators without a machine room employ a gearless traction machine positioned in the hoistway. Utilizing a counterweight aids the machine in spinning the elevator sheave, which propels the cab through the hoistway. As such, manufacturers redesigned the motors and all other equipment typically housed in a machine room to fit into the hoistway, eliminating the need to build a machine room (Figure 1). The reduced beginning current needed for the MRL also contributes to its energy efficiency. The MRL uses only 30 to 40 percent of the energy used by comparable traction and hydraulic motors. The MRL is a high-performance, space-saving, and energy-efficient elevator as a result (Retolaza et al., 2021). It becomes even more energy efficient if it is combined with regenerative drives (see next section). Today, MRL elevators are increasingly common. Out of its 57 elevators, Burj Khalifa employs twenty-four machine-room-less (MRL) elevators, Gen2. Similarly, Tianjin CTF Finance Centre operates 27 machine-room-less (MRL) elevators, Gen2.

2.4. Regenerative Drives

Regenerative drives are another remarkable advancement in energy-efficient elevator technology. They turn the heat produced by elevators during operation into useful energy for the building (Palomba et al., 2020). The regenerative drive can harness and save energy in multiple ways, including:

- When the elevator slows down, it applies brakes, creating energy. In a conventional elevator system, that energy is dissipated as heat through a heat resister. The regenerative drive harnesses that energy.
- Whenever an empty or lightly loaded elevator goes up, the elevator applies brakes to maintain the rated speed. As with slowing down, that energy is usually lost, but the regenerative drive harnesses it. Further, when an empty or lightly loaded elevator goes up, the motor spins, but the elevator's counterweight does most of the work. The regenerative drive harnesses

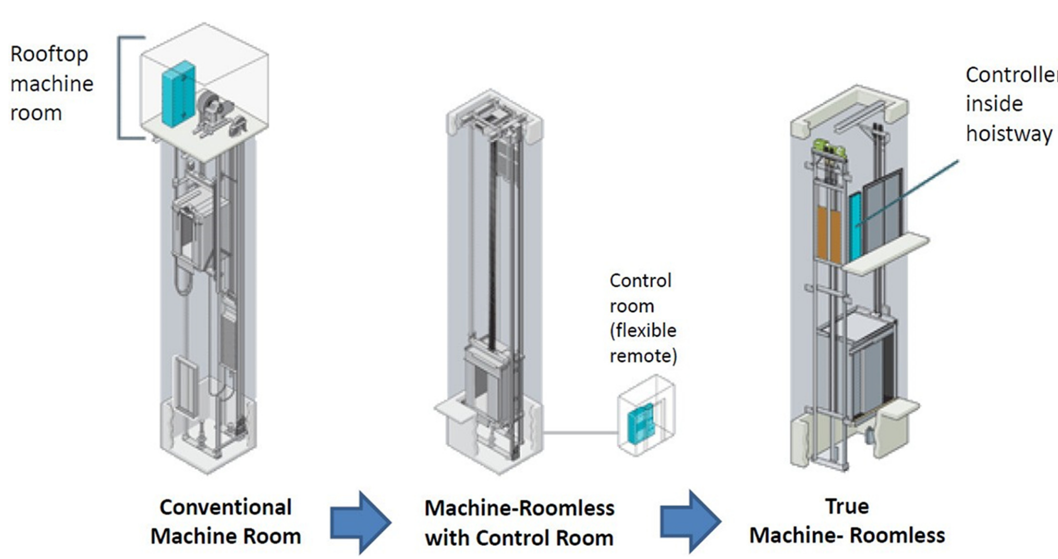

Figure 1. Gearless Machine-Roomless Revolution. (Source: adapted from http://www.otisworldwide.com).

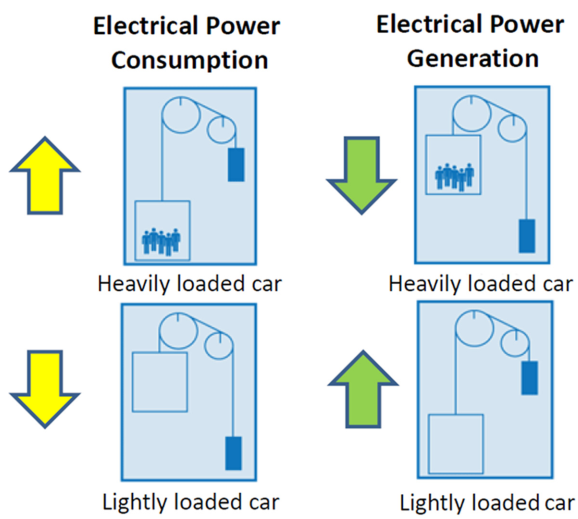

Figure 2. The regenerative drive system. (Source: adapted from http://www.otisworldwide.com)

that spinning energy by transforming mechanical power into electrical power.

- When a heavy elevator goes down, it applies brakes to maintain the desired speed. In a conventional system, the energy created by the braking system is lost. The regenerative drive harnesses that energy. Furthermore, when a heavy elevator goes down, the motor spins, but gravity does most of the work. The regenerative drive again harnesses that spinning energy by transforming mechanical power into electrical power.
- There is an additional energy saving that results from eliminating the need to cool equipment that gets exposed to excess heat generated by conventional motors (Figure 2).

These everyday modest quantities of power that are stored and harnessed over time result in substantial energy savings. Regenerative drives can cut building transportation energy consumption by 70% and minimize HVAC strain and cost by eliminating unwanted heat. The length of travel, frequency, the pattern of use, and device age affect energy savings. Longer distances and more trips generate more energy (Palomba et al., 2020) (Figure 3). The regenerative drives in the elevators of the One World Trade Center in New York City provide enough energy for the building's whole lighting system. Shanghai Tower also employs regenerative converters and group-control systems, lowering energy use by up to 30 percent (Zhu, 2019).

The 1,250-foot Empire State Building provides an exciting application of the regenerative drive. Recently, the building had a green retrofit that included upgrading its elevator systems, saving tremendous energy. The employed regenerative system, as explained earlier, harvests the "waste energy" from braking, which elevators frequently do. Conventional elevator machinery can lose more than 30% of its energy in the form of waste heat, and the new

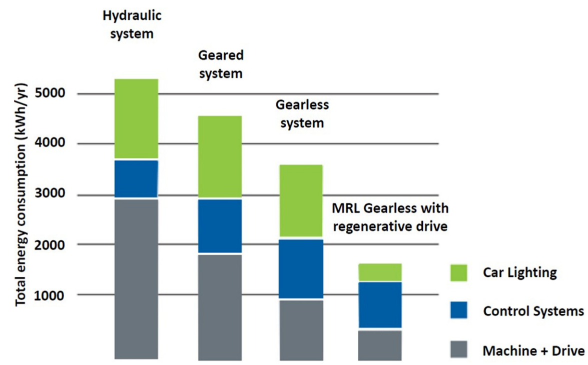

Figure 3. A comparison of energy consumption among different elevator systems.

retrofit reduces the loss to only five percent. The new elevator system channels the rest of the energy back into the building's electrical system. The second means of savings is a direct result of the first. In a conventional elevator system, waste heat gathers in the machine room, requiring substantial air conditioning to prevent overheating. In contrast, the regenerative system does not have this problem because the heat has already been captured, harnessed, and channeled to the electrical system as "surplus" power. The new elevator system results in significant savings that reduce demand on the city power grid (Dahlmann et al., 2016).

2.5. Elevator Rope

The elevator rope is an essential component of traction elevators because it connects the elevator engine with the cab, sheaves, and counterweight. A counterbalance on the other side of the sheave connects the car-lifting ropes. The counterbalance weighs as much as a 40%-full automobile. Thus, when the car is 40% full (average), the counterweight and car are balanced. This equilibrium saves energy. Steel ropes hold cabins. However, in very tall buildings, the rope gets too long and too heavy to the point that it cannot support its own weight. As height increases, starting currents and energy usage rise, increasing energy consumption. In response, elevator manufacturers have been strengthening cables. The Schindler aramid fiber rope is more robust and lighter than steel. Otis' tiny Gen2 elevators use ultra-thin wires encased in polyurethane instead of steel ropes. Mitsubishi produced a more potent, denser string with concentric steel wire. These more robust, lighter cords move elevator cabs more efficiently, conserving energy (Hrabovsky et al., 2021).

The KONE "UltraRope" is the most significant breakthrough. It has a carbon-fiber core and a unique high-friction coating, allowing cars to travel up to 1,000 m (3,280 ft). This is twice the 500 m (1,640 ft) limit. The 500-m UltraRope weighs 10% of steel ropes. For a 2000-kilogram elevator traveling 500 m, UltraRope weighs 2,500 kilograms, compared to 27,000 for ultra-high tension steel ropes. The 90% reduction in rope mass saves

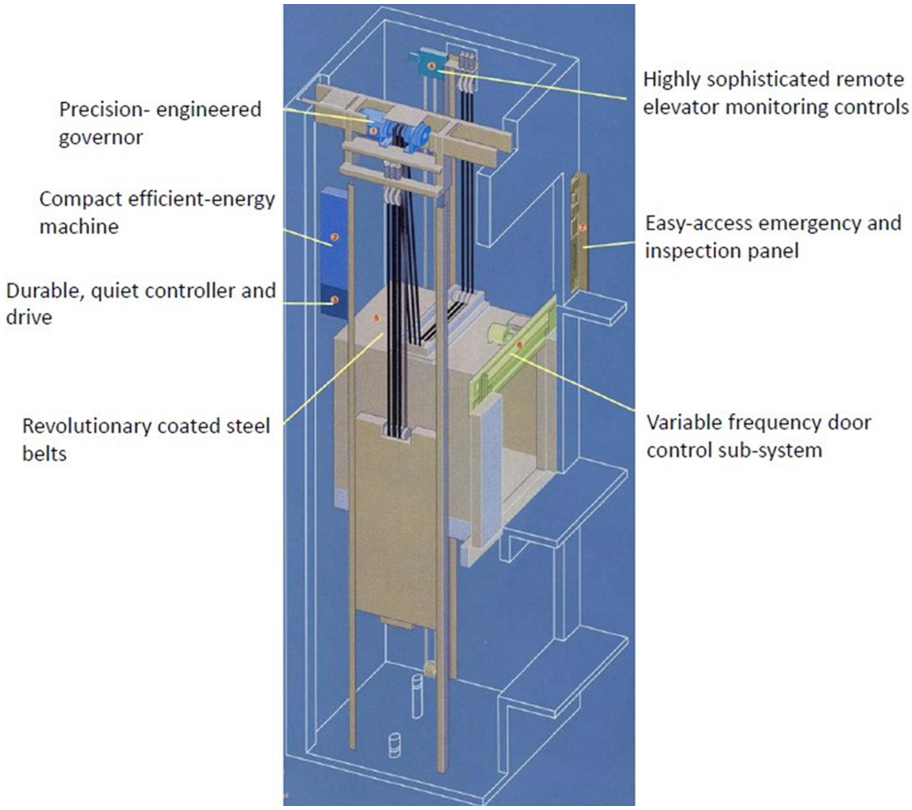

Figure 4. Diagram of OTIS GeN2 Lift. (Source: adapted from http://www.otisworldwide.com).

considerable energy (Figure 4). The 3,281-foot-tall Jeddah Tower in Saudi Arabia (construction on hold) plans to install the super-light KONE UltraRope elevators. Eight elevators of this type were installed in South Quay Plaza, a residential tower in London, UK -- one of the tallest residential buildings and the first to be equipped with KONE UltraRope in Europe.

2.6. Double-Deck Elevators

A double-deck elevator consists of two stacked cabs where one serves floors with even numbers, and the other serves floors with odd numbers. Double-deck elevators can reduce the overall energy usage of a building by reducing the number of stops and even the total number of elevators required if used with destination dispatch controls. As skyscrapers get higher, reducing the number of elevators needed becomes more important because they eat up valuable interior space on every floor. Double-deck elevators are most useful for applications in very tall buildings, particularly for shuttle services (Goldsworthy, 2018). For example, Burj Khalifa, the world's tallest building, employs two double-deck observation elevators, each with a capacity of 21 people. Likewise, Shanghai Tower, the world's third tallest building, uses four double-deck elevators between the ground floor and the hotel lobby on the 101st floor. Similarly, Guangzhou CTF Finance Centre employs 28 double-deck elevators to minimize the number of elevator shafts. In the same manner, the Petronas Twin Towers use 58 double-deck elevators because the towers lack the capacity for side-by-side elevator hoistways. Further, the Shanghai World Financial Center employs 22 double-deck elevators. Also, the International Commerce Center (ICC), Hong Kong's tallest building, uses 40 double-deck elevators. However, the double-deck elevators suffer from some operational challenges. Equal floor rise could present a limitation; i.e., for local service, double-deck elevators must load and unload two decks simultaneously. Even though traffic is reduced during off-peak hours, both decks will be operating (Cortes et al., 2021).

2.7. The TWIN Systems

Sharing similar characteristics with double deck systems, TWIN is an elevator system in which two standard cabs are installed within the same shaft but operate independently. A device that monitors the distance between two elevators prevents them from collisions. Simply, the system enables more elevators with fewer shafts – it is estimated to require one-third fewer shafts than conventional elevators, saving core space. Installing fewer elevator shafts and a smaller lobby on each floor of a 31-story skyscraper saves roughly 830 m^2, or 20 hotel rooms, for example. In addition to freeing up valuable space, the TWIN system reduces the required building materials for shafts, decreasing embodied energy. There is also one control machine for both elevators in the same shaft, leading to additional savings in space and energy. A computerized system optimizes travel for both cabins by assigning passengers to the most efficient locations, reducing wait time and empty journeys, and saving energy (Kong et al., 2021). The 97-floor Moscow Federation Tower employs ten TWIN cabins in five shafts. Similarly, the 21-story Coda building in Atlanta, Georgia, features ten TWIN cabins in 5 shafts – it is the first building to use this system in North America. The newly completed 32-floor Trinity Tower in La Défense district, Paris, also operates 16 TWIN cabins in 8 shafts, reducing waiting time by 30%. Interestingly, two of the Trinity Tower's TWIN lifts are placed on the exterior wall and extend the structure's full height. As a result, riders enjoy an unrivaled perspective of La Défense, while passersby get a glimpse of the red and yellow cabins ascending and descending the tower.

2.8. LED Lighting

Energy-efficient light-emitting diode (LED) cab lights within an elevator car and their adjustment to motion detectors are among the most critical factors in a building's efficient power consumption. LEDs are significantly more energy efficient than incandescent, halogen, and fluorescent light bulbs. LEDs emit less heat, which reduces the energy required to cool the cab. Numerous new structures currently incorporate LED lighting. Moreover, building owners are replacing conventional elevator lighting systems with LED illumination (Yanbin et al., 2020).

3. Energy-Efficient Software

Studies of elevator traffic have revealed that the elevator's cycle significantly impacts energy consumption. The operation of an elevator, the number of levels visited, peak load, low load, and empty trips may all be analyzed to develop energy consumption models. These models help formulate practical management suggestions and control tactics. New software are empowering this endeavor (Wut, 2020).

3.1. Destination Dispatching Systems

Elevators answer calls when users press the up and down buttons. This technique works fine in buildings with limited "vertical ridership" and does not experience "rush hour" traffic. In heavy traffic, many buttons are pressed, causing elevator stops and longer travel times. Each stop in a high-speed elevator at six m/s speed may take 10-13s. Elevator designers created the destination dispatching system (DDS) to address this problem. It was initially developed in the 1990s following the boom in more excellent microprocessor capability throughout the 1980s. A DDS is an optimization strategy for multi-elevator systems, which puts passengers for the same destinations into the same elevators. The technology analyzes passengers' data in real-time and efficiently groups destinations, reducing elevator stops. The destination operation panel (DOP), generally in the lobby, uses keypads or touch displays to swiftly notify and direct passengers to their elevators (Xu et al., 2018) (Figure 5). A computerized destination dispatching system was implemented in Burj Khalifa.

The DDS reduces energy use, waiting time, and lobby and corridor congestion. DDS makers claim a 30% reduction in trip time. Researchers report that the average elevator wait time in a typical 16-floor building with a dispatch system is 13s and 138s for a conventional system. The technology saves time and reduces pedestrian traffic by directing passengers to a specific elevator instead of

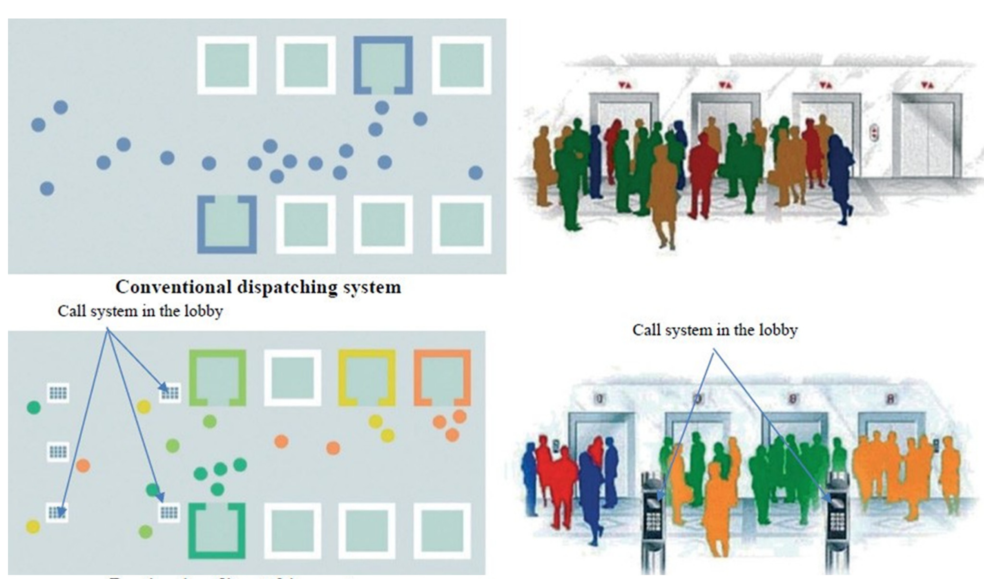

Figure 5. Conventional (top) versus destination dispatching system (bottom). (Source: adapted from http://www.ThyssenKrupp.com)

rushing to every elevator. As elevators make fewer stops, they reduce wear and tear. The way of using the DDS could lead to different levels of energy saving. For example, suppose the system has a passenger wait an extra 15s to get in an elevator already in transit rather than immediately sending another elevator. In that case, it should save energy without inordinately affecting passenger service. Some systems also reduce elevator speed during low traffic times by about ten percent. That also will save energy without substantially affecting the service.

3.2. People Flow Solutions

Like the DDS, People Flow Solutions are designed to smooth people flow and manage demand on elevators but mainly in extreme cases. This is illustrated in the case of the Abraj Al Bait Hotel Complex in Makkah, Saudi Arabia. The complex comprises seven towers, including the Clock Royal Tower, which reaches a height of 601 m (1,972 ft) with 120 floors, and a 15-story podium. It is situated near the Masjid Al Haram, the holiest mosque in the Islamic faith. The hotel's visitors travel to the Masjid Al Haram five times daily to conduct congregational prayers. The daunting task is to enable 75,000 people residing in the building complex to join the five daily prayers in the Masjid Al Haram within 30 min or less and then bring them back to the hotel in a similar period. This required a careful study to understand “people flow” and to provide optimal solutions. The study recommended the implementation of over 180 elevators and more than 100 escalators in the hotel complex: 94 elevators and 16 escalators in the Makkah Clock Royal Tower. The elevators include large shuttles that can hold 54 passengers each and take visitors up to the 15th level, one of the sky lobbies of the tower. KONE has implemented a special group control software with artificial intelligence capabilities to learn and track passengers' traffic patterns to optimize people flow solutions (Siikonen, 2021).

3.3. Standby Mode

Standby mode puts elevators in “hibernation” or “sleep” mode. At certain hours of the day, there isn't enough demand in the building to warrant the use of all elevators -- the majority of elevators operate between 20 and 30 percent of the time. Contrary to popular belief, elevators need power even when they are not in use. When cabs are idle, elevator systems must be kept powered, so they are prepared for the next passenger call. As such, the Standby solution shuts down elevator machinery when not in use, conserving energy. When unoccupied, in-cab sensors and software transition to “sleep mode”, turning off lights, fans, music, and television screens. Standby solution can save 25% to 80% of the elevator's energy, depending on the control system, lighting type, floor displays, and operating consoles in each floor and elevator cabin (Kutija et al., 2021).

3.4. Predictive maintenance apps

The creation of artificial intelligence- and machine learning-based algorithms have led to getting real-time updates on the status of an elevator. As such, new apps enable predictive maintenance. They empower building owners to use elevator data to diagnose, analyze, and notify owners of maintenance needs and possibly automatically resolve service issues before they arise. With an IoT device connected to the elevator controller, the owner can gather precise information about the elevator's parts, identify flaws and weak signals before a failure, and offer repair assistance to specialists. Apps give building owners real-time insights from their phones or mobile devices to operate better and manage their buildings (Ma et al., 2020).

4. Enhancing Elevator Energy Efficiency -- summary

Many elevators still use antiquated equipment, cumbersome cabs, and hazardous lubricants, which are expensive and harmful to the environment. In addition to improving energy efficiency, modernizing elevator systems has advantages from safety perspectives and operational costs. Owners can avoid spending much money by upgrading elevator parts over time. Further, upgrades and modernization can guarantee that elevator systems are current and safe while meeting new tight code criteria. Table 1 concisely explains methods for reducing the elevator's carbon footprint and energy consumption (Walsh, 2022).

5. Future Developments

The elevator industry has been working on energy efficiency long before the term “green” became mainstream. Its extensive experience and ambitious agenda will hopefully culminate in the “positive-energy” elevator. Research continues to concentrate on developing energy- and space-saving elevators with affordable motors, durable materials, and sophisticated dispatching systems. Some companies are working on solar elevators where solar panels installed on the hoistway will generate power to run the elevator and supply extra power to the city power grid. Also, the electromagnetic levitation system is among the exciting futuristic elevator designs (Harris et al., 2019).

5.1. Net-zero solar energy elevator

Solar electricity is becoming increasingly popular, so an elevator that runs on solar energy could be a plausible solution to save energy. A net-zero elevator system produces at least as much energy as it consumes over a year. German elevator manufacturer thyssenkrupp is working on a net-zero solar energy elevator prototype called the Synergy Elevator. It incorporates state-of-the-art energy-saving features, including a regenerative drive and LED

Table 1. Summary of recommended upgrades.

#	Strategy	Description
1	The Drive System	The drive system is typically where the majority of energy is wasted. Older drives, such as those found in motor generator sets, run continuously. These drives also produce a lot of heat, which takes additional energy to cool.
2	Gearless Modernization	The motor generator is removed in a gearless modernization. As a result, power usage and noise levels are reduced.
3	Regenerative Drive	An elevator's regenerative drive recycles the energy used when it slows down or brakes and feeds it back into the tower.
4	Starter Replacement	A new starter prevents brownouts from inadequate electricity, leading to a substantial saving.
5	Submetering	Submetering offers the most exact measurements, and some utilities will finance energy efficiency upgrades based on them. Many building owners avoid submetering because of the hefty upfront cost.
6	Lighting and Buttons	Lighting is an effective means of reducing electricity usage. In addition to being environmentally friendly, replacing the lighting and push buttons in elevator cars with LEDs is a powerful method to save money.
7	Controllers	Another excellent technique to reduce costs is using standby mode controllers. When not in use, an elevator can "sleep". The elevator restarts when a passenger touches the call button at the bottom.
8	Destination Dispatch	This method allows users to choose their chosen floor on a tablet or screen before boarding the elevator. The elevator uses passengers' input to organize them by floor and route them to a specific elevator.

cab lighting, a more efficient controller capable of a deep-sleep standby mode, and an auto-power-down feature that shuts off the cab lights and fan when the elevator is not in use. These features reduce the total standby power draw by about 75%. It integrates a rooftop solar photovoltaic (PV) array to offset the elevator's energy consumption. The 3.75 kW solar PV system, designed to produce about 4,000 kWh per year in a climate similar to that of Boston – this prototype was tested in USA CSE's Boston Headquarters.

Similarly, Schindler Elevator Corp. introduced a solar-powered elevator prototype. The Schindler Solar Elevator uses rooftop solar panels and a Hybrid Energy Manager (HEM) to store solar energy in batteries to power up to 100% of the elevator. Schindler claims the solar elevator saves energy, avoids power peaks when elevators start each journey and can operate independently of the power grid during power outages. The new solar elevator employs a regular Schindler 3,300 gearless machine roomless elevator, which is up to 60% more energy efficient than hydraulic elevators. The elevator system has a steady start, a frequency converter with an energy-efficient standby power mode, and controls that automatically switch car lights to standby mode and LED vehicle lights (Samion et al., 2021).

5.2. Electromagnetic Levitation Technology

Electromagnetic Levitation Technology, or maglev for short, makes super high-speed trains run frictionlessly along a track by applying magnetic power. ThyssenKrupp is working on a "multi" system, a rope-free elevator system that uses the same concept but on the vertical plane. The "multi" will move multiple cabins vertically and horizontally in a loop. It aims to increase the tube transport capacity by up to 50% with a continuous flow speed of 5 m/s and cabin arrivals every 15–30s while offering significant space saving because the compartments will be much smaller. The enhanced fluidity reduces wait times from 15 to 30 seconds. It also provides significantly increased transport capacity (up to 50 percent) and shorter trip times for users. Current elevator and escalator footprints can occupy up to 40% of a building's floor (Gao, 2019). Collectively, maglev is a promising technology that can save energy.

5.3. Circulating Multi-Car Elevator System

The Circulating Multi-Car Elevator System comprises multiple cars traveling along the shaft in a circular motion using a rotary magnetic array propulsion wheel. This system resembles a Ferris Wheel, but each car has a motor to operate independently while not requiring counterweights. In their prototype, ThyssenKrupp's researchers link opposing cars to balance one another and save energy usage. The circulating multi-car elevator also promises to increase capacity, reduce the required number of shafts, and reduce waiting time. Using a one-tenth-scale model, Hitachi has successfully verified this elevator system. This model will feature similar advantages to the "multi" solution presented by ThyssenKrupp. However, the present prototype will need further developments to meet international safety standards (Al-Kodmany, 2015; Gerstenmeyer, 2018).

5.4. Robotization

Certainly, robotics technology will impact the construction of elevators and their shafts. Using robotics technology instead of humans will improve multiple prime areas, increase construction speed, reduce the energy used for construction and involved costs, enhance precision, and improve safety. Schindler Company has created a robot for the safe and exact installation of cabins using artificial intelligence and technology, paving the way for increased automation. This robot is fully autonomous and self-climbing, and it moves through the elevator shaft to precisely measure and place the anchor bolts required for the installation of the elevator rails (Babel et al., 2022).

5.5. Drones

Similarly, drones are becoming more prevalent in the industrial and construction sectors and will have significant roles in constructing elevators. The installation of a new elevator entails numerous tedious, complicated, and costly activities, including the geometric measurements of wells to the certification checklists of field processes and inspection activities. Due to their mobility and ability to take photographs, drones can assist construction personnel. Drones might cut installation time by 21% to 26% and costs by 11% (Marani et al., 2022).

Conclusion

Natural resources, space, and energy will all face significant dead ends due to the planet's population expansion, which is anticipated to reach 11 billion by the end of the century. This is especially alarming given that most people (70%) will live in cities. We must begin considering how to reduce consumption and the urban energy footprint best as buildings multiply and rise even taller to accommodate our expanding population. Buildings are a clear target for cities looking to cut their carbon footprints as the fight against climate change gets momentum (Kougawa et al., 2017). More than seven billion elevator journeys are taken daily in the world's high-rise buildings. Elevators typically remain in a structure for many years and consume significant energy. Consequently, elevators' design and manufacturing enhancements will have a substantial economic and environmental impact (Walsh, 2022).

This paper highlights recent advances in elevator technology to save energy. New technologies promote the idea of energy-generating elevators, which transform the device's kinetic energy into electricity that can be redirected back into the building's electrical grid. New hardware and software technologies are applicable for both new and old structures (Yanbin et al., 2020). Numerous elevators use obsolete technology, heavy cabs, and dangerous lubricants, which are costly and detrimental to the environment. Taller structures require additional elevators and shafts, urging for new solutions. Hopefully, this paper will inspire tall building sectors, owners, and developers to use energy-efficient elevators. Future research will continue focusing on space-saving, energy-efficient elevators with economic motors, robust materials, and intelligent dispatching systems. Zero-energy and "positive-energy" elevators are promising areas of future research (Dbouk et al., 2021).

References

Al-Kodmany, K. (2014). Green Retrofitting Skyscrapers: A Review. *Buildings* 2014, *4*, 683-710.

Al-Kodmany, K. (2015). Green Towers: Toward Sustainable and Iconic Design. *Int. J. Arch. Plan. Res*. *8*, 11-28.

Dahlmann, F., & Veal, G. (2016). The role of umbrella agreements in achieving sustainability goals: Energy efficiency at the Empire State building. *Journal of Green Building*, *11*(1), 71-94.

Dbouk, T., & Drikakis, D. (2021). On airborne virus transmission in elevators and confined spaces. *Physics of Fluids*, *33*(1), 011905.

Du, P., Wood, A., & Stephens, B. (2016). Empirical operational energy analysis of downtown high-rise vs. suburban low-rise lifestyles: A Chicago case study. *Energies*, 9(6), 445.

Babel, F., Hock, P., Kraus, J., & Baumann, M. (2022, March). Human-Robot Conflict Resolution at an Elevator-The Effect of Robot Type, Request Politeness and Modality. In *2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)* (pp. 693-697). IEEE.

Cortes, P., Munuzuri, J., Vazquez-Ledesma, A., & Onieva, L. (2021). Double deck elevator group control systems using evolutionary algorithms: Interfloor and lunchpeak traffic analysis. *Computers & Industrial Engineering*, *155*, 107190.

Gao, S., & Ju, Q. (2019, December). Study on bilateral permanent magnetic levitation elevator. In *IOP Conference Series: Materials Science and Engineering* (Vol. 677, No. 5, p. 052027). IOP Publishing.

Gerstenmeyer, S. (2018, September). Traffic Analysis for a Multi Car Lift System Used as Local Group. In *9th Symposium on Lift and Escalator Technologies* (Vol. 9, No. 1, pp. 253-262).

Goldsworthy, K. (2018). *Burj Khalifa*. Weigl Publishers.

Harris, T. M., Eranki, P. L., & Landis, A. E. (2019). Life cycle assessment of proposed space elevator designs. *Acta Astronautica*, *161*, 465-474.

Hrabovsky, L., & Borovsky, D. (2021). Laboratory device for checking the functionality of the elevator rope sensors. *Management Systems in Production Engineering*.

Kim, S. H. (2017). *Electric motor control: DC, AC, and BLDC motors*. Elsevier.

Hamouche, W., Maurini, C., Vidoli, S., & Vincenti, A. (2017). Multi-parameter actuation of a neutrally stable shell: a flexible gear-less motor. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *473*(2204), 20170364.

Kong, T., Hu, T., Zhou, T., & Ye, Y. (2021). Data construction method for the applications of workshop digital twin system. *Journal of Manufacturing Systems*, *58*, 323-328.

Kougawa, Y., Omachi, A., Iwase, S., & Sakurai, K. (2017). Hitachi's Core Concept for Elevator and Escalator Products and Services, and Concept Model. *Hitachi*

Review, *66*(3), 197.
Kutija, M., Pravica, L., Godec, D., & Erica, D. (2021, April). Regenerative energy potential of roped elevator systems-a case study. In *2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC)* (pp. 284-291). IEEE.
Ma, X., Chengkai, L., Ng, K. H., & Tan, H. P. (2020). An Internet of Things-Based Lift Predictive Maintenance System. *IEEE Potentials*, *40*(1), 17-23.
Marani, Y., Telegenov, K., Feron, E., & Kirati, M. T. L. (2022, August). Drone reference tracking in a non-inertial frame using sliding mode control based Kalman filter with unknown input. In *2022 IEEE Conference on Control Technology and Applications (CCTA)* (pp. 9-16). IEEE.
Palomba, I., Wehrle, E., Carabin, G., & Vidoni, R. (2020). Minimization of the energy consumption in industrial robots through regenerative drives and optimally designed compliant elements. *Applied Sciences*, *10*(21), 7475.
Retolaza, I., Zulaika, I., Remirez, A., Cabello, M. J., Campos, M. A., & Ramos, A. (2021). New design for installation (DFI) methodology for large size and long life cycle products: application to an elevator. *Proceedings of the Design Society*, *1*, 2237-2246.
Samion, N., Yi, S. G., Sivalingam, A., & Badredden, S. A. L. S. (2021). Compact Solar Elevator. *Multidisciplinary Applied Research and Innovation*, *2*(1), 389-395.
Siikonen, M. L. (2021). *People Flow in Buildings*. John Wiley & Sons.
Walsh, P. M. (2022). "Strategies to Improve Elevator Energy Efficiency", *Facilities*, posted on 5/9/2022. https://www.facilitiesnet.com/elevators/article/Strategies-to-Improve-Elevator-Energy-Efficiency--19474
Wut, T. M. (2020). Elevator Energy-Efficient Projects in the Next Generation of High-Rise Green Buildings. In *Sustainable Energy and Green Finance for a Low-carbon Economy* (pp. 245-258). Springer, Cham.
Yanbin, Z., Shuangchang, F., Zheyi, L., & Jie, C. (2020, December). Research On Intelligent Lighting System Of Elevator Ground Gap. In *2020 International Conference on Intelligent Computing and Human-Computer Interaction (ICHCI)* (pp. 25-28). IEEE.
Xu, J., Rahmatizadeh, R., Bölöni, L., & Turgut, D. (2018, October). Taxi dispatch planning via demand and destination modeling. In *2018 IEEE 43rd Conference on Local Computer Networks (LCN)* (pp. 377-384). IEEE.
Zhu, X. (2019). Case III: Shanghai Tower: Lean Innovation Powered by Leading Technologies. In *Emerging Champions in the Digital Economy* (pp. 125-141). Springer, Singapore.