Energy-Saving and Sustainable Building Systems

Subjects: Agricultural Engineering
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Generally, energy used in a building can be accrued in various ways and a statistical process can be used for studying the building's overall performance and minimizing the energy requirement of the building. Different statistical models are used to interpret the real-world data in terms of individual theory to develop energy-efficient buildings. Underfloor air distribution, double-glazed windows, use of highly efficient electric motors and variable speed drives may play a great role in reducing building energy consumption. In the UK, the application of double-glazed windows in commercial buildings can save 39–53% energy. The proper maintenance of a building's central heating system can save up to 11% energy. The automatic HVAC control system can reduce up to 20% of the building's total heating load. Proper utilization of a VSD system in motor and building performance optimization by an ANOVA tool also proved instrumental in saving energy.

Keywords: energy ; sustainable building system ; energy consumption ; energy saving ; energy policy

1. Introduction

All over the world, energy consumption is growing very quickly because it is essential for modernization, economic growth, automation and social development. From 1994 to 2014, the growth rate of primary energy consumption and CO_2 emission was 49 and 43%, respectively, and the annual average growth rate was 2 and 1.8%, respectively [1]. In 2017, the growth rate of annual energy consumption was 3.2% in developing countries [1][2], while developed countries saw a 1.1% growth in the same year [1]. According to the International Energy Outlook report, energy consumption worldwide will grow by 56% from 2010 to 2040. It is considered that the building sector will be the largest energy-consuming sector by that time [3]. According to the IEA, buildings consumed 32% of total energy and contributed 33% of GHG emissions in 2012 [1][4]. In 2010 in the USA, 38.9% of total energy was consumed by the building sector, wherein 34.8% was consumed in cooling, heating, air conditioning and ventilation systems [1][4][5][6][7]. Moreover, the Hong Kong building sector consumed 60% of total energy and over 90% of electricity [4]. Globally, energy usage in the residential, commercial, industrial and transportation sector is 22, 19, 31 and 28% of total energy, respectively [8]. In the developed world, residential and commercial buildings' energy demand is 30–40% of the total energy [9]. It has been projected for China that building energy consumption will be 35% of total energy by 2020 [3]. A study has described how the domestic sector of buildings alone consumed 24 to 27% of total buildings' energy use [6]. Apart from the high percentage of total energy consumption, buildings contribute 19% of all GHG emissions, 33% of black carbon emissions and 51% of global electricity consumption per year [2]. In the last decade, the annual average building energy consumption growth rate all over the world was 2.2% from the year 2005 to 2015. [2]. Ma et al. [8] revealed buildings' energy use in different regions of the world in proportion to the total energy as shown in **Table 1**.

Table 1. Building energy consumption of different regions [1][2][3][4].

Country/Region	Building Energy Consumption (%)	Ref.
Europe	**40**	[4]
Spain	**23**	[4]
United Kingdom	**39**	[4]
Switzerland	**47**	[4]
Japan	**25**	[4]
China	**28**	[4]
Brazil	**42**	[4]
Botswana	**50**	[4]

Country/Region	Building Energy Consumption (%)	Ref.
USA	38.9	[1]
Hong Kong	60	[2]
India	35	[3]

The heating and cooling of space are two major factors in building energy consumption. At present, space heating and cooling consume 20% of the building's total energy; if this trend continues it will be 50% by 2050 [5]. In developing countries, the average energy consumption propagation rate is 3.2%. However, in developed countries, this annual average growth rate is 1.1%. For China, in particular, this growth rate is 3.7% [6]. **Table 2** shows the residential and commercial buildings' energy consumption worldwide. Buildings' energy consumption growth rate in the UK is 0.5% per annum, which is way below the European figure (1.5%). The annual building energy consumption growth rate in Spain is 4.2%, which is much higher than the EU (1.5%) and North America (1.9%). EU buildings consume almost 37% of total energy, which is higher than transport (32%) and industry (28%). In the UK, 39% of total energy is consumed by buildings, which is slightly above the European figure. Conversely, Spanish buildings consume 23% of total energy, which is 14 points below the European figure [6].

Table 2. Worldwide commercial and residential building energy consumption percentage [10][11].

Final Energy Consumption (%)	USA	UK	EU	Spain	World
Commercial	18	11	11	8	7
Residential	22	28	26	15	16
Total	40	39	37	23	24

In the USA and Europe, CO_2 emission rate related to building energy use is 38 and 36%, respectively [7]. It is assumed that buildings consume 32% of the total energy wherein 24% is consumed by residential buildings and the remaining 8% is consumed by commercial buildings. Space cooling and heating dominate the residential buildings' energy use, which is 32% of total building energy, followed by cooking, water heating, appliances, lighting and the cooling energy consumption being 29, 24, 9, 4 and 2%, respectively. On the other hand, space heating and cooling of commercial buildings consume 33% of the total building energy, followed by lighting, water heating, cooling and other equipment being 16, 12, 7 and 32%, respectively [8]. The rate of building energy consumption would be doubled by 2050 [8]. In the USA, 47% of the total building energy is consumed by 95% of the small and medium-sized commercial buildings. In European countries such as Finland, Bulgaria and Spain, building energy consumption per square meter is 320, 150 and 220 kWh, respectively. It is assumed that building energy consumption in developed countries such as the USA and Europe will be reduced by the appropriate use of building energy policies [4]. Still, in the USA per capita building energy consumption is far greater than in China because of its higher energy intensity and per capita building floor area. Nowadays, the per capita building energy use rate is rapidly increasing in China due to the quick growth of the Chinese economy. The energy intensity ratio of the Chinese building to the USA building has rapidly expanded from 7 to 12%. Building is the largest end-use sector in E.U. and it consumes about 40% of the total energy as well as 55% of electricity [9]. Most of the building's energy is consumed in space cooling, space heating, residential appliances, lighting and other requirements. The percentage of building sector energy demand growth up to 2050 is shown in **Figure 1**. The energy consumption growth rate in space cooling is higher.

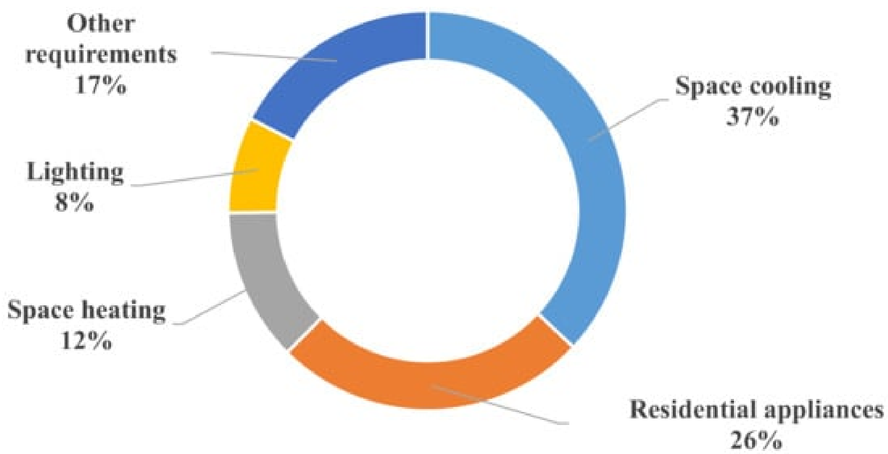
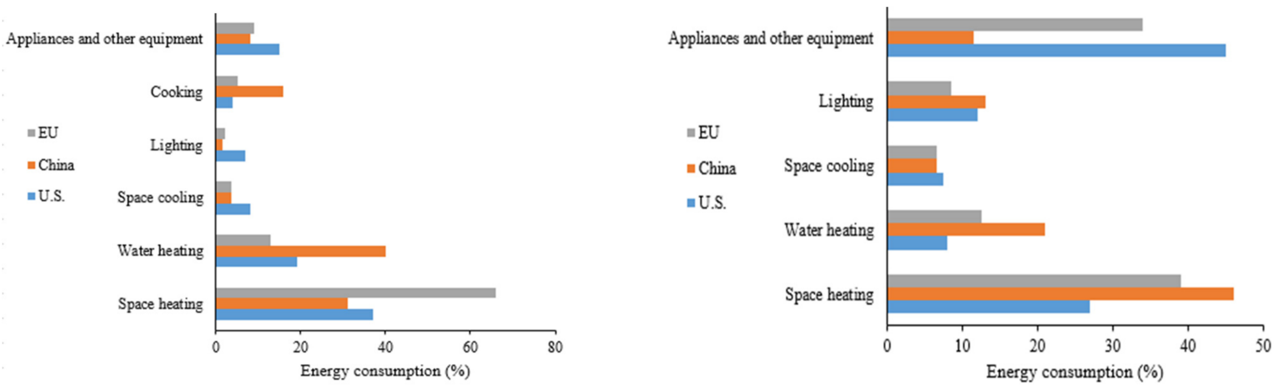


Figure 1. Building sector electricity demand growth percentage to 2050 [5].

Figure 2 shows the building energy use breakdown in the residential and service sector of the different regions in the world. In the residential sector, the EU used the largest amount of energy for space heating. On the other hand, China used the highest amount of energy in the service sector for space heating. For space cooling, in both the residential and service sector the USA uses the highest amount of energy compared to China and the EU. However, for water heating in both residential and service sectors, China used a larger amount of energy compared to the other two regions. Lighting used a lower amount of energy in the residential sector compared to the service sector. Both in the residential and service sector, for appliances and other equipment, the USA used the largest amount of energy compared to China and the EU. However, building energy consumption depends upon some factors which affect the buildings' energy needs. These factors are classified into two categories, namely "physical environmental factors" and "artificial designing parameters". The "physical environmental factors" include the amount of solar radiation, outdoor temperature and wind speed, etc., and "artificial designing parameters" include building form factor and orientation, transparency ratio, thermo-physical as well as optical properties of building material and the distance between buildings [10].



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

Figure 2. Building energy consumption breakdown in major regions of the world. (**a**) Residential sector and (**b**) service sector [9].

Dependence on energy sources or the type of fuel used to generate power for building consumption is shown in **Figure 3**. The USA uses the largest amount of electricity in building (50.3%), followed by natural gas (38.4%), oil (7.7%) biomass and waste energy (2.6%) and a very small amount of coal as well as other renewable energy sources. China produces the maximum amount of building energy by utilizing biomass and waste resources (47.1%), followed by electricity (15.2%), coal (14.3%), oil (11.6%), natural gas (7.4%) and commercial heat and other renewables are 4.1 and 0.4% correspondingly. Lastly, the EU utilizes the highest amount of natural gas (36.7%) to generate building energy. Electricity and oil use 31.1 and 13.6%, respectively, and some little amounts of other resources. Both the USA and EU give attention to electricity and natural gas to generate building power. However, China gives attention to biomass and waste energy sources which are quite good.

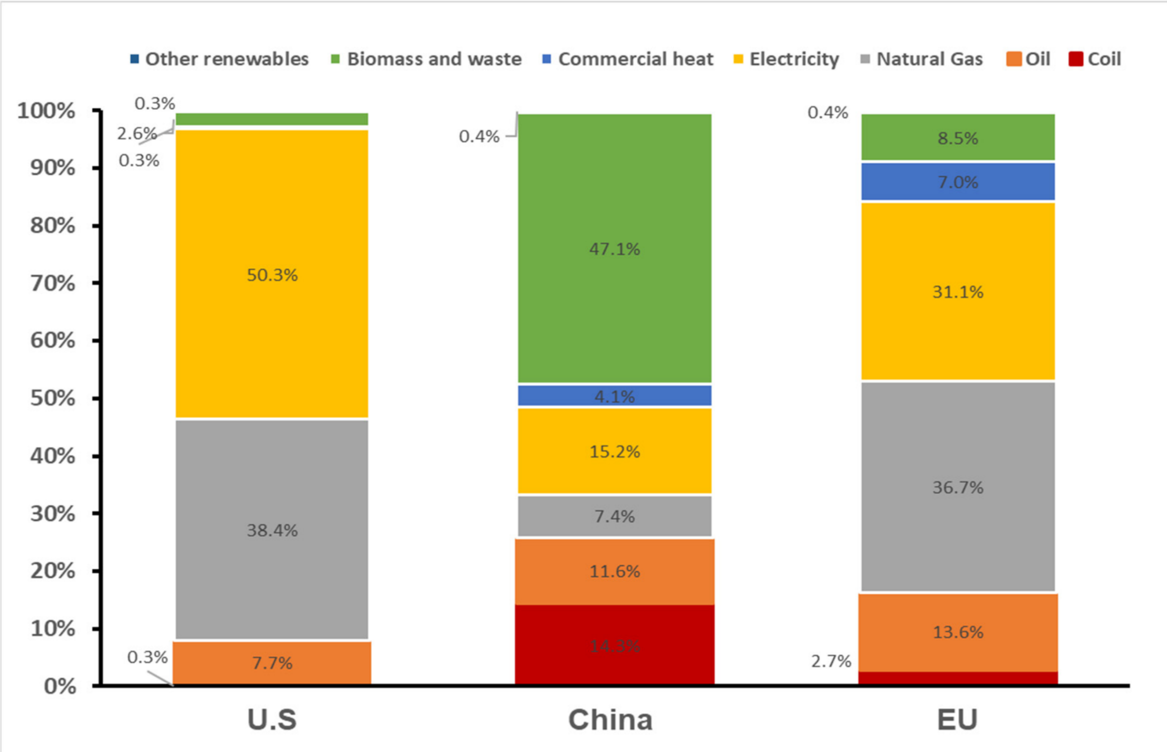


Figure 3. Building energy consumption according to the fuel type in the major regions of the world [9].

The increasing use of energy creates concerns regarding its early exhaustion along with heavy environmental impacts such as global warming, increasing GHG emission, ozone layer depletion and climate change [1][2][8]. Additionally, concern grows about the utilization of fossil fuels and their implications for the environment [11]. It has been estimated that building energy consumption produced 33% of global greenhouse gas emissions in 2010. The amount of GHG emission produced by building energy consumption was 10 $GtCO_2eq$/year in 2010 [8]. Since the building sector consumes a major part of overall energy consumption and produces GHG which has negative impacts on the environment, research related to the energy savings in the building sector is urgent. Analyzing the situation, it is highly needed to investigate the building energy consumption characteristics and to make it efficient.

Ma et al. simulated the residential building sector carbon roadmap for China, where it has been found that the emission mitigation from 2000 to 2015 is 1.817 billion tons of carbon dioxide ($BtCO_2$). They also predict that the peak value of carbon emission in the residential building sector will be 1.419 $BtCO_2$ around 2037. They claim that the strategies used in this study for emission analysis are more feasible and accurate, which would be very helpful for decision-making of residential building carbon mitigation [12]. In another study, Chen et al. used the carbon Kuznets curve (CKC) model to analyze the residential and commercial building's carbon emission changes across 30 provinces in China. They found that most of the samples fit the CKC model, thus it is considered as a robust model of emission analysis. The CKC model can be used for carbon emission analysis for different countries as well as for different types of buildings [13].

2. Energy-Saving Technologies in Building System

Generally, energy used in a building can be accrued in various ways and a statistical process can be used for studying the building's overall performance and minimizing the energy requirement of the building. Different statistical models are used to interpret the real-world data in terms of individual theory to develop energy-efficient buildings. However, the main objective of the present discussion is to detect the equipment which used a major portion of the energy and to apply energy-efficient options for that equipment. This part of the paper mainly identifies the components responsible for consuming most of the energy along with the energy-efficient options/alternatives for these components. **Figure 4** presents an overview of energy-saving techniques in buildings.

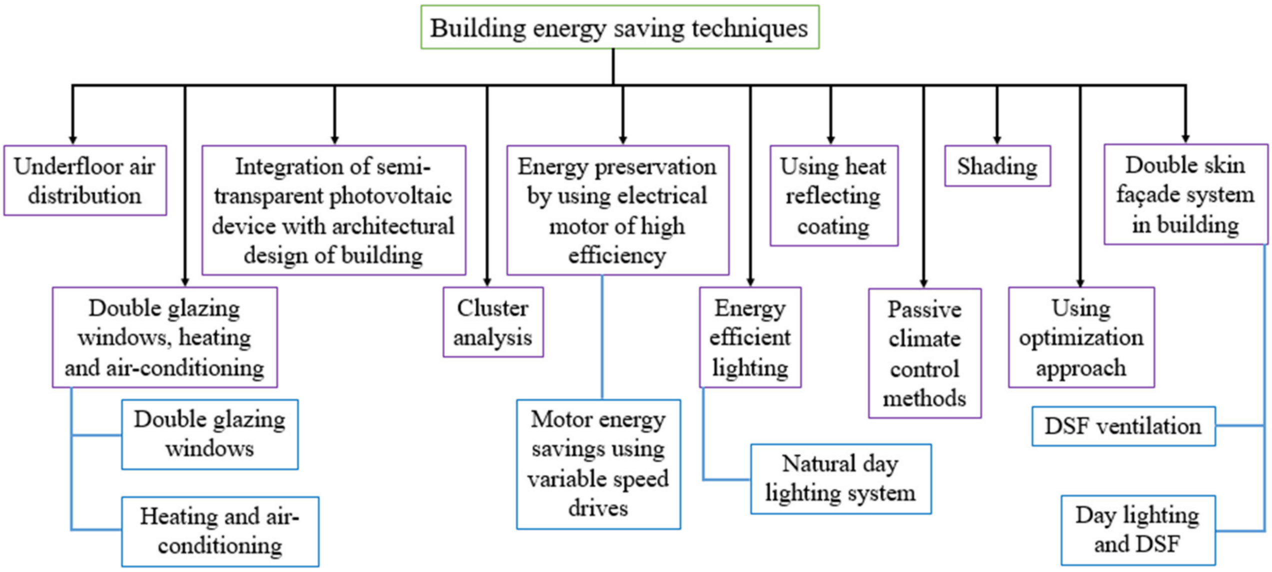


Figure 4. Building energy-saving techniques at a glance [14][15][16].

There are different ways to make a building net-zero energy-consuming one. **Figure 5** shows the connection between energy grids and buildings (it does not show the energy balance). The system boundary of a building is characterized by a certain load and some sort of energy generation source. The load includes the net energy demand and the proficiency of technical installations. On-site available renewable energy sources are used actively (e.g., ground source heat pump) and passively (e.g., solar gains through windows) to satisfy the building's load partially. Depending upon the temporal matching between generation, load and available storage possibilities the on-site renewable energies are also used to generate electricity which partly covers the load and is partly fed into the grid.

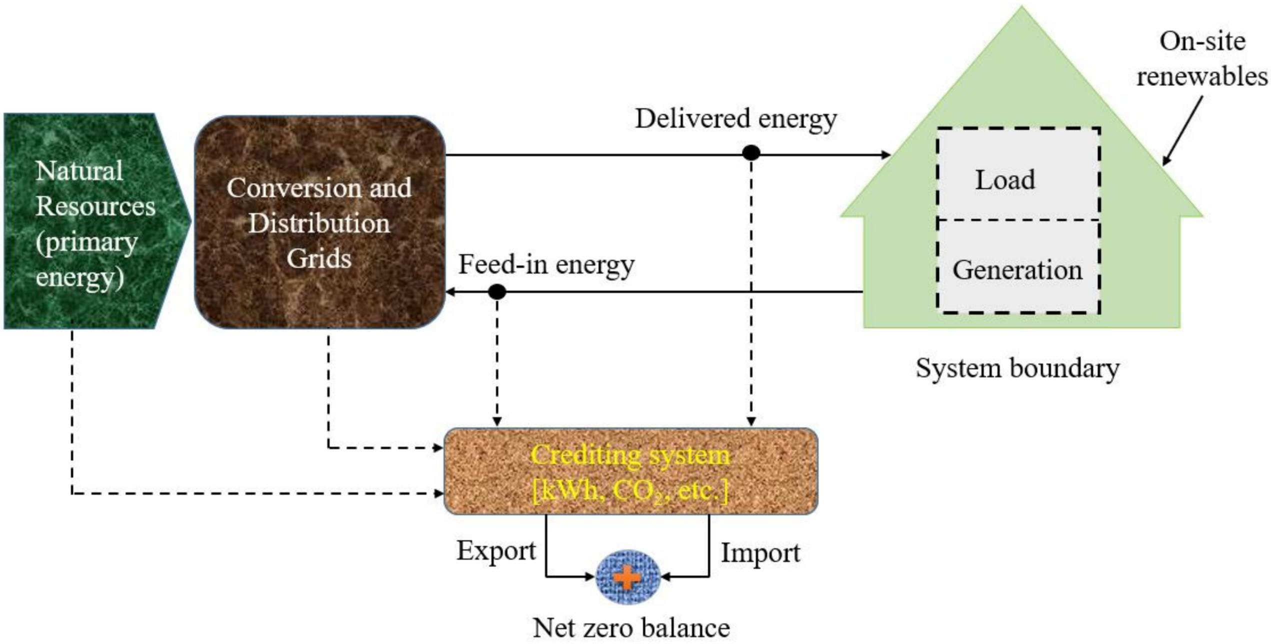


Figure 5. Schematic diagram of a typical net-zero energy building [17].

2.1. Underfloor Air Distribution (UFAD)

Underfloor air distribution (UFAD) is an advanced system that provides conditioned air in a building through an elevated floor plenum. Recently, this approach has become popular in commercial and office buildings. Brauman et al. reported that construction firms anticipate more than 35% of newly built office buildings prefer raised floors and one-half of those buildings might be using UFAD by 2004 [18]. Practically, the UFAD system has been practiced even though the codes, standards, guidelines and design tools have not been published yet. A recent investigation has reported that the UFAD technology is more energy-saving, effective as well as better than other conventional types [19]. The growing use of UFAD in North America gives an advantage compared with CBAD (ceiling-based air distribution), which does not have a way of recycling fresh air from the supply to the return path. This allows maximum utilization of fresh air, which improves the quality of indoor air. Floor grilles are also used to control the volume of air by changing the position of the damper. Another application of UFAD is to increase the pliability of space subdivisions. Generally, this type of air distribution system is more widely used for heating purposes, i.e., for warming the occupant's feet. A conceptual view of a UFAD system is shown in **Figure 6**. The advantages of UFAD systems in the air distribution of a building can be summarized as below [20]:

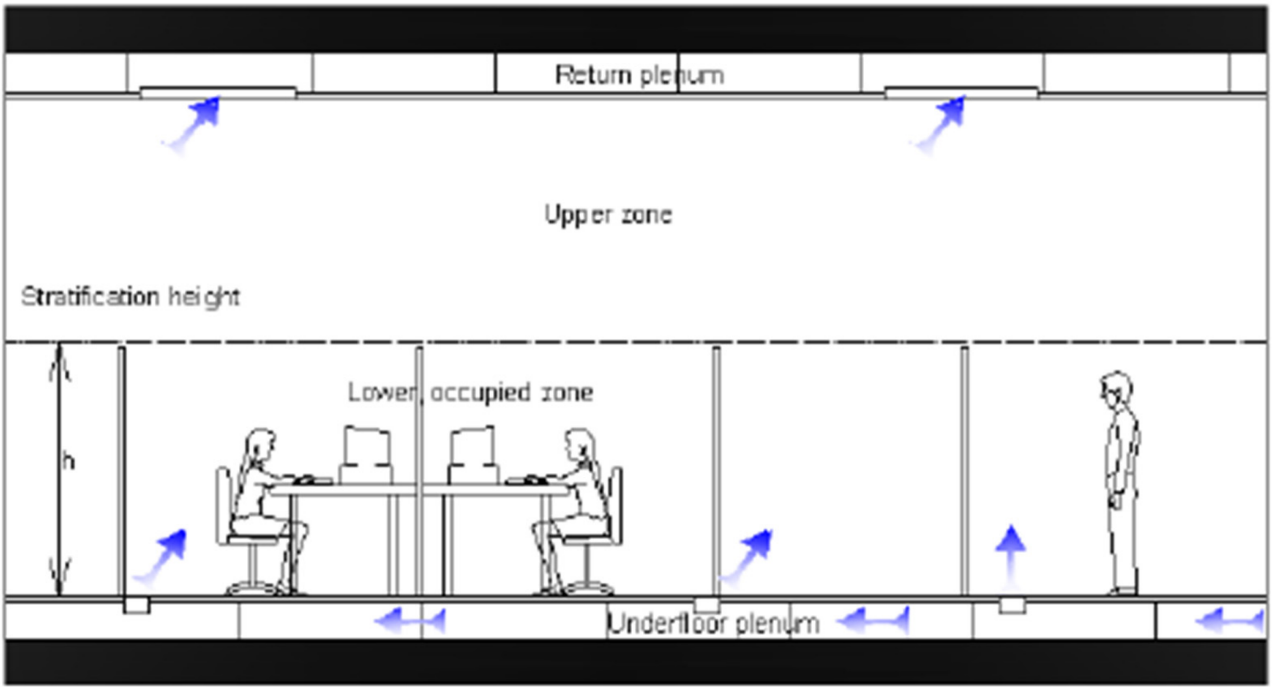


Figure 6. A schematic diagram of an underfloor air distribution system. Adapted with permission from Ref. [21]. 2013 Kim et al.

- Local environment can be controlled to increase the thermal comfort for individual occupants.
- Efficiency of ventilation and quality of indoor air can be improved by supplying fresh air at the zone of floor level or nearby the occupant.
- Energy use in the building can be saved by controlling the temperature of supply air between 17 and 20 °C for the UFAD system, or at 13 °C for overhead systems, to improve COP of HVAC.
- Energy savings from the fan are related to the lower atmospheric static pressure ranging from 12.5 to 5.0 Pascal. Depending on the design strategy it is necessary to reduce the central fan energy use compared to the overhead air distribution system because of extremely low operational statistic pressures (pressures are typically 0.1 in H_2O (25 Pa) or less) in the underfloor air distribution system.
- Height between two floors for newly developed construction can be decreased so that the average service plenum height would be reduced. About a 5–10% decrease in floor-to-floor heights could be reduced in a building that uses UFAD compared to CBAD. This can be achieved by minimizing the service plenum's overall height and/or by using a concrete (flat slab) structural approach.
- Health and productivity can be improved.
- Expenditure related to inhabitant churn, varying interior and remodeling can be reduced [22].

However, despite many benefits of the UFAD system, there are several drawbacks, too. One such example is that the temperature of supply air generally needs to be maintained above 18 °C or 65 °F to avoid the occupants feeling cold, otherwise UFAD would have to be designed in such a way that it would be 1 m from the occupant working station [23]. Furthermore, discharge of air should be calculated carefully and spread to the occupants' area to avoid noise. An elevated floor is needed for the air plenum, which increases the cost value and becomes essential for structural, architectural and service management. Some main problems that have hindered the widespread use of the UFAD system in the present days include [19][24]:

- Unfamiliar new technology that includes design of the entire building, construction of the building and its operation process.

- The lack of understanding of some new but fundamental elements, such as stratification of indoor room air, plenum performance of underfloor airflow and leakage phenomena considerations, as well as the performance of the entire building.
- Higher installation costs compared with the overhead system.
- Mold growth and condensation might take place in concrete slabs when the temperature of supply air is lower than 17 °C or 63 °F.
- Accumulation of mold and dirt, if a timely cleaning process is not conducted.
- Difficulty to maintain necessary plenum pressure, as all surfaces must be leak-proof and air leakage into the occupied space is wasted energy [25].

Jing et al. [26] suggested some special techniques for saving energy in buildings which are as follows:

- The wall should be heat-insulating.
- Architectural doors and windows for lower energy consumption. This is because the thermal characteristics of windows, as well as doors, give a major impact on air conditioning energy use which is the main thermal layout of winter and summer buildings.
- Energy-saving glass should be used.
- Composite doors or windows devoted to materials should be applied or improved.
- The door, curtain, wall and windows installation system should be improved.
- The roof should be heat insulating.
- Building energy preservation technology should be developed effectively.
- Building an energy management system should be implemented.

2.2. Heating, Cooling and Window Systems

Generally, heating, cooling, lighting and household appliances are the main energy consumers in the building systems where the air conditioning system consumes a major part [27]. Many countries give a relatively high priority to building energy saving [28]. It was identified through long limited studies that attention should be given to non-domestic building stock [29]. Improvement of physical ventilation in public and office building design can reduce energy consumption [30]. Considerable energy from air conditioning can be saved if using capacity is reviewed regularly and the unit which consumes excessive energy is replaced [31][32]. Investigation in [33] pointed out that the indoor environment thermal comfort can have an important influence on building energy requirements. Tsagarakis et al. [28] suggested specific measurements that can be consigned at the manufacturing and retrofitting stage by considering cost analysis for appropriate equipment selection. This paper emphasizes the use of double-glazed windows, air conditioning as well as heating for saving energy in a commercial building.

2.2.1. Heating and Air Conditioning

The heating process consumes major energy in the buildings system, which takes up approximately 40% of total energy use in a building [14]. All previous regulations related to energy savings in buildings have been summarized in a recent directive, i.e., 2002/91/EC on “Energy Performance of Buildings” [34]. The utilization of automatic controllers can conserve a huge amount of energy at the timekeeping comfortable environment for the occupants [35]. Proper maintenance of central heating equipment, approximately 11% of total energy use per annum can be saved [36][37]. On the other hand, energy required for cooling purposes could be saved by improving the building envelope, applying different methods for cooling and using more efficient AC equipment in office buildings [38]. Mortimer et al. [39] stated that use of HVAC equipment with advanced design and automatic control techniques could effectively save about 20% of the total load. By adjusting the set point of temperature [40] and using optimal control techniques [41], a great quantity of energy could be saved from the HVAC system. Therefore, experts are emphasizing the outcome of research regarding the use of HVAC equipment, the related cognizance quality and the consent to pay for consolidation of technologies about high energy savings, could be a vital part of fundamental law for designing and applying campaigns about energy cognizance and objected attention regarding the improvement and utilization of technologies of high energy efficiency. Technical professionals and local or regional authorities have planned and organized awareness campaigns regarding energy efficiency for the public at the same time objected to interventions about office buildings, considering the special socio-cultural body of the “targeted audience”. The above-mentioned assessment could be adequately incorporated in the energy-saving design of the generic building which complies simultaneously with the European Directive 2002/91/EC about building's energy performance [34]. Such steps can ensure the acquirement of energy-saving about 20% and reduction of greenhouse gases by about 20% within 2020, in the zone of the European Union.

2.2.2. Double Glazing Windows

Buildings with good insulation can reduce their energy consumption because there is a lower loss in cooling or heating systems [42]. It was found that most of the heat loss, or heat gain for the case of cooling, occurs through the windows of a building [43]. The use of double glazed windows can play a vital role in enhancing energy efficiency of lighting, building heating and cooling systems [44], along with the improvement of temperature and acoustic comfort environment of that building in the indoor condition [45]. **Figure 7** shows the heat transfer mechanism of double-glazed windows. The heat transfer coefficient of double glazed windows is about half of that of the single glazed window [14]. For these reasons, in the present time, the double-glazed window has become a widely adopted standard for newly developed housing or commercial buildings. In recent years, normally double-glazed windows have been used in the construction of new and commercial buildings. This led to a change in building regulation which inspired the reduction of heat loss through building construction materials. Double glazing can considerably lower the overall heat transfer coefficient of the glazed area of a building and it has become trendy [46]. Research on the energy saving of commercial buildings in the UK discovered that about 39 to 53% of energy could be saved by substituting single-glazed windows with double-glazed windows [39]. Effective replacement of window frames could also save energy in the building. The substitution of old windows frames with new ones improves energy efficiency but at a high cost [28].

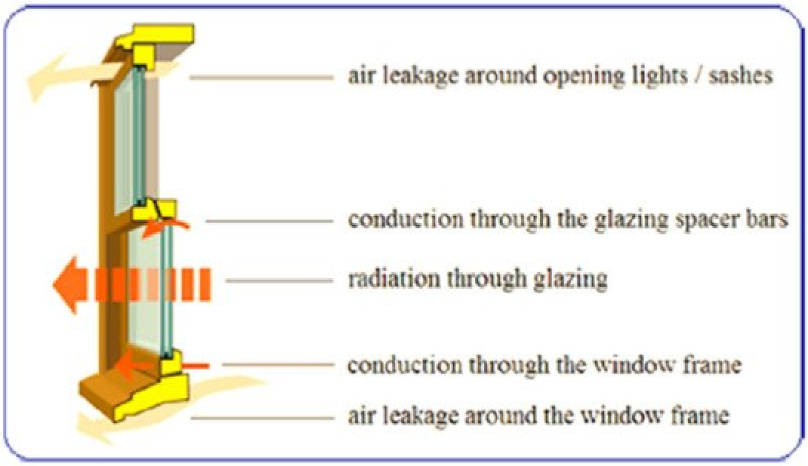


Figure 7. Heat transfer model through a typical double-glazed window. Adapted with permission from Ref. [47]. 2020 Nourozi et al.

2.2.3. Triple Glazing and Super-Insulated Windows

Gorantla et al. (2021) investigated triple-glazed window design strategies such as spectral characteristics, daylight factors, cost savings by the air conditioning system as well as payback periods. They found that the most energy-efficient glazing is the TWG35 glass unit with S–E orientation which saves 16.72 USD/m^2.year air conditioning cost compared to the other window glass units. The payback period of TWG35 was 2.2 years. However, the lowest payback period is 2.1 years revealed by the TWG33 window glass unit with a net cost recovery of 16.55 USD/m^2.year [48]. A multi-pane glazing unit reduces the heat transfer through it compared to a single-pane unit. **Figure 8** shows a triple glazing window unit with 5 mm thick reflective glasses. The total thickness of the triple-glazed window unit is 35 mm including a 10 mm air gap between two glass units [48].

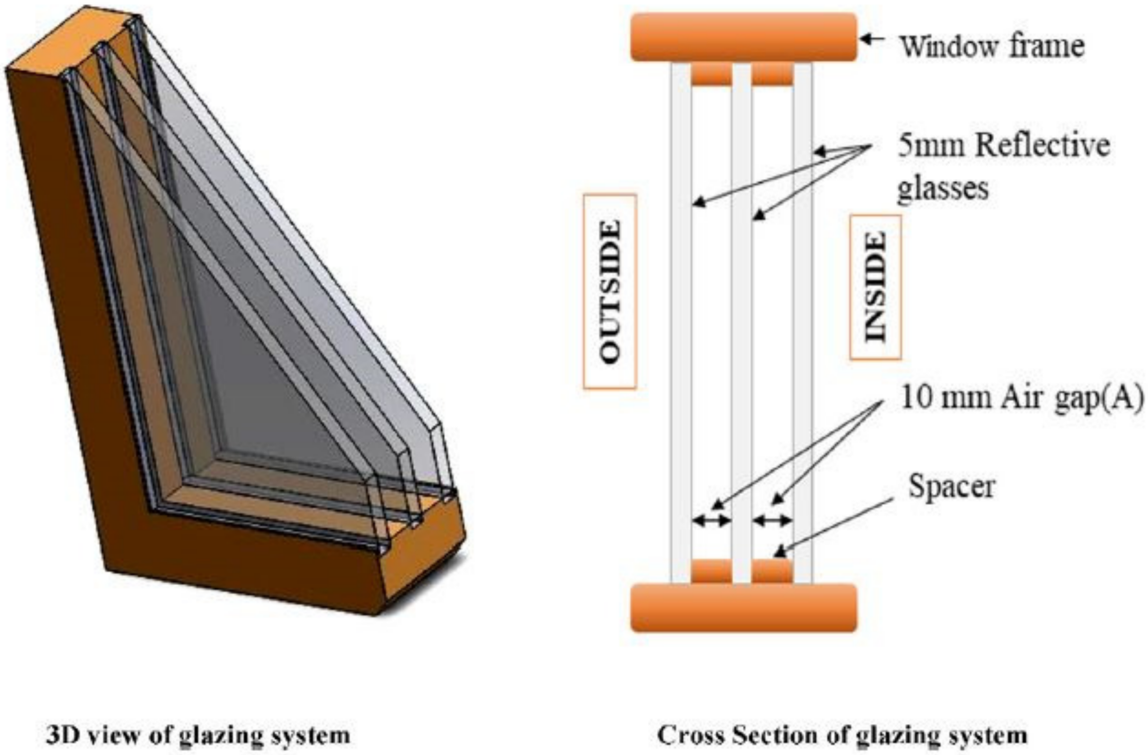


Figure 8. A triple-glazed window unit with reflective glasses. Adapted with permission from Ref. [48]. 2021 Gorantla et al.

Zhang et al. (2016) studied the thermal performance of switchable triple glazing exhaust air (SEA) window and found that it reduces 73.5 and 71.9% heat gain in summer, as well as 74 and 46.8% heat loss in winter, respectively, compared to the conventional double-glazed as well as triple-glazed windows [49]. **Figure 9** shows the schematic diagram of the switchable exhaust air windows. The main parts of the SEA window are three glass panes, two movable Venetian blinds and two air cavities. Different air cavities host different Venetian blinds in different seasons. The two air cavities act as an exhaust air ventilation channel to remove indoor air from the outside environment. The switchable components help to flow exhaust air in different cavities. The upper and lower switchable components are shown in **Figure 10**. In winter, the Venetian blind is on the indoor side, but, in summer it is on the outdoor side shown in **Figure 9** [49].

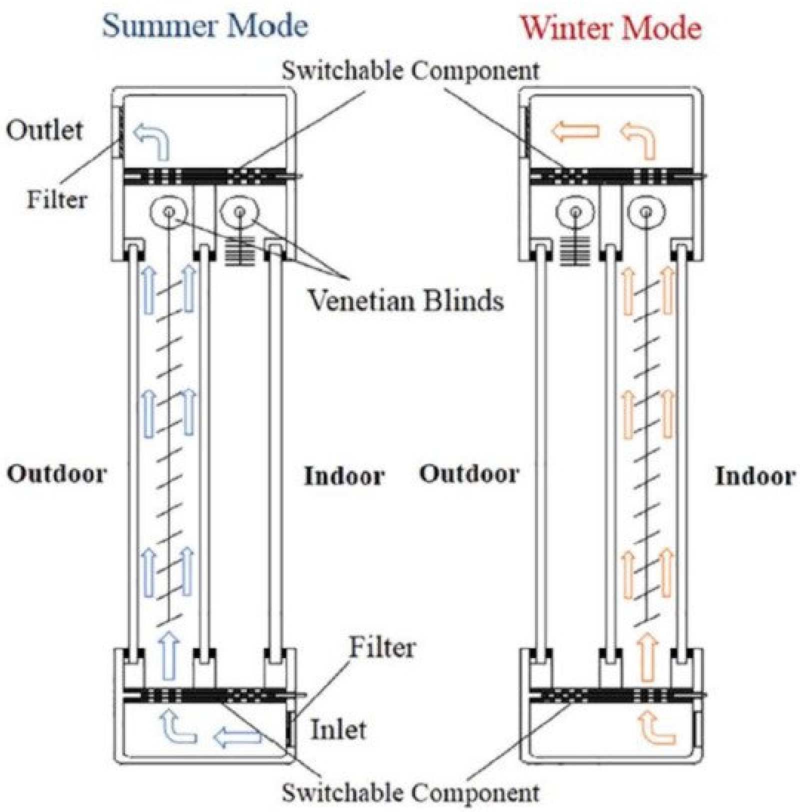


Figure 9. Schematic diagram of the SEA window. Adapted with permission from Ref. [49]. 2016 Zhang et al.

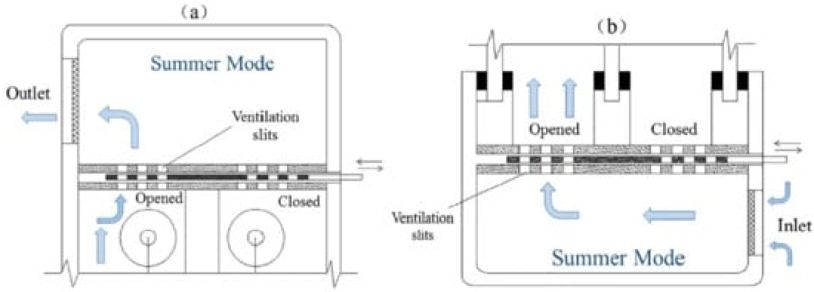


Figure 10. Switchable components of SEA window: (**a**) upper part, (**b**) lower part. Adapted with permission from Ref. [49]. 2016 Zhang et al.

Liu et al. (2018) studied heat transfer, daylight control and thermal comfort of triple-glazed windows. They found that the extra insulation around the window frame and lower installation level decrease thermal transmittance by more than 60% [50]. Su et al. (2019) analyzed the performance of multi-purpose triple-glazed fluidic windows, where they found that in an office room of size ratio 0.4 ensuring thermal comfort year-round and the energy consumption is as low as ~2.9 kWh/(m^{2}a) [51]. Liu et al. (2021) tested the thermal performance in the cooling operation of the triple-glazed window with water flowing through it. Surface temperature fluctuation of the inner glazing of the window was narrowed down. Compared to the IGU (insulated glazing unit) insulated water flow window (TWFW), the performance of VG (vacuum glazing) insulated water flow window (VWFW) is more favorable. The thermal performance of a triple-glazed water flow window is also promising. The thermal efficiency of TWFW and VWFW ranges from 21.9 to 36.13% and 24.69 to 45.95% correspondingly [52].

Larsson et al. (1999) studied super-insulated windows through numerical and experimental thermal analysis. A triple-glazed window with low emissivity in which the inert gas krypton filled the two closed spaces acted as the super-insulated window. One pane in each space was coated with oxidized metal with a low emissivity factor. The numerical and experimental investigation of windows has been operated for various winter cases. Due to good resistance to heat transfer, the window provides comparatively higher surface temperature in the inner pane [53]. Garnier et al. (2015) investigated the thermal performance of super-insulated aerogel windows and compared them with double-glazed argon-filled windows. The results showed that the heat loss index and daylight transmission of the aerogel window is significantly lower than the double-glazed windows [54].

2.3. Energy Preservation by Using the Electrical Motor of High-Efficiency

Demand-side management is a significant idea to increase efficiency by reducing load growth. This concept helps the motor manufacturing company to seek new technology for increasing the efficiency of motors, which leads to manufacturing energy-saving electric motors. Many renowned motor manufacturing companies, especially in Europe and the USA, have been producing energy-saving electric motors [55]. Saidur [56] suggested that a high-performance electric motor should use low-loss materials, that the energy loss due to copper or core losses can be reduced. It has been seen that the primary objective of a manufacturing company is to lessen the manufacturing cost, but the efficiency of the motor can be increased by developing its design which leads to conserving energy by using a motor. The energy-efficient design may include a bigger rotor conductor, more copper used in filling slot, using of ferrosilicon alloys plate in magnetic cores, and upgrading airgaps in core heads, bearings as well as fans. Dimensional parameters also should be improved for better design. Nevertheless, the cost can be a limiting factor to the widespread use of the high-efficiency motor, as it was reported that the cost of a high-performance motor was approximately 10 to 15% higher than a typical one [57]. The power consumption of the motor depends on the rated speed. The relationship between percentage power consumption and the rated speed of the motor is shown in **Figure 8**. The capacity variation of a motor by matching actual load requirements can improve the efficiency of such systems. As the power requirement in the motor varies with the cube of the speed, a large amount of power can be minimized by reducing a small amount of speed which is shown in **Figure 11**. The speed of the motors, pumps, compressors and fans can be modulated by variable speed drives (VSDs). It provides continuous control, matching motor speed depending on the specific requirement, which may reduce the cost of energy [16][58].

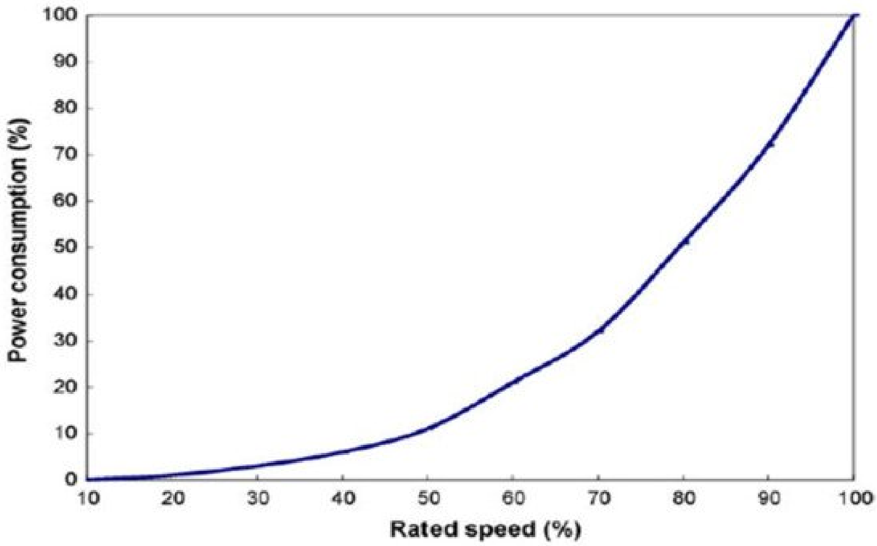


Figure 11. Relationship between percentage power consumption and rated speed of motor. Adapted with permission from Ref. [16]. 2010 Saidur et al.

Motor Energy Savings Utilizing VSDs

Instead of improving the performance of the motor itself, the overall efficiency of a motor-based application can be improved as well via the use of a variable speed drive (VSD). Most of the buildings are designed considering the maximum demand of the load. However, in most cases, different systems of buildings need to operate at maximum load for a very short time in a day. Sometimes few systems are running for a long time without any reason, causing unnecessary energy loss. Such inefficient operation is particularly common in the AC system of a building. In this case, VSD can be used to control the speed of the motor for the pump or fan according to their load demand. Since the power requirement of a fan or pump is proportionate to the cube of their speed, and energy can be saved by fitting the speed of the motor to the requirements of load using VSD to improve the overall system efficiency [58]. The advantages of using VSD in fan and pump applications include [59]:

- Savings of energy.
- Improvement of efficiency over increasing of power factor of the system.
- Simplification of pipe systems (removal of by-pass lines and control valves).
- Normal starting and stopping procedure.
- Dynamic response leads to better control compared to DC drives.

It was proven that for a fixed load that is lower than the rated load, the electrical motor with lower-rated power can be used rather than VSD in giving good cost-saving [59]. The basic mechanism used in the variable speed drive is shown in **Figure 12** while **Figure 13** reveals the basic components of VSD.

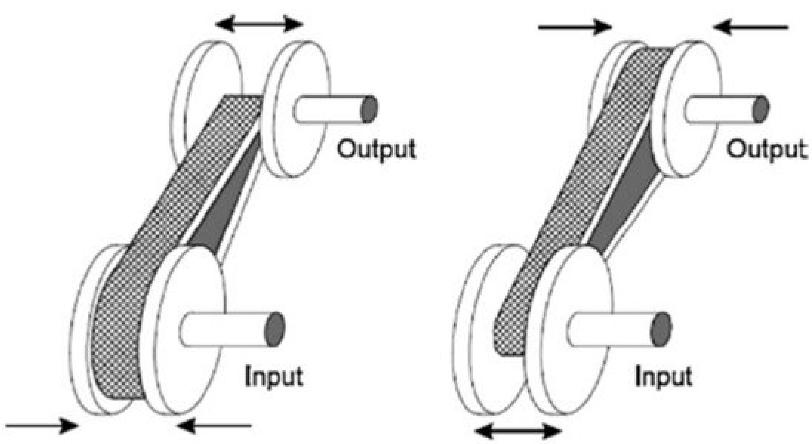


Figure 12. Adjustable sheave belt-type mechanism used in VSD. Adapted with permission from Ref. [60]. 2012 Saidur et al.

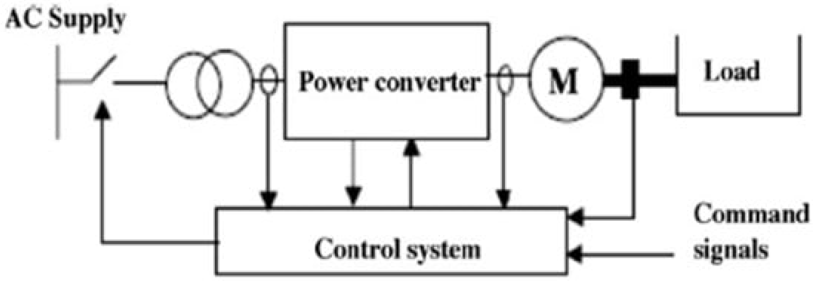


Figure 13. Basic components of a variable speed drive (VSD). Adapted with permission from Ref. [60]. 2012 Saidur et al.

Energy savings by utilizing VSD have been predicted by mathematical formulations. Many approaches are used to predict energy savings by utilizing VSD in industrial motors. The energy consumption by fans, pumps, motors, etc., varies with the third power of changing the speed, which is why a small change in speed will cause a huge change in energy usage. VSD is utilized to fit the load requirements to save energy. Typically, the appropriate design of VSD systems can save 20 to 70% of energy use compared to the conventional motor. By using VSD, the energy-saving by a motor can be predicted as follows [16][58][61][62]:

$$AES_{\mathrm{VSD}} = n \times P \times H_{avg\_usage} \times S_{SR} \tag{1}$$

(1)

where AES_{VSD} is the annual energy saving using VSD (kWh), n is the number of motors, P is motor power (kW), H_{avg_usage} is annual average usage hours and S_{SR} is the percentage of energy savings using speed reduction. Based on the annual energy savings by Equation (1), the yearly bill savings (*BS*) can be measured by the following equation [16][58]:

$$BS = AES \times UEP \tag{2}$$

(2)

A mathematical formula has been generated to predict the energy savings by utilizing high-efficiency motors. The annual energy savings by replacing the standard efficient motor with the highly efficient motor can be calculated as follows [16][61][62]:

$$AES_{HEM} = W \times L \times hr \times \left(\frac{1}{E_{std}} - \frac{1}{E_{ee}}\right) \times 100 \tag{3}$$

where *AES* is the annual energy saving in kWh, *W* is the rated power of the motor in Watt, *L* is the load factor in percentage, hr is the number of hours in yearly usage, E_{std} is standard motor efficiency in percentage, and E_{ee} is the energy-efficient motor efficiency in percentage.

2.4. Cluster Analysis

Cluster analysis, also known as clustering, is a common statistical analysis tool that can be used to identify the groups of data, which are intimately related to one another but distinctly different from others, from a pool of statistical data [63]. In the case of numerical data, cluster analysis can separate the data into clusters in which individual data are very close to the average of all data in that cluster. The main objective is to minimize the summation of the differences of individual data to their nearest mean. This procedure of clustering is the prototype-based or center-based procedure. Based on a statistical model, clustering analysis also can be developed which is known as model-based clustering [64]. In this way, one can find the best data for designing the statistical model. For building sector energy assessment, cluster analysis can be used for the classification of energy performance phenomena in cumulative frequency distribution [15][65]. A cluster analysis tool was used by Petcharat et al. [66] to evaluate the possible energy savings from lighting systems in buildings. It was reported that cluster analysis gives a set of selected data that can be used for calculating the total energy conservation gained from lightning equipment of commercial buildings, which are not like the single desired value of the normal averaging method. Unlike the normal averaging method, which delivers a single sample value, cluster analysis provides a group of typical values for calculating the total efficient energy preservation that could be achieved from commercial buildings lighting equipment, if a certain model of lighting power density, i.e., LPD value is mentioned in the code of building energy. In simulation investigation, the savings of desired energy can find out from clustering outcomings that have lower errors than the general approach from all general case studies. Besides, the clustering analysis method has also been used for categorizing meteorological data to find out the average characteristics in the planning of renewable energy usage schemes [67].

Another special type of statistical model which is very similar to clustering is known as the mixture model [68]. A mixture model is formed by many distributed statistical data, where every distribution is related to one cluster whose parameters can give detailed information of the respective cluster by its center and its distribution zone [69]. The application of another statistical technique, known as the Expectation-Maximization (EM) procedure [70], allows the characteristic value of any data to be determined from hitherto intractable ML (maximum likelihood) estimation or complicated ML cluster. There are some other applications of statistical techniques such as in dairy science, AIDS epidemiology and medical imaging.

2.5. Performance Enhance by Using the Optimization Approach

Building energy system design follows a series of decision-making processes that depend on various choices of solutions. The design variables are usually selected based on certain requirements, such as to increase energy saving. Generally, the problem is complex to explain and also difficult to solve, so designers normally have to depend on simple thermal design rules or rely on their experience [71]. The dependency on personal experience might give inaccurate or incomplete results, so there is a need for proper methods that can help the designers in designing energy-efficient buildings. In the last several decades, a huge amount of research has been carried out for selecting the suitable conceptual primary architectural design stage of a building, such that the building will be compliant to building code, energy-efficient and environmentally friendly [72]. The use of optimization technology in architectural design is comparatively new. Wang demonstrated a method to minimize the shape of the building floor by applying a genetic algorithm and approach to determine the life cycle effect on the environment and lifetime cost [73]. Caldas developed a productive tool applying a genetic algorithm to minimize the sizing and placing of windows for official buildings to evaluate their environmental impact [74]. In general, the optimization technique is complex; thus, it is required advanced mathematics and related tools [75]. A novel mathematical model, termed Analysis of Variance (ANOVA), was presented by H. E. Mechri et al. [72]. This solution is solved based on gradual alternative solutions to design choices. The motive of this model is to analyze the required energy for incertitude of cooling or heating based on some design factors. ANOVA is a statistical method where the variability of results is divided depending on the various input variables. The benefits of this assessing method are that every design-related variable can play a significant role in the energy output of a building. Thus, the ANOVA method is used to determine the output variable and its effects on input variables and it gives the gist of the conclusion depending on individual variables [72].

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