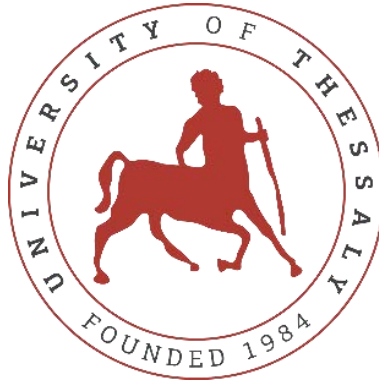




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Zero energy buildings: Current applications

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ
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Υπό

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**Υπεβλήθη για την εκπλήρωση μέρους των απαιτήσεων για την απόκτηση του Διπλώματος
Μηχανολόγου Μηχανικού**

Βόλος, 2024

Η έγκριση της διπλωματικής εργασίας από το Τμήμα Μηχανολόγων Μηχανικών της Πολυτεχνικής Σχολής του Πανεπιστημίου Θεσσαλίας δεν υποδηλώνει αποδοχή των απόψεων του συγγραφέα (Ν. 5343/32 αρ. 202 παρ. 2).

Οι υπογράφωντες Αβραάμ Θεοδωρίδης και Ραφαήλ Πράσιнос γνωρίζοντας τις συνέπειες της λογοκλοπής, δηλώνουμε υπεύθυνα ότι η παρούσα εργασία με τίτλο **«Κτίρια μηδενικής ενέργειας: Σύγχρονες εφαρμογές» αποτελεί προϊόν αυστηρά προσωπικής εργασίας** και όλες οι πηγές που έχω χρησιμοποιήσει έχουν δηλωθεί κατάλληλα στις βιβλιογραφικές αναφορές. Τα σημεία όπου έχω χρησιμοποιήσει ιδέες, κείμενο ή και πηγές άλλων συγγραφέων, αναφέρονται ευδιάκριτα στο κείμενο με την κατάλληλη παραπομπή και η σχετική αναφορά περιλαμβάνεται στο τμήμα των βιβλιογραφικών αναφορών με πλήρη περιγραφή.

Αβραάμ Θεοδωρίδης

Ραφαήλ Πράσιнос

Abstract

This comprehensive study offers a wide-ranging exploration of sustainable energy solutions. It all begins with a clear and compelling introduction, emphasizing the critical need to shift towards cleaner and more efficient energy sources given the current global challenges. It includes renewable energy sources such as solar, wind, geothermal, and biomass, each with its unique potential and characteristics. The study takes a deep dive into energy storage technologies such as various types of batteries and supercapacitors, unraveling their applications and significance. Moreover, it explores the innovative applications of solar energy for heating and introduces heat pumps as efficient heating solutions. The study also presents the cutting-edge domain of smart grids, meaning power generation, transmission, distribution, and control networks for optimized energy management. In the final chapter, an introduction to the new concept of Zero Energy Buildings is analyzed followed by a comprehensive framework definition. Then a briefly description of the fundamentals in the design of a Zero Energy Building is presented and a bibliography review summarizes current knowledge in this field by presenting some existing projects.

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CHAPTER 1

INTRODUCTION

In the last years, humanity has been threatened by the transformation of the climate combine with global warming. Some of the most important problems which have occurred are rising sea levels, extreme weather conditions, coral reef erosion, and also long-term droughts, and floods. Alongside the increase in population, urbanization rises, and with humans consuming more than 90% of their time in buildings, energy requirements such as thermal comfort require a large quantity of energy. The buildings are responsible not only for 40% of total energy consumption but also for 40% of direct and indirect total emissions of carbon dioxide [1]. **Figure 1.1** shows the global CO₂ emissions by sector for the year 2015. In the United States, the rate of building energy needs compared to the total energy consumption has undergone steady growth from 33.7% to 41.1% between 1980 and 2010 [2]. In China, fast urbanization and a huge economic boost have increased the demand for energy by 40% in the last two decades [3]. The energy usage in buildings in EU countries is equivalent to 40% of the total primary energy consumption and 36% of greenhouse emissions [4]. The amount of energy utilized globally in different sectors is depicted in **Figure 1.2**.

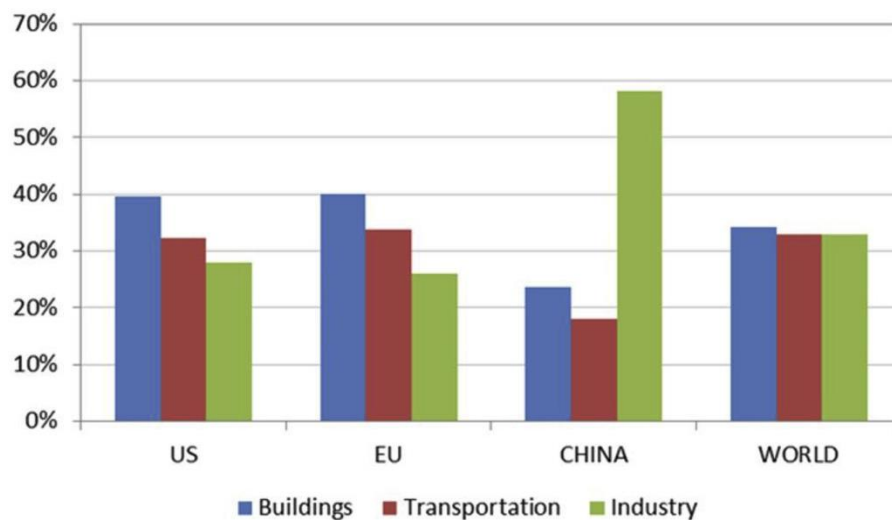


Figure 1.1: Global CO₂ emissions by sector for the year 2015 [5].

In this regard, it became a critical issue to find policies and establish measures to mitigate global emission levels originating from buildings' operation as it contributes to the increase in the average temperature of the Earth to a great extent. One major solution aimed at that target is focusing on clean

renewable energies for supplying the required building loads. The zero-energy building (ZEB) concept was introduced in 2000. However, by 2006, it became fast a mainstream concept. Although multiple definition frameworks have been attributed to this term, which will be discussed later, it can be simply understood as a building that produces its energy mostly via green renewable sources. The absence of a comprehensive definition blocks the ability to build an incontrovertible profile on the economic field and ultimately a wide global energy-efficient construction index but also creates serious problems in evaluating various strategies from different backgrounds [6].

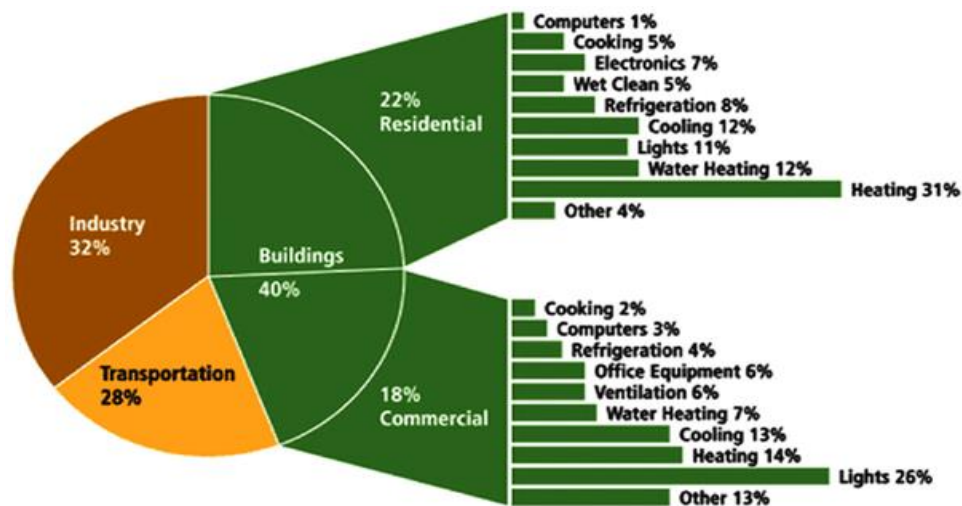


Figure 1.2: The amount of energy utilized globally in different sectors [7].

Two energy-based types can be utilized in developing and evaluating ZEBs. The first one is energy demand vs renewable energy production, which is applicable in the design phase, and the second one is imported energy vs energy returned to the grid, which could assess the performance of an existing ZEB. Renewable energy technologies can operate both on-site and off-site. In addition, green energy or CO₂ credit could also be directly purchased, which expands the applicability of ZEB projects. The buildings could be grid-connected or autonomous by generating and consuming their energy. The design strategies differ among the two types because autonomous buildings rely on energy storage units due to the intermittent nature of renewable energy sources [3]. Electrochemical devices can play a key role in both storing and producing energy and that is why a lot of research has been undertaken in this field over the past few decades. A ZEB's construction can combine many devices and techniques to achieve energy balance or the more ambitious aim of self-sustainability.

CHAPTER 2

ELECTRICITY PRODUCTION

Introduction

Humans have always relied on different energy sources since the dawn of civilization. With the growing demand for electrical energy and its impact on the environment, the need for clean, renewable energy sources has become increasingly important [3]. In 2000, all observed renewable energy sources together contributed to 15.5% of the world's energy generation, while in 2019, to 27%, with fossil fuels still dominating, as shown in **Figure 2.1** [8].

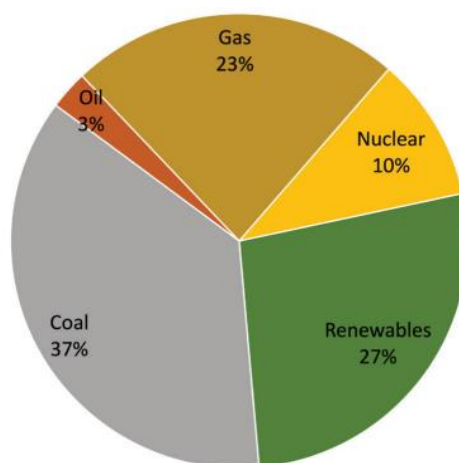


Figure 2.1: The total electricity produced by sources worldwide in 2019 [8].

In 2019, in the energy generation from renewable sources sector, hydropower was the first in the line of production and was responsible for 59% of the total energy generation. The second source was wind at 20% and then bioenergy. As a concern electricity from renewable sources has had an annual growth rate of 5% in the two last decades as can be seen in **Table 2.1**. This increase was caused by the wind with 22% and solar with 39% annual growth rates respectively. **Figure 2.2** illustrates the production of electricity from renewable sources in the year mentioned above [8].

Table 2.1: The production of electricity from renewable sources on a worldwide scale

Year	Hydro	Wind	Biomass	Solar	Geothermal	Tide	Total
2000	2,696	31	214	1.33	52.5	0.55	2,995
2005	3,019	104	298	4.33	58.3	0.52	3,485
2010	3,536	342	458	33.7	68.1	0.51	4,438
2015	3,982	834	620	254	80.7	1.01	5,772
2016	4,140	963	663	331	82.3	1.03	6,181
2017	4,190	1,135	701	442	85.5	1.03	6,553
2018	4,313	1,277	737	567	88.7	1.01	6,983
2019	4,329	1,427	768	694	91.1	1.00	7,311

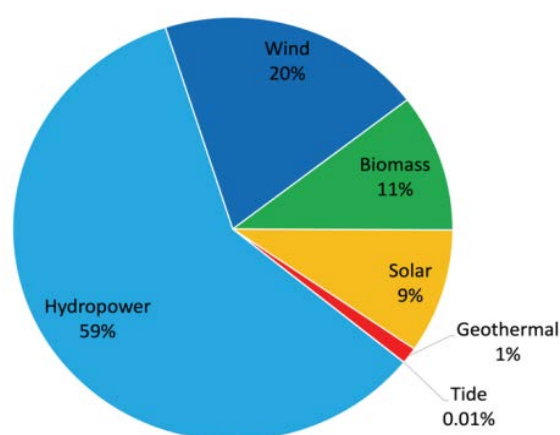


Figure 2.2: The production of electricity from renewable sources in the year 2019 [8].

2.1 Solar energy

Solar energy is considered the cleanest and safest form of energy compared to nuclear energy. Both active and passive forms of solar energy are cost-effective, making it an attractive option for countries looking to secure their energy supply while also considering sustainability and environmental impact. Solar energy has the potential to reduce the impact of global warming while providing energy at a lower cost than fossil fuels and other nonrenewable sources. However, due to the inconsistent nature of solar energy, a lot of research and investment are being conducted globally to find a more efficient and sustainable way of harnessing solar energy [3].

Energy consumption varies globally. Developing countries are experiencing high growth rates in energy use, while it is declining in western countries. A limited number of people in island nations have access to electricity, so they have high growth rates in energy consumption. The photovoltaic is the most accessible form of renewable energy, and it is expected to become the leading source of electricity generation among renewable energy options. The growth of photovoltaic installations

globally has surpassed wind power as the leading renewable source after hydropower in 2014. **Figure 2.3** illustrates the global growth of photovoltaic installations from 2000 to 2023 [3].

Figure 2.4 presents the allotment of global photovoltaic installation for the year 2023 showing that China, owns more than half of the world's solar energy production and outnumbers Europe's and the USA's generation percentage combined [9].

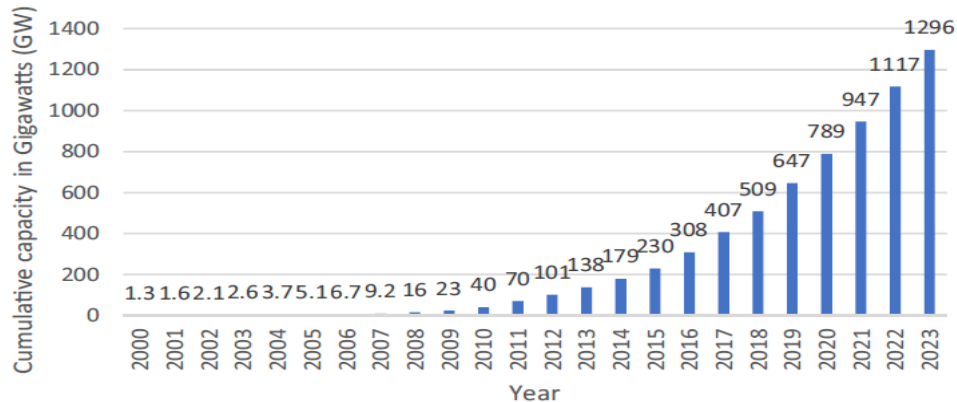


Figure 2.3: The increase of photovoltaic technology utilization worldwide in gigawatt [3].

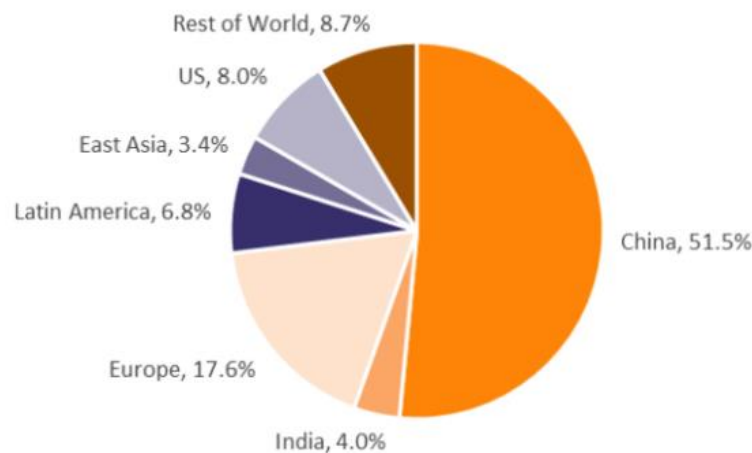


Figure 2.4: The worldwide solar power installation cumulatively in 2023 [9].

The types of off-grid solar systems can differ based on energy needs. Although these states make up a small portion of the global photovoltaic installations with access to the power grid. Available data on these systems is limited, especially in certain off-grid areas like islands such as Hawaii and Fiji. However, these systems have the potential to produce large amounts of power, measured in hundreds of megawatts. The use of PV in off-grid power systems is becoming more widespread. The development of photothermal electricity varies worldwide, with Asia, particularly China, and Japan, being ahead of

the US in terms of production. Photothermal energy has a significant impact on a country's energy consumption and cost, as it is one of the most affordable forms of renewable energy. In the past 10 years, the installed capacity of solar thermal heat has increased by 250% to exceed 470 GW [3].

2.2 Wind energy

The energy generated from the wind is a green source of energy and has a small impact on the environment. **Table 2.2** and **Table 2.3** show the nations which use wind energy the most. It is worth mentioning that there was an important extend in offshore wind capacity in 2018, largely driven by China, the UK, and Germany [3].

Table 2.2: The amount of onshore wind capacity that was installed in 2018

Country	The installed capacity of onshore wind (MW)
United States	23,276.5
China	12,048
India	2,564
Australia	2,005
United Kingdom	1,061
Romania	600
Egypt	545
Morocco	301
Mexico	250.5

Table 2.3: Countries with the largest installed offshore wind power capacity in 2021

Country	Capacity of installed offshore wind power (MW)
United States	7,963
Germany	6,380
China	4,588
Denmark	1,329
Belgium	1,186
Netherlands	1,118
Sweden	192
Vietnam	99
Finland	87
South Korea	73

Nowadays, due to the high costs of fossil fuels, the energy from wind is an attractive option not only due to its efficiency but also reduced environmental impact. The ability to predict this form of energy correctly is very important due to fluctuations in wind speed and weather conditions. In 2018, the total sum reached 597 GW. From that, above 50 GW was added in the previous year. That was a 9.6% increase compared to 2017. The trend in the use of wind energy is shown in **Figure 2.5** [3].

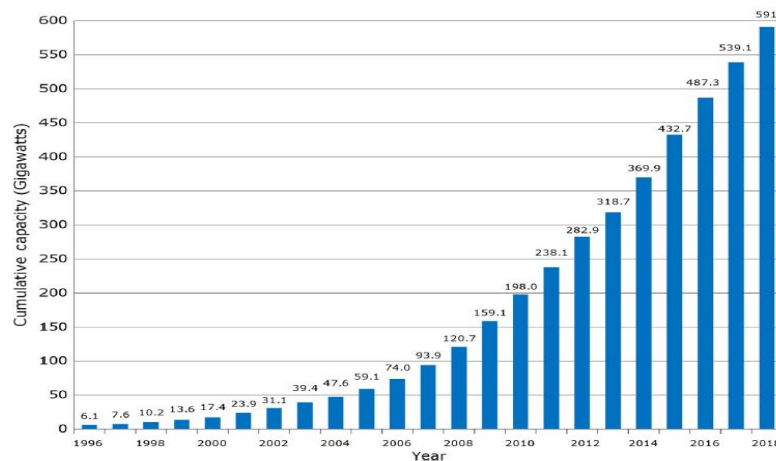


Figure 2.5: The total amount of wind power capacity installed globally by the end of 2018, measured in gigawatts (GW) [3].

The proportion of wind energy generated compared to the total energy generation is referred to as wind energy penetration. In 2018, 4.8% of the global generated electricity, was from wind power, instead of 3.5% in 2015, indicating the increasing acceptance of wind energy in the market. **Table 2.4** shows the country-wise wind energy penetration data. Despite its advantages, this energy source faces challenges such as energy storage, geopolitical issues, unpredictability, and economic factors. Last but not least, more and more companies are investing into wind energy market, and current research is conducted in order to face the merging problems [3].

Table 2.4: The proportion of electricity produced from wind power

Country (year)	Wind energy penetration
Denmark (2019)	46.9%
Ireland (2018)	29%
Portugal (2013)	23%
Spain (2014)	20.2%
Germany (2017)	18.7%
United Kingdom (2018)	18%
United States (2016)	6%

2.3 Geothermal energy

Geothermal energy is a type of renewable energy that harnesses the natural heat from within the Earth for the production of electric power, space heating, or industrial steam. The primary utilization of high-temperature geothermal resources, which are above 150°C, is through generating electricity. This type of energy can be found everywhere beneath the Earth's surface, but the most desirable resources are found in areas with active or new formed volcanoes [10].

Geothermal energy belongs to renewable energy because its origin is the interior of the Earth and is limitless. Despite the energy that comes from wind and the sun, geothermal energy is steady regardless of the variations that occur on a daily and seasonal basis. The electrical energy generated from geothermal energy is more reliable than the remaining sources from which electricity is produced. The Earth's internal heat flow is approximately 42 million megawatts of power. This power is enough to fulfill the need for energy for 1000 houses for each million megawatts [10].

The technology of geothermal energy can be set up in vertical installations in various locations, but the drilling cost can be quite high, especially if the installation is under stone or rock mountains which require drilling to go hundreds of meters deep. To minimize the capital cost, it's better to select a geological site that will reduce the drilling cost and also must have good thermal characteristics. Additionally, it's more cost-effective to place the installation close to the building which will use the energy it produces, as it saves money that would be spent on expensive transmission lines that tend to lose energy over long distances [11].

Despite the high initial cost, this kind of energy has concentrated global popularity, especially for thermal production. The increasing demand for this source of energy has resulted in an increase in the installations of geothermal units. This source of energy has been used since 1913 for electricity generation. In the last decade (2009-2021), the total capacity reached 15,644 MW in 2021 and spread to 27 countries. The countries that took advantage of this source the most in 2021 were the US, Indonesia, and the Philippines (see **Table 2.5**). **Figure 2.6** shows the global geothermal energy installation capacity between 2009 and 2021 [11].

Table 2.5: Installation capacities for geothermal energy of the top ten countries in 2021

Country	Capacity (MW)
United States	3,722
Indonesia	2,276
Philippines	1,918
Turkey	1,710
New Zealand	1,037
Mexico	963
Italy	944
Kenya	861
Iceland	754
Japan	603

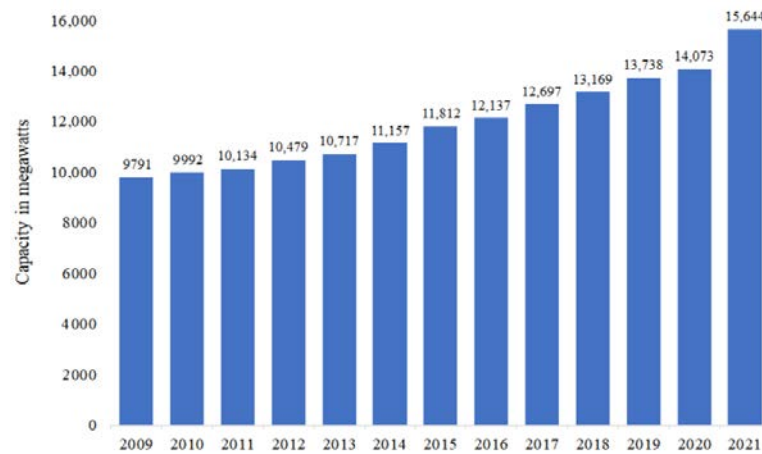


Figure 2.6: The global capacity of installed geothermal energy from 2009 to 2021 [11].

2.4 Biomass energy

Biomass is a term that refers to a diverse range of materials, such as animal and human waste, wood, and also agricultural residues. These materials can be used for various purposes, including facility heating, electric power generation, and combined heat and power [12].

To generate electric power from biomass, there are different methods available. The most used is direct combustion. Other methods include anaerobic digestion, pyrolysis, and gasification. The last one involves heating biomass with a limited amount of oxygen to produce a synthesis gas with energy content. Pyrolysis involves heating biomass rapidly with the absence of oxygen to produce bio-oil. As regards anaerobic digestion, this method involves decomposing organic matter by bacteria in the absence of oxygen to produce renewable natural gas [12].

One advantage of biomass over many other renewable energy sources is that it can be controlled and made available whenever needed, similar to fossil fuel-based power generation systems. However, a significant disadvantage of using biomass for electricity generation is that the procurement, delivery, storage, and payment of the fuel are required. Additionally, the combustion of biomass results in emissions, which must be strictly regulated and monitored to meet the required standards [12].

Electricity-only plants are specifically built to generate electricity without producing any heat from biomass, and they typically have an efficiency rate of around 30%. In the year 2019, these types of plants were able to produce a total of 428 TWh of biopower as presented in **Table 2.6** [8].

Table 2.6: Biomass energy production in TWh in electricity-only plants

Year	Municipal Waste	Industrial Waste	Solid Biomass	Biogas	Liquid biofuels
2000	29.9	4.97	40.6	10.1	0.00
2005	38.9	2.32	71.8	15.4	1.11
2010	47.6	19.3	120	25.7	1.41
2015	52.1	22.6	182	37.6	4.00
2016	51.7	28.1	223	36.9	4.32
2017	51.9	31.3	239	36.4	3.93
2018	54.1	31.7	273	37.5	4.26
2019	54.1	26.8	303	37.3	6.00

CHP (Combined Heat and Power) plants, also known as cogeneration facilities, are designed to produce both electricity and heat, and their efficiency rates vary widely. On average, these plants have an electricity conversion efficiency of around 30%. In the year 2019, globally, 280 TWh of biopower was generated from biomass-based sources in CHP facilities, representing one-quarter of all biopower produced. As shown in **Table 2.7** solid biofuels contribute to 66% of all biopower produced in CHP facilities, while municipal waste accounts for 17% of the total [8].

Table 2.7: Biomass energy production in TWh in CHP plants

Year	Municipal Waste	Industrial Waste	Solid Biomass	Biogas	Liquid biofuels
2000	17.6	11.7	57.5	2.59	0.00
2005	27.5	10.1	78.7	4.39	0.50
2010	34.2	11.2	101	12.6	1.53
2015	45.0	11.4	140	26.9	1.58
2016	48.1	12.1	155	28.1	1.43
2017	48.6	13.4	178	29.9	1.40
2018	47.1	13.7	180	31.3	1.67
2019	47.1	13.5	185	32.0	1.88

2.5 Electrochemical energy

Electrochemistry is an inclusive term, applied to two inverse processes. Either by using electricity to drive a chemical reaction (also known as electrolysis) or by producing energy from it. The common denominator of electricity and chemistry is the electric charge, which is distributed to

the different parts of the system, called a galvanic cell. **Figure 2.7** displays a typical electrochemical cell and its elements, both structural and chemical:

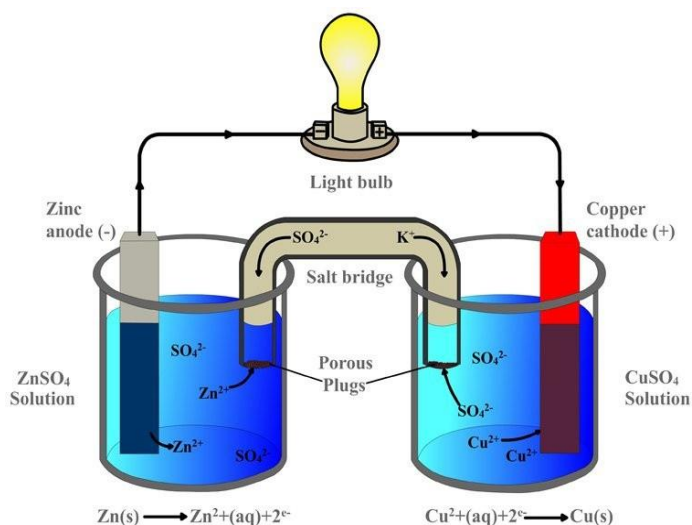


Figure 2.7: Electrochemical cell [13].

- Two electrodes, anode, and cathode, where oxidation and reduction take place, respectively.
- An external circuit for the electricity generated flows through a connected device either for storage or functioning.
- An electrolyte in liquid form, an acidic or basic solution that does not react with the reagents on both sides, but only with the ion products.
- A salt bridge is a U-shaped tube that regulates the electronic balance in the system by allowing negative ions to move into the oxidized section and cations to the other side.

The whole procedure is initiated by the spontaneous chemical reaction in the anode where zinc atoms release some of their electrons, generating electricity and turning them into zinc cations. The external circuit leads those electrons at the cathode to reduce copper cations to zero charge atoms. Copper cations emerge from copper sulfate's breaking because of the electric charge in the system. As a result, the concentration of sulfate anions is increasing, and they find access to the anode part and zinc cations through the salt bridge. To achieve that they are combined with the bridge's gel electrolyte, potassium nitrate, as they transfer from one side to another. There are special porous disks at the ends of the tube that are permeable to counter ions and minimize the mix of solutions inside and outside of the bridge.

Electrochemistry theory is the basis for the construction of all energy storage devices but also fuel cells (FC) that can produce energy in a green and very effective way.

2.5.1 Fuel Cells

Fuel cells are devices that convert chemical to electrical energy and reverse by using hydrogen and oxygen to produce heat, water, and electricity. Nonetheless, they are not necessarily friendly to the environment. If hydrogen fuel derives from hydrocarbons, such as petroleum there will be emissions, but in case hydrogen is produced through electrolyzing water, there will be zero emissions. Moreover, hydrogen fuel like the other types of fuel must be transported and stored. But for hydrogen, this process is difficult for now [14].

Their operation mode has similarities with battery operation, but a key difference is that they can be refueled instead of replacement or re-charging, like batteries. Another advantage is that they have no moving parts, such as piston, crankshaft, connecting rod, or valves and that means that fuel cells produce electrical power quietly and with more efficiency at the range of 50-70% (reducing energy loss due to friction at moving parts) than combustion engines [15].

The basic parts of a fuel cell are two electrodes and the electrolyte, which is placed between the electrodes. The first electrode is the anode where the oxidation reaction occurs (provides the electrons to the circuit, negative electrode) and the second electrode is the cathode where the reduction reaction takes place (positive electrode that accepts electrons). The materials from which they are made depend on the type of fuel cell used. There are many types of fuel cells. In this report, SOFC and PEMFC have a central part.

Catalysts are utilized at the electrodes to do the redox reactions. For that reason, the reinforcement of catalytic activity has been applied to many catalytic reactions, in order to control and determine the catalytic activity and selectivity of the reaction, which occurs in the gas phase. Using low-intensity currents or potentials on a metal catalyst, its output work can be affected, due to the electrochemical migration of ionic species through a solid electrolyte to the metal-gas interface [16,17]. This phenomenon, although it greatly affects platinum, is not limited to any specific solid electrolyte or metal. Due to the contribution of this effect, it has been shown that the rate of ion delivery is orders of magnitude lower than the catalytic rate. Finally, the connection between electrochemistry and catalysis seems to offer impressive technological possibilities [18]. The most common material used as a catalyst is platinum. Platinum-based materials in fuel cells are the most productive for oxygen reduction and

methanol oxidation reactions. That's the reason why researchers have focused their attention on finding methods by which these materials will increase their effectiveness. Some of them try to find materials with a multilayer structure to increase the active surface area of platinum. This increase will result in more redox reactions taking place at the same time which will cause an increase in efficiency. More information regards the composition of active sites that shape the performance of carbon-based catalysts can be found in the research of Najam *et al* [19].

Another way to enhance the use of platinum is to construct tiny catalysts with the main aim of reinforcing the oxygen reduction reaction. For that purpose, the researchers examine the octahedra structure which is based on platinum, nickel, and palladium as well as that containing gold (Au) instead of palladium. For the same reason, the formation of cobalt and platinum nanodendrite in nanoframe has been studied. Researchers also proved that the structures of palladium and platinum symmetry broken concave nanocube consist of another way to improve the performance and extend the life of the catalyst on which the oxygen reduction reaction takes place [20]. The catalysts of the above studies showed better efficiency and mass activity than the commercial platinum-carbon catalyst. Especially in proton exchange membrane-type fuel cells, it was found that by merging nickel and platinum precursors into very small palladium sheets, the mass activity in the oxygen reduction reaction can be up to 6.25 times greater than the commercial platinum catalyst with carbon [21].

However, because platinum-based materials are expensive, scientists are searching for other compounds that will improve the action of the catalysts and expand the fuel cell's efficiency. A common practice is to use pyrolysis to create such compounds. They found that the nitrogen-doped mesoporous carbon compound when fabricated using pyrolysis at 900 degrees Celsius not only exhibits greater stability than platinum concerning phosphate and sulfate anions but also greatly improves the oxygen reduction reaction [22]. Moreover, the researchers discovered that the creation of metallic nanoparticles contained in carbon nanotubes, through the process of pyrolysis followed by phosphating, expands the surface area and pores which improves the oxygen reduction reaction in the catalyst. However, at present, research shows that the platinum-based catalyst with the core-shell structure is the most efficient [23].

Since most of the used catalysts for oxygen reduction reactions show very good performance in basic media there is a great need and scientific interest in finding catalysts that show similar results in acidic media. Particular interest is concentrated in those that do not contain precious metals because they have lower costs. One such example is catalysts composed of carbon, iron, and

nitrogen. However, they face problems concerning durability from the creation of Fenton radicals. For this reason, the synthesis of iron-free catalysts is important. Current research has shown that the addition of nitrogen, manganese, and cobalt to mesoporous carbon nanostructures has high performance and resistance to oxygen reduction reaction not only to acid but also to alkaline solutions. Also, in recent research, it was discovered that the addition of core-shell structured FeOx nanoparticles to a nitrogen-implanted mesoporous matrix contains one of the best performances in acidic media [24].

Also, it is important to mention that there is great scientific interest in catalysts that come into contact with fuel such as methanol due to the fact that the materials used in methanol-fueled fuel cells without a reforming chamber are expensive and have not achieved the desired levels of durability for widespread commercial use. For this reason, there is a great need to find an anode catalyst that will improve these barriers. Researchers have conducted several investigations to achieve this goal. Some of the most notable ones suggest a) catalyst consisting of complex compounds of mesoporous tungsten carbide and carbon with the addition of platinum. This catalyst compared to the commercial catalyst PtRuC (40 wt.% Pt, 20 wt.% Ru) for methanol electrooxidation has a higher specific mass activity reaching a factor of 1.1 (per mg Pt) and 1.7 (per mg of noble metal) [25]. Especially if the mesoporous carbon with the tungsten carbide has a hexagonal structure which is made using ammonium by the soft-template method, it shows a mass activity coefficient of 2.4 (per mg Pt) and 3.2 (per mg metal). b) Also, efficient catalysts contain a nanoflower structure and are alloys of platinum and transition metals such as nickel and cobalt. c) Last but not least nanoflower structured catalysts consisting of many nanodendrites created by adding palladium, rhodium, and ruthenium to platinum and nickel nanoflowers. These catalysts showed a mass activity 9.9 times higher than the commercial carbon platinum catalyst in the oxygen reduction reaction. These catalysts showed equally good electrolytic behavior towards the methanol oxidation reaction [26].

Finally, in current days much scientific research is focused on a family of materials called MXenes. This family of materials includes transition metal carbonitrides and nitrides, among others. According to the research results, these materials show impressive properties such as thermal stability and very high electrical conductivity, which makes them ideal for use as electrode components in applications for energy storage and conversion such as batteries and fuel cells respectively [27].

2.5.1.1 Proton Exchange Membrane Fuel Cell (PEMFC)

There are two different types of PEMFC. To begin with the type of low-temperature, which operates between 50-100 °C, and the second regards high-temperature, which operates at 200 °C. This is the significant difference between the above kinds. The material used as a catalyst is platinum, which is an expensive metal. As an electrolyte, the low-temperature type uses a humid polymer membrane but the other type of PEMFC uses an acid and temperature-resistant polymer, which can uptake acid, which acts as an electrolyte, such as phosphoric acid-doped polybenzimidazole. The next section will describe how a PEMFC works [15].

The hydrogen inserts into the fuel cell from the side of the negative electrode. There is the so-called three-phase region. The first phase consists of the electrolyte, the second is the electrode and the third is hydrogen. These phases, together split the hydrogen atoms with the catalyst help which is located in the electrode, into hydrogen cations and electrons. The electrons are then moved from the anode to the cathode via an external circuit. The free movement of electrons provides the current. On the other hand, hydrogen cations pass through the electrolyte on the cathode side (the electrolyte only allows the ions to pass). There is the three-phase region where the first phase is the electrolyte, the second the electrode, and the third the oxygen (oxygen enters the fuel cell at the cathode.) These three (hydrogen cations, electrons, and oxygen) react with each other with the help of a catalyst, and water and heat are formed. The water drains from the cell. **Figure 2.8** shows the process.

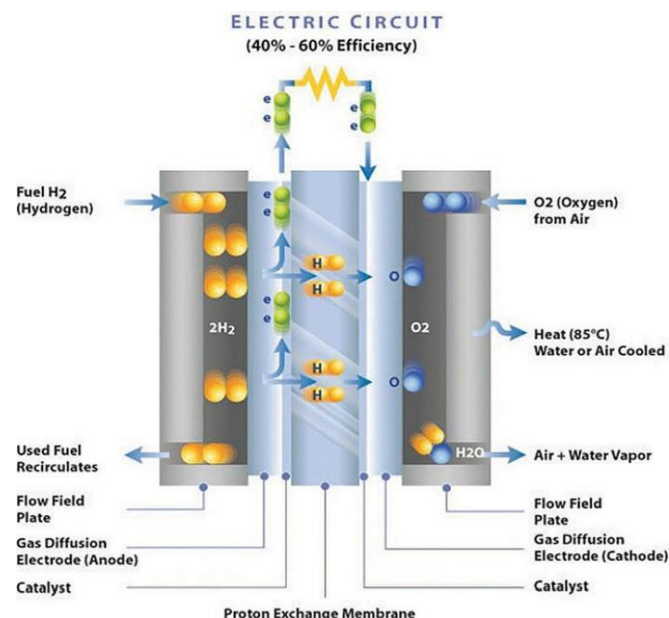


Figure 2.8: Operation of a proton exchange membrane fuel cell [28].

It is important to mention the significant problems in these fuel cells. One of them is the loss of current due to the leakage of fuel through the membrane from the anode to the cathode. Scientists are researching the effect of this phenomenon on cell performance [29]. Of this, it has been found that fuel leakage can reduce the efficiency of the cell by as much as 20% [30]. The catalyst which consists of nickel ruthenium and carbon shows not only a higher mass activity but also a smaller leakage current as it has a higher electrochemical stability compared to the platinum and carbon catalyst that is widely used in commerce [31]. Decomposition also consists of a main problem that occurs in that category of fuel cells, especially if hydrogen is used as fuel. This is caused by the tiny presence of carbon monoxide. Although much research has been done to find the catalyst that will achieve very high strength and stability, the results are not yet capable of accelerating widespread commercial use. Some notable examples of the literature are found in the research of Brouzgou *et al* [32].

2.5.1.2 Solid Oxide Fuel Cell (SOFC)

The solid oxide fuel cell operates at 500-1000 °C. The material used for the catalyst role is nickel oxide (NiO). This element is commonly utilized as the anode material. Also, the use of platinum is avoided (due to high temperatures), which is also an expensive metal. For the role of electrolyte, the SOFC uses a solid oxide material, such as yttria-stabilized zirconia. For this material, a lot of research has been carried out in order to determine its electrochemical behavior and its performance depending on the prevailing conditions. Some of the most significant conditions are oxygen supply, temperature, and fuel used [33]. The scientists also found that these fuel cells can be used for the synthesis of higher hydrocarbons using fuels such as methane [34]. The next paragraph will describe how a SOFC works [35].

The oxygen atoms enter the fuel cell from the cathode. There is the so-called three-phase region where one phase is the electrolyte, the second is the electrode and the third is oxygen. These three phases when in contact remake the oxygen atoms into oxygen ions with the help of catalysts located at the electrode. The oxygen ions are then moved from the cathode to the anode through the electrolyte (the electrolyte only allows the ions to pass). On the anode side, there is the three-phase region where the first phase is the electrolyte, the second phase is the electrode, and the third is the fuel (fuel enters the cell at the anode). These two (fuel, and oxygen ions) react with each other with the help of a catalyst, and water and heat are formed. The water drains from the cell. On the other hand, the electrons moved from the anode to the cathode via an external circuit. This free movement of electrons provides the current. The process is depicted in **Figure 2.9** [36]. Also, in order to find

the value of the electromotive force and the efficiency of the solid oxide fuel cell the scientists figure out simple models with high accuracy. These models accept two parameters. The first is related to the operating temperature and the second to the quantity of carbon in the fuel so that the model is not limited and can be used for all fuels [37].

Except for the classic SOFCs mentioned in the previous paragraph there is a subclass of SOFCs that use materials (such as BaCeO_3) that exhibit at lower temperatures greater proton conductivity compared to O_2 -conducting electrolytes [38]. In fact, research has shown that the addition of copper to these materials increases the conductivity and extension of the performance [39]. In this subcategory of solid oxide fuel cells, some problems such as high cost and ceramic degradation of the materials are solved [40]. Also, these fuel cells are necessary in several applications. A typical example is their use for the manufacture of generators, as at lower temperatures, on the one hand, the operating costs and purchase costs of the cell will be reduced since the materials of which it will be composed will be cheaper, and on the other hand, the cells will have a longer lifespan since the operating environment will limit stack degradation [38].

The basic advantage that SOFC has against high temperature PEMFC (as regards vehicle applications) is that it can use a lot of fuels, such as methanol, and ethanol directly into the cell without needing a reforming chamber to form hydrogen (due to high temperatures and catalyst Ni) [34]. More information on the factors which determine the operation and performance of PEMFC when using direct ethanol as a fuel can be found in the research of Andreadis *et al* [41].

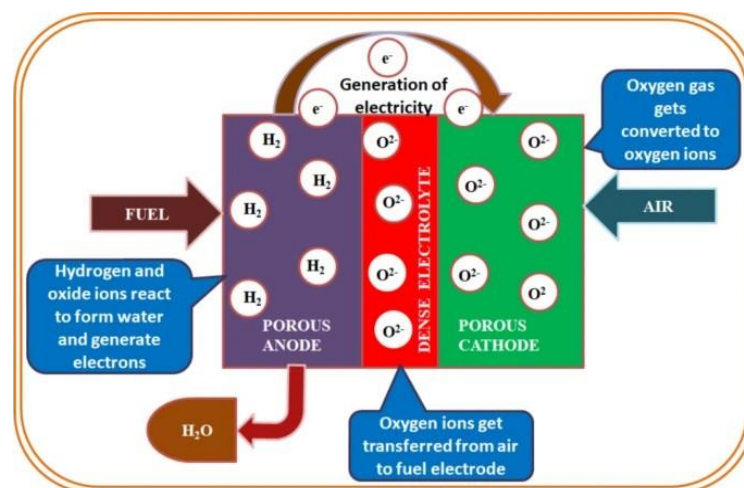


Figure 2.9: Schematic diagram of solid oxide fuel cell [42].

Despite their assets, it would be also appropriate to mention the most important failures that may occur in both types of cells (PEM and SOFC):

- Delamination of the electrode from the electrolyte would interrupt the operation of the cell.
- Cracks can form in both the electrolyte and the electrodes. The creation of cracks will be understood by the reduction of the efficiency of the fuel cell.
- If the water is not removed at a fast rate, then flooding can occur. This would stop the operation of the fuel cell (mainly concerning PEM fuel cells).

CHAPTER 3

ENERGY STORAGE

Introduction

Renewable energy systems decarbonize the environment. This happens due to the fact that they do not generate polluting emissions. However, since for energy production they rely on natural resources such as wind and sun, the amount of energy that will be produced is unpredictable and reliant on weather. To solve this problem, renewable energy needs to be stored and then used in a consistent and controlled way as required. Numerous scientists have made critical contributions to develop innovative and effective methods for energy storage, based on the flourishing electrochemical field and its technological breakthroughs [43].

3.1 Lead-acid Batteries

In 1859 a researcher named Gaston Planté discovered the lead-acid battery. Today, this kind of battery is one of the oldest chemical systems that store electrical energy. They are simple to install and have small purchase and maintenance costs. The performance of lead-acid batteries depends largely on ambient temperature and discharge rate, which is controlled by a system's power electronics. This battery consists of plates of lead and lead dioxide in an electrolyte solution of sulfuric acid and water [44].

During the discharge stage, the lead dioxide positive electrode and the lead negative electrode will convert to lead sulfate and consume the sulfate ions. The positive electrode is the major factor influencing the performance and cycle life of the battery. The negative electrode determines the cold-temperature performance [45]. **Figure 3.1** depicts a lead-acid cell during discharge.

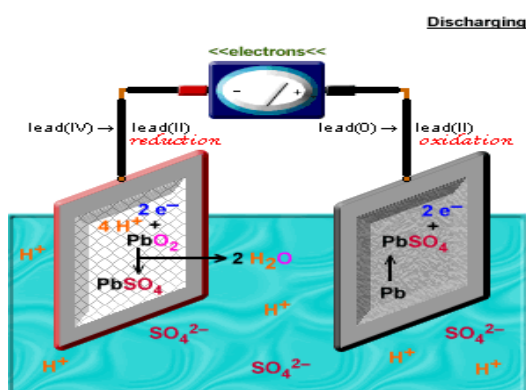
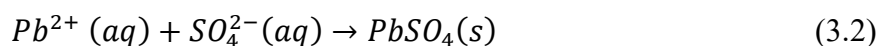
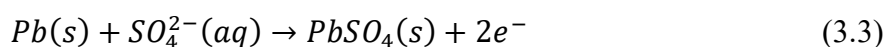


Figure 3.1: Lead-acid cell during discharge [46].

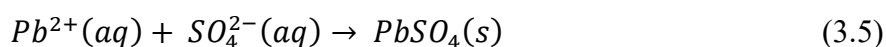
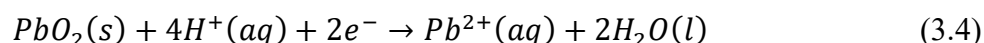
At the anode, lead oxidation occurs, and electrons are produced. As a result, the anode is negatively charged, and electrons go from the anode (-) to the cathode (+) along the wires that make the connection with the electrodes. Then Pb^{2+} reacts with SO_4^{2-} in sulfuric acid in order to produce $PbSO_4(s)$ which sticks to the lead frame of the anode. The following lines will show the chemical reactions taking place [47]:



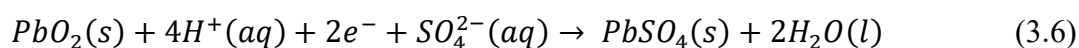
The overall reaction at the anode is:



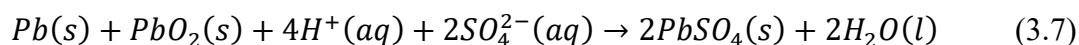
At the cathode during discharge lead dioxide is reduced by protons from the sulfuric acid and then Pb^{2+} reacts with SO_4^{2-} to produce $PbSO_4(s)$ which sticks to the lead frame of the cathode. The following lines present the chemical reactions taking place.



The overall reaction at the cathode is:



Finally, both oxidation and reduction reactions that occur can be used to write the total reaction to a single lead acid cell:



For the recharging process, more than 2 volts are needed to drive the spontaneous reactions in the opposite direction to convert electrical energy to chemical energy. This energy is stored in sulfuric acid, in the lead, and also in the lead dioxide of the cell. **Figure 3.2** shows a lead-acid cell during recharge.

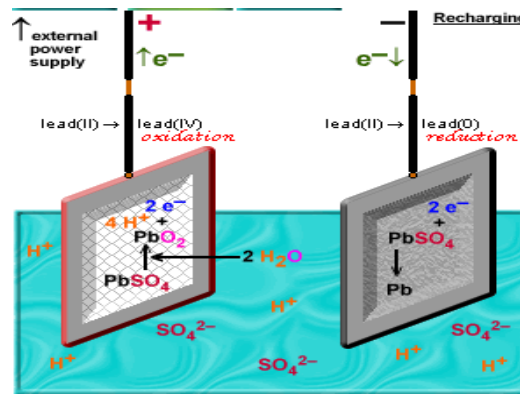
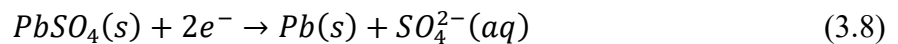
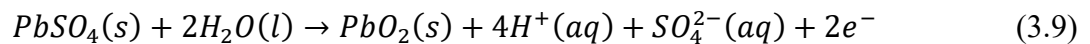


Figure 3.2: Lead-acid cell during recharge [46].

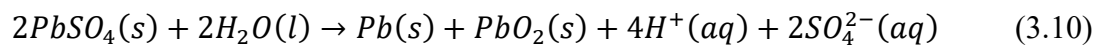
At the cathode electrons are being pushed from the recharger and as a result lead in lead sulfate sticking to the electrode is reduced back to Pb(s) [47]:



On the other hand, electrons are being pulled by the recharger out of the anode and as a result lead in lead sulfate sticking to the electrode is oxidized by water to reform lead dioxide:



The overall form of the reaction taking place in a single cell is:



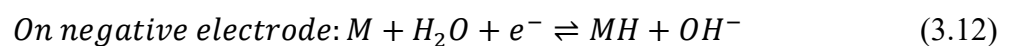
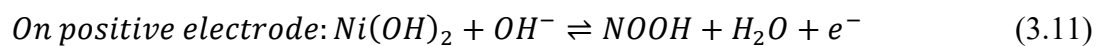
There are two styles of lead-acid batteries, starting ones and deep cycle. The main differences in their design are in the electrodes. The starting batteries utilize the surface area of their electrodes to maximize current flow to deliver larger instantaneous currents. This offers high currents at the cost of being unable to be deeply cycled (the plates become too corroded to conduct). Deep-cycle batteries have thicker electrodes, which make them able to be more deeply discharged and provide constant current but cannot provide the large starting currents needed to start motors. Lead acid batteries are inexpensive, simple to manufacture, and their technology is mature. Also, the self-discharge rate is among the lowest in rechargeable battery systems and they are capable of high discharge rates. Lastly, the only maintenance requirements are keeping them from discharging too far and there is no memory effect to deal with [48].

And in this kind of battery, there are some concerns. The electrical discharge beyond a certain point will ruin the capacity of the battery, making supervision mandatory, since they are very environmentally unfriendly because they contain lead. For the majority of applications, the size and weight of these units are the only criterion that limits the use of these batteries. By far the most common application of these batteries is with vehicles for starting engines, as they are heavy enough that the weight is not of much importance. They are also popular in larger energy applications that require constant current, such as solar power storage [48].

3.2 Nickel-metal hydride Batteries

In the 1970s the Ni-MH battery was discovered and at the end of the 20th century introduced into the market. This battery consists of a nickel hydroxide electrode as its positive electrode, a metal hydride as its negative electrode, and a potassium hydroxide solution as its electrolyte. These batteries have high power capability, and tolerance to overcharge/discharge. Moreover, they provide environmental compatibility and safety and that's the reason why these batteries are suitable for applications such as HEVs and portable power tools, recycling them would have some important benefits such as the limitation of the threats regarding the environment and due to the recovery of precious metals, for example, Ni, Co, and also rare earths [49]. In the previous decade they widespread their utility in consumer application but due to the lower energy density compared with the lithium-ion batteries their participation in the sector of rechargeable consumer batteries has been declining. However, the global production of Ni-MH batteries remains steady. If the batteries manufactured for HEVs are not taken into account the total amount of cylinder batteries produced was approximately 1.13 billion in 2018 which are used as power sources for cordless phones, toys, alarm systems, etc [50].

In terms of its operational mode, **Figure 3.3** illustrates the fundamental concepts of a Nickel-Metal Hydride (Ni-MH) battery, and it also depicts the electrochemical reactions involved during the charging and discharging processes, which can be summarized as follows [51]:



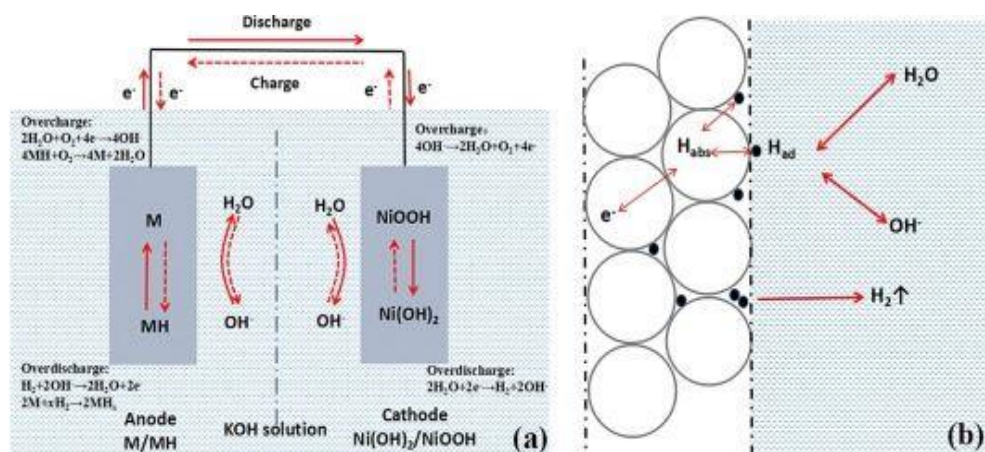


Figure 3.3: (a) Schematic representation of the electrochemical reaction mechanism within a Ni-MH battery, (b) and of the process of hydride formation and decomposition through electrochemical charge transfer reactions [51].

The principles for charge-discharge mechanism of these batteries are simple. It is about a motion of hydrogen between two electrodes in an alkaline electrolyte. When a charger is connected across the electrode electrical current flows into the cathode and the electrolyte splits into positive potassium ion and negative hydroxide ion. Then the hydroxide ion reacts with nickel hydroxide to produce nickel oxide hydroxide giving away water. Moreover, electrons are produced which flow through the external circuit and reach the anode. The water reacts with metal to form metal hydride giving away hydroxide ions. As regards the discharge process, at the cathode nickel oxide hydroxide is produced while at the anode metal hydride is produced. When a load is connected across the electrodes the potassium hydroxide electrolyte splits into potassium ion and hydroxide ion. Then the hydroxide ion reacts with metal hydride at the anode to form metal giving away water and electrons are produced. Finally, the electrons flow light up the load and reach the cathode where water reacts with nickel oxide hydroxide to form nickel hydroxide giving away hydroxide ions. Also, it would be important to mention what happens in two different limit conditions. To start with overcharge, as concerns the capacity, the negative electrode has a higher value compared to the positive. Moreover, during the overcharge process the oxygen generated from the positive electrode reduced at the surface of the MH electrode. As regards the over-discharge process, the hydrogen generated by the reduction process, is absorbed by the MH electrode (hydrogen elimination reaction). Last but not least, these batteries exhibit very good tolerability during the above-limit processes [52].

Since 1990 the volumetric and gravimetric energy densities of AA-size Ni-MH cells have evolved from 190 to 490 Wh/L and from 54 to 127 Wh/kg respectively. In addition to this

evolution, their power went from 200 to 1200 W/kg commercially, and as regards the research section up to 2000 W/kg [53].

Nowadays, 85% of the hybrid electrical vehicles are used as power sources the Ni-MH batteries. However, the need for energy density continues to increase. Due to the continued development of HEVs, the characteristics of long cycle life and high power are necessary for Ni-MH batteries. For these reasons, the scientists still doing research in order to improve the characteristics of Ni-MH batteries. Finally, it would be important to mention some differences between the batteries which have already been mentioned.

These batteries have a 30-40% higher capacity than a basic NiCd battery and are far less prone to the memory effect found in NiCd. Also, have simple storage, and transportation and are environmentally friendly. This battery has fewer disadvantages compared with the other batteries. In the situation of repeatedly deep cycled at high load currents, the performance begins to reduce after 200 to 300 cycles. For the above reason preferred shallow discharge cycles. They are also prone to damage when used for high discharges, and compared to newer technologies have a very high self-discharge. These kinds of batteries demand full discharge regularly in order to secure their electrodes from the formation of crystalline on them [48].

Nickel-metal hydride batteries are ideal for applications that need both attributes of NiCd and Li-ion batteries. They are more rugged than Li-ion but have a lower impact on the environment than NiCd batteries. Their cost is lower than Li-ion batteries but requires maintenance. They can find applications in technologies such as cell phones and computers but seem to be losing the market to Li-ion batteries [48].

3.3 Lithium-ion Batteries

The lithium-ion battery belongs to the category of rechargeable batteries. In this battery, lithium ions move from the negative electrode (anode) to the positive one (cathode) through the electrolyte during discharge and backward while charging. These batteries acquired huge success and prevailed in the field of mobile devices, like laptops, due to the following features: low load loss when not in use, low memory effect, and high-power density. It would be important to mention that Li-ion batteries have a wide range of uses apart from consumer electronics, such as space applications, electric cars, and military mechanical devices [54].

A significant asset is also the small weight of these batteries as regards other batteries for the equal power demands. One positive characteristic that these batteries have is that lithium is in abundance in the Earth's crust compared to lead and nickel (from 20 to 100 times). However, the reason that it is less common owes to the fact that lithium is much more reactive than any other metal and thus it is not in a free state but combined with other elements. **Figure 3.4** shows the relative abundance of the Earth's crust in chemical elements [55].

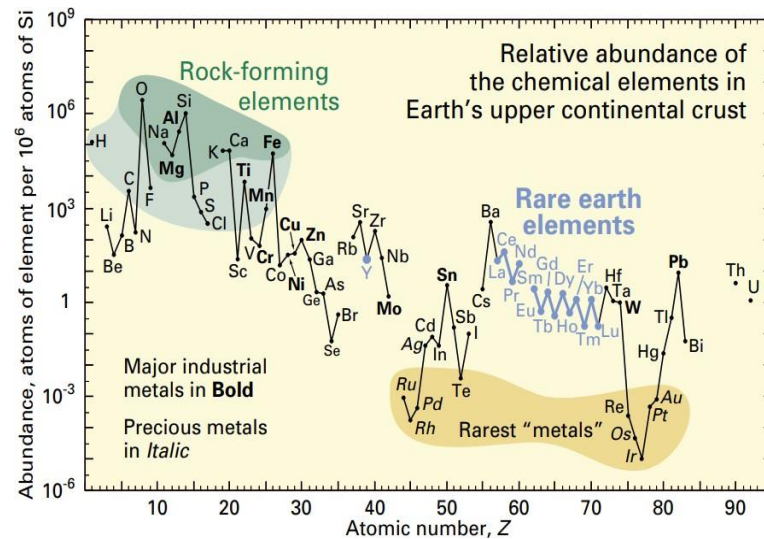


Figure 3.4: Relative abundance of the Earth's crust in chemical elements [55].

Lithium-ion batteries are divided into the following main categories according to their chemical composition. Each category has its advantages or disadvantages concerning the others. Comparison criteria are special power, specific energy, safety, cost, battery life, and performance [55]:

- Lithium Manganese Oxide (LiMn_2O_4)
- Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO_2)
- Lithium Cobalt Oxide (LiCoO_2)
- Lithium Iron Phosphate
- Lithium Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$)
- Oxide of Aluminum (LiNiCoAlO_2)

The three basic elements of a lithium-ion battery are the positive electrode, the negative electrode, and the electrolyte. As a concern the electrolyte of a regular battery is made of salt lithium in an organic solvent, the positive electrode is made of metal oxides, and the negative

electrode is made of carbon. The electrochemical roles of the electrodes change between anode and cathode depending on the direction of the current flowing in from the item. The most common type of electrolyte is a mixture of organics of coal, such as diethyl carbonate containing lithium-ion complexes or ethylene carbonate. The negative electrode usually consists of graphite, while the material of the positive electrode is usually an oxide metal with a layered structure, such as cobalt lithium oxide (LiCoO_2) [55]. Current studies have shown that from the anode materials the nanorods Fe_2O_3 on graphene oxide show marvelous electrochemical properties. These results are accomplished because this material has the ability to increase the contact surface between the electrode and electrolyte and reduce the diffusion zone of lithium ions [56].

Of particular interest is a subclass of lithium batteries that consist of carbon dioxide. Using carbon dioxide in this way is a positive step towards tackling the greenhouse effect. But some problems such as limited charge-discharge cycles as well as low efficiency prevent their application. For the above reasons, researchers are trying to solve these problems. In recent research by Liang *et al* [57], a cheap and effective cathode for this type of battery was discovered, which has nickel and iron as its main elements. According to the experimental data, this battery has a high discharge capacity of 6.8 mA h cm^{-2} and a stable cut-off capacity of $0.25 \text{ mA h cm}^{-2}$ for at least 109 cycles at a current density of 0.05 mA cm^{-2} . The next paragraph describes how a lithium battery works.

Lithium, which has the highest tendency to lose electrons, is utilized in lithium-ion cells. Lithium has one electron in its outer shell and always wants to lose this electron. For this reason, pure lithium is a highly reactive metal. It even reacts with air and water. Lithium, in its pure form, is a reactive metal, but if lithium is part of a metal oxide it is quite steady. If somehow, divide a lithium atom from the metal oxide, then this lithium atom is highly unstable and will instantly form a lithium-ion and an electron. However, lithium as a part of a metal oxide is much more stable than this state. If we can provide two different paths for the electron and lithium-ion flow between lithium and the metal oxide, the lithium atom will automatically reach the metal oxide part. During this process, we have produced electricity from the electron flow through one path. We can produce electricity from lithium metal oxide if we first separate lithium atoms from the metal oxide and secondly guide the electrons lost from such lithium atoms through an external circuit [58].

When a power source links to a lithium-ion battery, the positive side of the source will attract and remove electrons from the lithium atoms of the metal oxide. Then the electrons flow through the external circuit as they have not the ability to pass through the electrolyte and reach the graphite layer.

In the meantime, the positively charged lithium ions will be attracted toward the negative terminal and will flow through the electrolyte. Lithium ions also reach the graphite layer space and get stuck there. Once all the lithium atoms reach the graphite sheet the cell is fully charged. Nevertheless, this is an unstable state, and when the power source is removed and a load is connected, the lithium ions want to go back to their stable state as a part of a metal oxide. Due to this tendency, the lithium ions move through the electrolyte and electrons via the load (this movement of electrons creates the current). It is critical to mention that graphite does not have a role in the chemical reaction of lithium-ion batteries (graphite is just a storage medium for lithium ions). **Figure 3.5** displays the process [58].

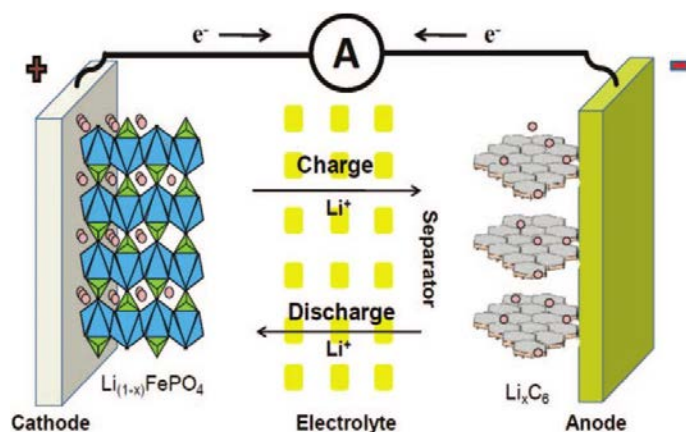


Figure 3.5: Chemical components of a Li-ion battery: FeO6 (blue), PO4 (green), C6-graphite (grey), Li (pink) [59].

3.4 Supercapacitors

Also, named ultracapacitors and it is about an electricity storage device. A capacitor in its traditional form consists of two parallel metal plates, the electrodes that are physically separated from each other by an additional layer, called dielectric. Dielectric prevents electrons from passing through it, sending them via an external circuit from one side to another. Despite the above kind of capacitor, a super one has its dielectric replaced by a thin insulator and a solution of ions, an electrolyte. The insulator allows it to pass only the ions. During the process of charge, the positively and negatively charged particles adsorb at the surface of the electrodes, depending on the voltage applied to the plates, and diffuse randomly in the solution at discharge. The supercapacitors concerning the storage mechanism are divided into two types, electrical double-layers, and pseudocapacitors.

3.4.1 Electric Double-Layer Capacitors (EDLCs)

This type of supercapacitor is based on the electrostatic attraction between the charges of the electrodes and the mobile ions of the solution [60]. When voltage is applied to the plates the ions are charged and as they approach the interface of oppositely polarized electrode/electrolyte they are organized in layers wrapping the whole surface of electrodes. At first, there is a molecular layer attached directly to the interface, and then the bigger dissolved ions attracted to the electrodes form a second layer, next to the previous one, yet, without passing through it. This is the so-called double Helmholtz layer. The inner layer can be characterized as a dielectric because it separates the charges of the electrodes from those of the solvated ions. As a result, a static electric field emerges and it polarizes the inner layer, leading to the formation of two conventional capacitors inside the supercapacitor, where the electricity is stored [61]. **Figure 3.6** shows a schematic depiction of the double layer and the ions/molecules involved.

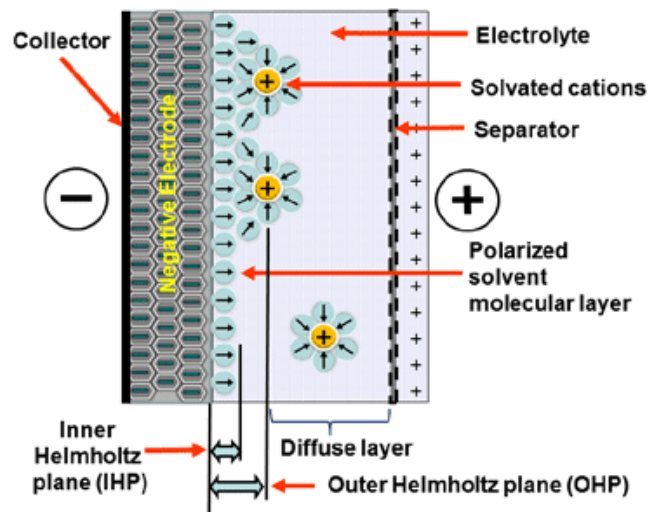


Figure 3.6: Double layer capacitance [62].

The common material for the plates is porous carbon, which increases a lot the surface area of the electrodes, as research has shown at the nanoscale. The unit order could be either slits or nanotubes but also not bear a specific shape [60]. The amount of capacitance depends on the nanostructure of the electrode as well as on the width of the double layer. The whole charge-discharge procedure is very fast because the two layers do not react chemically with each other making the power density the greatest advantage of this type. This phenomenon also contributes to the long-life operation cycles without any performance degradation [61].

Although EDLCs are the ultimate choice when high power distribution is needed, they are limited to the energy storage field. The amount of their electricity load can be measured between 3-5 Wh/kg, which is way too far from the typical Li-ion batteries that are mostly used in the market [63]. This can be explained because of the surface interaction of the particles, which results in the porous carbon electrode material increasing the active surface area.

3.4.2 Electrochemical pseudocapacitors

The second category involves charge transfer as a storage mechanism between the electrodes and the electrolyte. Specifically chosen materials allow the electrodes to host very fast redox reactions that enable them to store energy electrochemically. Electricity transfer undergoes three mechanisms: electrosorption, redox reactions, and intercalation [61]. All these cases are included in the faradaic mechanisms in which every process is accompanied by a flow of electrons through an external circuit that connects the electrodes. In **Figure 3.7** some typical examples of each mechanism analyzed below, are illustrated [63]:

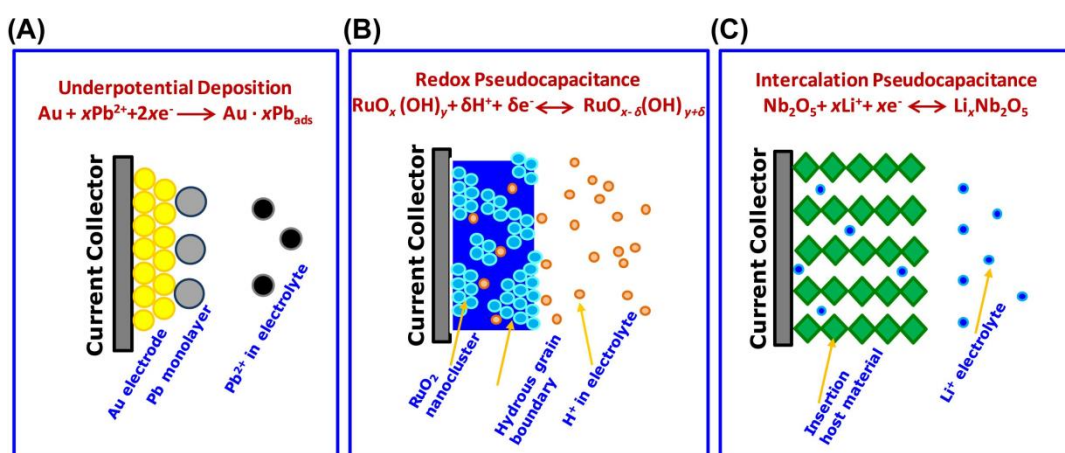


Figure 3.7: Reversible faradaic mechanisms inducing pseudocapacitance: (A) Electrosorption, (B) Redox reactions, (C) Intercalation [63].

Electrosorption: Underpotential deposition originates when metal ions are adsorbed and organize a monolayer owing to a difference in the attached metal surface, which is less negative compared to the equilibrium potential for the reduction of the metal.

Redox reactions: In this type, the ions approach only the surface of the electrodes, and the process character is electrochemical since the electric charge is being transferred from the reducing agent to the oxidizing one.

Intercalation: The ions involved in the process are hydrogen or lithium protons that cling to parallel aligned layers of electrode material. The process takes place on the bulk of the material increasing the active surface area.

Faradaic pseudocapacitance exists only in the presence of a static electric field, so a double Helmholtz layer is being formed in the same way as previously described. The pseudocapacitive ability starts when some desolated ions of the electrolyte flow through the separation layer and adsorb to the electrode's surfaces. Then, the redox reactions that occur during their interaction with the electrode molecules trigger an electric charge redistribution, where only one electron per unit charge is involved. The electrons flowing through the external circuit originate from the electrode's orbiters ending up in the oppositely charged plate where another double layer has been formed. However, they do not have any immediate connection with the electrolyte's ions because they attach to the ionized electrode molecules [64].

Pseudocapacitance is an ability that is mostly related to the chemical affinity of the electrodes' components and the solvated ions clinging to their surfaces as well as the pore size of their carbon derivatives. Such materials with redox behavior that supply the need for this kind of charge storage are the transition metal oxides (RuO_2 , MnO , etc), integrated by doping into conductive carbon-based electrode materials but also polymers, such as polyaniline, polythiophene, etc. that provide high conductivity too [64].

Compared to the EDLCs a far larger amount of charge transfers and storage is managed with the use of faradaic mechanisms. It has been estimated that the phenomenon of pseudocapacitance can increase the total capacitance by 100 times more. The fact that no chemical bonds occur during its reversible functioning also keeps the asset of high-power density. Last but not least, the internal stability of the system is affected due to the limitations regarding the kinetics of redox reactions [65].

3.4.3 Hybrid supercapacitors

As their name suggests, those devices incorporate the two above mechanisms to achieve higher values of energy density compared to the individual ones. Hybrid supercapacitors' electrodes include various materials that bear both EDLC and pseudocapacitive features. This combination allows for maintaining the cycle life and high-power density of EDLCs, cutting down cost and increasing specific energy density to stay closer to battery behavior. They can be sorted into two categories, composites and battery-like, depending on their structure, and thereby they can be symmetric or asymmetric based on

the similarity of the electrodes themselves. The choices are numerous, and they could be combinations of activated carbon, conductive polymers, metal oxides, etc. The EDLC part is activated by the carbon materials thereby providing a capacitive double layer and a larger surface area for capacitance. On the other hand, metal oxides or conducting polymers behave as pseudocapacitors [66].

The comparison between symmetric and asymmetric hybrid supercapacitors is regarding the composition of the electrode material. In a symmetric hybrid supercapacitor, the electrodes' materials are identical, thus posing a mix of EDLC and pseudocapacitive components. Therefore, they are all in the composite list. The most common example of a symmetric hybrid supercapacitor is PANI (Polyaniline). The presence of carbon materials provides a high surface area and enhances the internal stability of the hybrid form. On the other hand, in the conducting polymers, the redox reactions take place to store and release even more electricity owing to the faradaic mechanisms [66].

The asymmetric hybrid formation incorporates the advantages of cycling longevity and fast reversible processes of a non-faradaic negative electrode and a high capacitive positive electrode to achieve the double goal of high energy and power density. When it comes to pseudocapacitors, conductive polymers are in higher demand in the market due to their lower internal resistance. However, the limited efficiency of a negatively charged polymer electrode urged its replacement by a carbon derivative leading to the asymmetric hybrid supercapacitor. There are also asymmetric assemblies of activated carbon with metal oxides, such as potassium sulfate (K_2SO_4) or manganese dioxide (MnO_2) [65,66].

The type of hybrid battery assembly comes from the coupling of two different electrodes, one that secures the supercapacitor elements and one that plays the role of the battery. Coupling supercapacitors with lithium-ion storage systems is an important area of research because lithium ions have a high-density value. The density ranges from 120 to 200 Wh/kg, while the efficiency of EDLC is 2 to 5 kW/kg. The hybrid assembly uses $Li_4Ti_5O_{12}$ for the anode and connects it with activated carbon to play the role of double-layer capacitance [66].

Every type of supercapacitor has the same obstacle which prevents it from achieving its maximum capacity. Moreover, the internal resistance affects the power performance and causes problems in kinetics as a contribution of electrolyte resistance, current collectors, and electrodes. The improvement in energy density parameters can be accomplished by designing more developed

structures aiming at the best electronic conductivity, surface area, and maximum electrochemically active sites to facilitate ion transport [66].

3.5 Electrolyzer-Hydrogen fuel tank

The operation that uses electrical current to divide the molecular of water into its components for the production of hydrogen purposes nowadays has become one of the best options to change the shape of energy from big amounts of electrical energy from renewable resources into hydrogen. Hydrogen is the element with the highest energy density. It's utilization in fuel cells as fuel, has important advantages such as high efficiency as concern the energy conversion and also produces zero pollution because the final product of the reaction is water. For these reasons, the development of water-splitting cells to generate hydrogen has become a global issue [67].

Two half-cell reactions were utilized to describe the whole water electrolysis reaction: hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). Water reduction takes place at the cathode in the HER reaction, in order to make hydrogen. Also, water oxidized at the anode in the OER reaction to form oxygen, as shown in **Figure 3.8**.

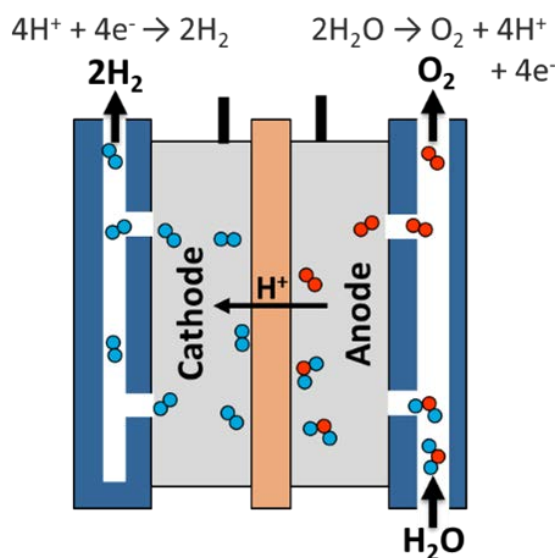


Figure 3.8: Schematic illustration of water electrolysis [68].

The electrocatalyst design depends on the operating environment of the electrolysis cell. Nowadays, there are three basic electrolyzers: alkaline, proton exchange membrane (PEM), and high-temperature solid oxide. The last one requires high energy consumption because of the raised temperature procedure [69]. For the PEM-based electrolysis cell, the water splitting takes place under acidic conditions

performing some advantages such as lower gas permeability and enhanced proton conductivity. It presents high energy efficiency and a fast rate of hydrogen production. However, the need for acidic media limits the OER electrocatalysts to noble metal and noble metal oxide catalysts, which are state-of-the-art in this field, though, leading to a greater cost for the cell. On the contrary, water splitting into alkaline cells broadens the options for electrocatalysts to include non-noble metals or metal oxides. The activity of HER in alkaline media is usually 2 to 3 orders of magnitude lower than that in the acidic environment. Therefore, the design of optimal electrocatalysts suitable for different media with low cost, high catalytic activity, and good durability for electrolytic water splitting is very challenging [67].

There are two main types of both HER and OER electrocatalysts: noble and non-noble metal-based electrocatalysts. Regarding the first ones, Ru and Ir-based catalysts are considered the most suitable electrocatalysts for OER, especially in the acidic electrolyte, which has a larger dissolution resistance compared to other metals. A notable example regarding the oxygen production reaction is cobalt oxide (Co_3O_4) based on silver-doped borophene. It requires an overpotential of 270 mV in order to achieve a current density of 10 mA cm^{-2} [70]. Some of these noble catalysts have also been thriving as bi-functional electrocatalysts. Scientists found that metallic glass ribbon composed of the elements IrNiTa and having a mesoporous structure show promising performance for OER and HER [71].

As regards the hydrogen production reaction it is a common secret that noble metals such as platinum, rhodium, iridium, and others are the most effective electrocatalysts. Due to their high cost and rarity, their application on a big scale, nowadays cannot be carried out. For these reasons, several strategies are being developed in order to construct catalysts, which will consist not only of precious metals but also of earth-abundant elements (such as nickel, iron, and Co) solving the rarity problem and lowering their price [72].

For example, alloying platinum with other small-cost transition metals could improve the utilization of platinum, and the synergistic effect of alloy could modify the electronic environments to boost mobility. Also, coupling Pt with other water dissociation promoters is an important method to enhance the alkaline HER activities which are very meaningful for industry practical use. Moreover, in recent research, it was found that the addition of boron to an alloy consisting of iron and rhodium produces a very high catalytic efficiency for the hydrogen generation reaction [73]. It was also discovered that the nickel-rhodium alloy with the addition of sulfur atoms improves the efficiency and has a similar effect to platinum in terms of the hydrogen production reaction [74].

For the non-noble-metal catalysts, the Earth-abundant oxide and (oxy)hydroxide electrocatalysts have concentrated a lot of interest as regards the OER, especially the Ni–Fe-based ones. In this category, some impressive results are achieved by the catalyst based on graphite and consisting of cobalt molybdenum nanosheets doped with fluorine. It achieves in an alkaline environment an overpotential of 256 mV for the oxygen production reaction at 10 mA cm^{-2} [75]. However, in this category of materials, some catalysts show very good performance results in both oxygen and hydrogen evolution reactions. Some notable examples are porous microflowers placed over nickel foam and composed of dinickel phosphide to which manganese has been added show very high stability and good performance especially in an electrolyte operating in an alkaline environment [76]. Also, other research showed that cobalt and nickel oxyhydroxide showed similar results in an alkaline environment [77].

Moreover, small overpotentials of the order of 280 for oxygen production and 160 for hydrogen production are displayed by Mo_2NiB_2 in order to achieve a current density of 10 mA cm^{-2} in alkaline media. In particular, if the above compound is deposited on nickel foams and used as cathode and anode electrodes, the voltage required for the aforementioned current density is equal to 1.57 V. The corresponding voltage value for the $\text{Pt/C}||\text{IrO}_2/\text{C}$ pair is 1.56 V which means that the compound can be replaced with platinum reducing the cost, achieving similar results [78]. Finally, it was found that the catalyst consisting of the compound of cobalt and phosphorus grown on carbon paper and to which copper has been added by the doping technique shows excellent performance in terms of hydrogen and oxygen production reactions in basic solutions. In fact, the catalyst has a small cell voltage corresponding to 1.72 V at 10 mA cm^{-2} , much better than the common $\text{Pt/C}||\text{IrO}_2$ pair (1.81 V) and most state-of-the-art bifunctional electrocatalysts [79].

Regarding non-noble metal options, transition metal carbides (TMCs) and transition metal phosphides (TMPs) have undergone extensive research in their implementation. In addition to their high electrical conductivity, TMC's properties of hydrogen adsorption and d-band electronic density state (similar to that of Pt) exhibits an optimal combination that is considered to be the main factor for the observed intense HER activity. TMP's exploration is one of the rapidly growing areas because of their high catalytic activity and stability in both acid and basic (pH universal). It has been proposed that the phosphatidic atom plays a significant role in TMP due to its excellent conductivity and unique electronic structure [42,80]. Also, a promising catalyst to replace platinum in the hydrogen production reaction in alkaline media is the monolithic electrode composed of

copper foam and titanium dioxide nanoparticles. According to experimental results, this electrode showed high electrocatalytic activity (potential 114 mV at 10 mA cm^{-2}) and great stability [81].

Another non-noble metal solution is the nitrogen-doped carbon catalyst. In recent research was found that increasing nitrogen quantity has improved the electrocatalytic activity, and as a result, the doped atoms of nitrogen must be the active sites. Also, it was found that the electrocatalytic activity depends on the solution pH. As for acid media, the increase in proton concentration leads to higher electrocatalytic activity. However, in alkaline media, the improvement of the catalyst activity increases with pH, because the pH increases the surface charge density and as a result smoothing the way for charge transfer which leads to improving activity [82]. Also, the bimetallic Ni-Co phosphides catalysts show high durability and a low overpotential of 85 mV. This catalyst could be applied for the hydrogen production reaction in alkaline media compared with other non-noble metal electrocatalysts [72]. Last but not least, scientists found that the phosphorus-doped carbon nanotube structure embedded in nickel foam has high stability and efficiency in the hydrogen synthesis reaction in acidic electrolytes [83].

After the electrolysis, the gaseous H_2 will be directed to the hydrogen tank for storage. There the hydrogen is stored in a liquid state at atmospheric pressure and temperature of -253°C . This tank is not designed to endure internal pressure, but rather to hold a cryogenic liquid. The vessel must be insulated to minimize the gain of energy due to heat transfer, which increases the pressure of the tank. Because the tank cannot hold high values of pressure, hydrogen is allowed to leave through a relief valve. But thermal insulation is never perfect, and if hydrogen remains stable in the tank it will eventually deplete itself. Lower and higher costs are related to larger and smaller reservoirs. Storage tank prices are not listed in this document, but it is important to mention the high cost of hydrogen liquefaction, both in terms of energy and equipment [84].

CHAPTER 4

PASSIVE SOLAR SYSTEMS

Introduction

The term passive solar systems describes structures on the south side of buildings that do not have mechanical moving parts such as fans. This orientation is chosen so that solar radiation is used to a greater extent. These constructions follow the laws of heat transfer, thermal stratification, natural airflow, and the mechanisms of radiation, conduction, and convection. Such systems are very important in cold climates where there is a great need for heating [85].

4.1 Historical Perspective

Although these systems are not widespread, they do not constitute an innovative technology as their roots come from ancient Greece. At that time, the need mainly for heating but also cooling led the Greeks to their discovery. Pioneers were Socrates in 470 BC with the information he gave about the appropriate solar house which is preserved in the memoirs of Xenophon, and Hippocrates with his work 'On Airs, Waters and Places'. Their purpose was for the buildings to have a harmonious relationship between man and the environment [86].

At that time buildings used stone for foundations and wall bases. On top of the stone, they put plinths with dry ties to raise the walls while as for the roof they either had a terrace or a roof where they put tiles. The northern wall was thicker and had few openings, while the entrance was placed mainly on the eastern side. In addition, on the north side of the buildings they placed evergreen trees such as olives as they were used as a natural protection against the direct exposure of the house to the north wind, while on the south side, they placed deciduous trees that in the winter allowed the sun to warm the house while in the summer their leaves provided shade [86].

However, in addition to this shading technique, they placed on the south side of the buildings above the windows and doors an extension of the roof which had a specific size so that in the summer it prevented the sun from entering the building while in the winter when the sun has a lower orbit it allowed him to enter and heat the interior of the building. Another of their practices was the use of arbors of a certain size (height and width). Even in sunny areas, they used white

color in buildings to reduce the heat from the sun. The reflectivity also depends on the color but also depends on the material itself, i.e. the ability of the material to reflect visible and infrared spectrum. The infrared spectrum is a carrier of large amounts of energy [86].

The buildings of antiquity later consisted of a central inner courtyard around which the building stood. The courtyard was exploited as a source of ventilation and lighting. Finally, as described by Xenophon and Aristotle, the orientation was south so that they would use the maximum light in winter and avoid the sun in summer when it is very high [86].

4.2 Passive solar systems operation

In order to heat the spaces of the buildings, these systems utilize the light and energy that comes from the sun either directly through openings or later through its storage in the materials of the construction which for this reason must have a high value of heat capacity. These materials will gradually begin to transfer the energy they have acquired into the interior of the house. However, in order to have thermal comfort, in addition to the temperature, the humidity levels inside the buildings must also be regulated. This requires natural ventilation of buildings and regulation of humidity. This is done by correctly positioning the openings and ventilation slots. These slots can be utilized in the summer months offering coolness. Even as the ancient Greeks did, through the use of vegetation, the building is protected from the wind and the sun [87]. However, in order to achieve thermal comfort conditions, proper insulation of the buildings is necessary. From the above, it follows that the shell must allow maximum solar collection, maximum heat capacity, and minimum losses [88]. The categorization of those systems distinguishes these solutions as direct, indirect, and isolated gain systems.

4.2.1. Direct gain systems

This type consists of the most common and simple way to use solar passive systems technology. The solar energy flows through the building's openings and is stored inside the building's space. These systems have two basic parts for their operation. The first is the sun collection which is achieved by panes of glass such as windows and the second is the sun storage such as walls and roofs. Direct gain systems can apply to a building's envelope with wide south-facing windows. An important role for the good operation of the system is the choice of types of glazing and structural elements (walls, floor, ceiling). The surface of these elements must be 9 times greater than the surface of the openings and must consist of high heat capacity materials [88].

In these systems, the glass panes absorb the maximum possible solar energy. Despite the notable quantity of this energy, there is not always enough to store inside the elements of the building, especially in the winter period. Generally, these systems have a rapid response to solar radiation due to their low storage capacity. The selection of glazing and good insulation of the openings to avoid thermal bridges is of great importance. The use of double glazing is recommended. The main advantages include the ease of integration and construction plus low cost. On the contrary, high temperature of indoor air swings, possible glare discomfort, or degradation from UV radiation, represent the main disadvantages. **Figure 4.1** shows the operation of direct passive solar systems [87].

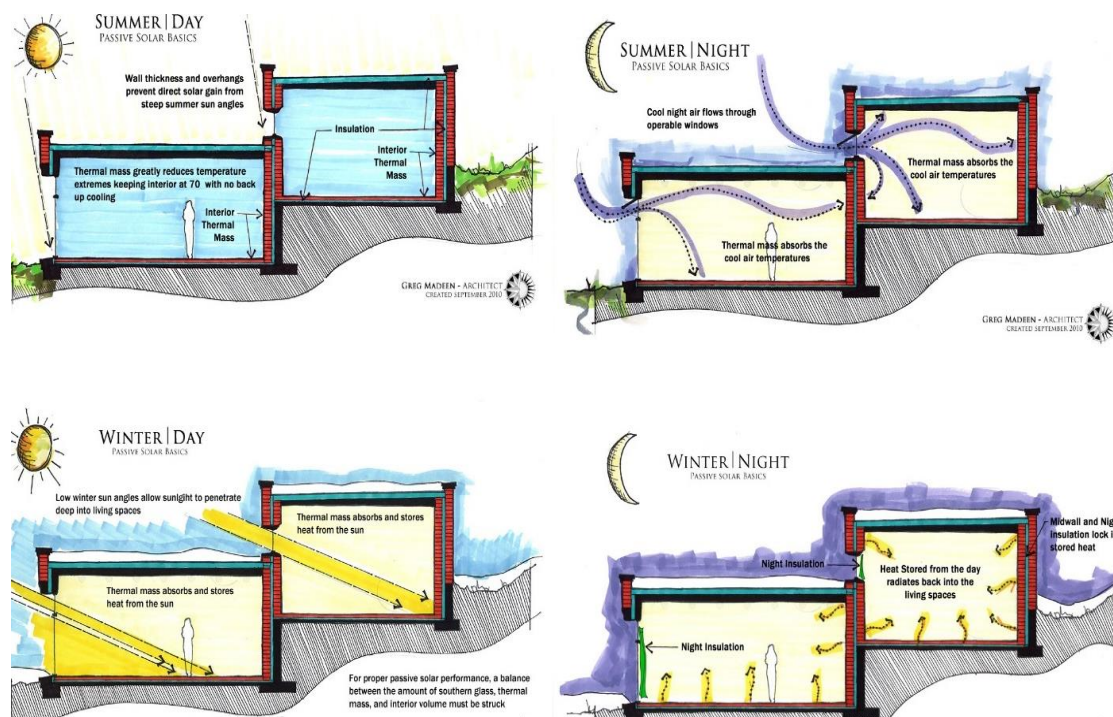


Figure 4.1: Operation of direct passive solar systems in winter and summer period [89].

4.2.2 Indirect gain systems

These systems include the surface of the glazing and the trombe wall. As mentioned before the optimum orientation of the system is the south but deviations of the order of 10 percent do not cause large losses. Regarding the trombe wall, its thermal capacity has a high value and is usually painted with black color to absorb the maximum quantity of solar radiation. In front of the wall, there is glazing, and it has been calculated that the optimum performance occurs for a length of

10cm. However, for easy access to clean the glass, the distance is shifted to 30-50 cm. Unfortunately, as the distance increases, so do the losses [87].

In addition, along the wall in its upper and lower parts, some openings facilitate the movement of air based on natural convection due to the difference in density of warm and colder air. During the day, the warm air passes into the interior of the building through the openings located in the upper part of the wall, while the colder air from the heated space is transported through the lower openings where the warmest was. For good operation, in summer it is necessary to shade the wall and open the skylight in the upper part of the glazing to let the warm air escape, while the openings in the lower part of the trombe wall remain open to achieve ventilation and cooling of the space [88]. **Figure 4.2** shows the trombe wall design.

Another application of this system is the use of water as a heat storage medium due to its ability to save large amounts of energy without taking up much space. This application is called a water wall. One more advantage of this method which is linked with the above ability is that the temperatures are on a lower scale which means lower losses. Also, due to the fact that the temperature of the water is more stable due to its large thermal capacity, and the temperature fluctuations in the interior of the space are smaller concerning the trombe wall [87].

4.2.3 Sunspace system

The greenhouse is a closed space located in the southern part of the building that is surrounded by glazing in order to concentrate the solar radiation and pre-heat the air in the limited area. This system is a mixture of the previous two. In contrast to the first one mentioned earlier, solar radiation "enters" the greenhouse area and not in the interior of the building, while the heat is transferred to the rest of the space behind the wall, used to contain the air, through natural convection as an indirect process. Compared to the two previous systems, the amount of solar energy stored is greater as the used glazing covers a larger surface. However, because of this fact, the losses during the night are also greater. This problem could be solved if the space is autonomous and isolated from the rest of the building, otherwise thermal insulation at night should be a critical concern [87].

However, for the proper operation of the system, especially concerning applications in Mediterranean climates during the summer period, the roof of the greenhouse should be opened to ventilate the space and cool the greenhouse in order to prevent further heating of the building. In general, the frames should be of good quality and have the correct assembly and air tightness during

the winter to avoid heat loss through leakage. In addition, it is appropriate to mention that the most common glazing is the double ones, as they present higher temperatures in the evening hours, preventing the condensation of water vapors. Dark-colored surfaces are also highly recommended as they absorb more radiation [87].

Finally, studies have shown that the efficiency becomes better if between the building and the greenhouse exists a wall that consists of materials with high heat capacity even better efficiencies could be achieved if this wall combined with openings at the upper and lower part of the wall for the air movement [88]. **Figure 4.2** shows the sunspace design.

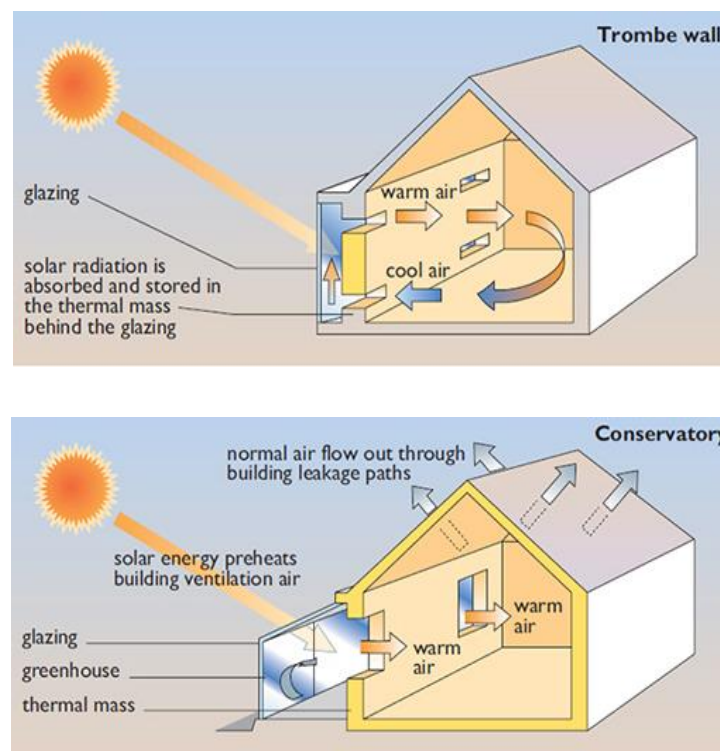


Figure 4.2: Passive solar heating systems – Trombe wall (upper) and Sunspace (bottom) [90].

The asset of indirect and sunspace systems compared to the direct ones is that they avoid ultraviolet degradation and glare. They, also, provide less indoor temperature fluctuations because their use mostly maintains the interior thermal balance assisting in heating and cooling the building naturally. Nevertheless, because there is no proper access to the wall cavity the indirect systems face problems in maintenance and disturb the lifespan of the system. They are less effective compared to the direct gain systems due to the high temperatures that exist in the gap between the glazing and the wall and more expensive to implement too [91]. Research has shown that equalizing the effective result, requires a 50-90% bigger surface of radiation collector from the indirect systems [87].

4.3 Shading and insulation

From a practical perspective, shading and insulation methods applied to existing buildings have low cost and are effective. In cold climates, the utilization of low-emissivity glasses is an effective energy-saving measure (see **Figure 4.3**). In such climates, the change of a double-layer to a low-emissivity glass leads the heat gain on an annual basis from 15% to 50%. The glass resistance defines the heat loss so methods, such as automatic louvers, roller-shade devices, and hinged insulation panels are profitable. Shading is the simplest method for passive solar systems to cooling, because not only it can easily integrate into existing buildings but also with a small cost it can add in new ones. Effective shading systems can mitigate the outward heat flow during winter and avoid overheating in warmer periods like summer guaranteeing excellent lighting levels. At low latitudes, recent research has shown that the use of blinds on the west and east windows cut down the heat gain by around 20% more than the south windows' orientation. From 20° latitude, the influence of the blind on the south facade increases and leads to similar results as those on the west and east. The louver tilt angle influences the energy performance in such a way that from 90° to 30° the cut down of heat gain went to 40-50% from 15-20% [91].

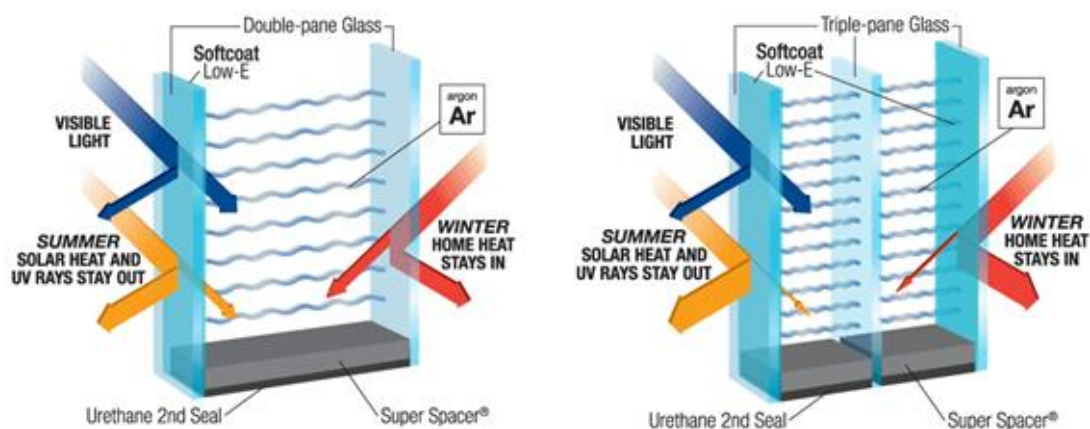


Figure 4.3: Representation of the effectiveness of double and triple insulating glasses [92].

The total performance of a passive solar solution is a sum of heat gains and losses. The related parameters can be categorized into two groups. The first namely extrinsic factors which include the altitude and latitude which define the solar radiation and the building's position. The second category is the intrinsic factors, such as collector inclination and orientation which determine the maximum collectible radiation. The building energy demand and the choice of the most suitable design solution determine the integration of the passive solar methods. They must be appropriate for

both the operation according to living patterns, providing heating and cooling, and the structure, among heavyweight and lightweight constructions which can take advantage of their volume as an intertwined thermal storehouse [91].

International and national legislations have determined specific design parameters as regards the installation and operation of active solar systems in buildings. From the above, it is understood that passive strategies miss the benefits of active devices from an economic perspective. Despite cost-benefit analyses of active systems, proper evaluation of passive methods must take into account various contributions, building services involved, operation, installation, and maintenance expenses, as well as energy savings in terms of quality and quantity. The absence of evaluation methods and design guidelines regarding energy performance represents their small application [91].

CHAPTER 5

SPACE AND WATER HEATING

Introduction

Even though passive solar solutions can be a part of the general heating and cooling design in a building, they mostly aim at maintaining the ambient temperature of the rooms by regulating the amount of solar energy that they absorb. The main heating/cooling system will provide the required heat for space warming or drain energy during cooling mode. Underfloor heating and heat pumps can be combined with traditional heating/cooling systems, if it is necessary, in a more sustainable and environmentally friendly way to replace the conventional use of fossil fuels. Water heating can also be achieved partially by regaining some wasted energy or using solar intervention.

5.1 Underfloor heating

The technique of utilizing the floor as a surface for heat emission is more than two thousand years old. The Chinese, Egyptians, and Romans all constructed heating systems that were modeled by this concept. The Chinese and the Egyptians construct simple systems. In practice, it was single-room heating, which involved creating an underground hearth and piping smoke beneath the flooring in order to heat the rooms. The Romans implemented a more complicated system. They utilized the smoke which issued from one external hearth, they were in a position to heat many rooms and also several buildings. They achieved the first type of central heating but at the start of this century, the central heating arrived in its current form [93].

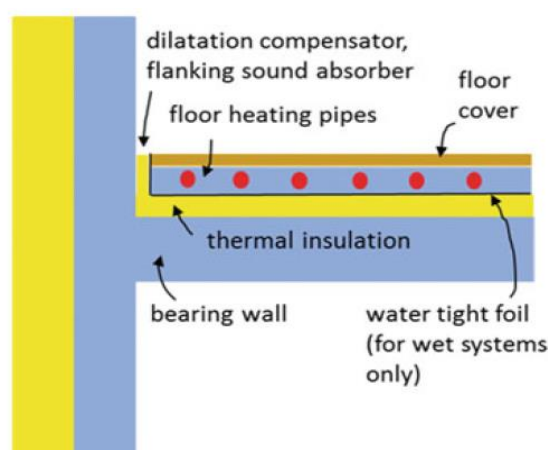


Figure 5.1: Structure's cross section showing the underfloor heating design [93].

Such radiant heat emitters consist of grids (called loops or registers) of pipes with a diameter of 12-18 mm that are deposited on a layer of thermal insulation to decrease heat losses and mitigate the transmission of impact sound. The top front is concealed from a floor cover, usually ceramic, vinyl, or wooden tiles (see **Figure 5.1**) [94]. There are three main types of pipe loops which are described as follows. Single serpentine configuration (see **Figure 5.2 left**) where the differences of temperature at the surface of the floor are limited to small values in a small territory. Also, for that method, the pipes must be flexible. The single serpentine configuration is ideal for residence applications. Helical supply and return configuration (see **Figure 5.2 middle**) are ideal for spaces that need high heating loads. Last but not least, the configuration of parallel supply and return pipes ensures a uniform mean temperature of the surface but a higher difference within a small territory of the floor temperature. This method compared with the methods above, consists of the perfect choice for large areas, like mosques and theaters (see **Figure 5.2 right**) [93].

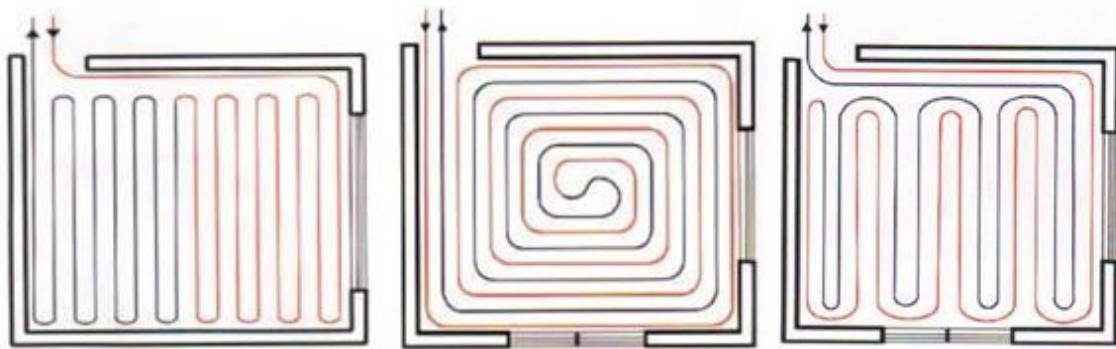


Figure 5.2: Single serpentine pipe arrangement (left), spiral or helical pipes arrangement (middle), and parallel supply and return pipes configuration (right) [93].

One of the most important advantages that underfloor heating can provide is that the gradient of the indoor air temperature over the room's height is close enough to the ideal thermal comfort conditions (warm legs, cold head). This happens due to the mechanism of heat transportation which is mainly by radiation towards all walls in the space. However, in order to prevent inappropriate comfort conditions such as the appearance of molds on the walls bordering the heated floors and humans walking barefoot, the floor must be constructed with materials that have high thermal inertia such as stone lining and tiles. Moreover, an asset of underfloor heating is that the big area of the heated surface gives the ability to reduce the temperature of the energy transfer fluid even to smaller values of 28 °C, which leads to smaller losses of heat to both the distribution system and heat generator. However, systems that use liquid energy as a means of transport have high thermal inertia. This means that they are not able to respond quickly to sudden changes in heat demand. In addition, these are expensive systems, and the fluid (water) may freeze

in the mains during long periods of non-heating. On the other perspective, the use of heat pumps which can take advantage of the energy generated by renewable sources is more efficient due to the fact that a lower energy supply of heat is necessary to provide the required indoor comfort conditions [94].

5.2 Heat pumps

Heat pumps consist of units of central thermal with multiple applications and interconnection installations with the whole thermal system of a building. During space heating, it absorbs heat from the environment either from the air or the ground. The most common type is the air source heat pump, as a cheaper solution and thus easily installed. The ambient air is pumped through a fan on the outside temperature and exchanges its thermal load with the refrigerant which is heated to the proper level before transferring its heat to the internal hydronic system of the building. Geothermal heat pumps work similarly by replacing the thermal source with preheated underground water. Despite its expensive and more complex and occasional implementation, the underground temperature is relatively constant at 17-18 °C the whole year, regardless of the weather conditions that affect the atmospheric air. Heat pumps can provide the amount of energy demand for radiant heaters across the building or combine with an underfloor heating system. However, the efficiency of the air source heat pump drops significantly when there is a big difference between the outside and the necessary indoor temperature. Radiant heater systems use high thermal load water (65-75°C), escalating during the coldest days of the winter, sharpening the temperature gap. Underfloor radiant heating systems, though, run at temperatures ranging from 35-50 °C, which is more cost-saving, and a geothermal heat pump poses as a suitable solution [95].

In warmer climates, heat pumps use fan coils in order to give heat in the cold period (winter) and cooling in the hot period (summer). Air space heating systems have many advantages such as they can easily upgrade to central ventilation and air-cooling systems and react quickly to rapid changes in cooling or heating demand. However, the combination of the recirculation of dust in the room (due to the velocity of the air) with the dry air generated by the emitters, decreases comfort, especially for people with problems like allergies [93].

5.3 Domestic heating water techniques

Water heating is of major importance to sustainability in a building for two reasons. The first one is related to the heating of the spaces mentioned earlier and the second one is heating water for reasons of hygiene such as the cleanliness of the body and washing. In this section, only the water heating methods that can be applied in a zero-energy consumption building will be mentioned. In order

to be correct, when planning the design of a building must be taken into account the loads of energy spent on domestic hot water. In fact, the amount of energy consumed for this purpose can be greater than that consumed for heating a building. This may seem strange but if the building is small and also uses passive solar systems then the load for space heating will be greatly reduced and that will lead to an increasing the percentage of the total energy that will be spent on domestic thermal water. Generally, the daily need for heated water for domestic use requires using it rationally. An important goal includes reducing the total amount of hot water. This can happen by applying methods, like low-flow showerheads and faucets as well as more efficient devices such as washing machines and dishwashers. Improvement in efficiency leads firstly to cost saving, because less energy demand requires a smaller load system design, and secondly lower energy sources harvesting from the environment [94].

Regarding the environment, higher water consumption minimizes the amount of drinkable water pumped from natural sources or by water cleaning systems. Also, less consumption causes a decrease in the amount of drain wastewater that must be processed in cleaning facilities. Managing the amount of used water is very important considering that of the 70% of the earth's surface covered by the water element, only 2.5% is non-saline and of that, only 0.3 is drinkable [96].

5.3.1 Wood water heater

A wood-fired water heater is a heating device that uses biomass such as wood and pellets as an energy source. There are two basic kinds of these heaters namely direct and indirect. The first has a water tank which is heated directly by the fire produced through burning biomass. The second type utilizes heat exchangers to transfer heat from the wood stove to the water in a storage tank. As concerns the exchangers, they can be placed around the stovepipe or in it, inside the stove. With the start of combustion, the water begins to move naturally following the thermosyphon principle or using a circulation pump. Nowadays these heaters are less used [97]. This technique has some important advantages. First of all, the operating cost is lower than the operation cost of electric water heaters or even heaters used as sources of conventional gas or oil. This happened because the material of biomass (wood specifically) is cheaper than the fuel from the other mechanism mentioned above. Also, wood is a clean source of energy whose availability can be determined by planting more trees. It is also a renewable energy source with zero impact on the environment since the carbon dioxide released during the burning of wood is captured by the new plants to produce glucose and oxygen. However, despite the advantages this technique has also disadvantages. From them the most common is the

difficulty in stabilizing the water temperature, also the combustion produces dangerous fumes locally and the energy content is smaller than that of traditional fuels.

5.3.2 Storage-type electric water heater

It's about a device that converts electrical energy into heat by using an electrical resistor. This type of water heating has several advantages. First and foremost, there are no emissions during the entire operation. Also, it has not only lower standby-losses than fuel-fired units because it is much better insulated but also safer due to the fact that avoids the problems associated with the combustion process. Moreover, presents low maintenance costs and usually has a longer life than fuel-fired units. However, must be caution with that system because, there is a possibility of a short circuit with the cables and cords involved, and that can be very dangerous for humans. Last but not least its lifespan is not quite long. The most common way they get damaged after a few years of use is to get punctured internally, so they can't be repaired. To delay this damage from appearing they need frequent maintenance [97].

5.3.3 Heat-pump water heater

This type uses electricity in order to operate a compressor to gain heat from a low-temperature source and channel it to a higher-temperature source. This source is the water stored in a tank. For whatever energy amount, these heaters are capable of heating two or even three times as much water as electric resistance heaters. There are a variety of heat pumps, such as air-to-air, air-to-water, water-to-water, and geothermal heat pumps. As geothermal heat pumps mentioned earlier, in the case of air heat pumps, they gain heat from the ambient air. They also can used for cooling the space. Indoor air is utilized to warm the water and during that process the energy leaves from the air and its temperature drops. These heaters can give hot water at 40 to 100 percent of the rate of electric resistance units and 30 to 50 percent of the rate of gas units, but they need warm ambient temperatures and a big heat pump or storage tank in order to provide a constant flow of hot water. These devices have backup heating constituents to warm water during cold periods. Also, they don't heat water as fast as other types of heaters. However, despite the fact that they are more expensive to install, they have a shorter payback period due to the big amounts of energy savings [98].

5.3.4 Solar water-heating systems

Every solar water heater consists of two main parts. The collector where it collects the solar radiation and the boiler where the hot water is stored. The solar collector consists of the plate where the solar energy is collected (which has a dark color to maximize the absorption coefficient of the radiation),

the crystal that surrounds the plate, and the pipes where the fluid moves. As the sun's rays fall on the crystal and penetrate it, they are trapped inside it and as a result, increase the temperature and are led to the plate which is heated. Then the plate heats the fluid contained. Its function varies according to its type. If the boiler is located above the plate, then the hot water in the pipes is transported by natural convection to the boiler and its place is taken by the cold water of the boiler which goes to the plate due to gravity to be heated. On the contrary, if the plate is higher than the boiler, it needs the help of a pump (urgent circulation). This technique for heating water provides low operating and maintenance costs and zero emissions. Nevertheless, this device has a high initial cost and should be avoided in the case of relatively hard water or climates that comfort freezing temperatures in case the plate has water as fluid [99].

5.4 Optimizing the heating water process

To limit standby losses observed on storage-type systems there is a need of insulating jackets. Better results are presented when the site of the hot water tank is picked outside of conditioned spaces such as attics. In this way, the large temperature difference between the used water and the surrounding space is avoided, reducing thermal losses. In addition, the use of heat traps on storage-type systems prevents the cold water from unity with the hot [100]. Last but not least, water waste heat can be utilized for preheating the cold-water line. A flow-through counter-flow heat exchanger must be added between the drainage and supply of the cold-water distribution pipeline (see **Figure 5.3 left**). For shower drain heat exchangers the heat recovery can reach an effectiveness of 30% and even 60% in the case of waste heat stored in water tanks that are inside a heat exchanger (see **Figure 5.3 right**) [89]. In conclusion, implementing the above strategies not only achieved significant reductions in energy consumption and standby losses which led to increasing the efficiency of the systems but also contributed to sustainable and environmentally conscious water heating practices.

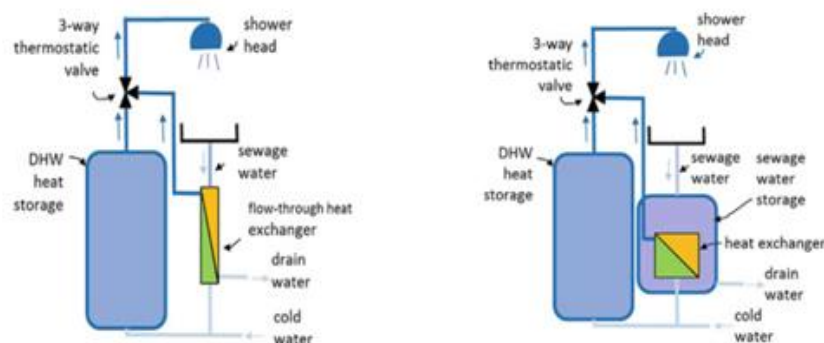


Figure 5.3: System for recovering waste heat from domestic hot water that uses a flow-through heat exchanger (left). Sewage water storage with a built-in heat exchanger (right) [89].

CHAPTER 6

SMART GRID

Introduction

Nowadays, the supply and the infrastructure of electrical energy have been under a lot of pressure. The need for electrical energy has increased. The maximum demand for electricity needs to be produced and sent and determine the nominal standards in the chain. This fluctuating demand leads to an increase in the minimal grid, and the efficiency of production has reached lower levels. Also, the reduction of emissions such as CO₂ emissions and production with the use of renewable sources are important topics nowadays. Although the production patterns from renewable sources have common elements with the electricity demand profiles, they are kilometers away from being the same. Therefore, supplemental generation is needed to maintain the demand and supply in equilibrium, which leads to an increasing to fluctuating production profile for the conventional power system [101].

A solution to mitigate these problems is to turn the customers into active participants in the electricity generation process. Consumers' involvement can be done through the new technological appliances that offer abilities such as manageable loads, and energy storage in the form of both electricity and heat and microgeneration. These domestic devices can choose when to use the electricity without harming the comfort of the residents. Some notable devices with optimization potential are smart fridges and freezers. These devices can shift their cooling cycles to modify their electricity load. However, the grade of the improvement in energy efficiency provided by these technologies is not clear yet and needs further investigation [101].

The optimization goal can differ. The goal for utilities or residents can be earning/saving money and for that reason, the target is to produce electrical energy when prices have high value and consume electricity when the value is low. For network operators, the task may be to keep the balance of the grid and reduce the required capacity. Also, from an environmental perspective, the goal is to improve the efficiency of power plants. From the above, it's clear that an optimization methodology should work towards many objectives depending on the different scopes: locally (inside the house), in a group of houses/neighborhood (microgrid), or on a regional/state level (virtual power plant) [101].

- 1) Local Scope: On a local scale, the optimization is done in individual houses. For instance, an example of optimization would be to shift power draw from times of max demand on the grid to times of low demand such as at night. With this move, the peak demands on the network would be decongested. One of the advantages of optimization from this point of view is that there is no external entity that determines which devices are activated and when.
- 2) Microgrid: In a microgrid, the optimization is done in groups of houses. In this type of network, the optimization would concern the adjustment of energy extraction and loads so that the production curve covers the consumption curve and also the reduction of the peak demand as in the previous category. In this way, the peak demands on the network would be decongested. One of the advantages of optimization from this point of view is that there is no external entity that determines which devices are activated and when. The goal is for the microgrid's production curve to cover demand. The advantage of this category is that their common optimization potential is higher than that of individual houses because the load profile is less dynamic (e.g., startup peaks of appliances disappear in the combined load). Also, a group of microgenerators combined can cover more demand than individual microgenerators because better distribution in time of the production can be achieved.
- 3) Virtual Power Plant (VPP): The idea of this concept is to run a set of microgenerators that will have a total capacity equivalent to a conventional power plant. These microgenerators have a higher efficiency. Also, they can counter any fluctuation in the energy part because it is much more flexible than a common power plant. The idea of this concept could apply to all domestic technologies. However, for that purpose communication with each house is mandatory and privacy issues may occur.

The Smart Grid is an evolved electric system that includes computational intelligence, information processing, and communication technologies. These characteristics are combined to achieve a system that is efficient, secure, reliable, resilient, and sustainable. The structure of the smart grid usually concludes subsections such as distribution, generation, transmission, and last but not least control network. Each network exchanges information and communicates through wireless or even an access point wired, with the smart communication subsystem. The information about the network performance or some problems that may occur is acquired by clever information subsystems like a smart meter, sensor, and phasor measurement unit. In the control network, they observe and manage in real-time the network. A typical illustration of a smart grid system is depicted in **Figure 6.1**.

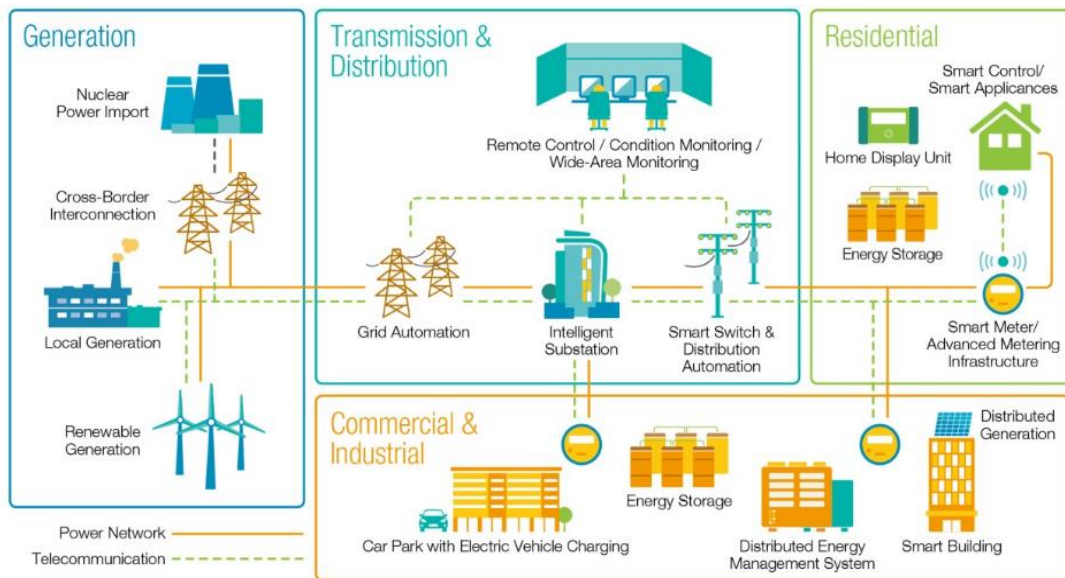


Figure 6.1: Overview of Smart Grid Technology [102].

Regarded as the next-generation power grid, the smart grid has transformed the interconnected network between electricity consumers and electricity suppliers and the operation of power systems infrastructure has evolved into a dynamic design instead of a static one [103].

6.1 Power generation

The fundamental difference between the smart and the conventional network is that at first the direction of the electrical energy is two-way despite the other where the direction ends up to the consumers without the ability to flow from the users back to the grid. The two ways give the ability to the users, to transmit electricity which they produce to the grid. This backward flow is also essential when a microgrid is ‘islanded’ due to power problems. Still, with the addition of the consumers' energy, it can maintain its current operation at a reduced level. Even though the participation of distributed generation in today’s power system is limited, it is expected to include many renewable generators to achieve an extended decentralized power system [103].

6.2 Transmission grid

The transmission section is responsible for channeling the electrical power and sending it from the production center to the distribution system through some substations. That section is typically operated by regional transmission organizations or independent system operators whose basic responsibility is to maintain equilibrium on the grid by matching supply with demand.

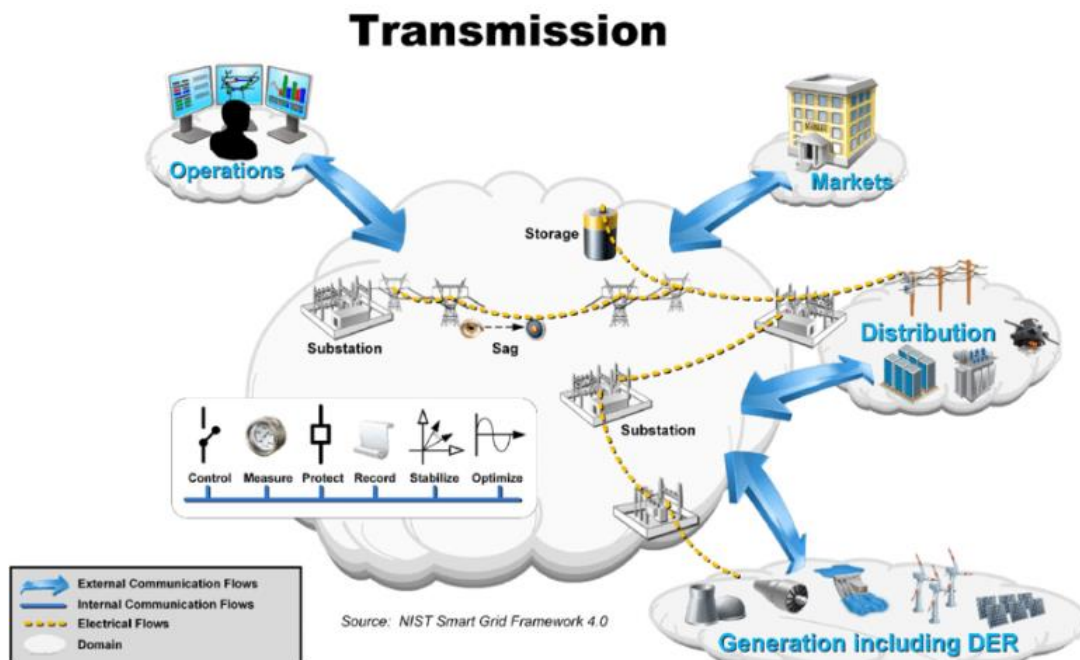


Figure 6.2: Configuration of the transmission grid [104].

The smart transmission section consists of three interactive smart components: control centers, substations, and power-transmission networks. It includes fault-recorders, protection relays, power quality monitors, and substation meters. The fundamental activity is in a substation and although the essential configurations of high-voltage substations have not altered much over the years, the monitoring, measurement, and control equipment have undergone a huge change in current years. A high-technology substation is divided into four basic features: auto-healing, digitization, atomization, and coordination. For these reasons, it can respond fast and provide better operator safety (**Figure 6.2**) [105].

6.3 Distribution grid

The distribution grid consists of constituents that provide electrical links between the transmission section, the users, and the distributed generation and storage. In the past years, distribution systems used the technology of telemetry to a small grade and almost all communications into the system were executed by humans. A user with the help of a telephone plays the role of the sensor in his domain, whose call alerts technicians of failures to fix them. For the above grid, the most serious problem is finding the best way to give power to serve users better. The addition of distributed generators consists of a step to solve that problem since these generators improve the flexibility of the system. The distribution network communicates in real-time with the operations domain to face the fluctuations in power flows [105]. As regard the distribution domain, is based on alternating current power distribution, but the operations domain based on a direct

current power dispatching system. A lot of electrical devices in the house run on direct current and can power switching circuits in order to convert the alternative current input voltage [103].

6.4 Control network

The expansion of the smart grid depends on two key factors. The first is the evolution of power equipment technology and the second is the evolution of computer control, monitoring, analysis, and optimization. The smart grid framework is shown in **Figure 6.3**. A smart information subsystem is utilized to keep information gathering, assessment, modeling, and optimization [103].

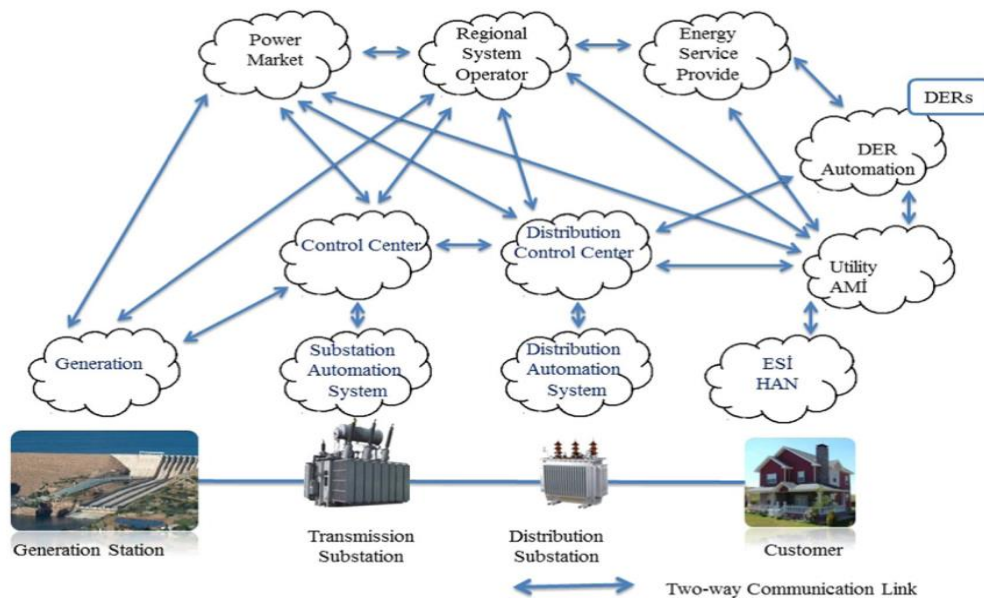


Figure 6.3: Smart grid framework (HAN: Home Area Network) [106].

a) **Smart Metering:** Smart metering plays a major role in the Smart Grid as regards obtaining information from the user's devices and controlling their performance. Automatic metering infrastructure systems are known as a good strategy for the operation of Smart Grid. These systems rely on automatic meter reading systems. The last systems have the technology of routinely gathering data from metering devices and sending them to a central database for processing. The two systems have an important difference. The metering infrastructure systems permit two-way communications with the meter. A smart meter is responsible for recording the use of energy and transferring that data daily to the utility for billing and monitoring. Also, can impact the user's devices by disconnect-reconnecting them to prevail in equilibrium between loads and demands. From the perspective of consumer smart metering offers a potential profit because they can estimate bills and regulate their consumption to reduce them. On the

contrary, the utility can utilize smart meters to know real-time pricing, whose goal is to encourage users to limit their consumption in max load periods, or to optimize power flows [103].

b) Smart Monitoring: Sensor networks should be added to the smart network so that the operators of the system would be in a position to recognize possible future malfunctions of the system to prevent them, but also if damage is caused to immediately proceed to its detection and by extension to its repair. Such potential failures are pipeline failures, and tower collapses. Wireless sensor networks consist of a good communication and sensing stage for remote system diagnosis given their low cost [103].

c) Smart Measurement: A phasor measurement unit is an appliance that detects the waves of the electrical energy on the grid. These units have branch current phasors and bus voltage phasors. Time synchronization gives the ability to the grid for simultaneous instantaneous measurements of various remote areas. The metered value is common knowledge as a synchrophasor. Phasor measurement units are suitable both for controlling and monitoring voltage stability providing situational awareness and even preventing blackouts it is possible to gather the data either in central locations or in local ones. In any case, the data is sent to an area monitoring system managed by an independent operator [105].

d) Information Management: The technology of information is accountable for modeling the data to give a guide of constant, data symbols from production to consuming devices. The management of the data includes some actions such as storing, collecting, analyzing, and giving the data to the users and to the appliances. The issues of validation, updating, and consistency across the bases of data should be taken into consideration. The kind of data is divided into two main categories) model data which includes static parameters and measurement prices and 2) configuration data which consists of security, logging, and also the operational status of components data. All the above are installed in control centers were utilized in order to optimize the operation of the network which includes automation, operation mode planning, dispatching, relay protection, dispatching, and others [107].

CHAPTER 7

ZERO ENERGY BUILDINGS

Introduction

As mentioned earlier in a period of environmental concern due to the emergence of extreme changes in the planet's climate, the reduction of man-made contributions in this phenomenon through the creation of zero-energy buildings (ZEB) is a beacon of hope. Using the latest technologies and design principles, such as passive methods, taking advantage of natural daylighting and ventilation or thermal mass storage, advanced insulation, efficient heating and cooling systems, renewable energy sources, and smart technologies these buildings try to produce as much clean energy as they annually consume. By emphasizing on mitigation of energy losses and employment of renewable energy sources these structures lower maintenance and operating costs, increase resiliency during power outages, and form the basis for another way of life based on a harmonious relationship between humans and the environment [108].

7.1. ZEB definition framework

The United States Energy Department divides the net zero energy buildings into four different groups, which are known as net zero source energy building, net zero site energy building, net zero emission building, and last but not least zero energy cost building. All of them are mentioned below [109]:

- Net zero site energy: The energy balance at the boundaries of the building equals zero. This definition is suitable for quantified measurements, but it is less used when it is important to identify the energy source. It, also, does not include details about the building's operation environmental impact.
- Net zero source energy: In this situation, the energy balance is also zero. The values for both energy production and consumption are calculated at their source. The waste of energy from the source and the distribution are also calculated and the estimations are more precise. Nevertheless, the design model is difficult when a lot of sources and distribution channels are added to the model. This model also cannot identify the kind of energy units and does not provide information about the building's operation environmental impact.

- Net zero emissions: In this case, the balance is about greenhouse gases, for every emissive energy consumed, an emission-free energy is produced. This term includes the most official standards designed regarding the goal of cutting down greenhouse gas emissions. The most important problem of this category is that it could permit emissive energy techniques, however they can be avoided as long as the greenhouse gas balance is equal to zero.
- Net zero cost: In this category, there is no cost for energy. In particular, if the building's energy income covers or exceeds the energy expenses, it belongs to this category. This category is preferred to be presented to investors and owners because it provides details concerning the economic performance of the building. However, it does not include details about the building's operation environmental impact [110].

The particular diploma thesis exceeds the boundaries of these frameworks and aims to present studies in which the energy covering the load demands of the buildings is being produced on-site. Most of the existing applications are connected to the local electricity grid, however, some research studies ensure that the building's operation can stand off-grid too. The high performance of these buildings owes to efficient conservation methods and renewable generation. Moreover, the origin of the energy is limited to green power sources held in abundance in nature, preventing any carbon emissions. Despite this, their unpredictable nature negatively affects their reliability. For that reason, there is a need for a storage facility. Many technologies for energy storage exist, but each of them individually has not proven to be technically and economically viable. So, combining various energy storage systems (ESS) in the form of a hybrid energy storage system (HESS) can fulfill all the demands simultaneously.

Figure 7.1 presents the integrated terms for a ZEB.

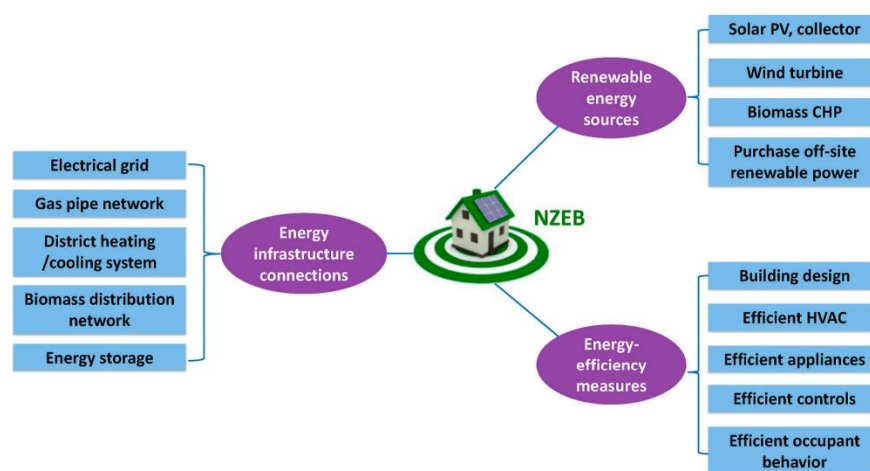


Figure 7.1: Appropriate conditions for a NZEB [111].

7.2. ZEB energy efficient targets and saving measures

To characterize a building as a Net Zero Energy Building (NZEB), the annual total amount of energy required, needs to be approximately equal to the renewable energy generated respectively on-site. Recently, the idea of NZEB has changed from theory to practice and if the power is not adequate, energy is harvested from the local electrical grid [112]. To achieve zero energy balance, mitigation of energy use should be a critical design requirement and a fundamental of NZEB. Even though energy efficiency is considered to be a design priority because of the highest payback of the investment, optimizing energy-saving methods would decrease the cost of integrated renewable energy projects [112]. An ambitious but logical target is to reduce the average energy load of the buildings to passive house levels, “passivehaus”, regulating the heating load demand to 15 kWh/m² and the total primary energy consumption to 60 kWh/m². This attempt would be feasible only if a great number of existing buildings were converted into NZEBs, according to a recent study on relatively cool countries. Current necessities for the building sector will accomplish 10-80% NZEBs, depending on the country, appearing there's room to develop the NZEB advertise and create more viable constructions [111].

Around 30% of the total energy used by a building is due to the heat loss from the exterior wall while the loss of energy in the form of heat due to the windows is approximately 24% of that energy. Also, the loss from the roof is around 8-10% [108]. Implementing energy efficiency measures is of critical importance because they enhance energy conservation, take advantage of nature's elements to boost certain processes, and reduce the total heat loss ratio, thus, lowering the total energy requirements of the building. These techniques focus on building envelope design, and efficient heating, ventilation, and air-conditioning equipment, devices, and energy control. Regarding the thermal loads leaking from the building's envelope, the use of enhanced wall thermal insulation, increased airtightness, insulation thickness, window glazing, and solar shading methods need to be carefully studied. Also, the suitable choice of the used materials depended on their thermal capacitance, optimized orientation/shape, optimized window-to-wall ratios, and passive solar heating/cooling methods drain/reject energy from/to the environment. Thermal masses absorbing heat, open space areas for natural ventilation, specific building orientation towards the daylight, and rainwater harvesting are the most widely concerned techniques [111].

7.3. ZEB energy generation

NZEBs need energy infrastructure to handle short-term mismatches between renewable energy supply and building demand. The electrical grid can be the source of energy during times of inadequate renewable resource supply and can absorb power when the generation exceeds the building's load. Excess electricity doesn't necessarily need to be exported to the electrical grid and instead could be stored in devices or converted to thermal energy for a district heating/cooling network. However, energy storage currently poses a high investment solution, and district energy networks are quite limited and require more money for expansion. Moreover, there are certain energy losses during the conversion process. As a result, the electrical grid appears to be the most cost-effective and widely used energy infrastructure for NZEBs, owing to the convenient connection and no additional cost for energy storage devices or other energy infrastructure [111].

Achieving NZEBs involves integrating various renewable energy sources (RES) that include solar, wind, geothermal, and biomass, all of which can be generated locally or offsite, where offsite resources will be purchased from the utility. The different forms can be used in diverse ways as they can be converted to electricity, heat, or both. The efficiency of different RES and the combination of technologies, also, need to be optimized. As concerns the RES, they have already been analyzed in detail in chapter 2. Gas pipeline networks are, currently, one more critical energy infrastructure but typically only facilitate energy import and must be integrated with other energy infrastructures to export energy. Synthetic natural gas can be delivered to the grid from renewable sources however, this poses a difficult procedure and demands substantial capital investment and technical expertise to fulfill the grid's quality standards requirements. Thus, synthetic natural gas production is more likely to occur at the utility scale rather than individual homes. Moreover, district systems applied in regions with larger heating loads because this system provides both high energy efficiency and decentralized energy conversion and management. Last but not least, district heating and cooling systems can support bidirectional energy flows, allowing excess thermal energy to return the hot or cold streams. For instance, surplus heat from solar thermal collectors or surplus "cold" from solar cooling systems can be exported. However, metering thermal energy poses challenges due to the high costs associated with measuring flow and temperature differences [111]. Traditional PV systems often fall short in densely populated areas due to inconsistent sunlight exposure. Using available spaces such as roofs, balconies, walls, and facades can help meet electricity needs, with roofs being particularly effective. Because solar energy has low energy density, bigger spaces are required for PV systems to produce

sufficient electricity. These issues could be arranged by implementing a new feature such as building integrated photovoltaic (BIPV) which is depicted in **Figure 7.2**. This technology combines PV materials into building components. They can significantly reduce cooling demands, and accounting for roof and façade PV setups together they can nearly double annual energy output. However, panel efficiency decreases by 5-7% with rising temperatures. For that purpose, proper air circulation is essential to prevent overheating and maintain efficiency. Studies on the heat transfer process in solar walls found that BIPV installation in building walls can reduce cooling loads by 30-50% due to the shading effects. Finally, a comparative study evaluated a 22.9 m² PVT system against a combined solar thermal (15 m²) and PV (7.9 m²) system for home use, finding that the solar thermal systems performance was consistent in both setups. The PVT system outperformed the standard PV panel by 43% in electrical efficiency [113].

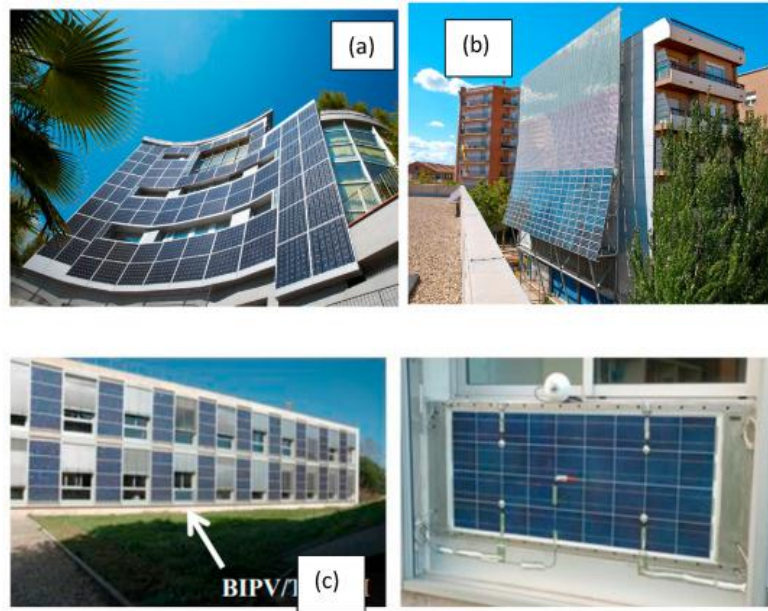


Figure 7.2: Photographic representation of (a) BIPV (b) BIPVTT (c) BIPVTT with PCM [113].

7.4. On-grid examples

The study of Khandelwal, Jain, and Gupta [114], a project that belongs to the work of the Ministry of Environment and Forests for the erection of new office buildings at Aliganj, Jor Bagh Road, New Delhi, is a recent on-grid example. The total investment cost was more than 25 million dollars. The working team emphasized energy-efficient and maintenance strategies at every step of building design and construction and the remaining annual load of 1.4GWh was covered by an on-site solar PV system to create the NZEB (see **Figure 7.3**). Its energy consumption is 67.3% less

compared to the Green Rating for Integrated Habitat Assessment (GRIHA) benchmark. All three stages - passive, active, and renewable design, were evaluated to determine the net-zero energy load of buildings. Analyzing the passive design techniques, adjusted materials used to control heat, specific daylight direction was taken into account, optimized free ventilation for cooling, and use of shade naturally or architecturally, to regulate heat gain.



Figure 7.3: Solar PV panels installed onsite [114].

The building orientation is set to balance both optimum solar access and shading. The building's roof, courtyard, and edges are entirely covered by solar PV panels which offers shading and contributes to a cooler microclimate. Two constructions facing north-south direction were built parallelly and in the middle, a linear open court, enhancing natural ventilation and mitigating heat penetration (see **Figure 7.4** and **Figure 7.5**). The courtyard has been filled with plants and trees keeping the surrounding temperature in low levels and boosting air circulation. The natural ventilation caused by the stack effect, at the interior courtyard in the center of the building, helps to cool that area too. Windows and latticed wooden screens, in favor of India's traditional architecture, add to cross ventilation. The courtyard sustained with skylight results in indoor natural daylight. 75% of NZEB floor space is filled with adequate sunlight, overcoming the need for artificial sources in the bigger part of the day. Regarding the building's envelope, rock wool insulation was preferred, and double-glazed, low-heat transmittance index windows were installed. Also, high reflectance terrace tiles are used on the roof to keep it rather cool. The building constructed by using local stone flooring and bamboo jute compound doors and frames. These are products characterized by low embodied energy. High visible light transmittance glasses with low solar heat gain coefficient and ultraviolet value, combined with sufficient shading help in energy saving. Light shelves have been designed for diffused sunlight. An on-site sewage treatment

plant with fluidized aerobic bio-reactor technology was implemented to recycle the total amount of utilized water finally accomplishing zero wastewater. Consequently, water consumption was reduced by 64% accompanied by water-efficient fixtures too [114].

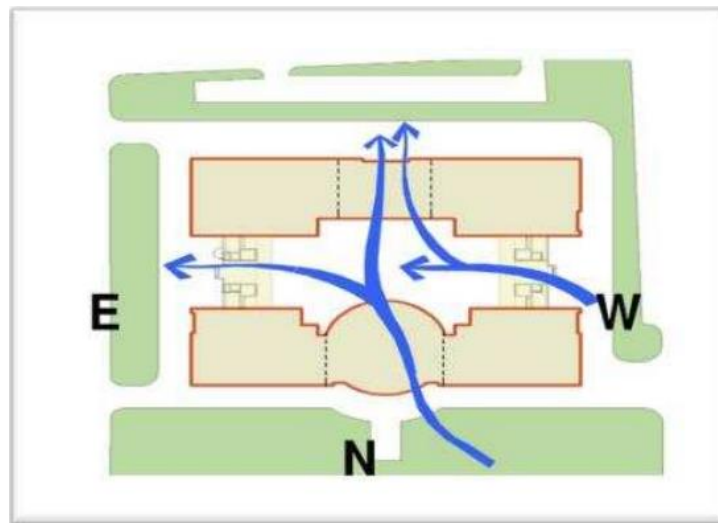


Figure 7.4: An efficient ventilation system due to the design of the building [114].

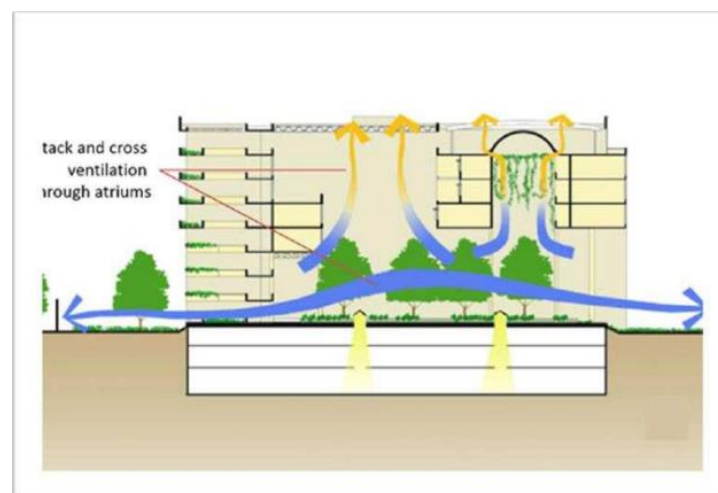


Figure 7.5: Ventilation via the courtyard [114].

The building is provided with a solar PV system installed in a 6000 m² area of 930 kW capacity. The panel's surface covers 4650 m² and numbers 2844 units. The artificial lighting system uses an energy efficient lux level sensor (see **Figure 7.6**). The building works with a chilled beam system to meet the air conditioning load that saves 50% of energy resources compared to a conventional system. A heat recovery system drains sensible & latent heat to pre-cool part of the exhaust air reused. Room temperature is preserved at 26 ± 1 °C. A geothermal pump was set up to

cover the cooling demand of the building which includes 180 vertical bores in a depth of 80 m with a minimum 3 m distance at the building's surroundings [114].

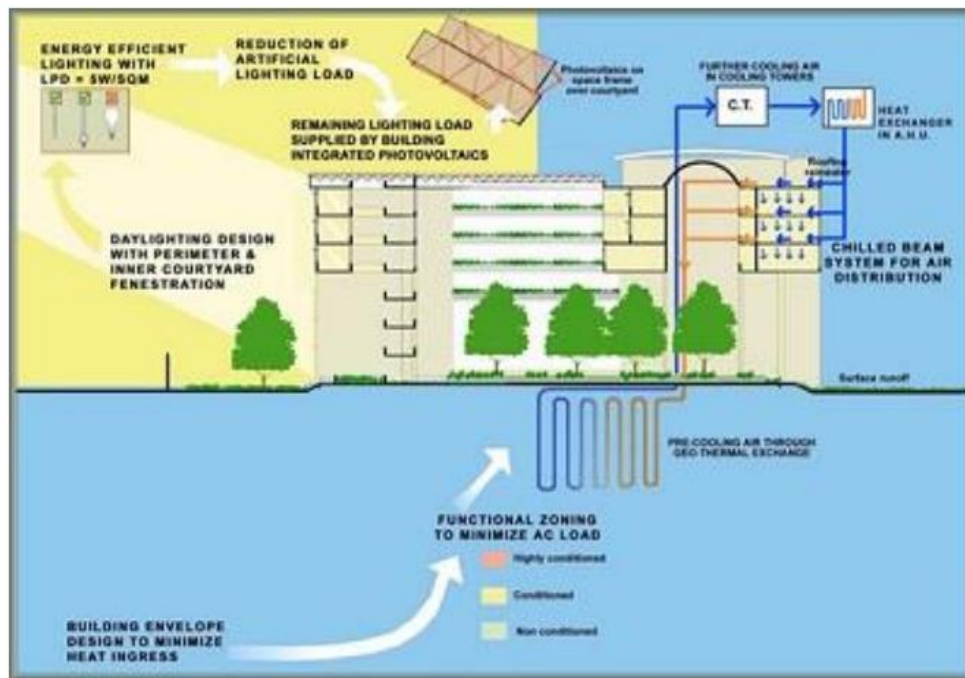


Figure 7.6: Active design strategies to save energy [114].

Another on-site example is the study of Bhavsar, Cupido, and Arriaga [115] regarding the Joyce Centre for Partnership & Innovation (JCPI) that was built in 2018 as a ZEB in the facilities of Mohawk College as a further attempt to minimize its holistic carbon footprint and manage to succeed its 2020 goal of greenhouse gas emissions (see **Figure 7.7**). The energy budget is calculated according to the building's end use, the electrical and mechanic systems, and the needs of auxiliary equipment, at the preliminary stage of design to achieve an appropriate energy performance. The different loads account for the type of users (e.g., students, facilities, and staff) and the essential equipment for their activities, including standard loads such as software devices, but also energy-intensive appliances installed at the laboratories. According to the National Energy Use Database of Canada, an average commercial and institutional building consumes 56% of its total energy in space heating and the rest of it in auxiliary equipment and lighting. Regarding JCPI, the end-use of the rooms is mostly classrooms, teaching laboratories, and co-worker learning space. However, the main capacity of energy is driven by the auxiliary equipment and plug loads, in a percentage of 50% of the total demand. The target settled at 730 MWh maximum load, which is ranked as a highly energy efficient building, given the fact that it only uses 20% of an average educational or office building in the region. The total cost of the building was 54 million dollars. Both passive and active methods were incorporated.

One of the main concerns was the building's envelope to be airtight enough to reach the heating and cooling system at low energy required levels. The windows covered 35% of the total vertical walls and for their glazing two layers were installed: a waterproof and a triple pane glass to prevent water infiltration and mitigate heat flow into the structure. The roof has also decreased thermal incomes, with planted areas and surfaces that reflect the sunlight to stop heat ingress. Lighting counts for almost 15% of the annual energy consumption being the 2nd largest end-use on the design. Natural daylight was the primary source for indoor lighting and LED light sensors were triggered when no sunlight was detected [115].



Figure 7.7: The Joyce Centre for Partnership and Innovation [115].

The electricity generated by solar PV panels, of approximately 8,177 m². Although, because JCPI's roof surface area covered only 30% of the whole PV array the remaining were installed on the surrounding buildings interconnected to the local campus grid (see **Figure 7.8**). PV panels were estimated to exceed the annual energy consumption, approximately by 10%, and comply with the provincial standards regarding the net metering configuration limit of 500 kW. As a result, the installed solar PV capacity was approximately 500 kW and the generation reached almost 730 kWh on an annual basis [115].

Space heating holds only 4% of the needed energy and a ground source heat pump system was designed to fulfill the heating and cooling requirements. During the summer season, the ground works as a heat sink and the inverse process takes place in the winter because underground temperatures are almost stable the whole year rather than the atmosphere temperatures. The small energy need owes to the variable refrigerant flow technology that can handle differentiated loads and saves energy by 32-40%. The geothermal system of the center includes 28 vertical bores, each 180 m deep and 4 m distant, covering approximately a 1,000 m² area. However, the building is also

supplied with a backup system to balance the fluctuations when peak times occur. As a heating backup, the building is equipped with an electrical temperature amplifier system able to provide a temperature boost when the geothermal system becomes insufficient [115].

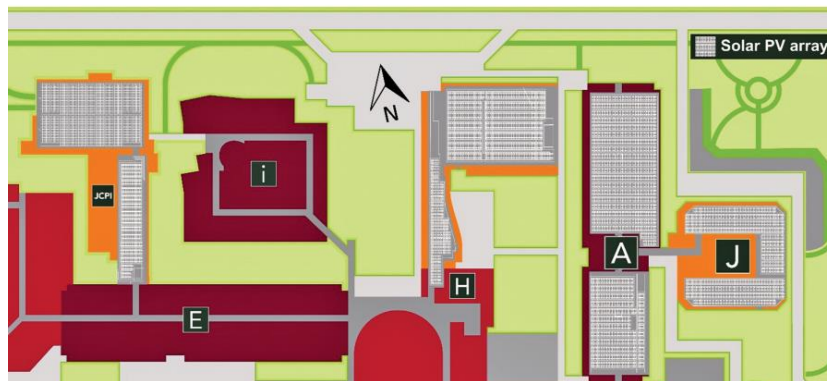


Figure 7.8: Solar PV installations used to meet the JCPI net-zero energy target, placed on a different building [115].

A solar thermal system is also installed to outcome the domestic hot water that consists of five flat plate collector panels and two 450 L tanks, one serving as a pre-heating system in conjunction with the solar thermal system and a secondary tank that provides the building with water. The whole system set in function only if there is a gap of 10°C between the solar collector and the first tank. Furthermore, when the pre-heating tank comes to a specified temperature, a recirculating pump set in functioning to balance the temperature difference in the two tanks. The amplifier system is also triggered when the temperature mismatch of the solar thermal collectors and the second tank can't be fixed by the usual process. A water recovery technique is implemented in the building too. Two underground cisterns use 228,000 L of rainwater, which is filtered and disinfected by radiation and then delivered in wastewater landscaping and plumbing systems, mitigating the clean water consumption. Even though the rainwater harvesting design aims to meet the non-potable water demand, the municipal water system is the backup solution [115].

In an attempt to create the largest commercial NZEB in the country, the NREL Research Support Facility was meant to inspire others in the building industry to achieve high energy efficiency and net-zero energy performance. The site orientation, massing, and envelope design are all based on daylight and natural ventilation to boost that building's efficiency (see **Figure 7.9**). The whole exterior configuration preheats the ventilation air, and by exploiting the exposed thermal materials and basement thermal labyrinth, the building manages to store thermal energy by itself. The architecture critically reduces the energy requirements. The design also included an ultra-

efficient lighting system, a heating/cooling system through radiation, and an underfloor air ventilation system, increasing the total energy performance. The roof presents a small slope towards the south to absorb greater amounts of daylight. Lighting is an integrated system of sunlighting, control daylight systems, and occupancy controls. Thermal comfort was achieved by using an incorporated system of thermal mass, radiant slabs, and natural ventilation while major concern was given to energy conservation. The building's energy load and capital cost were estimated at 110 kWh/m²/year and more than 90 million dollars respectively. Despite the roof being filled with PV panels of 450 kW only 17% of the total energy load was covered, so several adjacent parking structures were integrated with PV arrays. The combined power of the solar panels was 1.6 MW which overcomes all the RSF's annual energy needs, and the building's operation saved 42% energy compared to a typical office building. The design used passive architectural strategies to a great extent, taking advantage of the climate [116].



Figure 7.9: Building diagram [116].

The design of the RSF was highly based upon daylight as one of the most important factors. The configuration “lazy H” of the building was designed to allow daylight to enter the interior. On the south facade, external shading elements protect the lower windows. Light pours in from the upper light glass and very reflective louvers channel it towards the ceiling and deep into the interior. The north window is unshaded, as the softer and more diffused light from the north usually does not cause glare. Occupancy detectors, photo sensors, and manual switches guarantee that lighting with electricity is only activated when natural light is insufficient. The LED work lights, each consumes just 3 watts, provide local lighting through electricity. The designers chose the interior acoustic solutions, the furniture, and the color perception with natural lighting in mind. The paint used on interior ceilings and wall surfaces has a reflectivity of over 80%, ensuring maximum light reflection. Highly reflective acoustic ceiling panels enhance the distribution of natural daylight. Office furniture and cubicles with low walls are painted

light colors in order for light to be reflected. Additionally, the room walls are low, only 42 inches high, allowing daylight to channel deep into the space. Window dimensions and glazing combinations are selected to maximize daylight entry while minimizing glare and heat loss/gain. Each window's glazing is designed to operate efficiently. All glass windows on the north and south sides of the building are triple-glazed and the thermal protection conditions of the frames increase the unit's energy efficiency. To reduce the reflection of the south facade, the overhangs of the shade cast a shadow on the lower glazing (see **Figure 7.10**) [116].

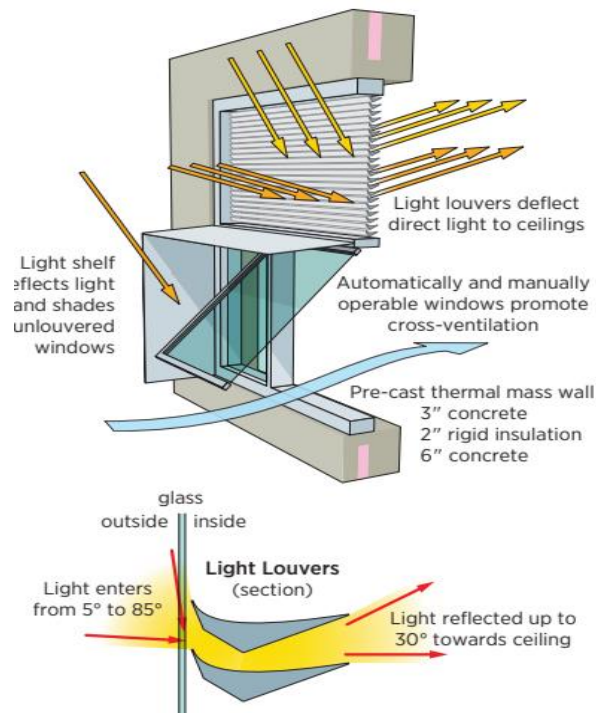


Figure 7.10: Light Louvers and Sunshade Overhangs [116].

The design of a thermally massive exterior wall configuration using an insulated panel system of precast concrete created significant thermal mass to temper the building's interior temperature. Transpired solar collectors are used to cover the south wing, a metal sheet penetrated with small holes. A large thermal labyrinth runs underneath the two main office wings and stores heat absorbed by the transpired vertical solar collectors. On sunny winter days, the air heated by the transpired solar collector rejects its heat to the thermal mass in order to preheat ventilation air. Fans drew air through the holes, during cold moderate days, to preheat building ventilation air and "charge" the labyrinth, acting like a thermal battery that is able to warm outside air by up to 2.78°C. During the heating season, this heat was utilized to passively moderate the ventilation air. The labyrinth was also used as a thermal sink to deliver the high latent heat amounts from the data center hardware, dramatically reducing the annual cooling load of the specific room [116] (see **Figure 7.11** and **Figure 7.12**).

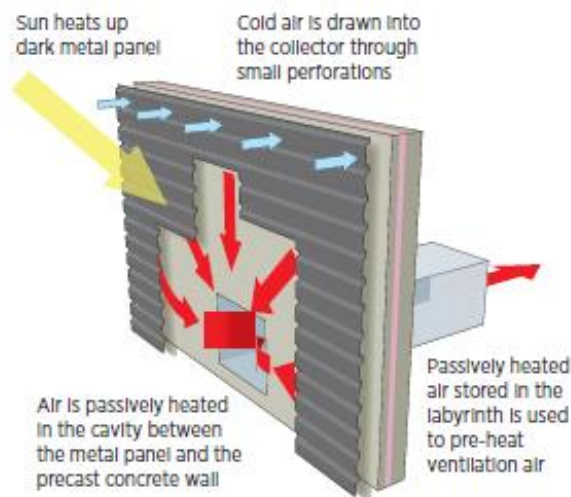


Figure 7.11: Graph demonstrating the operation of the transpiration solar collector [116].



Figure 7.12: Labyrinth thermal mass acting as a thermal battery [116].

Both office wings were primarily heated by a radiant ceiling slab that used water heated by NREL's central woodchip boiler and cooled by high energy efficient chillers that delivered cool water on the NREL campus. The building's ventilation is an integration of the natural air movement, taking advantage of the north-south direction of the windows and a mechanical ventilation system. Ventilation air was delivered by an air distribution system with swirl diffusers beneath the floor. During mild weather, opening the windows provided natural ventilation. When conditions do not allow that, an outdoor air system provides the required mechanical ventilation. Combining the ventilation with under-floor movement, the design led to low pressure and velocity, decreasing fan energy consumption. During dry Colorado summer, the evaporative coolers provided cool ventilation air. Finally, the RSF was equipped with a sensible heat recovery system (see **Figure**

7.13) to exploit either warm or cool air coming from the exhaust air system, to regulate the temperature of the outdoor air before it enters the main heating/cooling system [116].

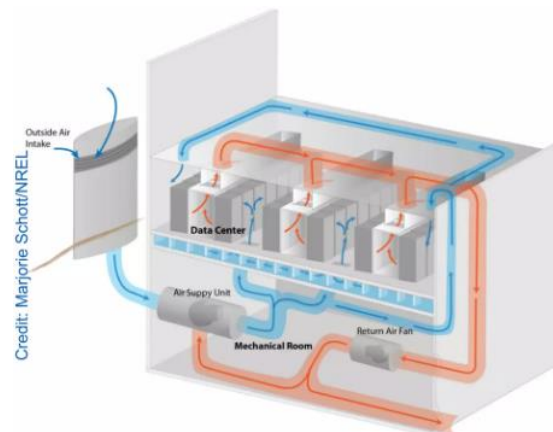


Figure 7.13: Heat recovery system [117].

7.5. Off-grid installation

Off-grid, autonomous, NZEBs stand only with on-site renewable energy production, plus an energy storage facility is mandatory to cover the building's demand. Energy storage regulates energy balance by storing when excessive electricity occurs and discharging during the lack of energy generation, providing monetary benefit to the owners by consuming their own energy while grid power is more expensive to exploit. Energy storage can also be used to achieve income by leveraging changes in the energy market. Power is purchased when the demand is at low levels and price and delivered to the grid during peak times of requirement and cost [111].

Fuel cells are a technology that can provide clean energy to the system when there is a lag between the primary energy sources and the load demand but has a slow dynamic response and very low power density. On the other hand, supercapacitors can complement that defect by supplying a large burst of power during maximum demand or fluctuation events. Their benefits include the long operating lifetime, their good impact on the environment, and they do not need maintenance. The power density of batteries is lower than supercapacitors but still enough for the good operation of the system. In addition, their storage capacity is way better than supercapacitors. The global use of batteries constitutes them as a cheap power solution despite their short operation lifetime and low response time. By combining two or all three of the energy storage devices, the electricity distribution remains permanent, and any fluctuations can be handled. Last but not least, a water electrolyzer is utilized for the generation of hydrogen which will be stored in a tank for later exploitation from the fuel cell (see **Figure 7.14**).

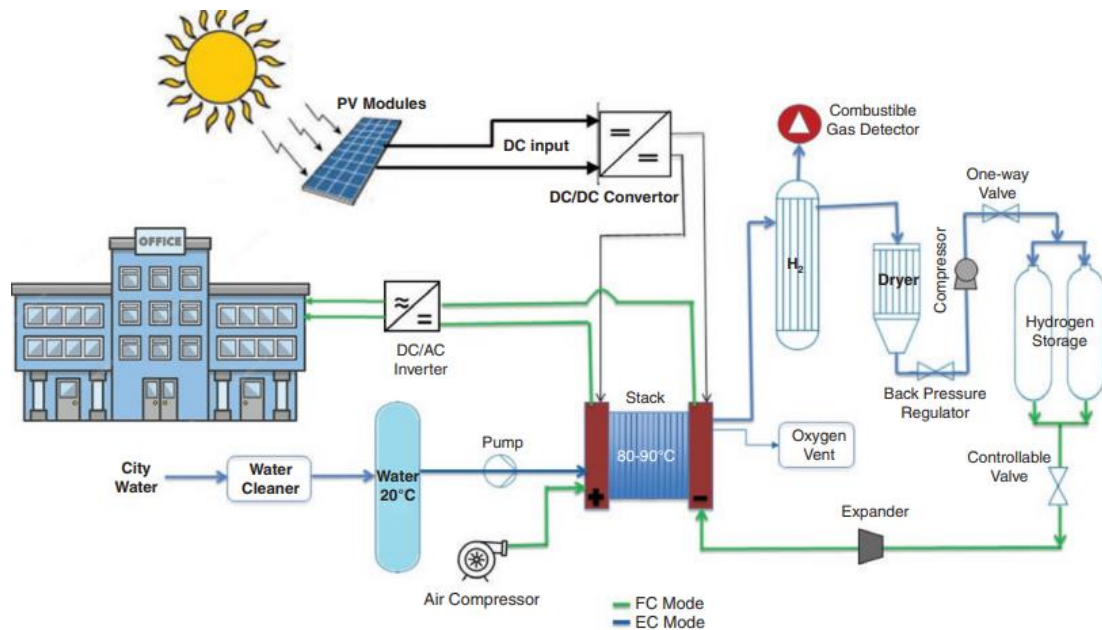


Figure 7.14: Techno-economic analysis of the Li-ion batteries and reversible fuel cells as energy-storage systems used in green and energy-efficient buildings [118].

In the recent study of Krishan and Suhag [118], a techno-economic analysis of two different systems, a fuel cell-battery system and a fuel cell-supercapacitor system (see **Figure 7.15**). Both were incorporated in a standalone photovoltaic based power system for a residential building. From the simulation results the photovoltaic-fuel cell-supercapacitor configuration had a greater response in covering the sudden power load swifts and keeping the voltage in rather steady position, whereas the photovoltaic-fuel cell-battery configuration requires more time to adjust to the power changes presenting small fluctuations in overall voltage of the system. It was also indicative regarding the high cost of such facilities installed in a single residential building of 20 flats [118].

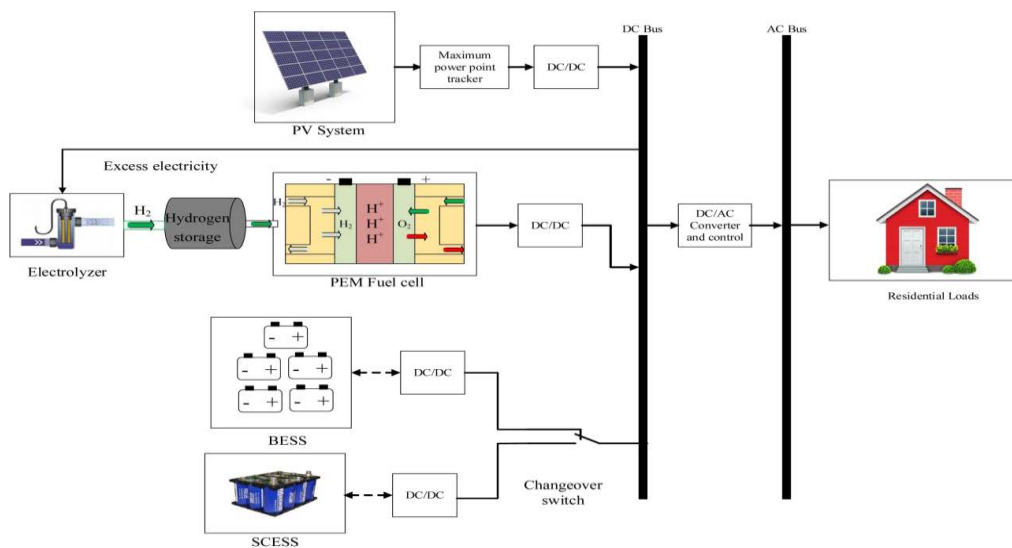


Figure 7.15: Configuration and components of PV power system [118].

CHAPTER 8

CONCLUSIONS

The interest of the scientific community in creating ZEBs has been increasing over the years, especially in the last two decades. This is because buildings contribute to 40% of the energy used globally and 1/3 of the greenhouse gas emissions. The fundamental principle of designing a ZEB is the reduction of its total energy consumption compared to that of the corresponding existing type of building through energy-saving techniques. An appropriate design takes into account the building's orientation, shape, envelope, shading methods, natural ventilation and daylight, thermal mass storage, and water and heat recovery systems. These passive energy strategies help to improve the total efficiency of the building either by preventing energy losses and waste or exploiting the elements of the environment. The remaining energy load can be covered by renewable sources. The technology most used to produce energy in ZEBs is photovoltaic systems. This is inferred from the examples formulated but also from the difference in the quantity of solar energy produced on a global level against the other green sources. Generally, renewable energy sources, have been widely studied, leading to large-scale implementation and a consequence reduction in generation costs. For example, since 2009, the benchmark cost of electricity generated by PV systems has decreased by over 75%. According to Bloomberg New Energy Finance, the cost of wind turbines has also been reduced by 32% since 2010 [119].

For the most efficient operation of a building with zero energy consumption, the use of only one energy production source is not enough, but an integrated system is needed. This happens because the performance of renewable energy sources is directly dependent on weather conditions. For example, photovoltaic systems lag on cloudy days, but mainly during the night hours. Similarly, wind turbines lag when there are no strong winds. From the above, it follows that a storage facility is necessary for the proper functioning of these buildings. It should be noted that these apply in the case of off-grid ZEBs. On the contrary, regarding the on-grid ZEBs, the photovoltaic systems can cover the demand by themselves, provided the appropriate study is done and the necessary installation space is available so that when a lack of energy generation occurs, they draw energy from the network and channel it back into it when they produce a surplus. Standalone ZEBs require an essential storage system. The main means of energy storage are batteries followed by

supercapacitors and hydrogen which is usually produced by the process of electrolysis and stored in high-pressure tanks for further use as fuel-by-fuel cells. Referring to grid-connected ZEBs, there is no need to use batteries since the network serves as a source. However, using batteries helps owners profit as they can store energy when prices are cheap and sell it to the grid when demand is high. They can also be secured by sudden blackouts. In any case, it is necessary to optimize the size and type of energy storage system according to the needs of the building.

Current examples of zero-energy buildings enhance the sustainability and reliability of these endeavors as they ensure a much cleaner and gas-free operation. Combining energy storage devices gives also the opportunity for autonomous building use so that it can cope with energy intermittent phenomena but also benefit economically by exchanging electricity with the grid according to the current prices in the market. At a secondary level, highly efficient smart buildings can be developed by integrating smart metering and energy management technologies to monitor in-house devices. These innovations enhance the quality of life by improving comfort, healthcare, safety, security, and energy conservation and can also be handled by mobile apps. Given the fact that the technical part is already implemented and it's a thriving field the expansion of these ventures depends on the incentive policies and financial support worldwide.

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