HOW TO STORE RENEWABLE ENERGY FOR LONGER PERIOD OF TIME AND WHICH TECHNOLOGIES ARE USEFUL

Lappeenranta–Lahti University of Technology LUT

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Examiners: Mehar Ullah (Post Doc Researcher)

Abstract

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This thesis provides a comprehensive overview of various renewable energy sources, followed by an in-depth analysis of three key energy storage methods – batteries as short-term storage, hydrogen and methane as long-term storage. The first part of the thesis offers a detailed introduction to several renewable energy sources, emphasizing their potential and limitations. Subsequently, it delves into the complexity of battery technology, highlighting its suitability for short-duration energy storage. The focus then shifts to exploring hydrogen and methane as feasible solutions for long-term energy storage, examining their production processes, storage mechanisms, and potential applications.

The second part of the thesis bridges the gap between renewable energy storage and the latest technological advancements by introducing four cutting-edge methods: Internet of Things (IoT), big data, edge computing, and machine learning. This segment discusses how the Internet of Things (IoT) can improve the efficiency and reliability of energy storage systems by enabling real-time monitoring and management. The examination of big data's role is important in enhancing storage system optimization and advancing predictive maintenance methodologies. Edge computing is presented as a solution for processing large volumes of data closer to the source, thereby reducing latency and improving response times in energy management. Lastly, the application of machine learning is discussed in terms of predictive analytics, which can forecast energy demand and optimize storage and distribution.

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1 Introduction

The use of renewable energy sources has become increasingly important in global initiatives focused on sustainable and environmentally friendly energy options (Liu et al., 2023). The desire for a dependable power supply, enhanced grid security, and consumer cost efficiency drive this increased demand. Extended and long-term energy storage solutions are key in managing the variable nature of renewable energy sources, helping to reduce the risks linked to decreasing dependence on fossil fuel for consistent energy production (Hargreaves & Jones, 2020). However, sustaining a steady and dependable power source is difficult due to renewable energy's intermittent nature, which depends on sunshine and wind patterns (Wali et al., 2023). This common obstacle is a characteristic of systems that now have a high level of renewable energy integration. Alongside traditional fossil-based generation, both electrochemical storage and hydroelectric power have been employed to tackle the challenge of balancing the daily fluctuations in electricity supply and demand. Among the array of electrochemical solutions, lithium-ion batteries have emerged as the predominant selection for daily applications, offering benefits in terms of energy storage, capacity, and ancillary services (Hargreaves & Jones, 2020). Developing effective and long-term storage systems for renewable energy has become a key area of emphasis within the energy technology discipline to tackle this difficulty and optimize the integration of renewable energy sources (Wali et al., 2023).

Multiple long-term storage technologies, including the Internet of Things (Al-Ali, 2016), Big Data, AI(Machine Learning), and other pioneering approaches, play a significant role in this undertaking (Mostafa, Ramadan & Elfarouk, 2022). The integration of the Internet of Things (IoT) in the context of renewable energy storage proves to be instrumental in addressing various challenges and optimizing energy systems. IoT facilitates the collection and delivery of informative data throughout different stages of energy processes, playing a crucial role in the transition from physical to cyber-physical domains (Ullah, Gutierrez-Rojas, et al., 2022). Big data transforms the process of knowledge dissemination. It moves beyond just gathering and converting measurements into extracting information, and further into developing knowledge. Ultimately, the accumulation of this knowledge provides the wisdom necessary for decision-makers (Mostafa, Ramadan & Elfarouk, 2022). Artificial Intelligence (AI), particularly Machine Learning (ML), has undergone significant expansion in its application capabilities, particularly in the context of managing and interpreting data related to energy production and management. This expansion is driven by the exponential growth in global data generation, facilitated by advances in data storage, the Internet of Things, wearable devices, and sensors. AI, characterized as the computational system's ability to learn and adapt to its environment, emerges as a key player in addressing sustainability challenges. ML, a subset of AI, employs algorithms to make inferences from data sets, enabling predictions and descriptions of various phenomena, offering great promise in promoting sustainability within energy-related systems (Mostafa, Ramadan & Elfarouk, 2022).

These technologies facilitate the equilibrium of supply and demand dynamics for grid operators and allow people and communities to harvest and store their renewable energy in a longer period. The potential for transformation inherent in renewable energy storage goes beyond the sole objective of maintaining grid stability. It presents prospects for achieving energy independence, enhancing resilience, and diminishing dependency on conventional power-generating methods reliant on fossil fuels.

In the pursuit of ambitious sustainability objectives, renewable energy storage emerges as a prominent factor in the shift towards a cleaner and more resilient energy framework on a global scale. This thesis aims to comprehensively examine the approaches used in the long-term storage of renewable energy, focusing on the technical breakthroughs crucial for shaping the future course of sustainable energy storage problem, research questions, limitations, and thesis structure.

2 Renewable Energy

Renewable energy represents a critical component in the global effort to reduce carbon emissions and combat climate change. It encompasses a range of technologies that harness energy from natural and sustainable sources, offering an environmentally friendly alternative to fossil fuels. This section provides an in-depth exploration of renewable energy, focusing on its diverse sources and the innovative methods for storing this energy. By understanding both the generation and storage aspects of renewable energy, we can appreciate the complexities and potential of these technologies in contributing to a sustainable future.

2.1 Renewable Energy Sources

Renewable energy accounts for a significant and growing share of global energy production today. According to the National Resources Defense Council (NRDC), renewables contribute to over 12 percent of U.S. energy generation, with applications ranging from large-scale offshore wind farms to individual rooftop solar panels, even empowering entire rural communities (*United Nations* 2022).

The advantages of renewable energy extend beyond environmental considerations. Economically, renewables are becoming more cost-effective than fossil fuels in many countries, and they create three times more jobs, contributing to sustainable economic growth (*United Nations* 2022). To further enhance the adoption of renewable energy, there is a pressing need to modernize and integrate national electricity grids, ensuring they are smarter, more secure, and capable of efficiently managing diverse renewable sources (*Renewable Energy: the Clean Facts* 2022).

Figure 1. below shows the global renewable energy generation from 1965 to 2022. Starting from 941.19 TWh in 1965, the total renewable energy has grown substantially to 8532.57 TWh in 2022. This overall growth indicates a global shift towards greater reliance on renewable energy. Hydropower has been a dominant force in the renewable energy landscape, consistently contributing a substantial portion of the total. Although its growth rate has slowed compared to other sources, it remains a significant and reliable source of renewable energy.

This graph highlights a remarkable and accelerating growth in wind energy generation, especially in the latter part of the dataset. Starting from negligible values in the mid-20th century, wind energy has surged to 2139.23 TWh in 2022. This trend suggests increasing global investments and advancements in wind energy technology. Solar energy has experienced significant advancement, with a clear, rapid growth trend. Starting from virtually no

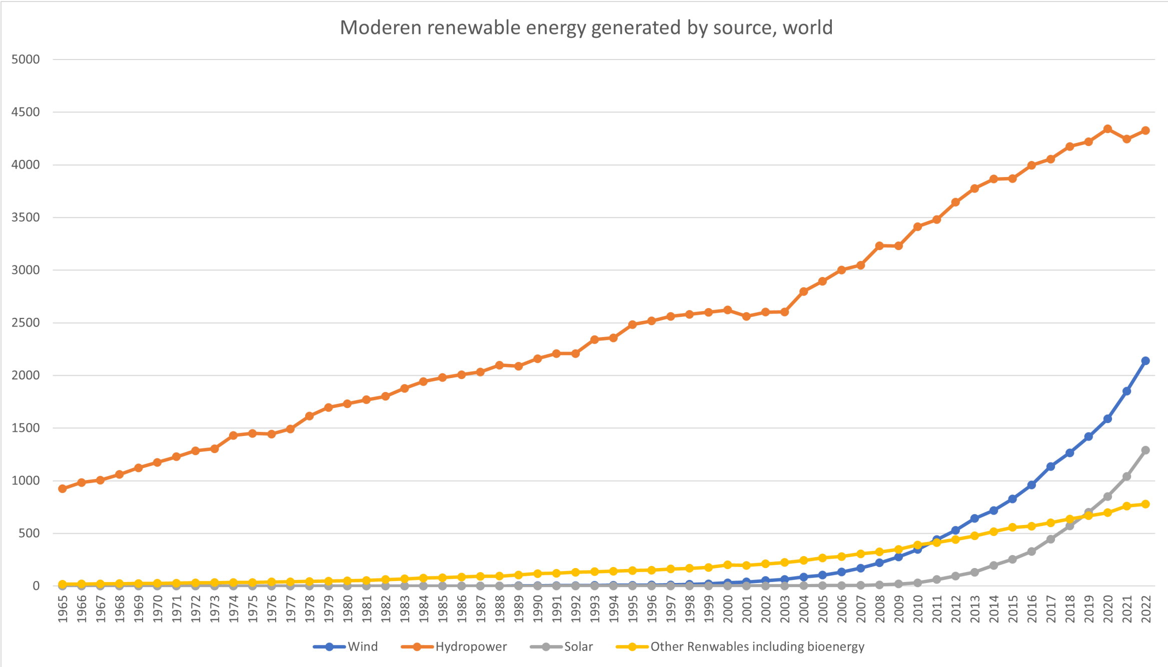

Figure 1: Modern renewable energy generation by source, world
(Ritchie, Roser & Rosado, 2020)

contribution in the 1960s, solar energy has reached 1289.27 TWh in 2022. This exponential growth indicates increasing adoption of solar technologies, likely driven by decreasing costs and improved efficiency.

The category encompassing other renewables, including bioenergy, has shown steady growth, contributing 777.31 TWh in 2022. While not growing as rapidly as wind and solar, this category consistently contributes to the overall renewable energy mix. The early 2000s marked a turning point, with a noticeable acceleration in the growth of renewable energy. This period is characterized by a significant increase in wind and solar energy generation, suggesting that global efforts and policies to promote renewable energy gained momentum during this time.

Here are four common Renewable Energy sources:

2.1.1 Solar Energy

Solar energy, recognized as a symbol of environmental responsibility, has the potential to supplant traditional fossil fuels in the worldwide energy framework. Solar energy, a renewable resource, has made substantial progress, accounting for about 31% of the overall installed capacity of renewable energy in 2022 (Pourasl, Barenji & Khojastehnezhad, 2023). According to the International Renewable Energy Agency(IRENA), it now has an amazing installed capacity of 1053 GW, and now accounts for 3.6% of worldwide electricity output, making it the second most widely used renewable energy technology (*IRENA – International*

Renewable Energy Agency 2023).

The amount of solar energy that reaches the earth is enormous—roughly 10,000 times more than what humans need (Arvizu et al., 2011). Solar energy is geographically unrestricted. Solar resource availability differs among countries, direct solar energy has the potential to contribute significantly to the energy composition of any country. The United Nations emphasizes the significant potential of solar energy to be widely adopted as a direct and influential contribution to sustainable energy practices (*United Nations* 2022).

Solar energy has been used from thousands of years to fulfill vital requirements, such as agriculture, heating, and food storage. According to the National Renewable Energy Laboratory, the Earth receives an amount of solar energy in only one hour that surpasses the total energy consumption of the whole globe in a year (*Renewable Energy: the Clean Facts* 2022). Currently, we use solar energy for various applications such as residential and commercial heating, water heating, and powering numerous electronic equipment.

An essential factor contributing to the increase in solar energy is the significant decrease in the production cost of solar panels in the last decade. The decrease in cost has not only made solar panels more accessible but has also established them as one of the most economically feasible sources of power. Moreover, the extended lifespan of solar panels, which typically lasts around 30 years, along with a diverse range of colors derived from different production materials, further boosts its appeal as a viable and environmentally friendly energy alternative (*Renewable Energy: the Clean Facts* 2022).

2.1.2 Wind Energy

Wind energy is a pivotal player in renewable and clean energy, tapping into the kinetic force of moving air through innovative technologies such as wind turbines. From small turbines capable of powering individual homes to large offshore wind farms, wind energy has become key to the global shift to sustainable and carbon-free energy solutions (Wiser et al., 2011).

The value of wind energy extends beyond electricity production. In the drive towards sustainability, the significance of wind energy in achieving a carbon-neutral future is becoming clearer, offering environmental benefits and creating economic opportunities for landowners through leasing agreements with wind energy projects (Wiser et al., 2011).

This thorough investigation presents wind energy as a vibrant and influential element, delving into its technological complexities, environmental aspects, and its integral role in the wider context of a sustainable energy future.

2.1.3 Geothermal Energy

As the planet's initial creation and radioactive material decay produce heat in the Earth's core, geothermal energy develops as a crucial renewable energy source (Goldstein et al., 2011).

The earth's core, boasting temperatures exceeding 4000°C, triggers the melting of rocks, forming hot molten rocks known as magma. Additionally, these high temperatures induce plastic behavior in the mantle, causing portions of it to convect upwards due to its lighter density compared to surrounding rock (Goldstein et al., 2011).

Geothermal energy harnesses this natural thermal energy, extracting heat from geothermal reservoirs through wells or other means. Reservoirs are categorized as hydrothermal when naturally hot and permeable, while enhanced geothermal systems involve hydraulic stimulation to improve permeability (Goldstein et al., 2011).

The historical importance of geothermal energy is significant, with its use for heating dating back several millennia and its notable rise in electricity generation starting in the 20th century. Geothermal facilities exhibit a distinct advantage over other renewable sources, providing a consistent power generation capacity unaffected by fluctuating weather conditions (Wikipedia, 2023).

2.1.4 Hydropower

Hydropower, a crucial component in renewable energy, captures the kinetic energy of water moving from higher to lower levels. This form of energy can be generated using different methods, such as through reservoirs and run-of-river systems (*United Nations* 2022). Reservoir hydropower plants utilize the stored water in large reservoirs, while run-of-river plants capitalize on the natural flow of rivers, without significant storage.

As of now, hydropower stands as the predominant source of renewable energy in the electricity sector and is expected to maintain this position into the 2030s (*Hydropower - IEA* 2023). Its reliability generally depends on consistent rainfall patterns, but it faces challenges such as climate-induced droughts and ecological changes that affect these patterns. However, the infrastructure necessary for hydropower can have adverse effects on local ecosystems. This concern has led to a growing interest in small-scale hydroelectric projects, particularly for remote communities, as they are often viewed as more environmentally sustainable options.

Looking ahead, the role of hydropower in the global energy mix is expected to change. While wind and solar are expected to surpass it, it remains essential for decarbonizing the power system and increasing flexibility, especially as a dispatchable source of power that complements variable renewable energy sources such as solar and wind (*Hydropower - IEA* 2023). Pumped storage, a method of storing energy in the form of water in an elevated reservoir, could become increasingly important for balancing the intermittent nature of other renewable sources.

Despite its significance, the expansion of global hydropower is predicted to slow down in this decade. This slowdown is attributed to reduced project development in regions like China, Latin America, and Europe, although this is partially offset by growth in the Asia Pacific, Africa, and the Middle East. Furthermore, climate change-induced irregularities in rainfall are impacting hydropower production in various parts of the world, underscoring the need for adaptive and sustainable approaches in future hydropower projects (*Hydropower - IEA* 2023).

Figure 2. presents hydropower generation data from 2015 to 2023 under the Net Zero Scenario, showcasing an overall increasing trend. Starting at 3902.6 TWh in 2015, the generation sees gradual yearly rises with occasional dips. After a small decline in 2021, the figure ascends again, with the latest available data indicating 4558.3 TWh for the year 2023, with a prediction, will reach 5503.1 in 2030.

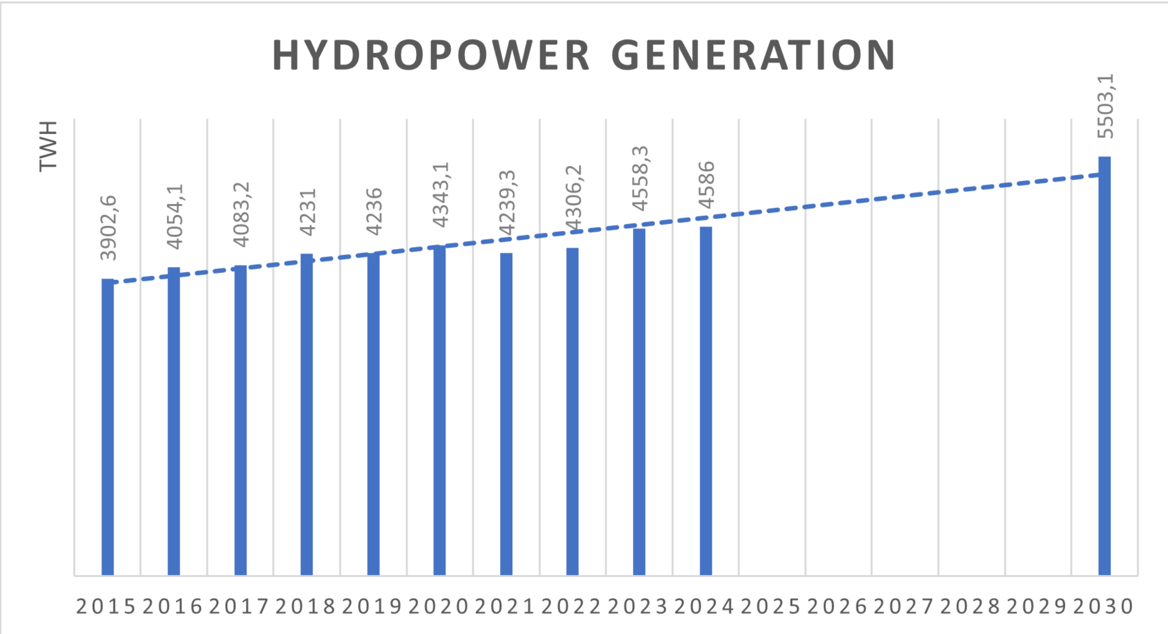

Figure 2: Hydropower generation in the Net Zero Scenario, 2015-2030
(International Energy Agency (IEA), 2021)

2.2 Renewable Energy Storage

Energy storage plays a crucial role in advancing a sustainable, low-carbon energy landscape. As the adoption of renewable energy sources such as wind and solar power grows worldwide, driven by the imperative to mitigate climate change and decrease dependence on fossil fuels, challenges arise due to the inconsistent nature of these energy sources. This variability can impact the stability and dependability of the power grid. Therefore, it is essential to focus on creating and applying efficient energy storage methods to address these challenges.

Energy storage systems store surplus energy when demand is low and release it during high-demand periods, contributing to grid stabilization (Chu et al., 2023). Furthermore, these storage technologies play a key role in facilitating higher incorporation of renewable energy into the grid, improving both the efficiency and dependability of the energy infrastructure (Chu et al., 2023).

One of the most promising developments in this field is the concept of Power-to-X, an innovative approach where excess renewable energy is converted into other forms of energy or materials, such as hydrogen, ammonia, methanol, and dimethyl ether, or even into valuable commodities like lubricants and aviation fuels (Biswas et al., 2020). This method not only addresses the storage issue but also creates opportunities for utilizing renewable energy in various sectors.

However, the storage and transportation of these energy carriers, particularly hydrogen, present significant challenges. Hydrogen, despite its high gravimetric energy density, has a low volumetric heat content and poses difficulties in storage and transportation, including energy losses in compression and challenges with the mechanical properties of storage materials (Biswas et al., 2020). Overcoming these hurdles is crucial for establishing a robust renewable energy economy and ensuring a sustainable and reliable energy supply in the future.

Figure 3. below outlines three different kinds of renewable energy storage systems that integrate both long-term and short-term storage mechanisms. In the long-term storage system depicted, CO2 is captured directly from the atmosphere or industrial outputs. This captured CO2 then undergoes a chemical reaction with hydrogen, produced through the electrolysis of water using surplus renewable energy. The resultant methane gas is then converted and stored in tanks for future use as an energy source. Concurrently, electricity is generated from renewable sources, such as wind turbines and solar panels. Surplus electricity from these sources produces hydrogen through water electrolysis, which is then stored for extended periods. This hydrogen is combined with the captured CO2 in a reactor to create

methane, which is also stored as a long-term energy source. Methane can be utilized in a gas power plant to generate electricity when needed. For immediate energy demands, the system employs short-term storage in the form of lithium-ion batteries. The electricity from these batteries is converted to the appropriate current for the power grid through a conversion inverter. This comprehensive setup ensures a balanced and sustainable energy supply to the grid, leveraging the strengths of both immediate and prolonged storage solutions.

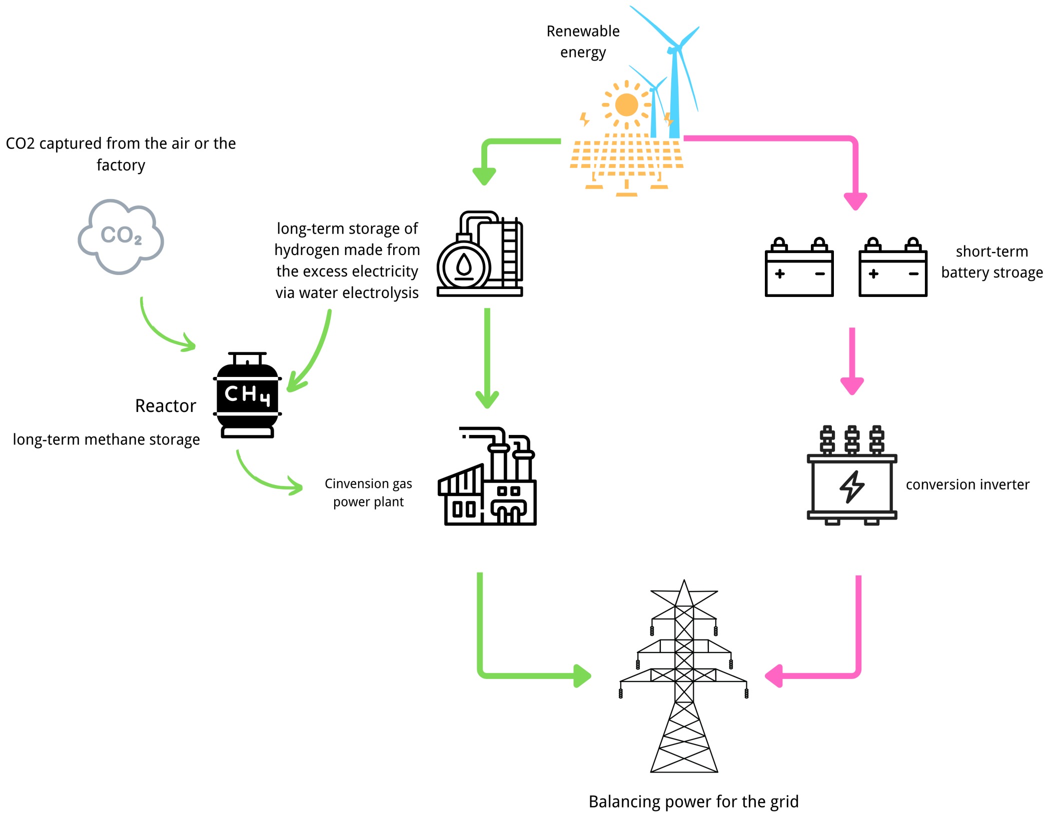

Figure 3: Various ways to store renewable energy

2.2.1 Battery

Renewable energy storage, particularly in the short-term context, is a critical aspect in managing and effectively utilizing intermittent renewable energy sources such as wind and solar power. Among the array of available storage technologies, lithium-ion (Li-ion) batteries have emerged as a predominant choice due to their unique attributes and widespread application in both small and large-scale storage needs.

Lithium-ion batteries, first brought into commercial production in the early 1990s by Sony, were initially used for small consumer electronics like cellphones (Environmental & (EESI), 2019). Over time, their use has grown to include larger-scale battery storage and electric vehicles, representing a notable expansion in the range of their applications (BloombergNEF, 2019). These batteries are particularly favored in the renewable energy sector due to their high energy density and lightweight characteristics. The evolution of Li-ion technology, with ongoing innovations such as the replacement of graphite with silicon, is aimed at enhancing the batteries' power capacity. As of 2017, lithium-ion batteries dominated over 90 percent of the global grid battery storage market (Environmental & (EESI), 2019).A notable aspect of Li-ion batteries is the significant decrease in their cost. By the end of 2017, the cost of a lithium-ion battery pack for electric vehicles fell to $209/kWh, with projections indicating a further reduction to below $100 kWh by 2025 (BloombergNEF, 2019). This cost-effectiveness has been a crucial factor in their widespread adoption.

Li-Ion batteries, known for their superior energy density and longevity, have become increasingly popular, particularly in consumer electronics. These batteries come in various compositions, each with distinct costs and functionalities. A significant concern with Li-Ion batteries is the risk of ignition, primarily due to lithium's reactivity, especially when paired with oxygen, coupled with the batteries' high energy density. Additionally, lithium batteries are sensitive to cold temperatures, leading to a faster discharge rate (BloombergNEF, 2019).

Despite their advantages, Li-ion batteries pose certain challenges. The performance of these batteries degrades over time, which limits their long-term storage capability. The recycling of these batteries, once they reach their end of life, is another significant concern, alongside ethical issues surrounding the sourcing of lithium and cobalt. Li-ion batteries are known to be flammable, and incidents in energy storage plants, particularly in South Korea, have raised safety concerns. These incidents were attributed to factors like poor installation practices and a lack of awareness of risks such as thermal runaway (Energy, 2020).

While lithium-ion batteries are currently at the forefront, but alternative technologies like lead-acid, flow, and solid-state batteries are also being explored. Each of these technologies presents its own advantages and challenges, and their development is essential for diversifying the options available in renewable energy storage (Environmental & (EESI), 2019).

2.2.2 Hydrogen

Hydrogen storage is a key aspect of renewable energy systems, particularly in the context of its application in energy conversion systems with hydrogen storage (RESHS). Hydrogen, produced through electrolysis using surplus energy from primary renewable sources such as wind turbines and photovoltaic arrays, serves as a long-term energy storage medium. When renewable energy supply is insufficient, this stored hydrogen is reconverted into electricity through fuel cells to meet energy demands (Kélouwani, Agbossou & Chahine, 2005).

This energy storage method addresses the intermittency and unpredictability of renewable energy sources (RES). Unlike fossil fuels, RES like solar and wind energy are abundant, replenishable, and environmentally friendly, but their power output is characterized by randomness. This makes it challenging to forecast their output precisely. To mitigate this, hydrogen storage offers a solution with its high energy density and low self-discharge rate, providing a way to store energy compactly over longer periods, unlike batteries which are more suitable for short-term storage due to their higher power density, quicker response to power fluctuations, but shorter energy storage duration (Ellabban, Abu-Rub & Blaabjerg, 2014).

Figure 4. shows hydrogen energy storage systems, electrical power is converted into hydrogen through the electrolysis of water. This is a straightforward process with relatively high efficiency when inexpensive power is available. There are three primary types of electrolyzers: Alkaline (AEL), polymer electrolyte membrane water electrolysis (PWE), and Solid Oxide Fuel Cell Electrolysers (SOEC) (Moioli, Mutschler & Züttel, 2019). AELs operate at temperatures up to 80°C and pressures of 30 bars, achieving efficiencies as high as 70%. PEMs can generate hydrogen at temperatures up to 100°C and pressures of 200 bars, offering the benefits of operating at higher current densities and having a more compact design, although they are more expensive than AELs. SOECs operate at higher temperatures, reducing electricity use by up to 25% compared to other types, but they are less developed and have higher investment costs (K. Zeng & Zhang, 2010). Currently, AEL is the most popular technology for small-scale applications due to its maturity and lower cost (Moioli, Mutschler & Züttel, 2019).

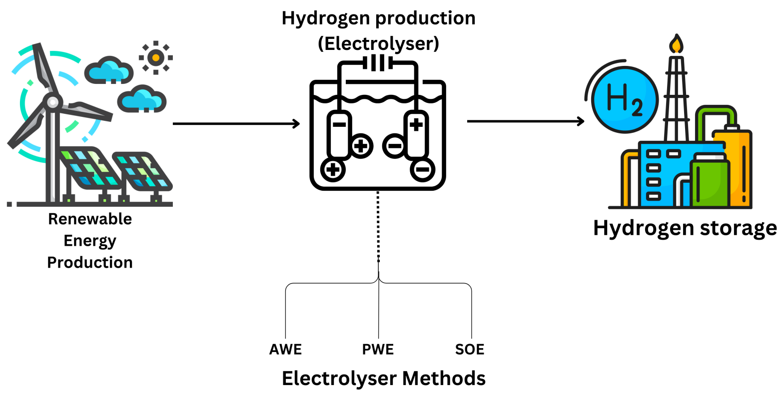

Figure 4: Hydrogen energy storage system

Hydrogen must then be stored, either in underground caverns for large-scale storage or steel containers for smaller scales. It can be used as fuel in combustion engines, gas turbines, or, more efficiently, in hydrogen fuel cells. The interest in hydrogen energy storage is mainly due to its potential role in a hydrogen economy, where it could replace fossil fuels in many applications (Luo et al., 2015). Hydrogen storage can be achieved through various methods, each with its unique characteristics and applications. Figure 5. shows the different ways of hydrogen storage based on two methods- The physical-based method and the Material-Based Method.

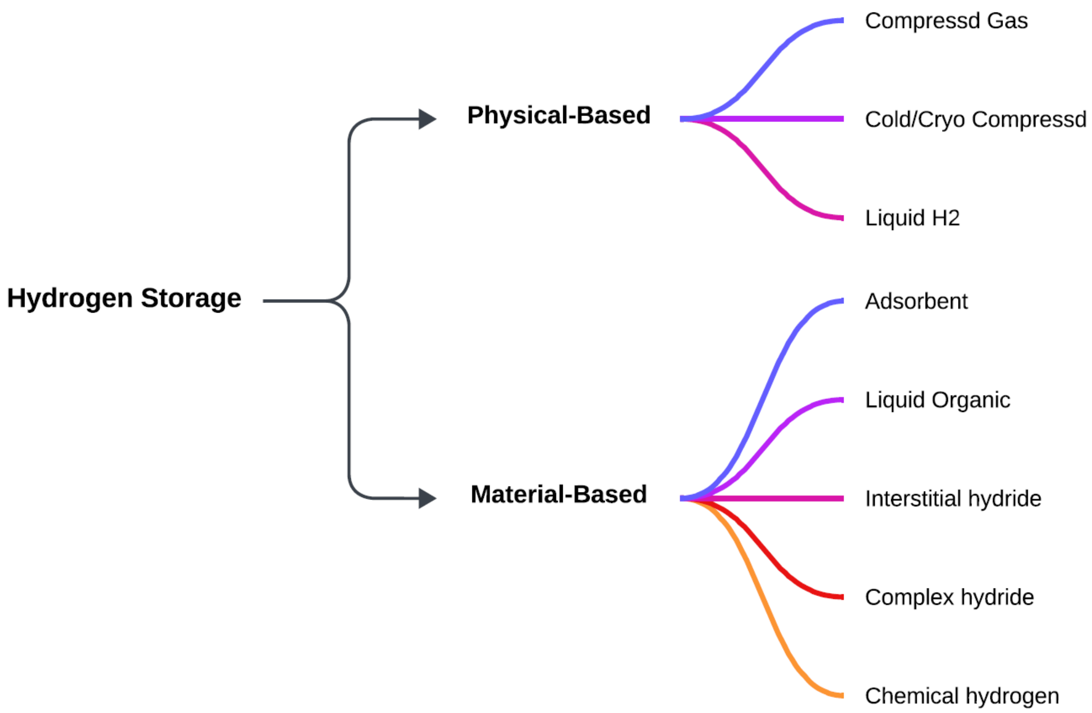

Figure 5: Hydrogen energy storage methods

High-pressure gaseous Storage involves storing hydrogen gas under extreme pressures, typically between 350 to 700 bar (5000 to 10,000 psi), requiring robust, high-pressure tanks. In Cryogenic Liquid Storage, hydrogen is kept as a liquid at temperatures below -252.8°C to maintain its state and prevent it from turning back into gas (*Hydrogen storage* 2019); this method offers higher energy density but is cost-intensive, and the storage tanks must be well-insulated to reduce heat transfer and evaporation, making it ideal for high-purity needs like space exploration. Cold-and-cryo-compressed hydrogen combines cooling and compression for even higher energy density, but it's more energy-consuming. Overall, these hydrogen storage techniques are energy-intensive, with about 9-12% of the energy used for compression and approximately 30% for liquefaction (*Hydrogen storage* 2019), prompting ongoing research to find more efficient and cost-effective storage solutions.

Materials-Based Hydrogen Storage represents an innovative approach to hydrogen storage, utilizing specific materials to store hydrogen in various forms. The Adsorption method relies on hydrogen molecules or atoms attaching themselves to the surface of materials with extensive surface areas, like metal-organic frameworks (MOFs), zeolites, or carbon nanotubes, leading to high volumetric storage densities (*Hydrogen storage* 2019). In the absorption process, hydrogen is dissociated into atoms that become part of the internal solid structure of a material. Another method, Hydride Storage, involves hydrogen forming compounds with metals such as palladium, magnesium, lanthanum, or certain alloys, creating metal hydrides. These hydrides can absorb hydrogen into their metallic lattice, which can then be released through heating. This technique allows for storing large volumes of hydrogen, providing an efficient way to store hydrogen at lower pressures and near room temperatures (*Hydrogen storage* 2019). Hydrogen can also be stored by chemically binding it with liquid organic carriers. Using compounds such as N-ethylcarbazole or toluene, this method can achieve high hydrogen absorption capacities. Material-based storage methods allow for the efficient storage of large amounts of hydrogen in smaller volumes, at lower pressures, and near room temperature, offering greater volumetric storage densities than liquid hydrogen. However, this technology is still being refined due to the high costs and time-consuming processes associated with hydrogen charging, discharging, and processing (*Hydrogen storage* 2019).

A significant advantage of using hydrogen in renewable energy systems is its role in facilitating the transition away from fossil-fuel-based economies. When integrated with wind and solar energy, hydrogen technologies can substantially increase the amount of dispatchable renewable energy generation. This is particularly beneficial for remote and rural areas, improving the reliability of energy access. Additionally, hydrogen-powered vehicles can significantly reduce carbon emissions, contributing to environmental protection. The success of these systems, however, depends on effective governmental policies, financial investments, and optimal planning and design (Kélouwani, Agbossou & Chahine, 2005).

2.2.3 Methanol

Hydrogen storage is an essential component in the field of renewable energy, particularly as it relates to methanol storage and synthesis. The process of hydrogen production and its subsequent storage is a key element in the Power-to-X (P2X) pathway (Ullah, Gutierrez-Rojas, et al., 2022).

The connection between hydrogen storage and methanol synthesis is further elaborated in the process of converting hydrogen and carbon dioxide into methanol. This synthesis process typically occurs in reactors like the Lurgi-type multi-tubular fixed-bed reactor, utilizing catalysts such as CuO/ZnO/Al2O3. The resulting methanol serves as an efficient medium for long-term energy storage, offering advantages in transport and storage compared to gaseous hydrogen (Meyer et al., 2016).

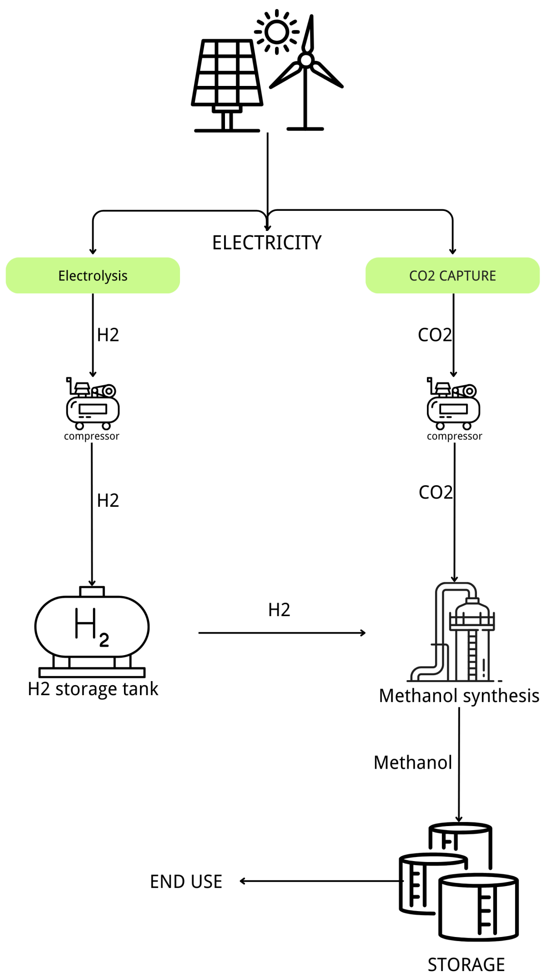

Figure 6: Methanol synthesis

Methanol's role extends beyond storage; it is also used as a fuel in combustion engines and fuel cells, and as a raw material in chemical manufacturing (Ullah, Gutierrez-Rojas, et al., 2022). Methanol's diverse uses greatly enhance its worth in the renewable energy field, positioning it as a viable solution for employing surplus renewable energy. The combination of hydrogen and methanol storage strategies exemplifies the creative methods in renewable energy aimed at realizing a future that is both sustainable and robust, as emphasized in several important references (Meyer et al., 2016).

The methanol synthesis process depicted in Figure 6. begins with the generation of electricity from renewable sources, such as solar panels and wind turbines. This electricity is then utilized in two separate pathways. The first pathway involves electrolysis, where electricity is used to split water into hydrogen (H2) and oxygen. The hydrogen is then compressed and stored in an H2 storage tank. Concurrently, the second pathway involves capturing carbon dioxide (CO2) from the atmosphere, which is also compressed. Both the stored hydrogen and captured carbon dioxide are then fed into a methanol synthesis process. During this chemical process, hydrogen and carbon dioxide react under pressure and temperature to form methanol. The produced methanol is then stored, ready for end use as a fuel or chemical feedstock.

3 Advanced technologies for Renewable Energy Storage

This section explores cutting-edge technologies that are transforming the way renewable energy is stored. Technological advancements have led to the development of groundbreaking solutions that not only improve the efficiency of storing renewable energy but also facilitate its smooth incorporation into current energy infrastructures. This discussion is divided into key technological areas: the Internet of Things (IoT), Edge Computing, Artificial Intelligence and Machine Learning, and Big Data. Each of these technologies plays a pivotal role in addressing the unique challenges posed by renewable energy storage. Furthermore, we will explore how the synergy between these advanced technologies and renewable energy storage methods is paving the way for a more sustainable and efficient energy future. Through an integrated approach, combining the strengths of each technology, we aim to highlight the transformative impact these innovations have on the renewable energy sector.

3.1 Internet of Things

The Internet of Things (IoT) represents a transformative technology trend that has been evolving and expanding its influence across various sectors since its inception. Originally introduced by Kevin Ashton in 1999 during a presentation to Proctor & Gamble, and further explored at the MIT Auto-ID Center, IoT stands as a concept that bridges the physical and digital worlds (Wei, Hong & Alam, 2016). At its core, IoT involves connecting physical objects through a network, allowing them to communicate and interact with each other and with computing systems.

The foundational technology of IoT, which initially utilized Radio Frequency Identification (RFID) technology, played a crucial role in its early development. This technology enabled the identification, tracking, and monitoring of objects using RFID tags, facilitating wireless communication between these objects and readers (Hussain et al., 2020). However, the scope of IoT has significantly broadened over the years, moving beyond simple RFIDs. Modern IoT applications now integrate various types of data collected from sensors, and processed through advanced computing devices. This evolution reflects a shift towards more complex and diverse applications of IoT technology.

IoT's relevance is evident in numerous sectors, including transportation, healthcare, industrial automation, and education, showcasing its versatility and the growing momentum in its adoption (Ullah, Nardelli, et al., 2020). This widespread applicability stems from IoT's ability to provide a seamless integration of the physical and digital realms, offering enhanced efficiency, data-driven insights, and automation capabilities.

The advent of IoT platforms has been pivotal in supporting this expansion. These platforms offer a range of services and features crucial for the deployment of IoT applications, such as endpoint management, connectivity, data analysis, security, and more (Saqlain et al., 2019). The rapid growth in IoT technologies since 2015 has led to an increase in the number of connected devices and platforms, illustrating the dynamic nature of this field (Saqlain et al., 2019).

However, this technological growth also presents challenges, especially for businesses and governments with limited experience in IoT infrastructure. Selecting a suitable IoT platform is a critical task, requiring consideration of both current and future needs. The market features hundreds of IoT platforms, each with varying functionalities and technological underpinnings (Saqlain et al., 2019). Understanding the key building blocks of IoT and identifying the key factors for platform selection are essential steps in navigating this complex landscape.

3.1.1 Architecture of IoT

The Internet of Things (IoT) is often conceptualized using a three-tier architecture(Kavitha, 2022), which includes the physical layer, the connectivity layer, and the application layer. Each of these layers can be associated with specific blocks or components of IoT, Figure 7. below shows the three-tier architecture.

1. Physical Layer (Perceptual Layer)
Identification Block: This block is essential for identifying devices within the network, using object IDs and addresses. These identifiers allow devices to be recognized and located within the communication network, primarily using IPv6 and IPv4 addressing methods (Ullah, Nardelli, et al., 2020).

Sensing Block: The sensors in this block are crucial for collecting data from the surrounding environment or objects. This data is then transmitted to databases or cloud storage for analysis. The block also includes actuators (Hussain et al., 2020), which perform functions opposite to sensors, like operating switches in mechanical devices (Ullah, Nardelli, et al., 2020).

2. Connectivity Layer
Communication Block: This block encompasses a variety of objects that exchange data and services with each other and the IoT platform. It includes IoT communication protocols like MQTT and CoAP for connecting different objects to the IoT and managing data transfer (Ullah, Nardelli, et al., 2020). This layer also involves communication technologies such as ZigBee, NFC, UWB, Wi-Fi, SigFox, and BLE (Kavitha, 2022), which connect sensors and

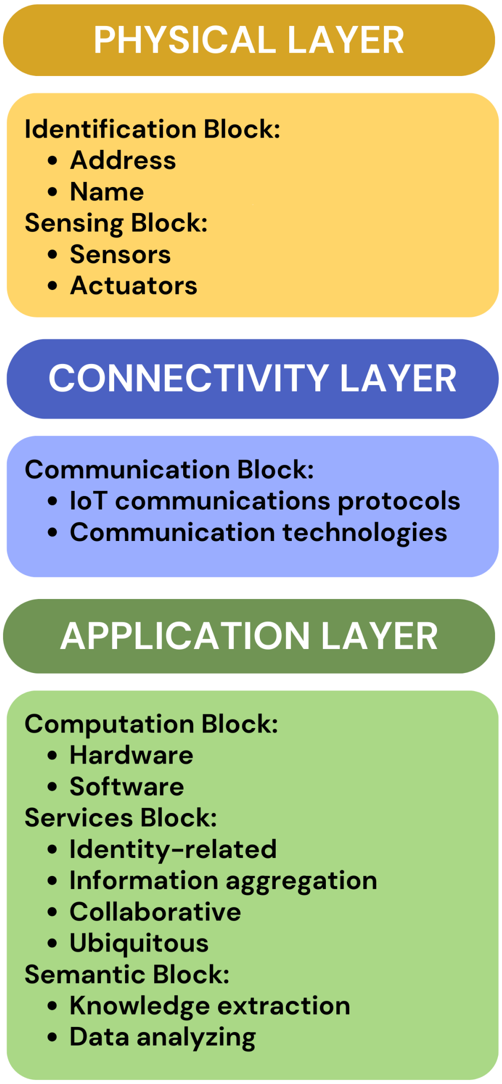

Figure 7: Internet of Things Architecture

other devices to the Internet (Ullah, Nardelli, et al., 2020).

3. Application Layer

Computation Block: Comprising both hardware and software, this block includes platforms like Intel Galileo, Raspberry PI, and Arduino (Ullah, Nardelli, et al., 2020), which run IoT applications. The operating system is a key software component, running almost continuously on the device. Cloud platforms also play a computational role by facilitating real-time big data processing and helping users extract knowledge from this data.

Services Block: This block assists IoT application developers by providing foundational services for development (Kavitha, 2022). It includes identity-related services (both active and passive), information aggregation services, collaborative-aware services, and ubiquitous services, all of which support various aspects of IoT applications.

Semantic Block: Often regarded as the 'brain' of the IoT, this block involves knowledge extraction, which includes finding resources, modeling information, and analyzing data to make informed decisions and provide appropriate services (Ullah, Nardelli, et al., 2020).

3.2 Edge Computing

Edge computing is an innovative technology that addresses the inefficiencies and limitations of traditional cloud computing, especially in sectors requiring real-time data processing and analysis. This approach involves processing data at the "edge" of the network, closer to its source, rather than solely relying on centralized cloud servers. This paradigm shift offers significant benefits, such as reduced latency, lower data transmission costs, and enhanced data security, particularly relevant in industrial settings where large volumes of data are generated by devices (Ullah, Narayanan, et al., 2021).

In industrial environments, edge computing is increasingly adopted to manage the vast data volumes more efficiently. Traditional cloud computing often involves transferring substantial data amounts to a central repository, leading to network congestion and increased storage costs, especially when much of this data might not be operationally relevant. Edge computing addresses these issues by analyzing data at the data collection point, thereby speeding up the decision-making process and reducing network bandwidth and storage load (Ullah, Narayanan, et al., 2021).

The application of edge computing is particularly prominent in smart grids, power systems enhanced with information and communication technologies to allow two-way flows of electricity and information. Smart grids generate significant real-time data, and the limited computing and storage capabilities of edge devices in these grids pose challenges in processing this data using complex AI algorithms. Edge computing provides a solution by offering localized data processing, crucial for real-time, intelligent, and secure grid operations (P. Zeng et al., 2023).

In terms of security in smart grids, edge computing is instrumental. Various research efforts have focused on developing lightweight security methods suitable for edge computing environments. These methods aim to enhance network security and protect against cyber threats like wormhole attacks, especially in 5G network architectures (P. Zeng et al., 2023).

Furthermore, edge computing is crucial for optimizing smart grid operations, including short-term load forecasting, fault detection, and load analysis. These applications are essential for maintaining the grid's stability and efficiency (P. Zeng et al., 2023).

However, the adoption of edge computing is not without challenges. These include increased bandwidth requirements at the network's edge, additional storage and maintenance costs on the client side, and the complexities associated with distributed computing. Moreover, while edge computing can enhance overall data security, it also introduces security concerns at the local level due to the distributed nature of the nodes (Hossain et al., 2023).

Figure 8. presents a clear structure of the Edge computing process which consists of three layers, cloud layer, edge node layer and edge device layer. Also, demonstrates how network edge nodes carry out various functions, including computation, caching, device control, and even the training of machine learning models. This strategy significantly reduces the amount of data needing to traverse the internet to reach cloud-based systems.

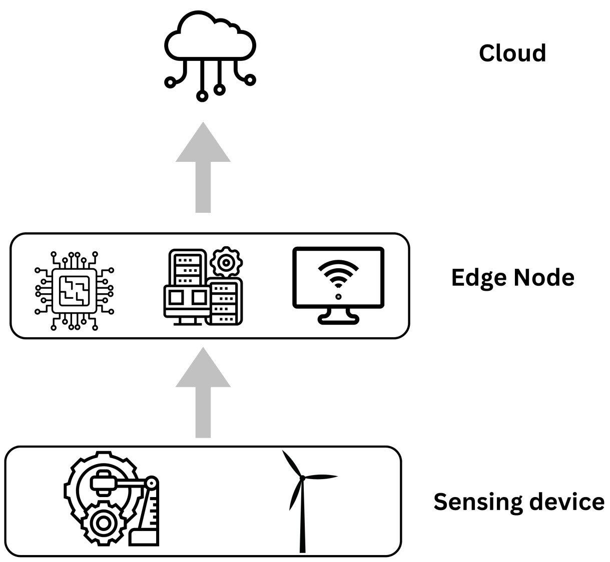

Figure 8: Edge computing infrastructure

The decision to choose between cloud and edge computing involves careful consideration, particularly in light of the trend where many industries are incorporating cloud computing into their operations, alongside the growing presence of IoT devices that generate substantial data volumes. In industrial contexts, this influx of data from numerous devices leads to several issues. First, there's a need to sift through large amounts of data, much of which might not be relevant to operational needs. This leads to increased data flow to central data repositories and additional costs due to the unnecessary storage of irrelevant data. Second, transmitting this large quantity of data to cloud servers is a time-intensive process, which is critical in industrial applications where timing—differences between seconds and milliseconds—can be crucial. Lastly, the act of sending data to the cloud and retrieving it can be expensive.

Edge computing addresses these challenges by selectively filtering and analyzing essential data on-site and in real-time. This method speeds up data analysis and streamlines decision-making processes. By relocating the storage and processing capabilities typically associated with cloud computing to the network's edge, closer to end-users, edge computing effectively mitigates communication delays in applications where latency is a key concern.

3.3 Artificial Intelligence and Machine learning

Artificial Intelligence (AI) and Machine Learning (ML) mark significant progress in computer technology. AI is about machines doing things that usually need human intelligence. This means they can understand language, identify pictures, and make choices, just like we do. These technologies are making complex computer tasks possible. Machine Learning, a subset of AI, focuses specifically on algorithms and statistical models that enable computers to learn from and make predictions or decisions based on data, without being explicitly programmed for each task (International Energy Agency (IEA), 2023).

In recent years, the application of AI and ML in complex systems, particularly in the energy sector, has become increasingly significant. ML, for instance, is employed to approximate relationships in complex engineering systems where traditional, physics-based models are computationally intensive or less effective (Lin et al., 2022). This approach has been utilized in various applications, such as optimizing power system operations and predicting energy market trends.

The synergy between AI and ML is particularly evident in their ability to handle the growing complexity and data-intensive nature of modern power systems. With the increasing integration of renewable energy sources and the need for efficient energy distribution, ML algorithms are vital for processing large datasets and extracting meaningful insights. These algorithms can forecast energy demand and supply, enhance grid management, and even predict revenue streams from renewable energy and storage systems (International Energy Agency (IEA), 2023),(Lin et al., 2022).

The machine learning process depicted in Figure 9. begins with training data that is processed by a training learning algorithm to create a learning model. This model is then evaluated to assess its performance; if the model's predictions are not satisfactory, the model is refined to improve its quality. Concurrently, new input data is introduced and processed by a predictive learning algorithm that utilizes the learning model to make predictions. These predictions lead to a decision, which is contingent on the evaluation indicating acceptable performance. If the evaluation suggests further refinement is needed, the model may undergo additional training and adjustment in an iterative cycle to enhance its accuracy.

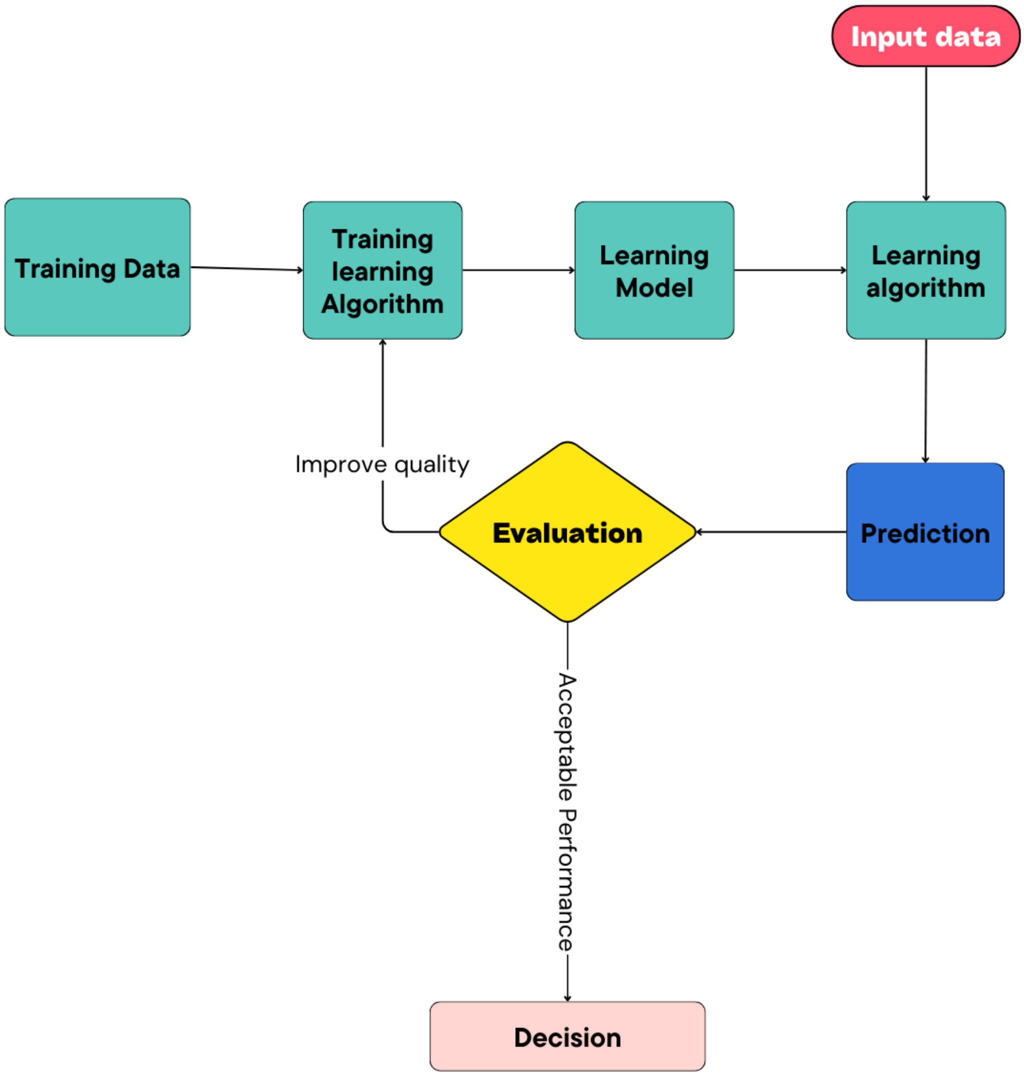

Figure 9: Machine Learning Process

Moreover, the advancements in AI technology, such as self-learning and code modification capabilities, further amplify the potential of ML in these applications. The result is a more adaptive, efficient, and intelligent approach to managing energy systems, aligning with the global shift towards sustainable and resilient power infrastructures (International Energy Agency (IEA), 2023).

3.4 Big Data

Big data, a term that has become increasingly prevalent in the digital age, refers to the vast amounts of data generated from various sources such as social media, sensors, digital devices, and software applications. This data encompasses a range of formats including structured, unstructured, and semi-structured data, often exceeding the processing capabilities of conventional data processing tools and techniques. The concept of big data is typically characterized by three primary dimensions, known as the 3Vs: volume, velocity, and variety (Ullah, Narayanan, et al., 2021). Volume refers to the massive scale of data, often measured in terabytes or even larger units like petabytes and exabytes. Velocity denotes the rapid rate at which data is generated and processed, often in real time. Lastly, variety indicates the different types of data, ranging from structured to unstructured forms (Ullah, Narayanan, et al., 2021).

In the context of energy systems, big data technologies play a crucial role. They enhance traditional data processing methods by integrating block calculations and clustering for comparative analysis. The energy sector employs big data in several key areas, including data acquisition and storage, correlation analysis, crowd-sourced data control, and data visualization (Mostafa, Ramadan & Elfarouk, 2022), (Ullah, Narayanan, et al., 2021).

Big Data process has four stages which will be presented below:

1. Data Acquisition and Preparation: This stage is centered around gathering and organizing data from multiple sources. Using tools such as Flume, data is collected, processed to correct format inconsistencies, and made ready for further use. This process includes correcting or discarding partial or flawed data and integrating data from diverse devices. The processed data is then dispatched to the Hadoop cluster's master node (Ullah, Gutierrez-Rojas, et al., 2022).

2. Data Serialization and Storage in HDFS: At this stage, data is moved to the Hadoop Distributed File System (HDFS) where it undergoes serialization and is formatted for storagcie. HDFS is designed to store different types of data, including structured, unstructured, and semi-structured. It distributes large file blocks across various data nodes connected to the master node. The storage and management of actual data alongside filesystem metadata are handled by DataNodes within the HDFS clusters (Ullah, Gutierrez-Rojas, et al., 2022).

3. Data Querying and Analysis : This phase involves executing SQL queries on the HDFS-stored data using platforms like Hive and Impala. Hive is particularly employed for tasks such as querying, selecting, analyzing, and computing the data of interest. This phase is critical for deriving valuable insights from the processed data.

4. Data Analytics and Decision Support: In the final phase, the focus shifts to conducting data analytics and disseminating the analyzed data for decision-making purposes. Tools like Scalable Advanced Massive Online Analysis (SAMOA) (Ullah, Gutierrez-Rojas, et al., 2022), a distributed streaming machine learning framework, are used within Hadoop for in-depth data analysis. This stage is key in converting data into practical knowledge for supporting business or institutional decision processes.

Particularly in renewable energy grids, big data aids in transitioning from mere data collection to the generation of actionable insights. This process involves converting raw data into information, which then forms the basis for expanding knowledge and ultimately supports decision-making for stakeholders. Renewable energy data can be classified into two main categories: geospatial data, which deals with location information, and temporal data, which relates to time-specific characteristics of energy consumption and production. With advancements in Internet of Things (IoT) technologies, even smart buildings contribute to the data pool through smart metering and sensor systems (Ullah, Narayanan, et al., 2021).

The role of big data in energy systems extends to supporting a variety of analytical and operational processes. This includes failure event analysis, risk analysis, forecasting, maintenance management, and assessing the performance of systems like HVAC in buildings. A big data framework for renewable energy grids often comprises multiple layers, each responsible for different aspects like data storage, management, sharing, and mining. Tools such as Hadoop, Apache Drill, and Storm facilitate real-time interaction with data in power systems (Ullah, Narayanan, et al., 2021).

Moreover, the integration of big data with cloud computing offers a robust architecture for managing renewable energy grids. This involves managing data storage, retrieval, and distributed storage across multiple nodes, while also taking into account customer consumption patterns, supply-demand histories, and predictive analytics. In this setting, big data analytics plays a pivotal role in forecasting the needs of power systems, especially in relation to renewable energy sources, thereby contributing to more efficient and reliable energy management (Ullah, Narayanan, et al., 2021).

3.5 Integration of renewable energy storage methods and advanced technologies

This section describes the architecture of an integrated system that combines renewable energy storage methods with advanced data-centric technologies. These technologies include the Internet of Things (IoT), big data analytics, edge computing, and machine learning techniques. As an illustrative example, we use methanol storage to demonstrate a type of renewable energy storage. Figure 10. provides a visual representation of how renewable energy storage methods are integrated with these cutting-edge technologies using methanol synthesis as an example (Ullah, Gutierrez-Rojas, et al., 2022).

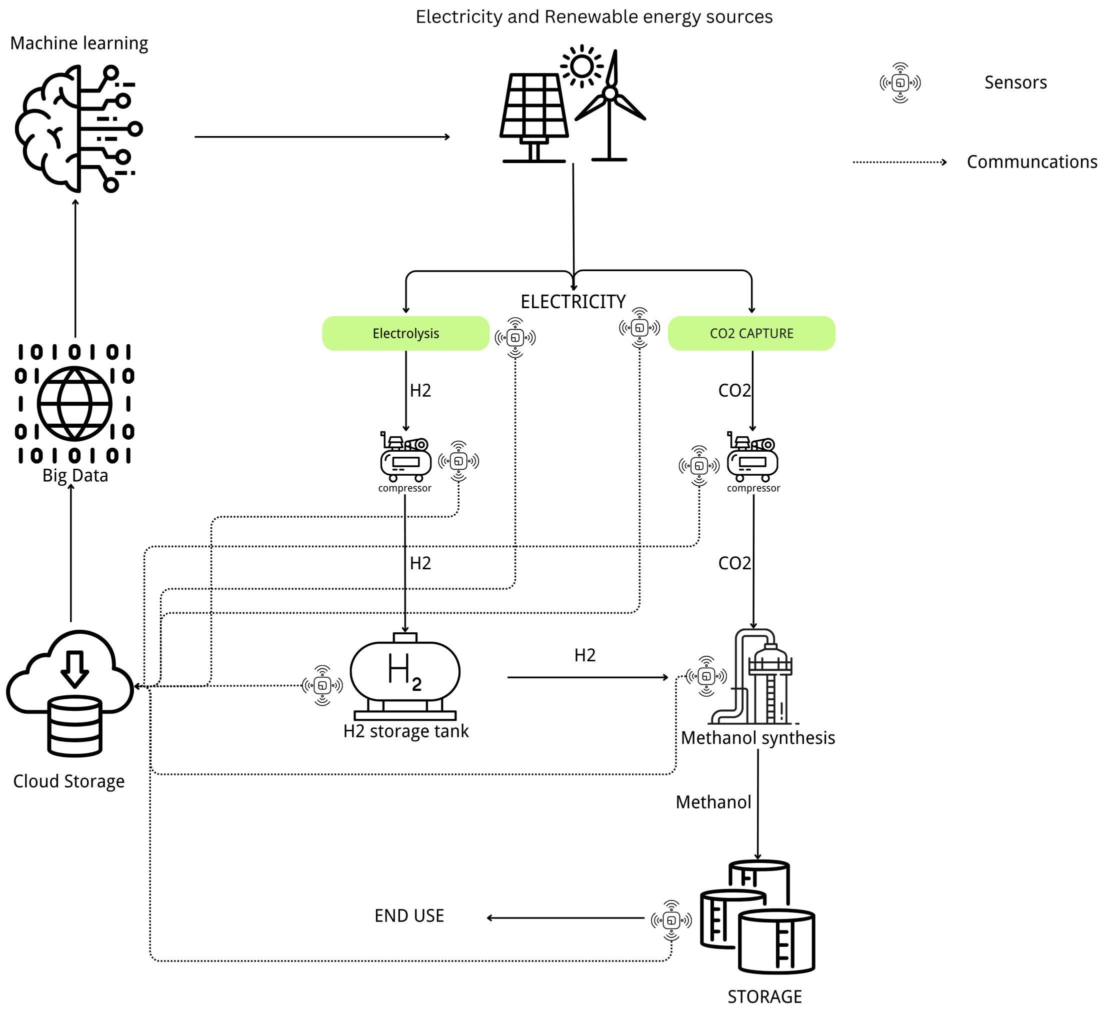

Figure 10: Methanol Synthesis example
(Ullah, Gutierrez-Rojas, et al., 2022)

3.5.1 Data collecting and communication network structure

Figure 11 shows the four stages of the IoT-based system. In the **initial stage**, IoT sensors are used throughout the entire system. This system encompasses renewable energy sources, the electrolysis process, and the storage facilities for hydrogen and methane. During this phase, data collection occurs from various components of the designed framework. This includes measurements from solar panels, wind turbines, as well as monitoring environmental factors like air pressure and atmospheric temperature. Additionally, information regarding the electricity market prices, the quantity of electricity supplied for electrolysis and CO2 capture, the production and storage levels of hydrogen, the usage of hydrogen and CO2 in methanol synthesis, and the total methanol output is gathered.

In the **second stage**, the data previously gathered by IoT sensors is transferred and stored in cloud storage. This process utilizes Edge Computing to efficiently complete the task.

In the **third stage**, big data analysis tools will be employed to examine the extensive data gathered from IoT sensors in the first stage. This real-time data from IoT sensors will enhance decision-making and operational efficiency in the future. Big data process was illustrated in the section 3.4.

The prediction phase forms the **fourth stage** of the process.Dedailed process was presented in the section 3.3. During this stage, the refined data from the big data repository is supplied to either the machine learning algorithms or the expert system. This data serves dual purposes: it can be utilized as a training set for machine learning models or as a decision-making aid in the expert system.

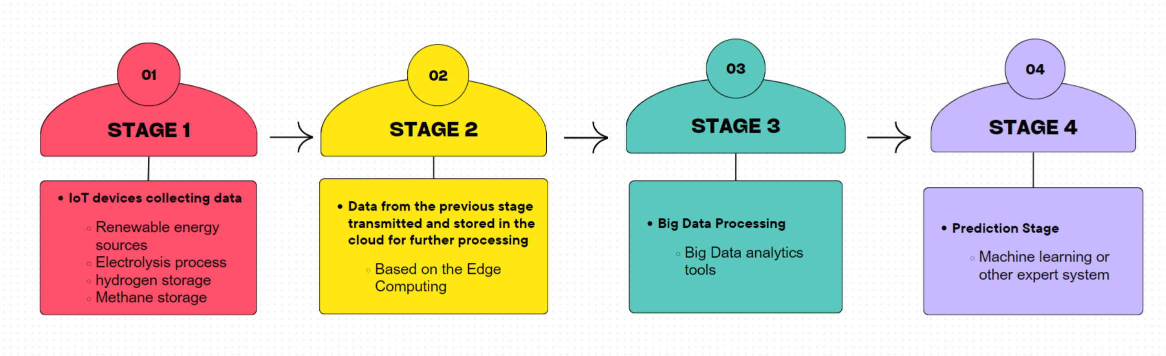

Figure 11: Data collecting and communication network structure

4 Discussions & Conclusions

The thesis has provided an extensive exploration of renewable energy sources and storage methods, emphasizing the integration of advanced technologies like IoT, Big Data, AI, and Edge Computing. The discussion on various renewable sources – solar, wind, geothermal, and hydropower – highlighted their potential and challenges, particularly focusing on their intermittent nature and the consequent need for effective storage solutions.

The exploration of energy storage technologies, notably lithium-ion batteries, hydrogen, and methanol, revealed their critical role in bridging the gap between renewable energy production and consumption. The thesis emphasized the importance of these technologies in stabilizing the grid and enabling a more consistent energy supply.

Advanced technologies such as IoT and Big Data have been shown to be instrumental in optimizing the energy storage process. The integration of these technologies enables more efficient management and monitoring of energy systems, ensuring that renewable energy resources are utilized effectively and sustainably.

Key findings of this research include:

Renewable Energy Integration: The successful integration of renewable energy into the power grid is heavily dependent on the development of robust and efficient energy storage systems.

Technology Synergy: The convergence of IoT, Big Data, AI, and Edge Computing with renewable energy storage presents a promising pathway towards optimizing energy systems and enhancing grid stability.

Challenges and Solutions: Despite the advancements in renewable energy and storage technologies, challenges such as cost, scalability, and environmental impact remain. Continued innovation and policy support are essential to overcome these hurdles.

In conclusion, the journey towards a sustainable energy future is complex and multifaceted, requiring the integration of renewable energy sources with advanced storage methods and technologies. This thesis has demonstrated that the key to harnessing the full potential of renewable energy lies in the development of efficient storage solutions and the strategic use of cutting-edge technologies like IoT, Big Data, AI, and Edge Computing.

The findings underscore the necessity of continued research and development in these areas. As we advance, it is crucial to address the remaining challenges through innovative solutions and supportive policies. The ultimate goal is to create a sustainable, reliable, and efficient energy system that leverages the strengths of renewable resources and modern technology.

This thesis contributes to the ongoing discourse on renewable energy and storage, offering insights into how advanced technologies can be integrated to enhance the efficiency and reliability of renewable energy systems. The future of energy is undeniably green, and with continued innovation and collaboration, a sustainable and resilient energy landscape is within reach.

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