VAASAN AMMATTIKORKEAKOULU
UNIVERSITY OF APPLIED SCIENCES

Shubham Mishra

Adeel Aziz

ROLE OF ARTIFICIAL INTELLIGENCE AIDED INSPECTION METHODS FOR SUSTAINABLE PERIODIC MAINTENANCE AND RENOVATION OF RENEWABLE ENERGY SYSTEMS PROJECT

A Literature Review

Technology and Communication

ACKNOWLEDGMENTS

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With Best Regards,

Shubham Mishra & Adeel Aziz

VAMK, Vaasa, Finland.

VAASAN AMMATTIKORKEAKOULU
UNIVERSITY OF APPLIED SCIENCES Project Management

ABSTRACT

Author Adee Aziz, Shubham Mishra
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This thesis explores the integration of Artificial Intelligence (AI) to enhance the performance, maintenance, and sustainability of renewable energy projects. The primary objectives are to identify AI methods and techniques for detecting defects, faults, and anomalies in renewable energy systems; analyse AI's role in contributing to the longevity and sustainability of these projects through predictive maintenance and optimized operations; and provide insights into the most suitable AI algorithms for detecting defects in renewable energy equipment.

A systematic literature review was conducted, categorized into sections focusing on general renewable energy, AI, wind energy, solar energy, hydropower energy, and combined wind/solar energy sectors.

The findings reveal that AI-supported inspection processes significantly contribute to the sustainability and longevity of renewable energy projects. Techniques such as computer vision, machine learning, anomaly detection, time series analysis, and reinforcement learning were found effective in diagnosing faults and optimizing system operations. The research concludes that AI-supported inspection processes enhance the longevity and efficiency of renewable energy systems by providing proactive, data-driven maintenance solutions.

Keywords: Artificial Intelligence, inspection methods, renewable energy, sustainability

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ABBREVIATIONS USED

ABBREVIATIONS	
AI	Artificial Intelligence
CNN	Convolutional Neural Network
DQN	Deep Q-Learning
DRL	Deep Reinforcement Learning
TN	Target Network
AN	Action Network
EL	Electroluminescence
RNN	Recurrent Neural Network
WTB	Wind Turbine Blade
LSTM	Long Short-Term Memory Networks
SCADA	Supervisory Control and Data Acquisition
IM	Induction Motors
GBM	Gradient Boosting Machines
ML	Machine Learning
R-CNN	Region Base Convolutional Neural Network
VAMK	Vaasa University of Applied Sciences
IR	Infra-Red
ReLU	Rectified Linear Unit
GR	Gaussian regression
PSO	Particle Swarm Optimization (PSO)
GA	Genetic Algorithm
MLR	Multi-Linear Regression
STFT	Short Term Fourier Transform
PV	Photovoltaic
ARIMAX	Auto-Regressive Integrated Moving Average with Exogenous variables.
WI-FI	Wireless Fidelity
WT	Wind Turbine
ANFIS	Adaptive Network-Based Fuzzy Inference system
ANN	Artificial Neural Network
YOLO	You only look Once
SSD	Single Shot Multi-Box Detector
MCDM	Multi-Criteria Decision Making
SVM	Support Vector Machine
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
AC Voltage	Alternating Current Voltage
DC Voltage	Direct Current Voltage

1 INTRODUCTION

The economy of the world is primarily dependant on the efficient production of power and electricity and further its management to address our needs. Old methods of power production are not good for climatic stability and are constantly affecting the global climate. Renewable energy sources, such as solar, wind, hydro, biomass, and geothermal energy, are abundant and naturally replenished. They emit minimal or no greenhouse gases or pollutants into the atmosphere. (Nations, 2024). Fossil fuels remain the primary source of global energy, comprising over 80 percent of production; however, cleaner energy sources are increasingly being adopted. Presently, approximately 29 percent of electricity is generated from renewable sources. (Nations, 2024). Renewable sources will be driving to a safer future by reducing the amount of carbon emissions to the ecosystem. Around 30 million jobs are expected to be created by 2030. (Nations, 2024). With the growth we are seeing right now, it is expected that a total of 90 % of total world electricity production shall be coming from renewable sources. (Nations, 2024). With the constant shift towards renewable energy sources, we can see its expected demand in buildings, various industries, agriculture, and transport. Please see below Figure 1. showing the status of total renewable energy consumption for various sectors.

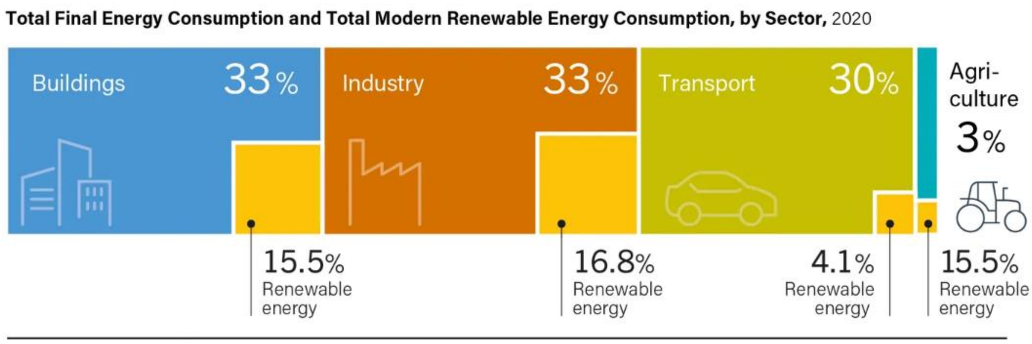


Figure 1. Total Energy Consumption by Sector, (Report, 2023)

As per the statistics gathered and released in the latest report of total energy consumption in buildings and daily home usages is 33 percent, in industry 33 percent, in transportation 30 percent and in agriculture it is 3 percent. The countries are empowering their policies with the moto of increasing the renewable energy production. (Report, 2023). A lot of countries are now aligning policies to enhance renewable energy consumption in various forms. Agriculture and transport have achieved a growth rate of adoption with more than seven percent increment. Please refer below Figure 2. representing the total modern renewable energy consumption by sectors.

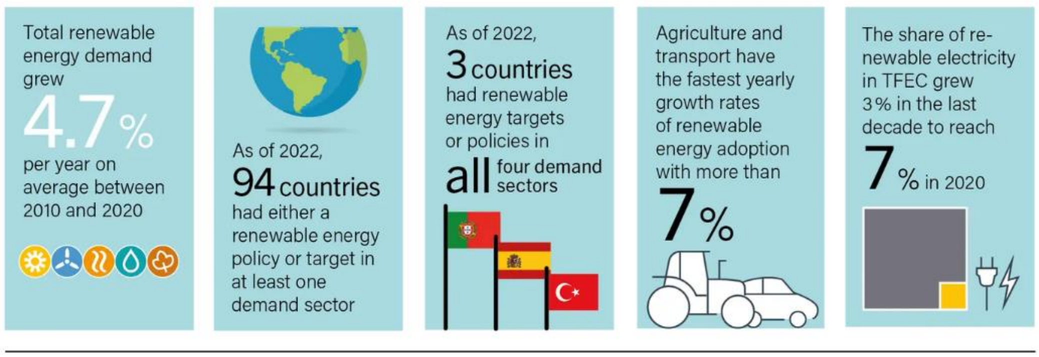


Figure 2. Total Modern Renewable Energy Consumption by sector, (Report, 2023)

The increment in energy consumption can be depicted in REN21 latest report showing the upward notion for its usage in all the four major consumption sectors. (Report, 2023). REN21 is a policy network and a multistakeholder governance group which is focused on renewable energy policy. It provides updates and reports related to latest developments and enhancements made in renewable energy sector. Electricity shares and renewable electricity shares have also seen a surge in the consumption values. Their utilization in each industry including building, industry, transport and agriculture have been increased. Please see below Figure 3. depicting the growth made in renewable energy consumption in building, industry, transport, and agricultural sector.

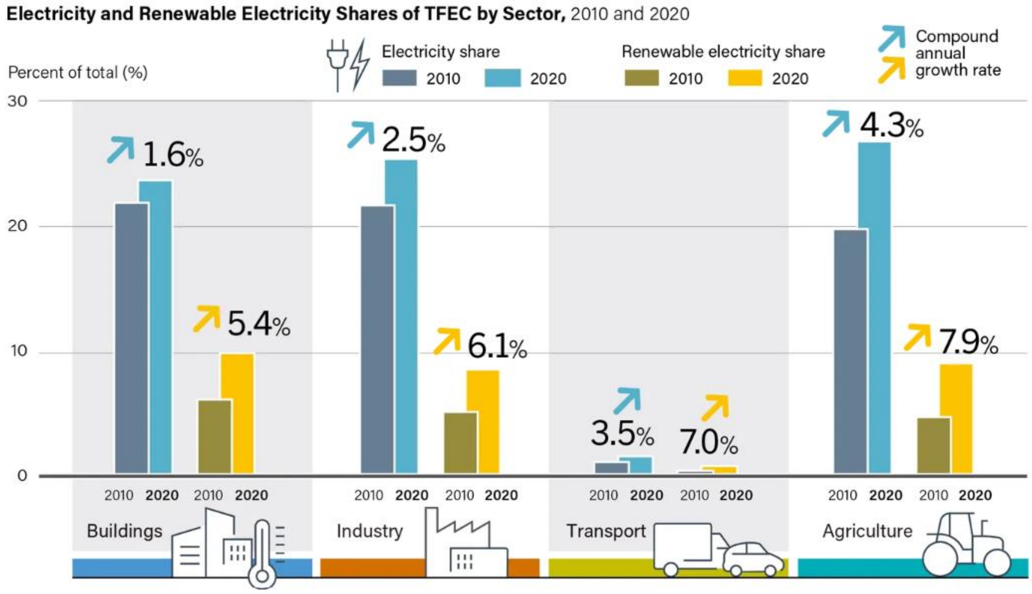


Figure 3. Electricity and Electricity Shares of TFEC by Sector, 2010 to 2020, (Report, 2023)

According to IEA's latest report on renewable energy market, an updated renewable electricity net annual capacity can be shown in below figure. Please see below Figure 4. showing all renewable sources from 2016 to 2021 providing up to 300 GW.

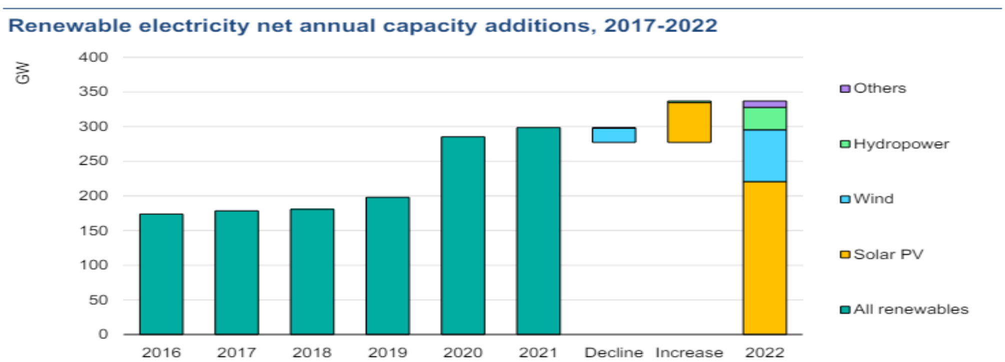


Figure 4. Renewable Electricity Net Annual Capacity Additions, 2017-2022, (Agency, 2024)

Solar PV renewable sources have seen an upward rise whereas hydropower renewable energy source has declined moving into 2022. Net renewable electricity capacity additions with respect to technology is observed to be mainly in offshore and onshore wind farms industry and PV based solar energy. Bio energy and hydropower energies have slight addition to an overall addition to electricity capacity addition. Please see below Figure 5. showing the historical data from year 2017 to 2022 followed by recent additions to the electricity capacity for the year 2023 and 2024.

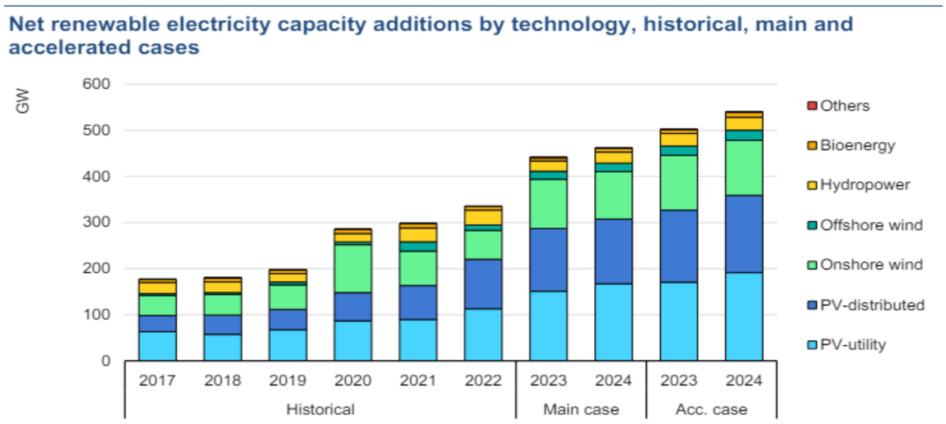


Figure 5. Net Renewable Electricity Capacity Additions by Technology, Historical, Main, and Accelerated Cases, (Agency, 2024)

1.1 Research Gap

In the recent past, we have seen good contributions on Artificial Intelligence support in various fields such as health Care, economics and finance, power plant operation and maintenance Industry, robotics, machine Learning, agriculture, automobiles, cyber security, chat bots, social media, etc. The most furnished information that could address artificial intelligence and its role in renewable energy systems was presented in (Sunil Kr. Jhaa, 2017).It depicted the role of all three major sources of renewable energy by defining artificial intelligence's specific role in design, optimization, control, distribution, and management; however, it did not address the AI role in maintenance and inspection assistance on renewable energy systems projects. A profound approach and explanation of AI's role in renewable energy applications in the building was explained in Kalogirou (2005). AI's role in Micro-Grids integration and their relative management of hybrid renewable energy sources models were described (Talaat, 2023).These research works had good approach however it did not address the electrical equipment in renewable energy projects and overall did not include the remaining sectors of renewable energy. We can see important knowledge sharing and explanation of AI benefits for cyber security enhancement (Basnet, 2022). AI and its deepening effects on financial systems specifically dealing in purchase invoices have been well explained by (Jalonen, 2023). B2B business ventures and AI's role in boosting business development have been captured under (Fahli, 2021).

These research topics had good information on AI techniques for business related sectors; however, they were far away from our actual required study on renewable energy system projects. To signify the importance of logistics that are developed by the useful integration of AI techniques into the logistics field have been narrated through (Bogomolova, 2023). The topic was very informative; it still lags any reference and inclusion of renewable energy projects. AI contribution in supporting marketing strategy in project management with the utilization of data and statistics has been captured in (Araf, 2023).

Renewable energy projects and industries affiliation has also been signified in various research works. Atomization and optimization impact of domestic renewable energy for production and storage in electrical vehicles has been explained in (Manyonje, 2023). The research work profoundly explained the latest AI developments in electrical vehicles however it did not provide any composite and authentic information towards our subject Work. Electricity generation and its enhancement from renewable sources in Finland has been explained in (Pozdnyakova, 2009). Utilization of fossil fuels to renewable sources of energy with minimum environment effects and low carbon emission policy was the conceptual study, texted in (Ndonku, 2022). Certain AI techniques and their utilization in renewable energy was addressed during the research; however, it did not encapsulate our intended study portion of AI methods and their role in maintenance of renewable energy system projects.

To measure the potential of renewable energy, a well-written thesis has been studied in which the author evaluated the complete presence of 6 major renewable energy systems available in Finland namely wind power, solar power, bio energy, geothermal heat pumps, hydropower, and untapped potential hydropower. Actual electrical usage for each region was compared and evaluated to the potential that these regions possessed. (Shanab, 2015) However, it was a region-based study and did not concluded role of AI in renewable energy system projects. An informative thesis for developing methods for cooling real estates, industrial processes and premises was studied for significance in building management system (Lipsanen, 2019). The thesis covered only building sector and did specify its support in renewable energy system projects.

We can see a good approach in the research work, (Latifa A. Yousef, 2023) showing summary of methods in which artificial intelligence (AI) techniques have been applied in the management of variable renewable energy however it covered mainly Machine Learning and Deep Learning methods and that was not specifically related to any renewable energy system's equipment. A good research work and data analysis was made by (Gu, 2020) on the integration of renewable energy in distribution systems using AI and had maximum techniques addressed. The research work did address the functioning of AI technique however it did not cover all the aspect of renewable energy and had partial information and knowledge related to a single technique.

After the review of relative research work on AI it can be observed that there is not much work available related to utilization of AI techniques and methods in renewable energy projects in these articles, journals and research works and none of them specifically addressed the AI role in maintenance and inspection of renewable energy system projects.

1.2 Research Objectives

We will be exploring the data and information gathered from various latest peer reviewed articles, journals, research work, international websites, relative reports and writings to provide the knowledge on renewable energy projects. Furthermore, the same data shall be utilized for defining role of AI in enhancing performance and maintenance of renewable energy system projects. We will be focusing on major sources of renewable energy in this regard.

Moreover, we will source information from various citations to explain AI methods and techniques utilized in renewable energy projects for finding defects, flaws, faults, abnormalities, and anomalies in renewable energy system projects. This shall include the utilization of various AI techniques and methods combined into better working models. This research shall include knowledge for effective utilization of most suitable AI algorithms or models for detecting and analysing defects in renewable energy equipment. These models when incorporated into inspection process shall contribute to overall sustainability and longevity of renewable energy system projects with its support in periodic maintenance and renovation of renewable energy systems project for efficient performance and functioning.

1.3 Research Questions

Based on the above objectives, the following research questions are addressed.

Question No. 1.
How can AI-supported inspection processes contribute to the overall sustainability and longevity of renewable energy system projects?

Question No. 2.
What are the most suitable AI algorithms or models for detecting defects in renewable energy equipment?

The first question addresses the sources and importance of renewable energy projects. Brief knowledge and information regarding the major sources of renewable energy sectors shall be included while addressing this question. Furthermore, it includes information regarding the role of AI aided inspection methods and techniques employed in renewable energy sector. It explores how AI-supported inspections can enhance sustainability and longevity by reducing the duration of inactivity, optimizing the timing of maintenance tasks, and decreasing the utilization of resources.

The second question will be answered by examining various AI techniques, such as machine learning, computer vision, and neural networks, utilized during the inspection and surveillance of equipment, devices, and instruments of renewable energy systems projects. The thesis will explain the inspection process advantages and its employment in renewable project equipment such solar panels, wind turbines, inverters, mounting structures, and electrical and monitoring systems to enhance their production and operational capabilities.

1.4 Structure of the Thesis

The research is structured into six chapters in all, each serving a specific purpose in the overall thesis writing. Chapter 1 will end with this section.

Chapter 2 explains the methodology utilized for writing this thesis, narrating how we have carried out the literature review. It includes the explanation of the process and methodology utilized by us to process the review of various articles, journals, online material, previous work from scholars etc. All the stages that we have gone through, for finalization of the content, shall be explained in it.

Chapter 3 explains the primary part of literature review by providing the overview on the renewable energy systems projects. It includes all the major kinds of renewable energy system projects and details regarding their operation and maintenance. This section also provides brief knowledge and information on functioning of each one of them. Moreover, we shall also explain advantages and disadvantages of renewable energy system projects.

Chapter 4 provides detailed study on secondary part of literature review by describing all major AI techniques and methods utilised during inspection process for analysing defects, faults and flaws of equipment and devices of renewable energy system. Their support in measurement and detection of abnormalities and anomalies for the same equipment shall also be explained in detail. We will describe each AI techniques stepwise and its utilization during inspection process.

Chapter 5 provides the outcome of the literature review which include the results made after studying the reference materials and citations. We have identified and segregated the references into respective renewable energy categories and sections.

Chapter 6 narrates the conclusion of the thesis by providing the answers to the research questions with regards to the literature review presented in above sections. In addition to that it includes utilization of various AI techniques and methods in our study references for addressing this literature review. Moreover, future discussion and ethical considerations noted by us have been included in this section as well. We found three main limitations to our literature review study, and we included in this portion in the last heading of this section.

2 LITERATURE REVIEW AS METHODOLOGY AND DATA COLLECTION

This research employs a systematic literature review to examine the gathered studies on renewable energy projects and role of AI aided techniques and methods in renewable energy projects. The aim is to enhance existing knowledge, support and explain various developments in recent times in overall AI methods and techniques for sustainable development in renewable energy system projects. A total of 63 study references were utilized to write down this thesis.

2.1 Search Strategy

Key words such as “Artificial Intelligence”, “Inspection Methods”, “Renewable Energy”, “Sustainability” were used for finding articles, journals and previous research works by scholars and students. The search strategy combined all notions searched together and separately as well. Boolean Operators were used to have link between keywords such as “and, or not”. This helped in processing the right phrase intended for search. Relative filters intended to get the required article, journals, and thesis was provided to search engines as well. Websites including but not limited to Google Scholar, VAMK Tritonia, MDPI, Mendeley and Research Gate were utilized to search the required material. This wide range of databases ensures a comprehensive search for relevant articles. Each platform provided a lot of articles on each keyword searched for. After each search there was skimming performed on topics and title of search produced material. Source credibility was evaluated for future inclusion in thesis.

2.2 Filtration for Selection Criteria

The search carried out was not specific to any publication time, place, location, or institution. We had in our minds that whatever article that is not going to address the research objective shall be discarded. The dissertation was made based on the article topic and abstract of the thesis. A total of 387 research supporting references were downloaded and checked to address each aspect of thesis however after early screening their number was reduced to 124. After reading through these set of articles, journals, and research works, we observed that 61 do not directly address our concerns and thus the number were then reduced to 63 which were finally shortlisted to be made part of our thesis.

2.3 Research Approach Outcome

This study conducted a thorough analysis of 63 study materials (articles, journals, on-line links, organization websites and other research works) emphasizing on renewable energy and utilization of AI aided inspection methods for maintenance of renewable energy equipment. Among these, 3 references were used to address the introduction part of the thesis. To define the research gap and objective we needed a thorough study of the articles that were close to our study topic, or which partially addressed our subject. We concluded this very important section with 15 articles from recent past. To explain the renewable energy sources and AI advances in major renewable energy projects we needed extensive data and information. It took 21 study references from various research work and articles to pen down literature review for section 3. To explain the AI methods and techniques utilized in renewable energy projects, 24 articles and references were used.

3 RENEWABLE ENERGY SYSTEM PROJECTS

3.1 Renewable Energy

Renewable energy is the energy that is taken from natural sources that possess a continuous source of energy and on the timeline, scale does not vanish or is minimized. Renewable energy consists of a major part of the world's energy supply. These encompass sunlight, wind, rain, tides, waves, and geothermal heat. In contrast to finite fossil fuels, renewable sources offer cleaner options with notably lower environmental footprints. Mainly, we can categorize renewable in 5 major sources of energy. (Nura Garba, 2024). Please see below Figure 6. presenting the major renewable energy sources.

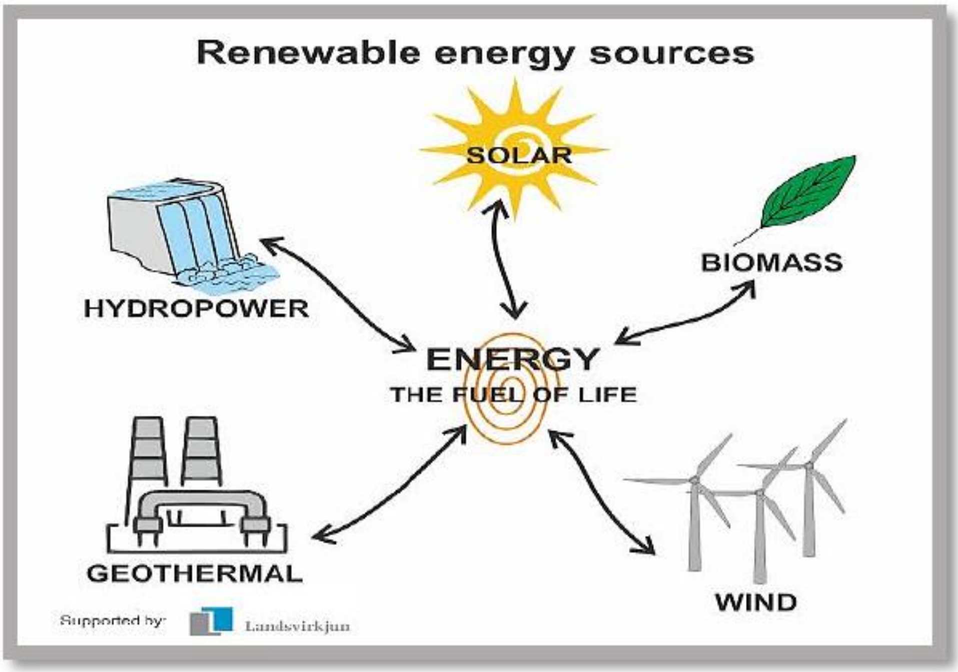


Figure 6. Major Renewable Energy Sources, (Nura Garba, 2024)

Solar energy is taken from sunlight with the application of solar farms using solar panels. Wind energy is generated by converting the energy from the wind by utilizing turbines. The source of energy conversion is based on the kinetic energy induced by the flowing wind. Hydroelectric energy is produced by fluid (water) flow generating the energy which is captured though generators. Water is once stored in dams and reservoirs and then allowed to move in one downward direction with speed to generate energy. Biomass energy is produced by waste material utilization and natural consumables which helps in generating energy. Geothermal energy is the energy produced from the under-earth reservoirs by extracting hot water and steam. (Nura Garba, 2024)

Renewable energy demand and utilization has seen a considerable growth in recent past. Its primary utilization can be depicted from below figure with a rapid growth shown in its past and expected usage in future. In 2035 it is expected to be raised to 20 % in transport, 25 % in heat Demand and 31 % in electricity consumption. (Hosam M. Saleh, 2023). Please see below Figure 7. for graphical representation of renewable energy with respect to its utilization.

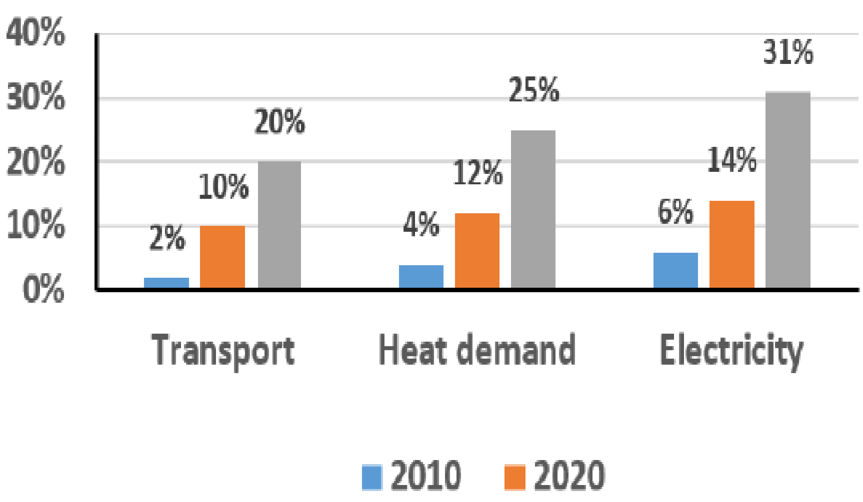


Figure 7. Allocation of Renewable Energy Sources with Respect to Utilization. (Hosam M. Saleh, 2023)

3.1.1 Advantages of renewable energies

Renewable energy provides a sustainable and infinite supply of energy. The error and faultiness percentage are lower than other energy supply sources. It provides reduced greenhouse gas emissions and thus supports a viable and healthy environment. To run the operations a very low cost is required. There is no special need of equipment, devices, or instruments to run the ongoing energy production. With new developed business creation in renewable energy sector, the job creation ratio is expected to increase.

3.1.2 Disadvantages of renewable energies

Renewable energy projects require high initial value to be constructed. The initial assembly and deployment of equipment and machinery require a lot of cost. Furthermore, the whole new setup requires land and water reservoir requirements that must be fulfilled prior to functioning of the whole plant. For wind farms, a large area is required for operations. Similarly, for hydroelectric plants we require big water reservoir and Dams for operations. We face geographical limitations in which we must operate and does not have liberty to construct or to build anywhere without the presence of these resources (Zand, 2024).

Renewable energy consumption has increased with the passage of time and the rate is intended to escalate further. An intended estimation has been predicted and shown in (Hosam M. Saleh, 2023). Please see below Figure 8. shown in the form of graph with its representation.

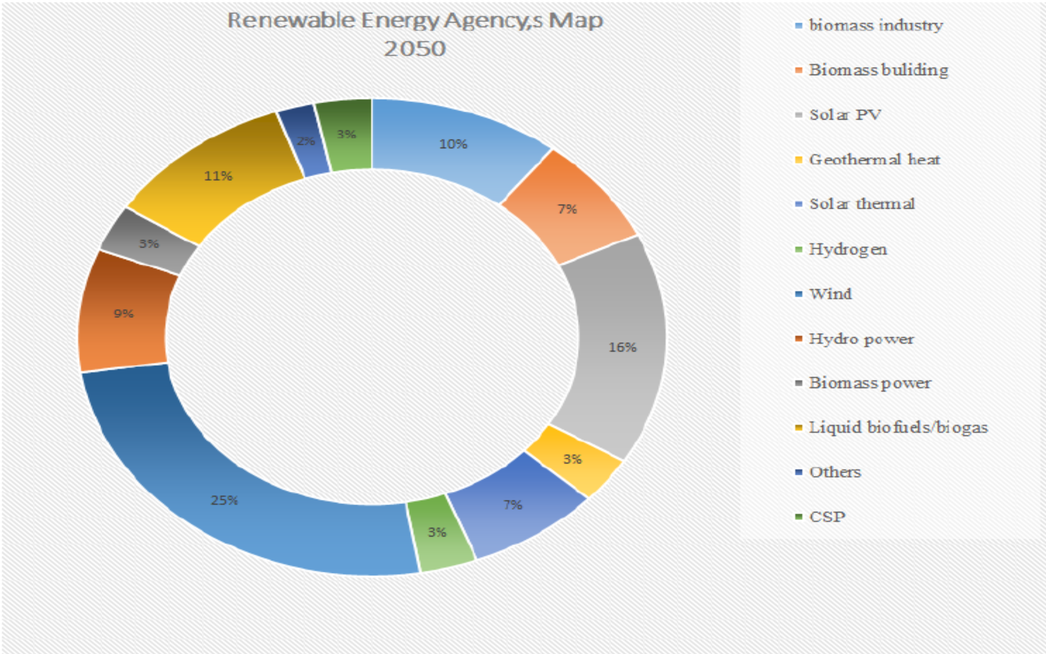


Figure 8. Deployment of sources if Renewables in Terms of total final energy consumption according to REA, (Hosam M. Saleh, 2023)

Solar Energy, Wind Energy and Hydro-Power energy are major source of Renewable Energy and mostly used by human beings for extraction and production of energy from natural means. The projects developed and executed to generate renewable energy are termed as Renewable Energy System Projects.

3.2 Solar Energy Projects

Solar energy projects consist of a wide variety of applications utilizing solar radiations to generate electricity or provide power supply for various implementations. Solar energy projects have multi scale installations engineered to produce solar energy and convert it into power. They usually involve the deployment of solar panels or solar collectors which collect sunlight and change it into electricity using photovoltaic effect. Solar power plants capacity has increased in the recent past and their installation numbers have also escalated. Please see below Figure 9. specifying the solar farms installation capacity with respect to each region.

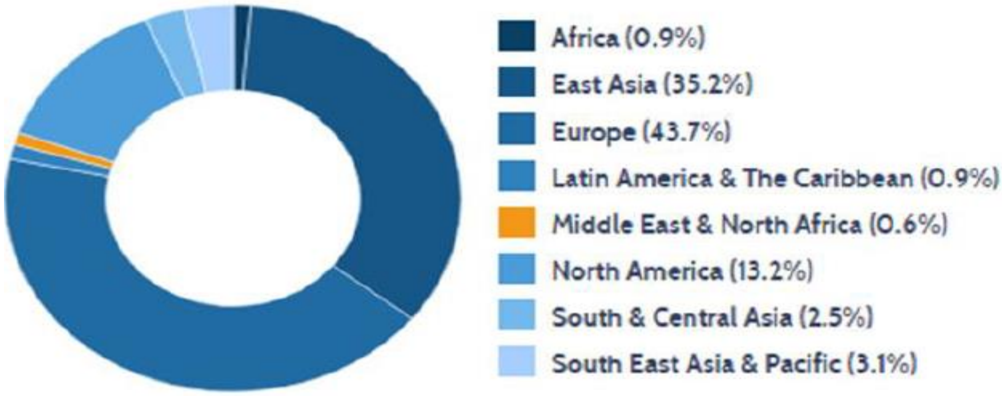


Figure 9. Capacity of Solar Farms installed with respect to each region (World Energy Council 2016), (Deeb, 2019)

Solar Power plants are built on larger scale in open areas with wide availability of land and good source of Sunlight. Please see below Figure 10. indicating installation of Solar farms in various plains.

Figure 10. Installation Solar Energy Power projects, (Tanay Birişçi, 2023)

Amount of sunlight is the main factor for deciding the location of solar pant installation. There are a few other factors which shall also be considered and helps in finding out the total amount of forecasted solar energy such as its geographical location, weather conditions, the seasons of the region and its duration they face, and local area landscape. The sunlight is received by the solar panels in 2 forms that is direct sunlight and diffuse sunlight. Diffuse sunlight is the minimal sunlight that reaches the solar panels after it has been reduced due to a lot of environments and surrounding limiting factors including dirt, scattering, deflections, and reflections etc. Direct sunlight is the sunlight received directly by solar panels without any interruptions. Solar panels are then put to function to convert the solar energy to electricity and power needs. It is expressed in kilowatt hours. (Jingcheng, 2010).

Solar Panels work on the principle of Photovoltaic effect. Solar cells are the main components of Solar panels. (Sitaula, 2018). Please see below Figure 11. showing a schematic diagram for a conventional solar cell.

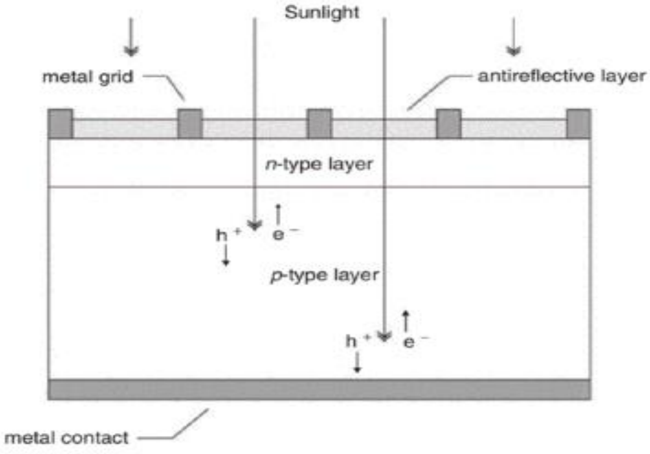


Figure 11. A Conventional Solar Cell (Sitaula, 2018).

They are various types of PV cells including Mono-crystalline, Poly-crystalline and Thin Film. Their usage in various solar farms is dependent on the solar power plant requirements. Apart from their usage, the installation does play an important role to get the maximum output and efficiency of solar cells. Please see below Figure 12,13 and 14. presenting a mono crystalline Solar Panel, Polycrystalline and Thin Film Solar Panel respectively.

Figure 12. Môn crystalline Solar Panel (Deeb, 2019)

Figure 13. Polycrystalline Solar Panel (Deeb, 2019)

Figure 14. Thin Filmed Solar Panel (Deeb, 2019)

Solar panels can also be built on smaller scales and for home and house usages. A web-based solar system for roof top application is an economical model which can be used for long-term in-house usages. A web-based roof top- complete solar system includes Solar cells, DC voltage supply, AC voltage supply, the solar converters, distribution components, micro controller and WIFI module. (Angga Wahyu Aditya, 2023). Please see below Figure 15. showing a flow chart diagram for a web based low-cost solar power plant for household application.

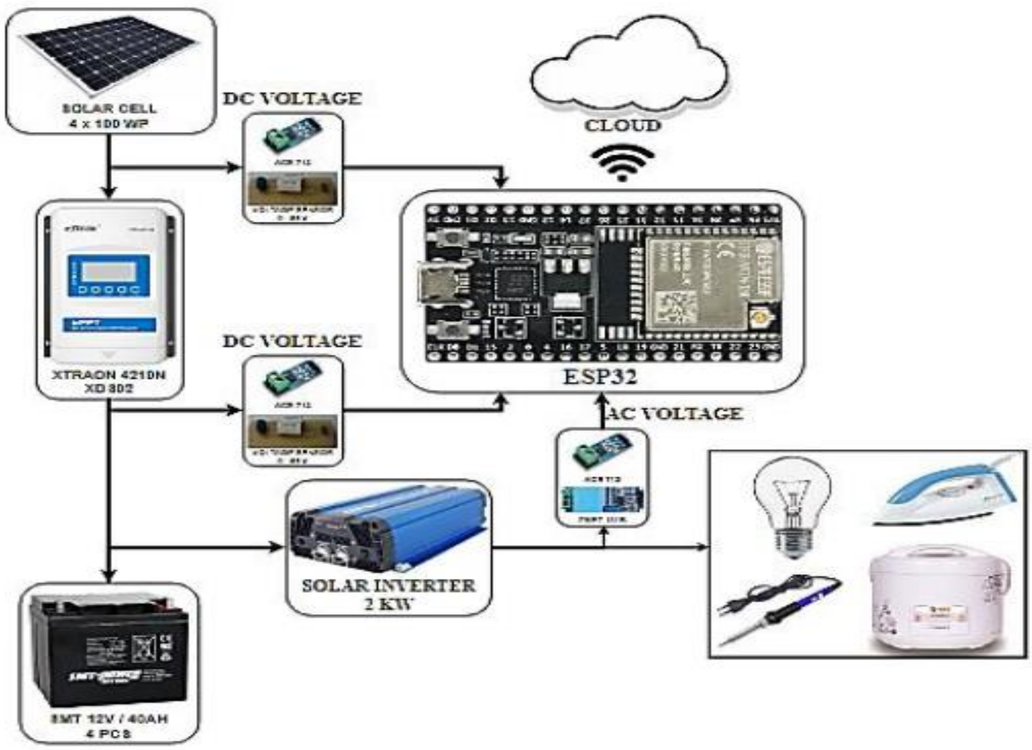


Figure 15. Process Flow Diagram for a Web-based low–cost solar power plant installed on a roof (Angga Wahyu Aditya, 2023).

3.3 Wind Energy Projects

Wind energy projects are the kind of renewable energy projects that are executed by utilizing wind power for generating electricity. These projects typically involve the installation of wind turbines in areas having larger wind availability, such as open coastal areas, deserts, and offshore regions. (Carlos Cacciuttolo, 2024). Please see below Figure 16. showing installation of various wind turbines power projects from various regions.

Figure 16. Wind Turbines Power Projects Installed in Various Regions (Carlos Cacciuttolo, 2024)

Commonly they are categorised between off-shore and on-shore wind farms. On-shore projects can be constructed from small projects to large scale projects covering hundreds of acres of land whereas offshore wind farms are only constructed in water bodies, usually in coastal areas or off- shore locations. These projects usually have larger turbines and can benefit from stronger and more consistent wind speeds however we can observe them to be more difficult to revamp and maintain. Recently there have been newly developed models prepared and functioned by integration of wind and solar power systems. Such hybrid models are good to function and carry a lot of benefits for energy production. They are more reliable in consistently providing power and energy.

A typical wind energy system includes wind turbines, foundation, electrical Infrastructure, controlling system, civil Infrastructure and grid Connection (Mudhar, 2024).Please see below Figure 17. showing a typical wind energy system.

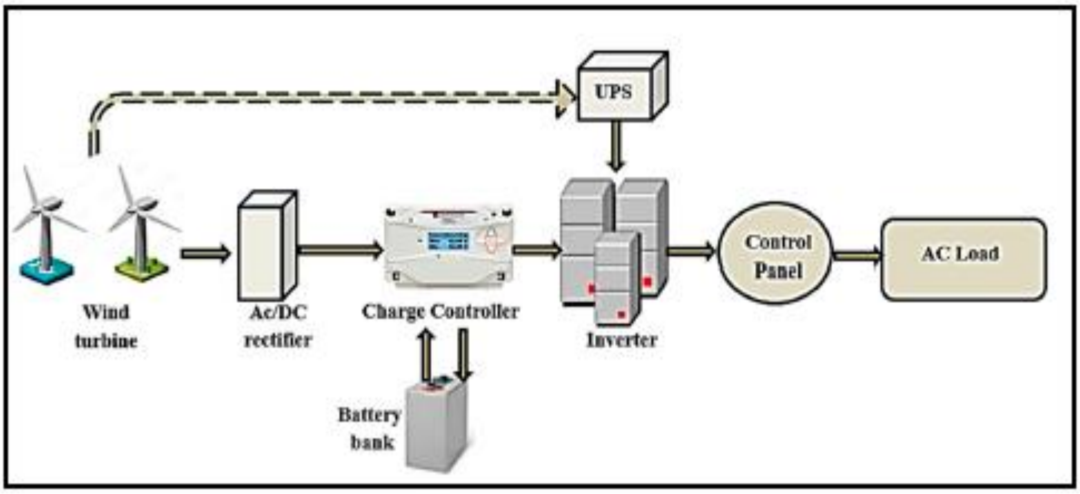


Figure 17. A Typical Wind Energy System, (Mudhar, 2024)

Wind energy produced is utilized in various functions. The energy output is measured by the amount of wind energy produced by the turbines. It is mostly environmentally friendly source of renewable energy. Please see below Figure 18. showing Wind Energy utilization in running a desalination plant.

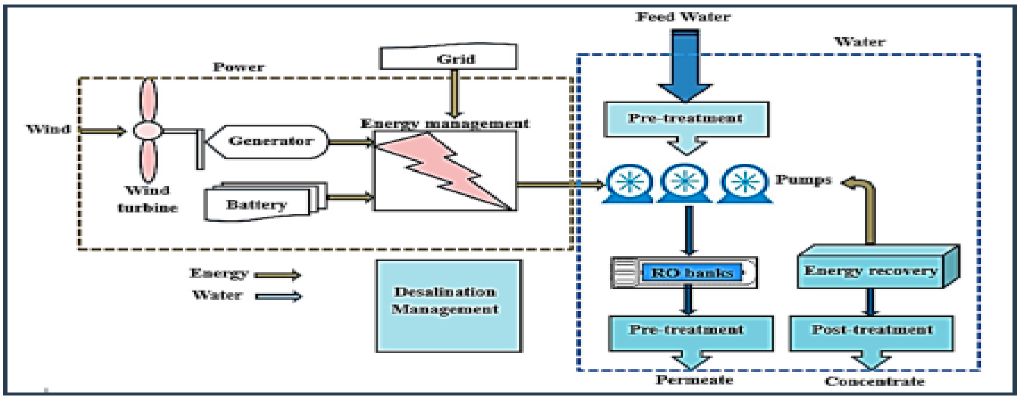


Figure 18. A Representation of a Typical Wind Driven Desalination Plant, (Mudhar, 2024)

Similarly, wind energy systems are also used to govern large scale projects and facilities. They can be used to run thermal energy storage units as well. The energy production can be gathered in a 2 step multi-function operation. Please see below Figure 19. showing a thermal energy storage system using a two-tank principle.

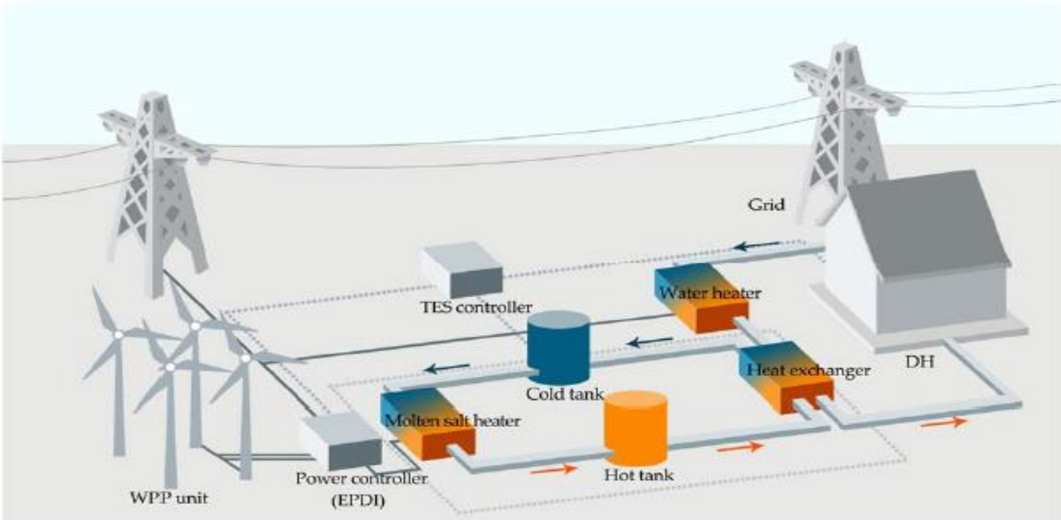


Figure 19. Diagram of the WTES (wind-thermal energy storage) system using Two-Tank Theory. (Chang Liu, 2017)

The major equipment or we can say system component responsible for the energy production is the wind turbine. Wind turbine can primarily be classified into 2 main kinds. The horizontal axis wind turbines are mostly utilized in wind sector since they induce more efficiency and produce more electricity than vertical axis wind turbine. VAWTs are presented in the system near the earth and thus less accessed to the wind, generating less power production; they are built in with less reliability. In addition, VAWTs have a high cost since they require more material and far larger size than HAWT to generate the same amount of output as HAWT. (Enas Taha, 2023). There are other types of turbines however there use and employment is limited to certain material specification and project requirements. Please see below Figure 20. showing pictorial representation of main wind turbine types.

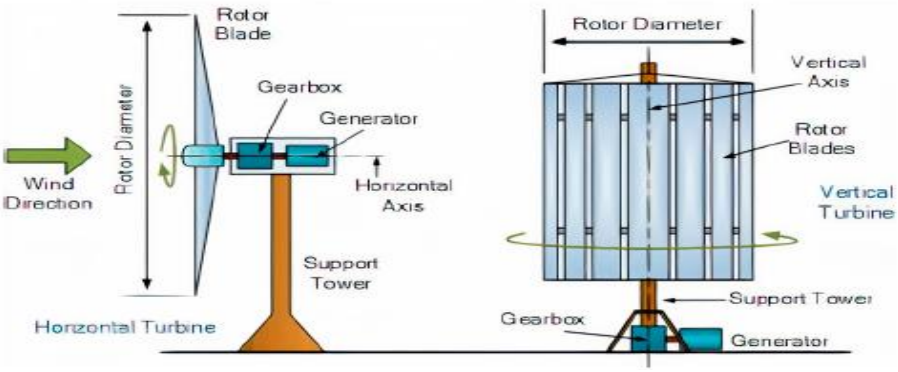


Figure 20. Wind turbine types: VAWT and HAWT, (Enas Taha, 2023)

3.4 Hydro Power Energy projects

Hydropower, also commonly stated as hydroelectric power, is a form of renewable energy that generates energy from flow or pressure of water in the form of electricity. We generally utilize dams and huge water reservoirs for concentrating water and then making it to release with force. The force of the flowing fluid moves the turbines, which then drives generators to produce electricity. Please see below Figure 21. showing a typical working of a hydropower plant.

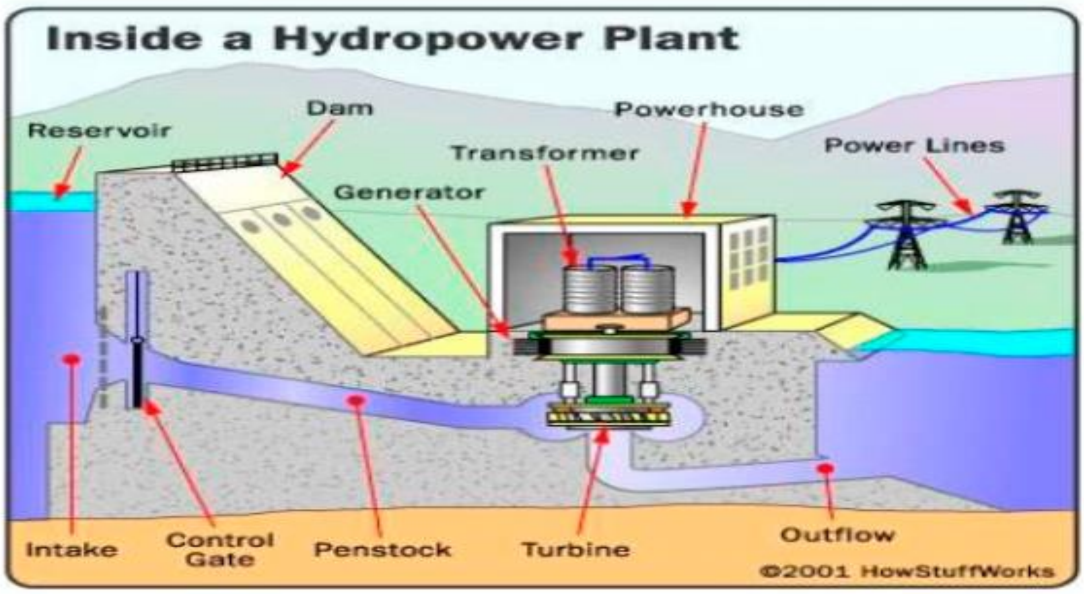


Figure 21. Hydro Power Plant, (Evrencan Özcan, 2019)

Hydro power plants can generally be classified based on the capacity and hydropower plant facility’s construction. The facility construction may take place on a riverside, on a reservoir, a pumped storage facility and on a in stream running water. Capacity wise it can be sub divided into large, medium, small, mini, micro and Pico. Please see below Figure 22. showing Hydro-power plants classification.

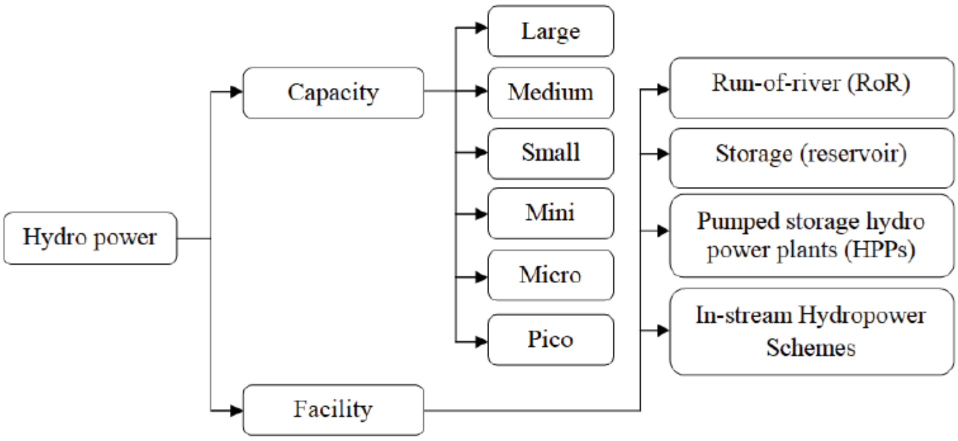


Figure 22. Hydro-Power Plants Classification, (Rajendra Prasad, 2022)

Hydro power energy projects are expected to see an increase in construction with almost double numbers by 2050 to which they were operating in 2021. Other energies majorly functioning through combustion plants are expected to be limited by a high decrement. Probably the shift with world, moving forward and focusing on renewable means of energy and easily built monitoring systems such as hydro power facilities would be preferred. (Uzakov, 2024).

Please see below Figure 23. showing graphical representation for the distribution of the amount of energy sources in the world as they were in 2021 and further as expected in 2050.

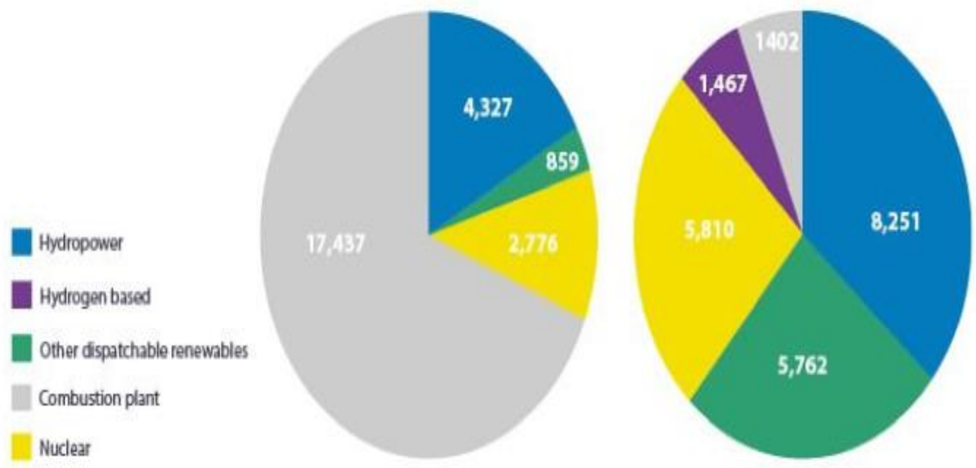


Figure 23. Distribution of the number of energy sources in the world in 2021-2050, (Uzakov, 2024)

It is the oldest method utilized in the industries and most widely used renewable energy sources globally. It produces electricity without releasing greenhouse gases or other pollutants that are usually discrete in the factories and industries. On the other hand, building a dam or water reservoirs is a way in which nature is disturbed and cause ill effects to the geological conditions of the region.

3.5 Role of AI in Solar Energy Projects:

AI aided methods and techniques play several important roles in solar energy projects. It can help in site selection, optimization of design, predictive maintenance, energy forecasting, grid integration and data analysis however its AI role in inspection comes during operation and maintenance activities only. Solar panels can be monitored in both ways that is by using human workforce and by remote monitoring systems. (Nallapaneni Manoj Kumar, 2018). Please see below Figure 24. showing various physical monitoring techniques for monitoring condition of PV cells.

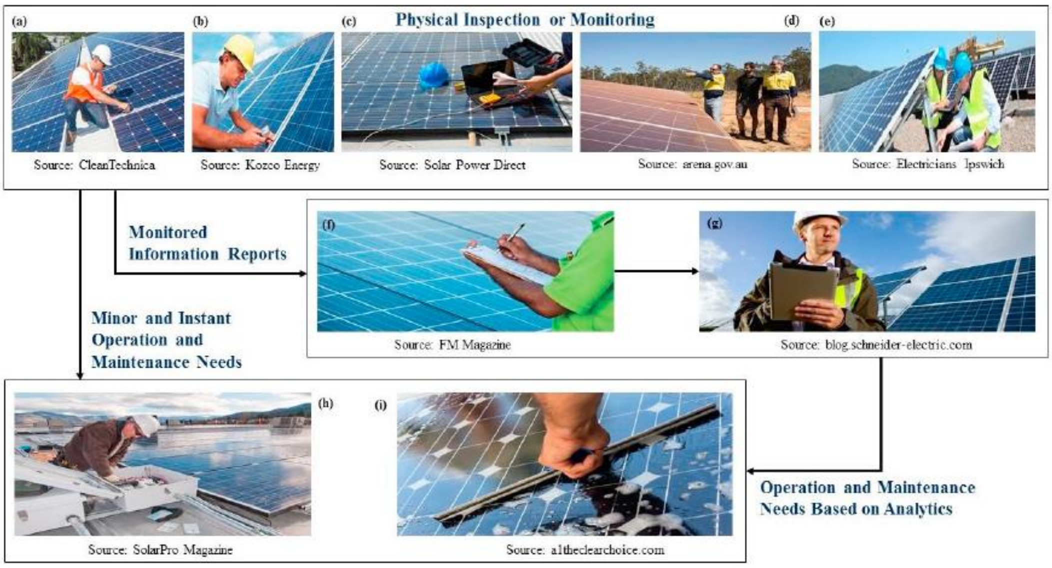


Figure 24. Methods of Physical Condition Monitoring of PV Cells, (Nallapaneni Manoj Kumar, 2018)

Physical monitoring inspection can be carried out by various techniques including String electrical parameter monitoring, array output monitoring, array monitoring and feeding the data to laptop, accumulation inspection on the PV array, installation structure monitoring, making note of monitored data on paper, making note of monitored data in Tablet, operation and maintenance execution and manual dust cleaning process. (Nallapaneni Manoj Kumar, 2018)

Actual and major utilization of AI is undertaken during remote monitoring. In this kind of mechanism, the monitoring system is equipped with the sensors, a unit to process the signals forward, means for data transmission, followed by storage of data and logging facilities. It may also base itself on the integration with cloud-based data analytics approach. (Nallapaneni Manoj Kumar, 2018)

Please see below Figure 25. showing remote monitoring techniques for condition monitoring of solar photovoltaic power plant.

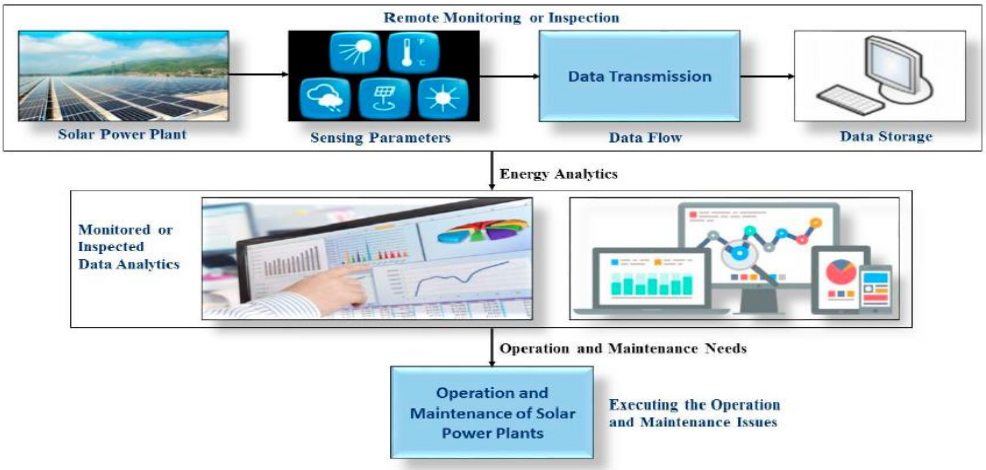


Figure 25. Condition Monitoring by Remote Methods of Solar Photovoltaic Power Plant, (Nallapaneni Manoj Kumar, 2018)

Remote inspection uses various equipment and tools to gather data remotely. Generally, drones are utilized in the industry for inspection of larger solar farms. There are 2 types of drones that are mostly utilized in this function that is Quad copter and Tri-copter Drones. Please see below Figure 26. representing various drones being utilized for the remote monitoring purpose.

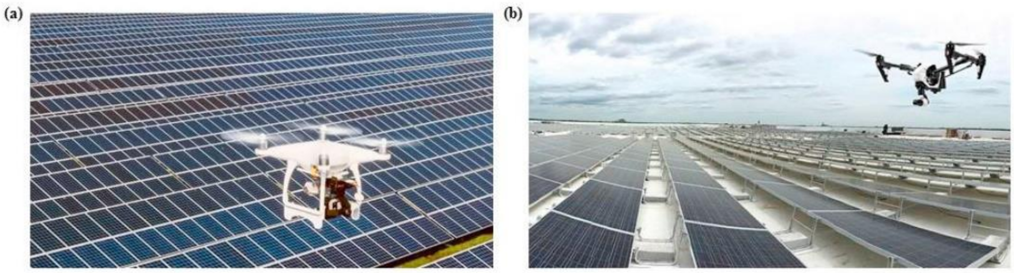


Figure 26. a) Quad copter Drone b) Tri-Copter Drone, (Nallapaneni Manoj Kumar, 2018)

Drones are fed the data with the help of Machine Learning, Recognition technologies, and Artificial Intelligence Techniques which serve as the inspection criteria while their movement across the Solar Farms. (Nallapaneni Manoj Kumar, 2018). Please see below Figure 27. showing various Artificial Intelligence techniques utilized for empowering the intelligence in drones.

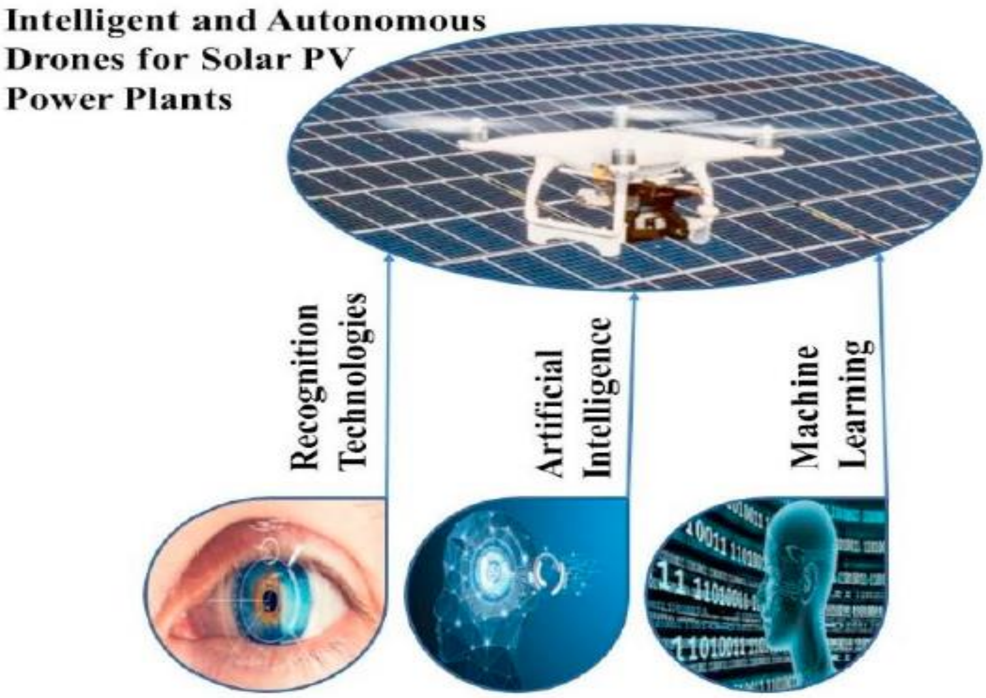


Figure 27. Technologies Empowering Intelligence in Drones, (Nallapaneni Manoj Kumar, 2018)

The facilitation provided by various technologies helps in governing the function of drone monitoring. Recognition technologies help in extracting the data and support in evaluating the thermal image and visual image of the photovoltaic module and other system components, authentication, and authorized entry. Artificial intelligence technologies are used in data processing, fault checking, historical data base fault identification, helps in communication between the drones and the working team. Machine learning provides the data to drones to learn about the process happening based on historical data and further supports strategic monitoring plans with pre-processed algorithms (Nallapaneni Manoj Kumar, 2018).

3.6 Role of AI in Wind Energy Projects:

Artificial intelligence can offer several benefits over traditional methods in wind farm inspection. AI-based inspection techniques contribute by automating the inspection procedure as they support with the validated data that can help in defining the time intervals and limiting the required resources. Drones and remote imagery with the support of AI algorithms can quickly scan effected regions of wind turbines. It can support in scalability measurement of the large wind farms and support in defining the periodic inspection dates. Moreover, it can also help in inspection of limited access areas on the equipment and thus saves a lot of maintenance cost. Wind farms can be found in off-shore as well as on-shore. An offshore wind farms are typically constructed in sea water. Usually, the aim to construct in the sea near the shore is to generate more output than the ones available in on-shore. They have strong turbines, more efficient and have less Noise effect in the communities living nearby. As far as the inspection is concerned it is somewhat difficult to handle with respect to the onshore wind farms. In- offshore farms we have strong winds and marine environment which makes operation and maintenance difficult to be managed. Transmission of energy and connectivity is another issue that we must face with off-Shore wind farms. On the other hand, On-Shore wind farms are easy to construct wind farms with less energy output and less operation and maintenance cost. Inspection procedures are easy to handle with less effort and cost. They are easy to connect with local needs such as agriculture, sewage, and drainage system to support the power needs. Taking offshore wind farms as example, please refer below picture showing complete off-Shore wind farm structure. Please see below Figure 28. showing an offshore wind farm representation.

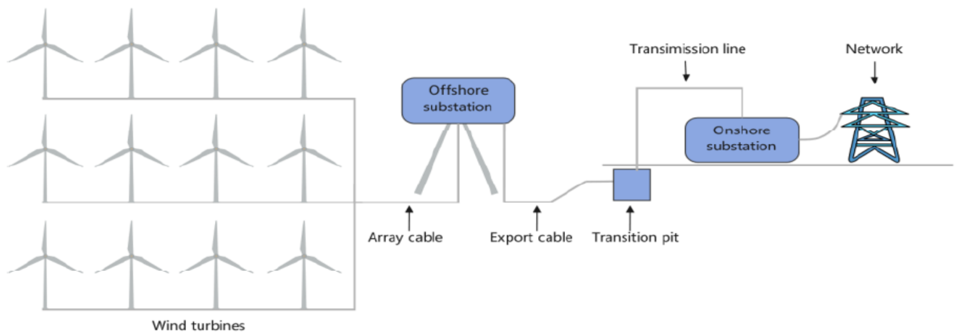


Figure 28. Off-Shore Wind Farm Structure, (Xue Zhou, 2023).

Off-Shore wind farms require continuous monitoring during its operation and maintenance process. A smart offshore wind farms can be categorized with below mentioned activities that are performed for continuous monitoring during operation and maintenance. Please see below Figure 29. showing activities for monitoring, operation and maintenance smart offshore wind farm

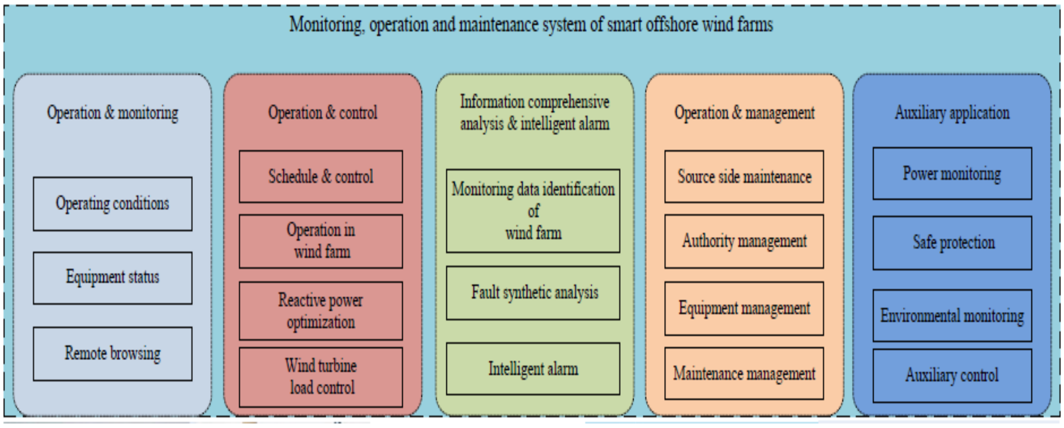


Figure 29. Monitoring, Operation and Maintenance Smart Off-Shore Wind Farm, (Lei Kou, 2022)

The monitoring of wind farms mainly includes checking the condition of wind turbines as a whole equipment which is the main functioning unit for the wind farms and mainly responsible for energy production. All the internal components are checked for its functionality and condition monitoring including tower, blades, foundation, generator, gearbox, and other remaining auxiliaries. Most time-consuming monitoring part of the wind turbine is tower that is it consumes 29.4 percent of the total amount of time required for condition monitoring followed by turbine blades that comprises of 24.9% percent. Gear box monitoring takes 14.5 percent of total time allocated while generator and foundation monitoring use 9.5 and 5.8 percent respectively. All the remaining parts of wind energy equipment takes around 15.9 percent of the whole time allocated. Please see below Figure 30. showing the percentage time chart for time required for monitoring specific part of wind turbine unit.

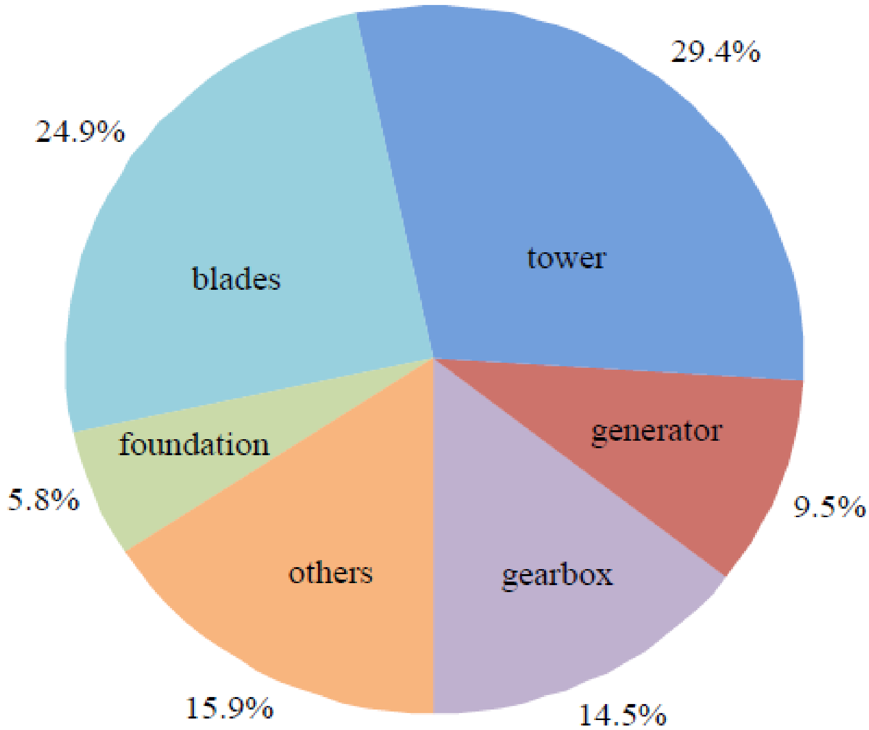


Figure 30. Time Distribution for Each Part Use in Turbine Monitoring, (Lei Kou, 2022)

AI aided techniques support in overall condition monitoring and maintenance activities of Wind Turbines. A depiction of percentage evaluation of AI techniques for wind turbine maintenance can be represented from below picture. The primary AI techniques with major utilization are artificial neural networks (ANN) with 36%. Genetic Algorithms (GA) and fuzzy logic coming in at 15% and 8% of the total research made so far. Other highlighted AI techniques are data mining with 5% and particle swarm optimization (PSO) with 4 % of publication. Categorizing various models employed for monitoring and maintenance is 10%. Rest The utilization of the rest of techniques is minor. (Fausto Pedro, 2021). Please see below Figure 31. showing percentage for distribution of various artificial intelligence techniques utilized for turbine maintenance.

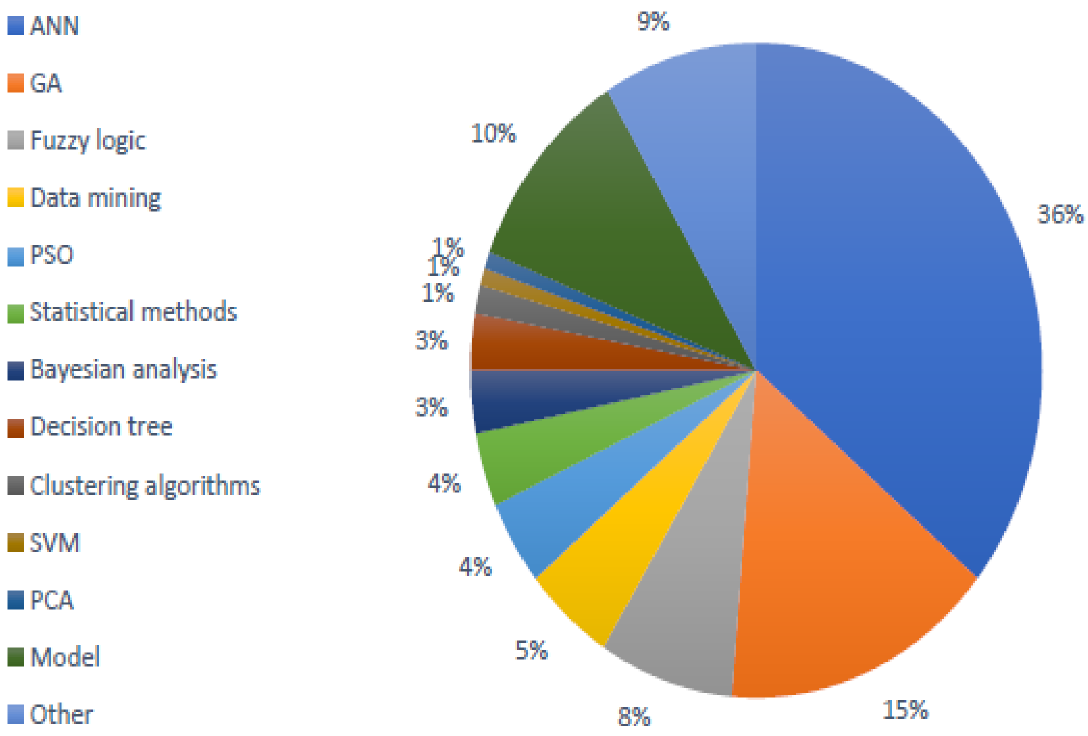


Figure 31. Various Artificial Intelligence Techniques Utilized for Wind Turbine maintenance. (Fausto Pedro, 2021)

While performing monitoring activities on wind turbine, the utilization of AI techniques can support in performing a variety of evaluations. The evaluations made helps in fault detection, optimization, decision making, planning, and scheduling, fault prediction, false alarm detection, maintenance, forecasting and Fault prevention. One technique, either alone or with the integration of other techniques may be utilized in plenty of evaluations. A model technique that can be specifically designed and put into function to support all functions. Please see below table 1. showing summary of all the applications of AI techniques utilized in wind turbine projects for measurement and evaluation of various perimeter at different instances during wind turbines projects construction, operation and maintenance.

Table 1. Summary of applications of AI techniques, (Fausto Pedro, 2021)

	ANN	GA	PSO	Fuzzy logic	Data mining	Statistical methods	Model	Bayesian analysis
Optimization	X	X	X	X		X	X	
Fault detection	X				X		X	
Decision making	X	X	X	X			X	X
Planning & scheduling	X	X	X	X			X	
Condition monitoring	X				X	X	X	X
Maintenance	X			X		X	X	X
Fault prediction	X				X	X	X	
Forecasting	X					X	X	
Fault diagnosis	X				X		X	
False alarm detection	X				X		X	
Modelling		X	X	X			X	
Fault prevention					X		X	

3.7 Role of AI in Hydro-Power Energy Projects

AI-aided inspection processes play an important role in hydro-power facility inspections. It can support remote monitoring by accessing real-time data and insights from anywhere with an internet connection. The physical inspection procedures can be replaced with monitoring inspection. It supports data analytics and provides decisions by analysing the trends and correlations in the data. AI-powered image recognition technology can support in inspection of physical components of hydro-power facilities, including process piping, fluid processing equipment and turbines. With the help of imagery, it can support in detection of defects, damages, and cracks inside the equipment. Overall, AI applications can be utilized in prediction and forecasting, monitoring and control, policy and feature selection, feasibility study, evaluation and capability assessment and performance optimization (Saini, 2021). Please see below Figure 32. showing all AI application areas benefitted in hydropower energy projects.

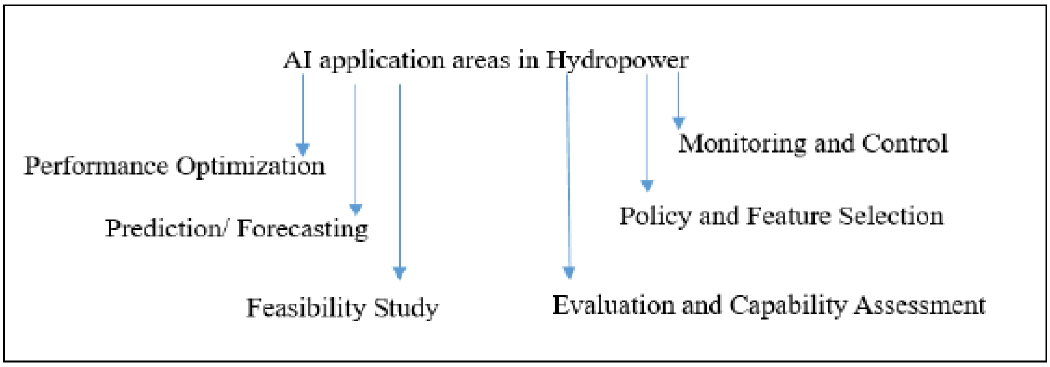


Figure 32. AI application areas in hydropower (Saini, 2021)

There are a lot of perimeters that are required to be measured to encapsulate the forecasting of hydro-power parameters. The parameters further govern the measurement made for energy consumption, flow rate prediction, prediction of sediment loading, performance of hydro power plant, inflow forecasting, discharge prediction, head prediction, water level prediction, baseline estimation, aggregate demand forecasting, short term energy forecasting, generation prediction etc. Please see below table 2. depicting summary of AI applications used for performance optimization.

Table 2. Summary of Applications of AI for Performance Optimization (Saini, 2021)

Method (s)	Objective (s)	Findings
ANFIS	Optimal load shedding that can shed the required amount of load for grid stability	The intended quantity of load can be shed at a faster rate and enhances the stability of the system
Fuzzy logic controller	The operation of the turbines for the power potential and power demand constraints optimization using FL algorithm	Selection of the number of units to optimize the energy generation

Please see below table 3. showing summary of AI application used for forecasting hydro power parameters.

Table 3. Summary of the Applications of AI for the Forecasting of Hydropower Parameters (Saini, 2021)

Method (s)	Objective (s)	Findings
ANN	Prediction of sediment loading	REPTree model provides better insight with less computational time
ANN and ANFIS	Energy consumption forecasting	DELM is much better than ANN and ANFIS for short-term and long-term energy consumption projections
Machine learning	Flow prediction	The neural network approach is superior to the other techniques
Fuzzy logic controller	Flow rate prediction	When the speed reaches 254.8m/s, the fuzzy logic controller gives a better result
TS-FIS model	Inflow forecasting	The value of the mass curve coefficient (performance indices) varies from 79% to 98%
ANN	Energy generation prediction	One day ahead energy generation has been predicted to stabilize the grid
GA-SVM	Energy generation prediction	The GA-SVM model is an effective method for improving short-term forecasting accuracy
Fuzzy logic controller	Cost prediction	The cost overrun of hydropower projects was calculated with ease and less computing time
Deep neural network	Generation prediction	HGDNN method gives a better prediction of hydropower generation
ANFIS	Discharge prediction	A comparison of the various membership functions for ANFIS shows that TRAPMF performs best in long-term discharge prediction
ANFIS	Energy generation forecasting	GWO-ANFIS can forecast the hydropower generation satisfactorily
MCDM and ANN	Performance of hydropower plant prediction	In terms of predictive power, the ANN model outperformed the regression model
ANN, SVM, and DL	Short term energy generation forecasting	The correlation values verified that the Deep Learning model gives results more accurately with high performance than ANN and SVM
ANN	Head prediction	The ANN modeling can be used to predict the behavior of small hydropower plants
ANN	Rockburst prediction	The MIVA-MFA-PNN model is performing well for Rockburst prediction
ANN and Fuzzy logic controller	Water level prediction	The NF computing technique is suitable for modeling of the groundwater level
SOM	Predictive maintenance	SOM can be used for daily silt data analysis and to plan the maintenance of the machines
Gaussian Copulas	Aggregate demand forecasting	The utilization of the distribution transformers and feeders can be improved
SOM, K-means	Baseline estimation	In DR management, the data-driven approach is a possible method for CBL estimation where a large amount of smart metering data is collected
Nonlinear regression, ANN	Baseline estimation	Among the techniques, machine learning produces the smallest bias
ANN	Baseline estimation	Baseline calculation by neural networks using the LM algorithm is the most accurate method
ANN	Baseline load forecast	The versatile and adaptive algorithm based on artificial neural networks (ANNs) is suitable to predict building energy consumption accurately

Please see below table 4. showing summary of AI applications for monitoring and controlling hydro power plants.

Table 4. Summary of the Applications of AI in Monitoring and Control of Hydro-power Plant, (Saini, 2021)

Method (s)	Objective (s)	Findings
Fuzzy logic controller	Reservoir control	Tabu Search Algorithm (TSA) predictive accuracy of the fuzzy model is reasonable
ANFIS	Reservoir control	Design of Neuro-fuzzy controller to regulate water levels and control the flow
ANN	Parameter for monitoring	The ART model predicts variable values correlated with potential abnormal circumstances

Please see below table 5. stating AI applications used in policy and feature selection.

Table 5. Summary of the Application of AI in Policy and Feature Selection, (Saini, 2021)

Method (s)	Objective (s)	Findings
Fuzzy logic controller	Best criteria selection	The Archimedean screw is a better alternative than the Kaplan turbine for a specific case of WWTP
Fuzzy logic controller	Optimal operation rule selection	It helps to operate a machine in its efficiency zone.

Please see below table 6. stating AI applications used for making the feasibility study for carrying out the Hydro power project.

Table 6. Summary of Applications of AI for Feasibility Study, (Saini, 2021)

Method (s)	Objective (s)	Findings
ANN	Investment feasibility	The economic viability of a project can be analyzed
Fuzzy logic controller	Risk assessment	Risk index can be used as an early indicator of project problems
ANN	Site selection	MLP-GA can accurately prioritize potential sites

4 AI-AIDED METHODS AND TECHNIQUES

4.1 AI Algorithms and Models:

An AI model is a program that uses statistical data and factual knowledge to identify specific patterns or render decisions without additional human involvement. These models are based on efficient techniques that use various algorithms and Networks to process pertinent data inputs and complete the pre-determined tasks or provide desired results as programmed, (Boucher, 2020).

4.2 How AI Algorithms and Models Work

Al algorithms act as programming for the AI models to run the system on the rendered design inputs. Program may encapsulate itself in the form of a device, ornament, a network, a system etc. whichever best serves the purpose whereas AI programming is a set of instructions that empower machines to analyse data, execute tasks, and render decisions. They represent a subset of machine learning, instructing computers or machine learning devices to independently learn and function.
AI algorithms and models collaborate in a mutually beneficial partnership, with algorithms serving as the foundational rule and mechanism enabling machines to learn from data and execute tasks (Wikipedia, 2024)

The following are the most common and suitable AI Models and Techniques utilized in Renewable Energy system projects.

A) Computer Vision Techniques
B) Machine Learning (ML) Algorithm based Techniques.
C) Anomaly Detection Techniques
D) Time Series Analysis
E) Reinforcement Learning (RL)

Machine learning algorithms-based techniques are one of the major AI techniques utilized in renewable energy projects and can further be divided into three major subcategories. Please see below Figure 33. presenting major categories for machine learning techniques.

ML Class	Main features
Supervised learning	Labeled Data and Task Driven Classification/Regression Algorithms Suitable for Diagnostics/Prediction Application
Unsupervised learning	Unlabeled Data and Data Driven Clustering/Dimensionality Reduction Algorithms Suitable for Pattern/Structure Recognition
Reinforcement learning	Rewarding/Punishing Mechanism Clustering/Association Algorithms Suitable for Decision Making Process

Figure 33. Machine Learning Techniques and Features, (Farrokh Aminifar, 2021)

AI based methods and techniques works in conjunction with deep learning, machine learning and feature learning methods and techniques. Please see below Figure 34. for best illustration for the formation of Artificial Intelligence techniques and methods.

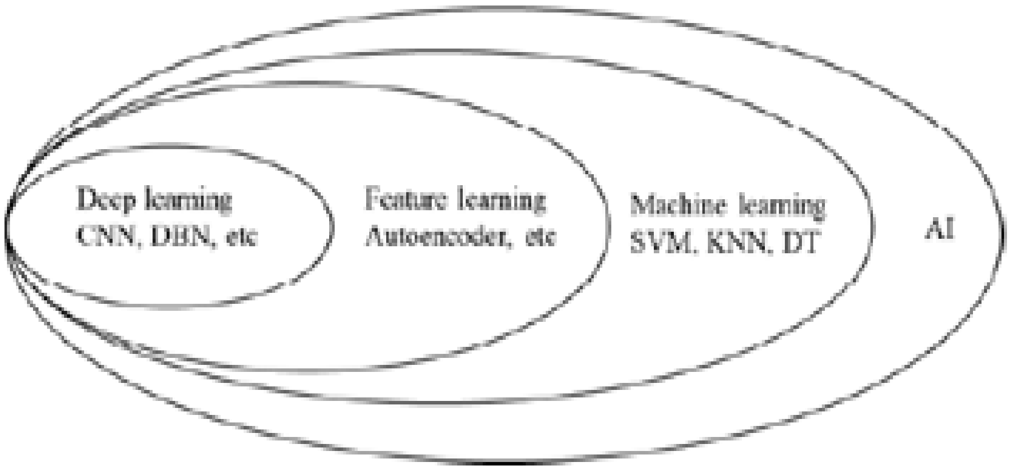


Figure 34. Relationship Of Artificial Intelligence Methods, (Syahril Ramadhan Saufi, 2019)

In our literature review we will focus on the primary methods and will explain in detail the initially listed five main techniques and their relative algorithms for finding out flaws and defects on concerned equipment and devices during operation and maintenance of renewable energy system projects.

4.3 Computer Vision Techniques

4.3.1 Convolutional Neural Networks (CNN)

Most commonly and widely used technique in renewable projects is Convolutional Neural Networks (CNN). CNN exhibit significant capability in recognizing images, rendering them for examining visual information like images or videos depicting renewable energy apparatus. By furnishing labelled data containing both typical and faulty occurrences, we can educate a CNN to identify flaws or irregularities in equipment like solar panels, wind turbine blades, hydro power energy equipment, Bio-Mass Fuel system equipment, electrical transmission and distribution and other equipment elements.

CNN are a special kind of deep neural networks operated mainly from the imagery input. CNNs operations start by using inputs to function through special functioning layers called convolutional layers. These layers use filters, also known as kernels, to look at small parts of an image. Each filter is trained to find certain characteristics in the image, like edges, textures, or shapes. It moves across the image, checking different areas to see if it finds those patterns. The result is a map that shows where those patterns are in the image. After this, pooling layers are used to shrink the maps while keeping the important information intact. There are different types of pooling, like max pooling and average pooling, which help to simplify the information and make it easier to process. (Zhang, 2022)
Please see below Figure 35. explaining the layering method forming the Lenet Network.

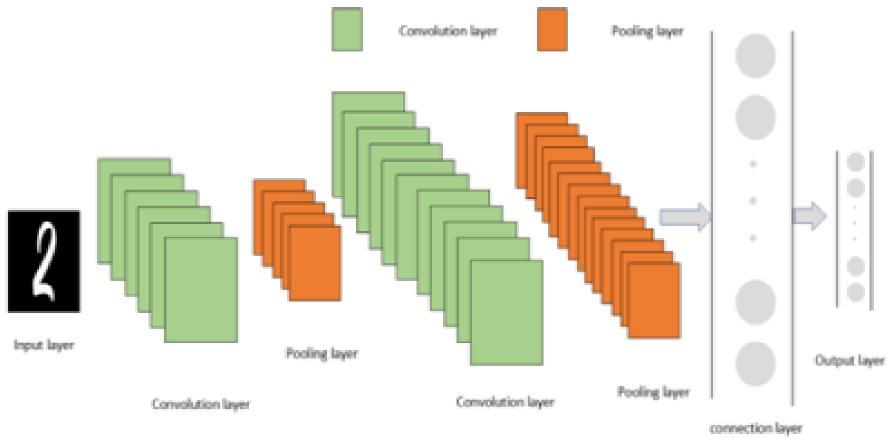


Figure 35. Lenet Network Example, (Zhang, 2022)

Then, activation functions like ReLU are applied to make the network learn better to process the layers. ReLU helps the network understand complex things in the image. The maps are then flattened into a list and passed through dense layers. These layers make decisions based on what the earlier layers found.

To prevent mistakes and speed up learning, techniques such as dropout and batch normalization are used. During training, the CNN adjusts its filters and layers to get better at its task. It does this by looking at how wrong it was and trying to fix it. Once it is trained, the CNN can look at new images and make assessment based on what it has learned from the earlier training. Overall, CNNs are good at understanding images and are used for things like recognizing objects or finding boundaries in pictures. (Zhang, 2022).

Computer vision with CNN functions by providing eyes and functioning to computers so they can see and understand images just like we (humans) do. This technology can be used to look at different kinds of renewable energy equipment to find problems and figure out how well they are working. Particularly CNN's operations are used in solar panels, wind turbines, hydro power equipment and geothermal inspections.

A) Solar Panels Flaws and Defects Detection

CNNs can look at pictures of solar panels taken by drones or cameras to find any issues like cracks or dirt that might stop them from working properly. They can also keep an eye on how well solar panels are doing over time by looking at old pictures. This helps us know when they need fixing or replacing.

CNNs are trained to recognize various flaws on solar panels, including cracks, scratches, hot spots, discoloration, and malfunctioning PV cells. They are utilized to ensure the quality of solar panels during their manufacturing or installation phases. Through image analysis, CNNs assesses alignment, proper and right installation, and manufacturing defects that might have an ill-effect on panel efficiency or its durability. CNNs are effective in monitoring the performance of solar panels over time by analysing field-installed panel images. They detect factors like dirt accumulation, shading from nearby objects, or material degradation, aiding in optimizing array performance and scheduling maintenance. For thermal imaging analysis, Infrared (IR) or thermal imaging are commonly employed to identify abnormalities in solar panels which are induced due to overheating or faulty cells. CNNs are trained to analyse thermal images and pinpoint areas of concern, such as hot spots or thermal irregularities, signalling potential panel issues. Continuous CNN-based monitoring of solar panels enables the early identification of degradation or failure patterns, allowing for proactive maintenance actions. (Akram, 2019)

This proactive approach helps in minimizing downtime and extending the lifespan of solar panel installations. Please see below Figure 36. explaining the Electroluminescence imaging setup for solar panels defects detection.

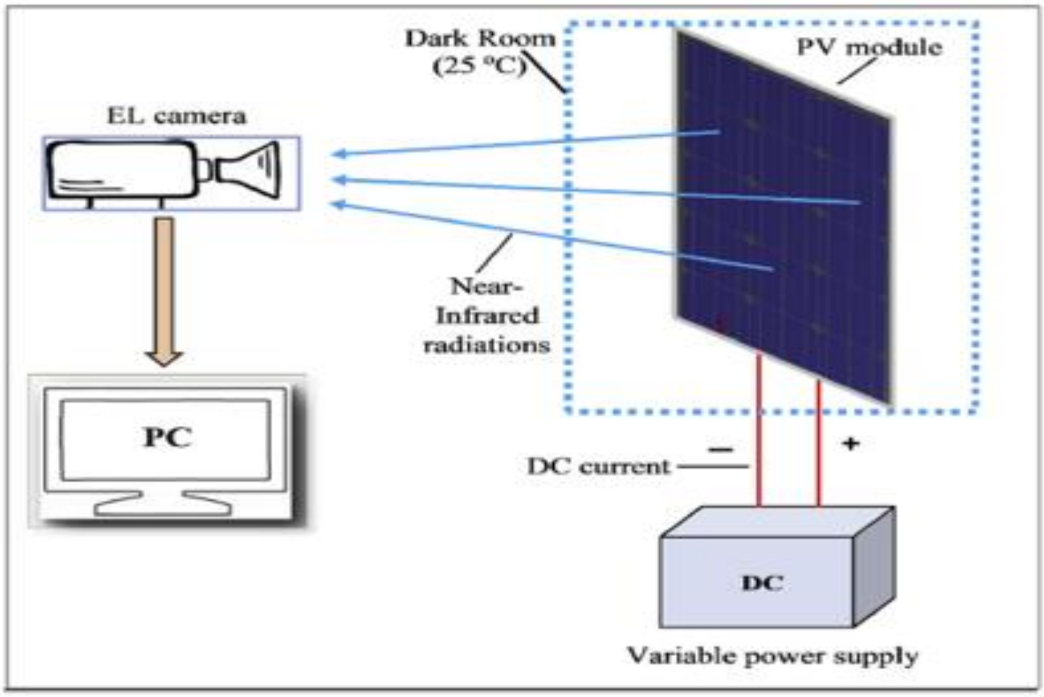


Figure 36. EL Imaging Setup, (Akram, 2019)

PV cells go through various kinds of faulty conditions that leads to failure or malfunction of the PV cells. These faulty conditions can be observed in PV modules and its electroluminescence functioning. These cracks and defects can be observed in different size, dimensions, and proportionality. Manufacturing process of these cells is main source of the crack formation. Furthermore, we can categorize the sources of crack in mainly 7 ways.

By the stress experienced during soldering, due to needle pressing on silicon wafer in between the manufacturing process and cells being pushed by a counter force. Other reasons may also include thermo-mechanical loads being faced by the cells. By the look the crack may be found in any of the below formation.

1.A big crack partitioned in between cells, giving an appearance in black colour. They happen once they are not in connection to electricity.

2. A cell crack that gives the look of a grey line. The width and darkness of the line are mostly the same all along.

3. A wavy crack that's at an angle of about ±45 to about ±5 to the lines on the cell.

4. A dark grey line crack in a silicon wafer that was made next to another one in the same batch.

5. If the brightness of the special image changes quickly along a grey line, it's probably a crack.

6. Cracks made through contact and make electricity difficult to flow.

7. Cracks usually start or stop at certain parts of the cell, Small Cracks that go across or lines of cracks. (Akram, 2019).

Please refer below Figure 37. showing the cracks orientation of PV images observed in various formations and directions.

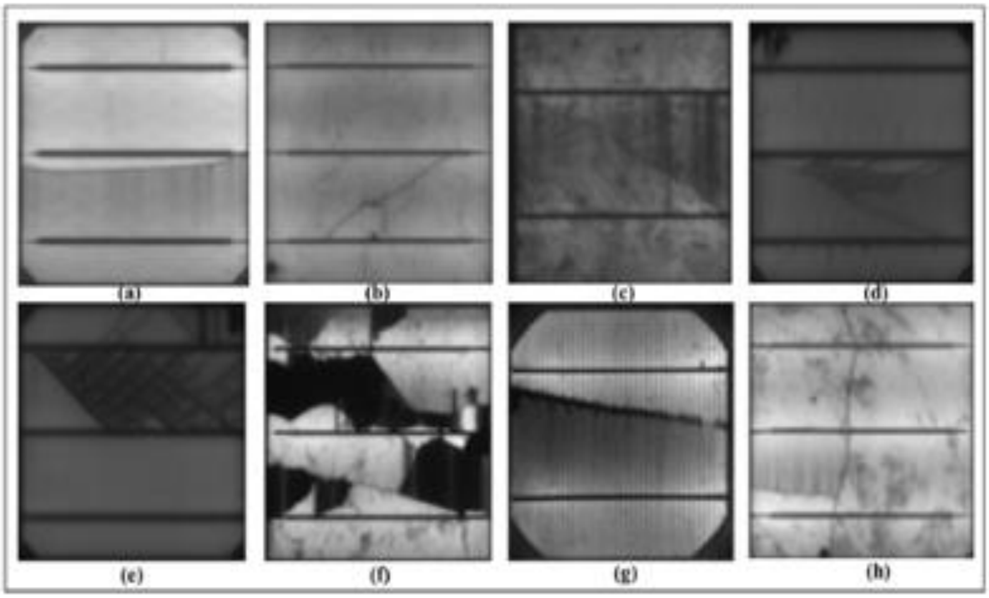


Figure 37.Cracks in the Orientation of Photovoltaic (PV) Module Images observed as a) aligned with bus bars, b) at a 45-degree angle, c) at a -45-degree angle, d) in multiple directions, e) branching out, f) deep cracks isolating cells, g) crossing lines, h) perpendicular to bus bar, (Akram, 2019)

Please see below Figure 38. showing EL images of PV modules four various formations.

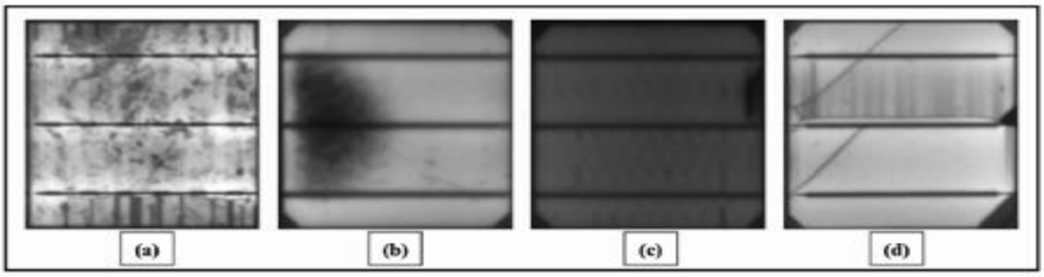


Figure 38. Crack patterns observed in electroluminescence (EL) images of PV modules include a) finger failure, b) defects in silicon material, c) failures in contact formation, d) finger failure coinciding with crack locations, (Akram, 2019)

Detection of cracks in photovoltaic (PV) solar panels employs EL (Electroluminescence) images data, using methods including data augmentation, evaluation on testing data, model training, optimization, and prediction. EL images show the internal formation of solar panels, helping in identification of cracks and other flaws. Data augmentation techniques are utilized to enhance the availability of training data further increasing the effectiveness of the CNN model.

The CNN model is trained on a dataset having EL images of solar panels with highlighted crack areas and portions. During training, the model learns to recognize patterns indicative of cracks in the images. Evaluation on testing data involves assessing the performance of the trained model on unseen data to determine its accuracy, precision, recall and other relevant metrics. This step ensures that the model generalizes well to new data and effectively detects cracks in solar panels. Model training and optimization entail fine-tuning of CNN architecture and adjusting extended parameters to improve performance. Techniques such as transfer learning may also be employed to leverage pre-trained models and accelerate training. Once trained and optimized, the CNN model can be used for crack detection in PV solar panels. By analysing EL images, the model can predict the presence

and location of cracks, enabling timely maintenance and ensuring the reliability and efficiency of solar panel installations, (Akram, 2019).
Please see below Figure 39. presenting the flow chart of CNN based approach supporting in prediction of defects formation.

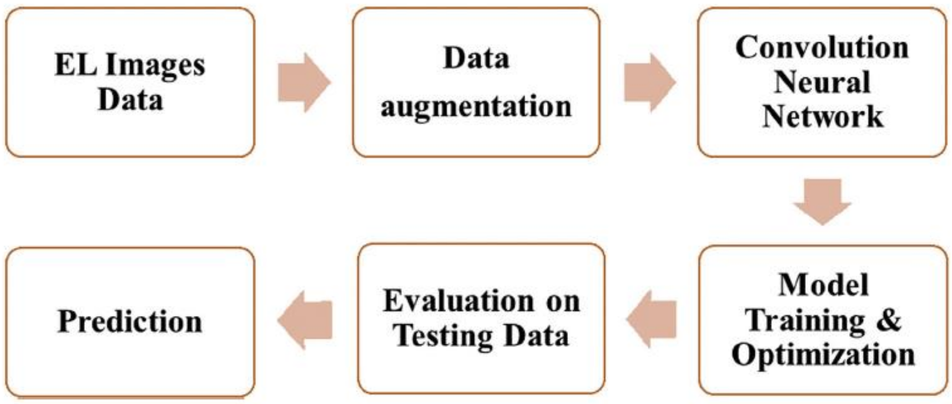


Figure 39. Flow Chart of CNN Based Approach, (Akram, 2019)

B) Defects Detection in Wind Turbines

The CNN method is used in condition monitoring of wind turbine blades for any kind of issues such as like cracks or wearing out by looking at pictures or videos taken by drones. This can support in verifying those issues earlier and can avoid worries at the end or at any predictive maintenance.

They can also look at data from the turbines to check any areas or indication that something unusual has happened. It somehow follows the same process steps as of PV cells in solar panel including collection of data followed by data processing, its labelling, training the data with information about defect. The training data up skill the CNN computer system to get recognition of the defects while validating and evaluating its performance. An architecture model is designed that consists of multiple layers including convolutional layers for feature extraction and pooling layers for dimensional reduction. During training the model get used to identify those patterns and features with different types of defects. The trained model is checked with the available authentic set to confirm its performance. Once they

have been trained to handle them, they are deployed in the real on-site job applications. This involves integration into inspection system where it can analyse new data.
The process can help in visual inspection, predictive maintenance, efficiency optimization and integration with the monitoring system. The complete systems can be used in software platforms used in wind farms. They function by using the seamless data integrated with the monitoring system providing real-time analysis, and automated reporting, streamlining the condition monitoring process and facilitating timely decision-making.

This technique can help find defects and flaws such as cracks, erosion and delaminating on the turbine blades which is lethal for the structural integrity. The severe atmosphere is one of the reasons for these kinds of defects and damages. Furthermore, it can support in evaluating wear and tear in the gear box, misalignment associated with the gear further effecting in efficiency of power transmission. The wearing of gear and the damages associated with constant working of the gear are caused by friction and vibration ultimately leading to the failure. It also helps in checking the foundation stability that affects the structural integrity. Moreover, it supports in inspection of electrical system such as cables, connections, and control systems for signs of damage and malfunction. (Majid Memari, 2024)

Tower structure defects are also measured that are part of structural strength and stability. As wind turbines work open to the atmosphere, they are prone to lightning damages which can cause structural damage and even fires. The most common of damages expected and seen can be depicted in the below pictures. Please see below Figure 40. depicting the wind turbine blade damages incurred by various catastrophes.

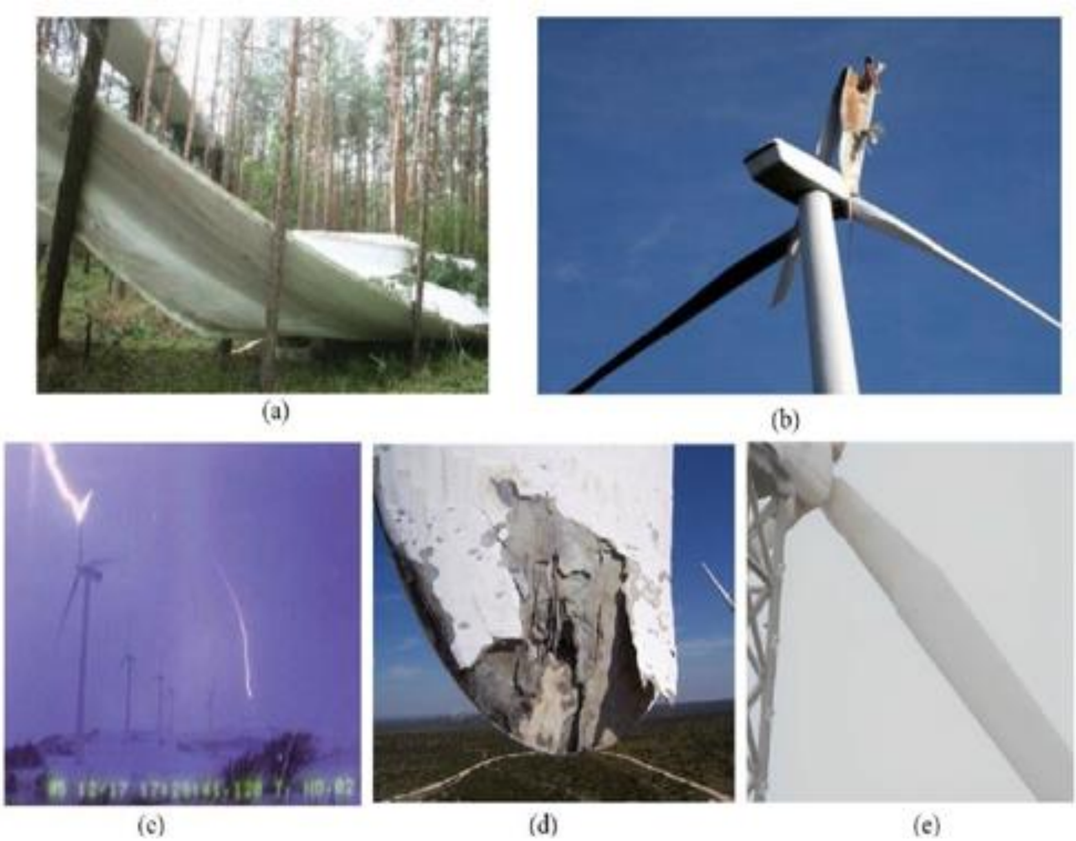


Figure 40. Wind Turbine Blade Damage) Intense Storms, b) Strong Gusts, c) Lightning Strikes, d) Effects of Lightning Strikes, e) Accumulated Ice., (Majid Memari, 2024)

Wind turbine blades often undergo erosion on the surface. Such erosion propagates from the surface of blades further affecting the painted surface and the steel surface as well. Please refer below Figure 41. showing the erosion propagation and the effected surface of turbine blade.

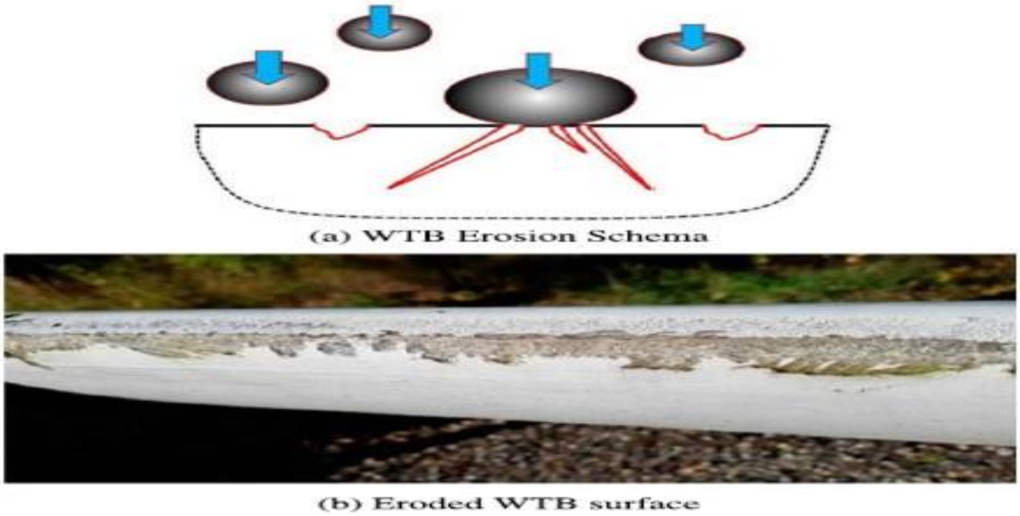


Figure 41. Erosion on Wind Turbine, (Majid Memari, 2024)

Please see below Figure 42. explaining the damages occurring at various regions and cross-sections of blade such as leading edge, outer surface and at the spar flanges.

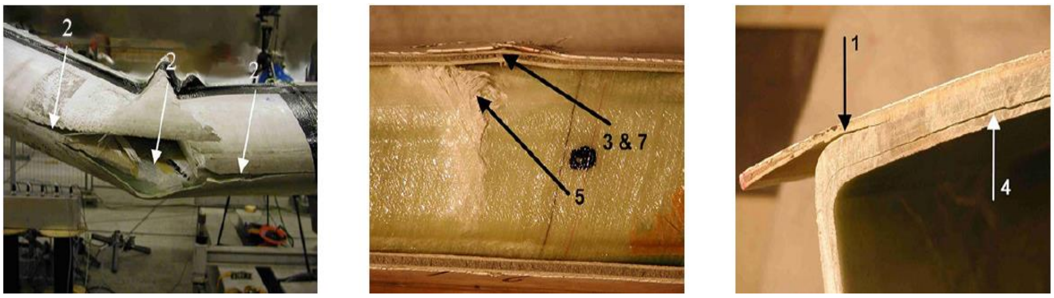


Figure 42. a). Damage in blade section at the leading edge, b) Damage at outer surface of main soar c) Damage at main spar flanges of blade section, (Majid Memari, 2024).

A simple working principle of defect detection of wind turbines by CNNs can be shown in the below diagram. Acoustic signals are gathered through the front-end acoustic acquisition system and identified. The time-domain of acoustic signals are changed into spectrograms while retaining the time-domain and frequency domain data. Spectrograms are further trained, validated, and tested by a stratified sampling method, accounting the percentage at 70%, 10% and 20%, respectively.

Data augmentation is done which are used to train the model and adjust the learning rate, respectively. The testing further governs the performance of the complete system network. (Liu, 2023). Please see below Figure 43. presenting the CNN working principle of wind turbine.

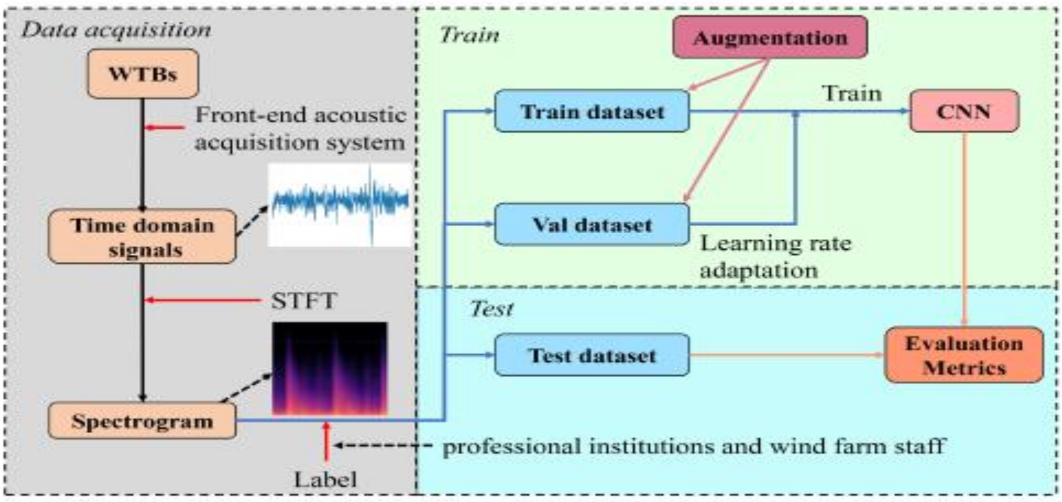


Figure 43. Principle Working of Wind Turbine, (Liu, 2023)

However, there are systems that have outperformed the traditional CNN models. The model existing approaches, such as Faster R-CNN and Mask R-CNN, are more of a shift in market nowadays with extended capabilities for flaw detection. They work on various enhanced principles such as enhancement of Image, extended precision capabilities, extended discrepancy count etc. Please see below Figure 44. and 45. describing the extended CNN versions. Figure 44. showing the objection detection procedure model using the faster R-CNN model for automated damaged systems whereas Figure 45. shows a schematic diagram of faster R-CNN method. Figure 44. illustrates all the activities involved in the functioning model and in Figure 45. we can verify the working principle involved for both the stages of a faster R-CNN model.

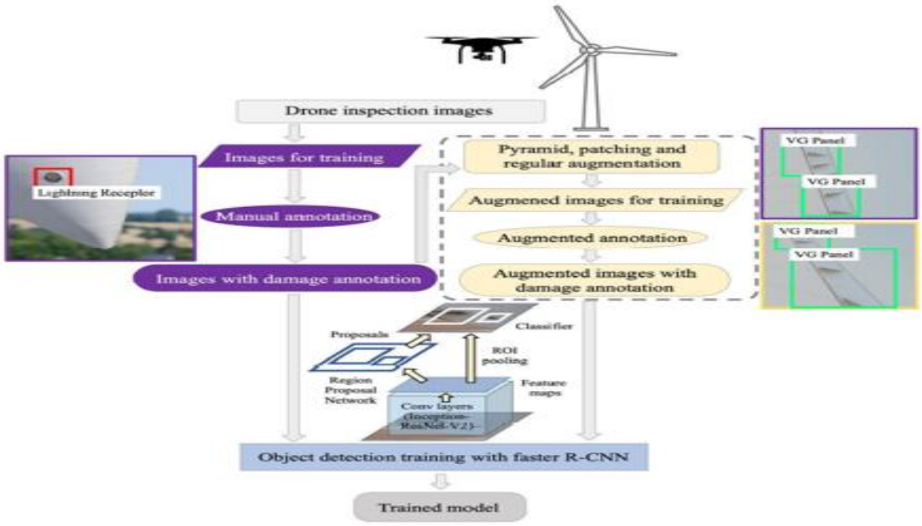


Figure 44. Flow Chart of Automated Damage system, (Majid Memari, 2024)

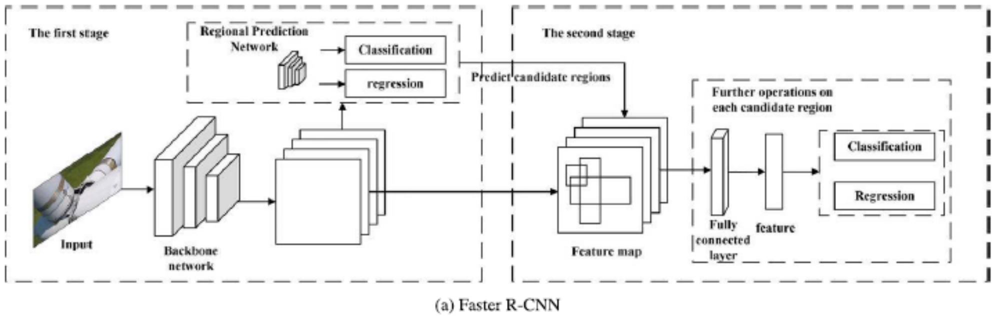


Figure 45. Schematic Diagram of Faster R-CNN, (Majid Memari, 2024)

C) Hydropower Equipment and Facilities Monitoring

(CNNs) supports in hydro power equipment inspection in various ways. CNNs can analyse aerial photographs to check the condition of dams and reservoirs. All signs of structural damage including cracks, laminations, upper damages, erosion and areas with hazards and other abnormalities can be measured. They support in turbine inspection and other machinery inspection within hydroelectric power plants.

With images verification and data censoring, corrosion, wear and tear, or other defects can be detected which are directly related to the performance and functionality of the equipment. They can be utilized in measuring the water quality data collected from sensors deployed in rivers, dams, and water facilities. Any changes in water chemistry can be detected that further affects the water quality and is cause of contamination. They can also help in measuring the fish populations and behaviour near hydroelectric facilities. Their migration plan and patterns can be measured which are crucial for hydro electrical facilities. Any vegetation, fungus and bacteria growth can also be measured on dams and Penstocks that effect the functioning of Dams and related water reservoirs. With the help of security cameras, CNN can help in monitoring unauthorized access or suspicious activities around hydroelectric facilities. They can support in improving the capabilities of its measurement. A support in predictive maintenance for various components of hydroelectric infrastructure can be achieved with its use (Weizhen Fang, 2021),

For monitoring Dams and water reservoir conditions, a proposed CNN method with high resolution imagery can be shown and proposed as below. (Weizhen Fang, 2021)

The data set is developed through Google earth high resolution images and classified and labelled into data set and further fed into the global data set. This data is further augmented for sequenced processes, trained, and validated and further fed into the CNN model process. Once the CNN model is trained with the imagery data, it is then put into on-site application. Please see below Figure 46. showing CNN framework for dam condition monitoring as part of hydropower facilities maintenance.

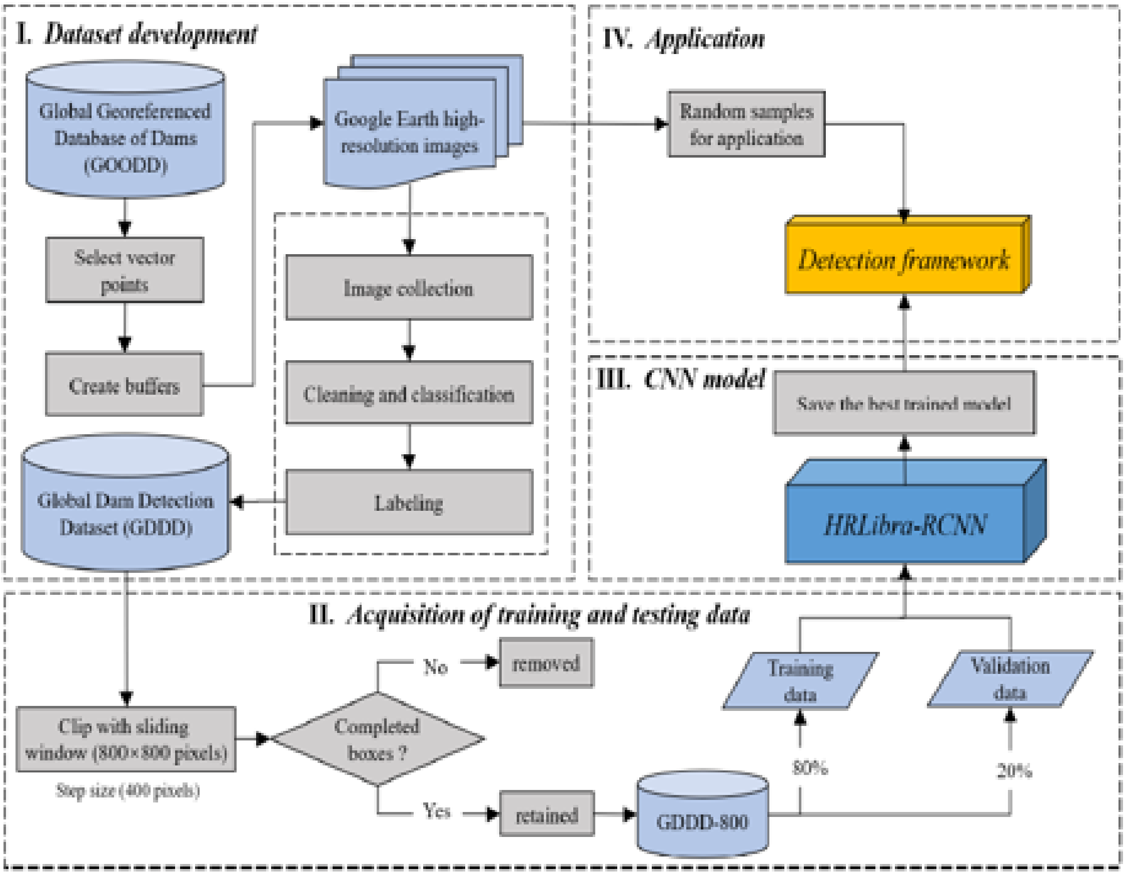


Figure 46. Framework for Dam Recognition, (Weizhen Fang, 2021)

For water level and water quality monitoring, the architecture can be indicated with a below diagram. Radar image is fed into the CNN model having convolutional layer and ReLU layer. With batch normalization it is fed into fully connected layer and Mix Pooling Layer. Prior to fully connected layers additional information is fed including water level, temperature, operation information and evaporation values. (Sang-Soo Baek, 2020).

Please see below Figure 47. explaining the architecture CNN for measuring the water level and its various perimeters supporting the functions.

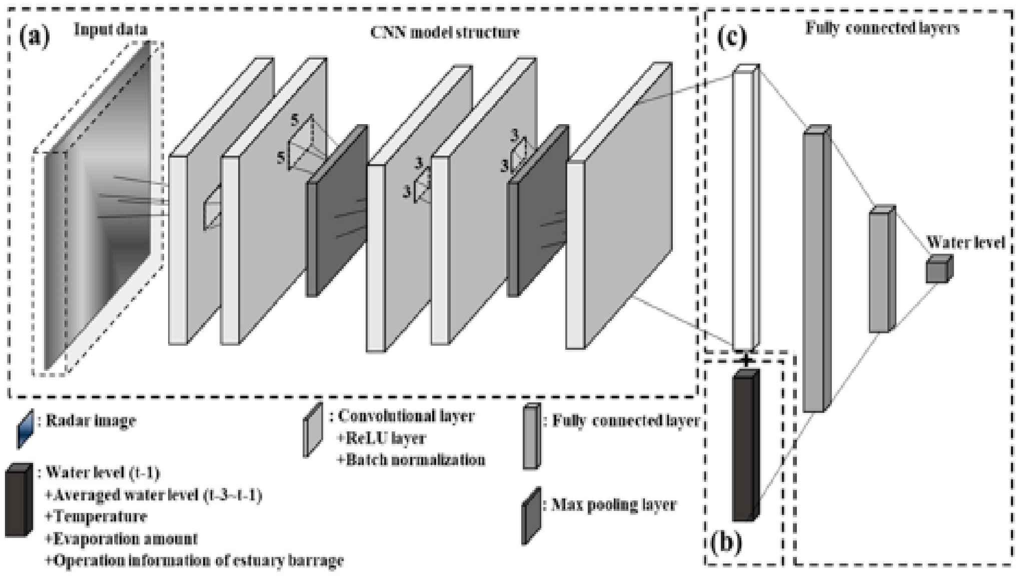


Figure 47. CNN Simulation for Water Levels(a) For analysing radar images, (b) For analysing supplementary (c) For analysing a fully connected layer (Sang-Soo Baek, 2020)

For underwater fish detection, surveillance videos are used to generate the data set. These videos which are available in raw data are used to create training and testing data which is further set as training data with feature vectors for recognition and fed into the classifier box for further classification. Once classification is finished, it then enters the detection and tracking phase of the system. The system using high classification of CNN method for a better image quality and accurate fish detection, extracts feature from training sets. A similar set of sequence is formed through the classifier box of previous and current image frames with continuous tracking and dynamics classifying algorithm. Below referred figure taken from Automated fish detection and tracking system using pre-trained Mask R-CNN for ecological biodiversity shall be helpful for a better understanding (Suja Cherukullapurath Mana, 2022). Please see below Figure 48. explaining the employment of CNN method for fish identification and tracking.

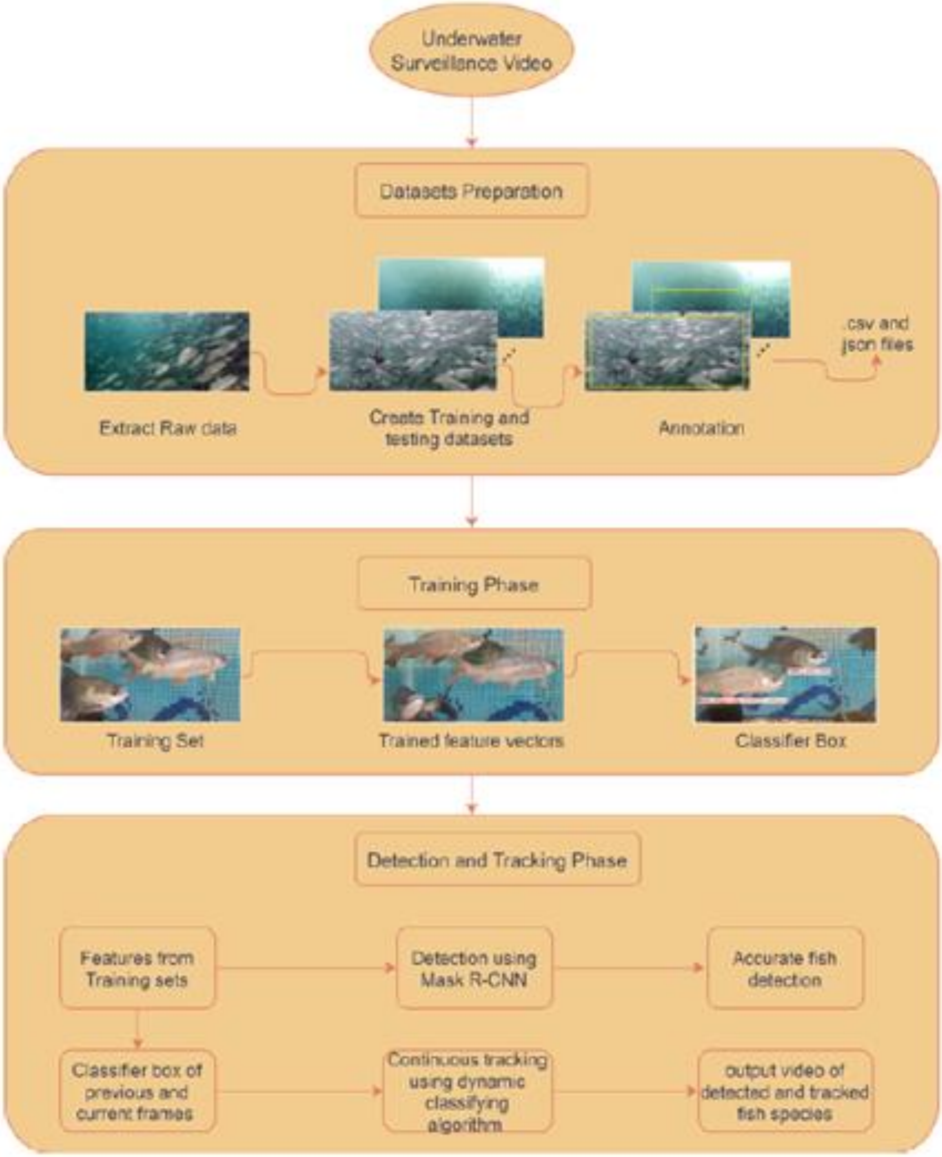


Figure 48. Fish tracking, (i) Gathering fish data (ii) Defining Regions of Interest (ROI) (iii) Training the model (iv) Developing a real-time Interface (Suja Cherukullapurath Mana, 2022)

D) Vegetation Growth Monitoring on Water Reservoirs

With the support from drone images vegetation growth can be monitored which usually propagates in hydroelectric facilities. It can check and evaluate the en-croachment of vegetation on infrastructure such as dams and penstocks, which directly affects the functionality and performance of these facilities. Figure 49 below depicts below depicts a scheme of a CNN mainly having four convolutional layers. After filters, visualization is made from the feature maps which are formed for the activation of these layers. Feature attribution maps further help in revealing the individual pixels and its quality. (Teja Kattenborn, 2021). Please see below Figure 49. presenting a CNN based model utilized for tree species classification.

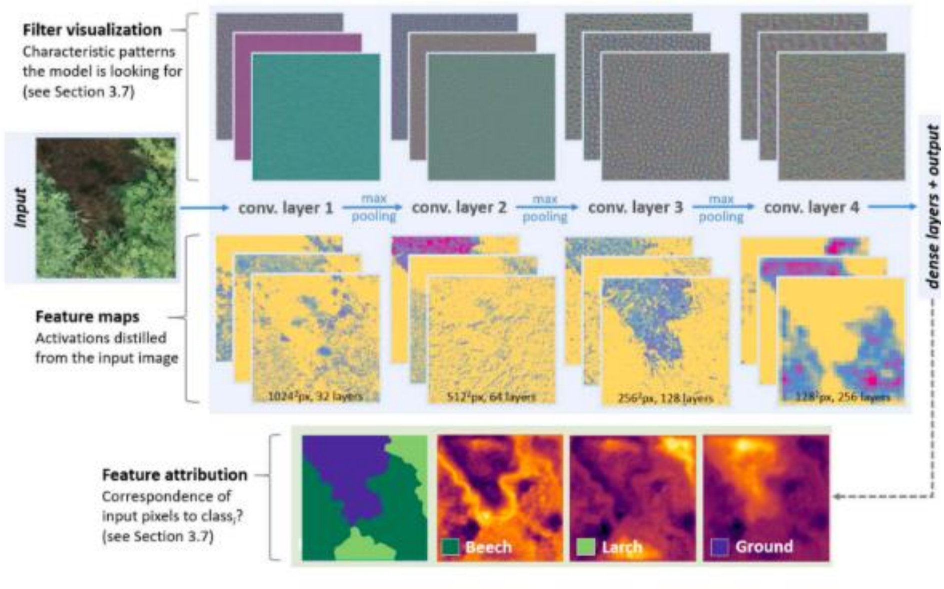


Figure 49. Scheme of a CNN composed of four convolutional layers and subsequent pooling operations trained for tree species classification. (Teja Kattenborn, 2021)

The visualization of convolutional filters (top) indicates characteristic patterns the CNN is looking for and were derived by gradient ascent; a technique revealing artificial images maximizing each filter’s activation. The feature maps (centre) are the dot-product of the preceding layer and individual filters. Feature attribution maps (bottom) can reveal individual pixels that were decisive for the tree species assignment, (Teja Kattenborn, 2021)

We can optimize the CNN with extended support from R-CNN and Mask RCNN methods which helps in better imagery and high-resolution pixels for better image detection. Please see below Figure 50. for an extended CNN method (Faster-R-CNN and Mask-RCNN). (Teja Kattenborn, 2021).

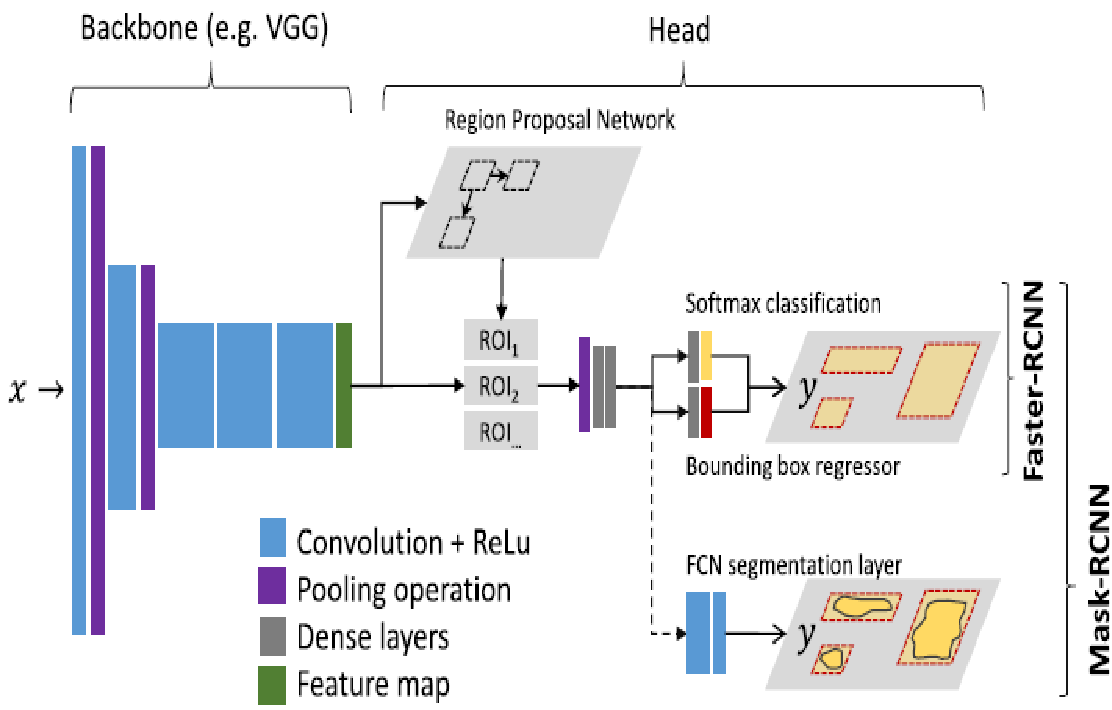


Figure 50. Faster-R-CNN and Mask-RCNN, respectively, (Teja Kattenborn, 2021)

4.3.2 Recurrent Neural Networks (RNNs)

Similar to CNNs, RNNs can support flaw detection in renewable energy projects through their ability to examine the sequential data, including time series data from sensors to verify the equipment's working and functionality. RNNs are made and encrypted to process the sequential data, making them suitable for analysing time series data taken from the sensors operating in a renewable energy system project. Steps include data processing, checking for long-term dependencies, detecting the anomaly, adapting to various data sources, and processing the data for continuous learning. Similarly, CNNs they are also used in solar panel inspection, Wind Turbine inspection, hydropower equipment inspection, battery storage system and transmission and distribution systems equipment.

A) Solar panel defects and Flaws Detection

Similarly, CNNs functioning, RNNs can analyse image data from drones or cameras to find flaws and defects such as cracks, hotspots, soiling, or shading on solar panels. The degradation and damages can be checked and observed in solar panels, induced with the passage of time.

Simulation data is extracted from the initial data which is then included into the training data and further fed to the RNN model. The data included in the trained RNN model further validates with the training data supplied earlier and helps in build-up of a predictive profile. (Filipa Barros, 2024). Please see below Figure 51. with the 3 step RNN model explaining the creation, development and employment of the model.

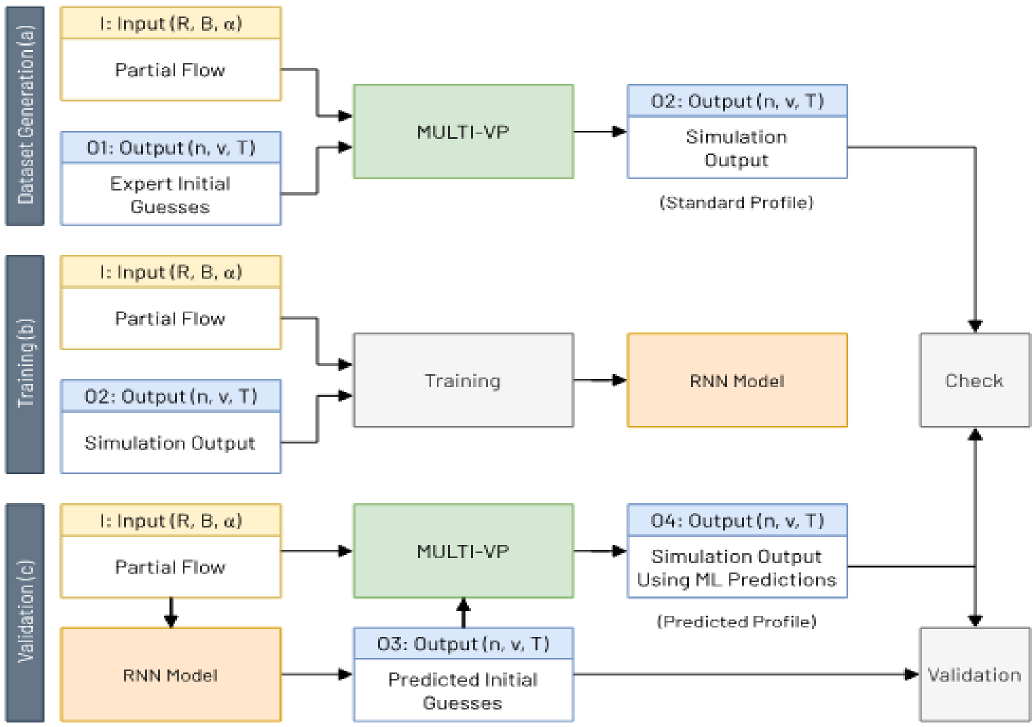


Figure 51. Three Step RNN(a) Creating the dataset (b) Developing a model (c) Employing the model (Filipa Barros, 2024).

B) Wind Turbine Monitoring

RNNs can probe the time series data from sensors that are erected on the wind turbines, including sensors measuring temperature, vibration, and noise. The abnormal functions created can help in detecting the turbine performance and functionality which eventually governs the rotor speed and power output of the turbines. This indicates mechanical issues and prospect of wear and tear in the turbine moving components. Designing of the RNN model include inclusion of RNN attributes such as training hyper parameters, cell number, and network depth being put into the system for a better optimization. Please see below Figure 52. showing an RNN model step wise functional view.

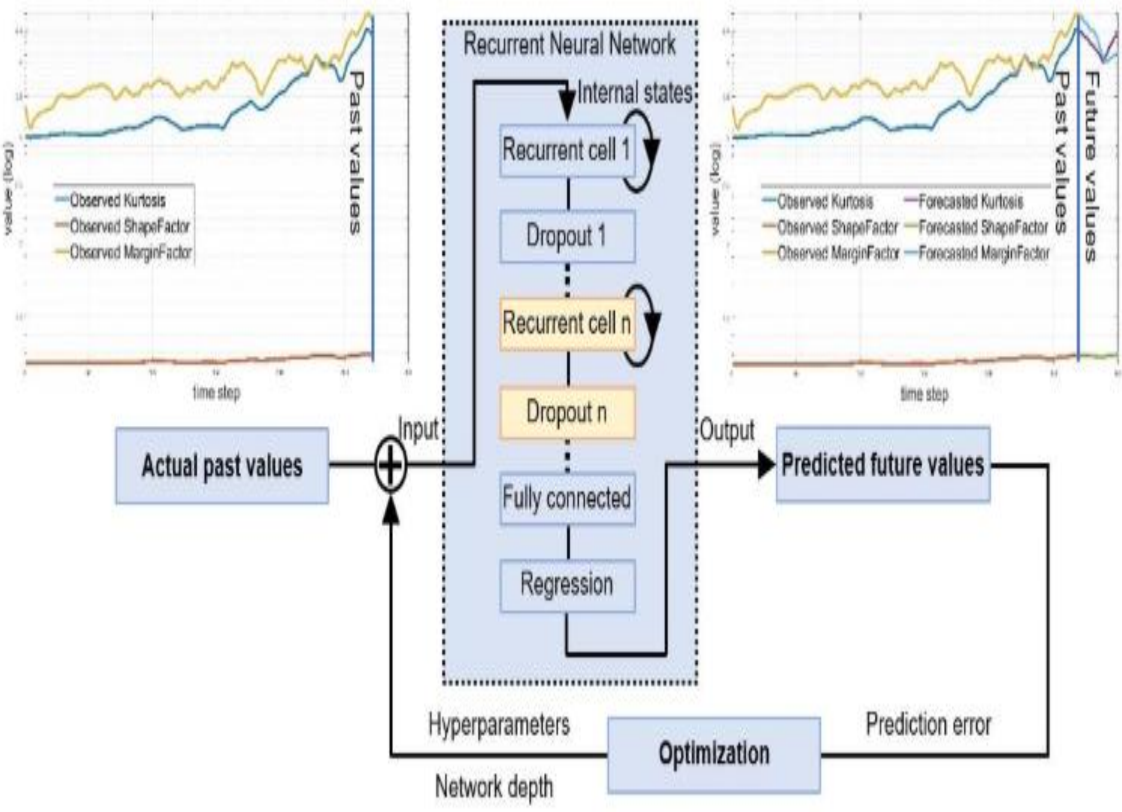


Figure 52. Overview of Optimization Loop, (Adlen Kerboua, (2022)

C) Geothermal System Monitoring

RNNs can help in inspection of geothermal and fossil-based power plants by utilization of time series data from sensors that are available inside the plant's monitoring system including the processing lines. They measure various parameters that help in running the whole equipment mechanism. This includes but it is not limited to fluid flow rates, temperature, vibration, and pressure sensors. Faults related to combustion controls and faults can be found in steam generator unit and can be measured utilizing this RNNs technique. In this way the plant's integrity and equipment performance is measured and further helps in predictive maintenance to avoid any future failures. Please see below Figure 53. showing a typical functioning of steam generator system to assess the variables that directly or indirectly effect the unit's performance. (Jose Hernandez, 2008)

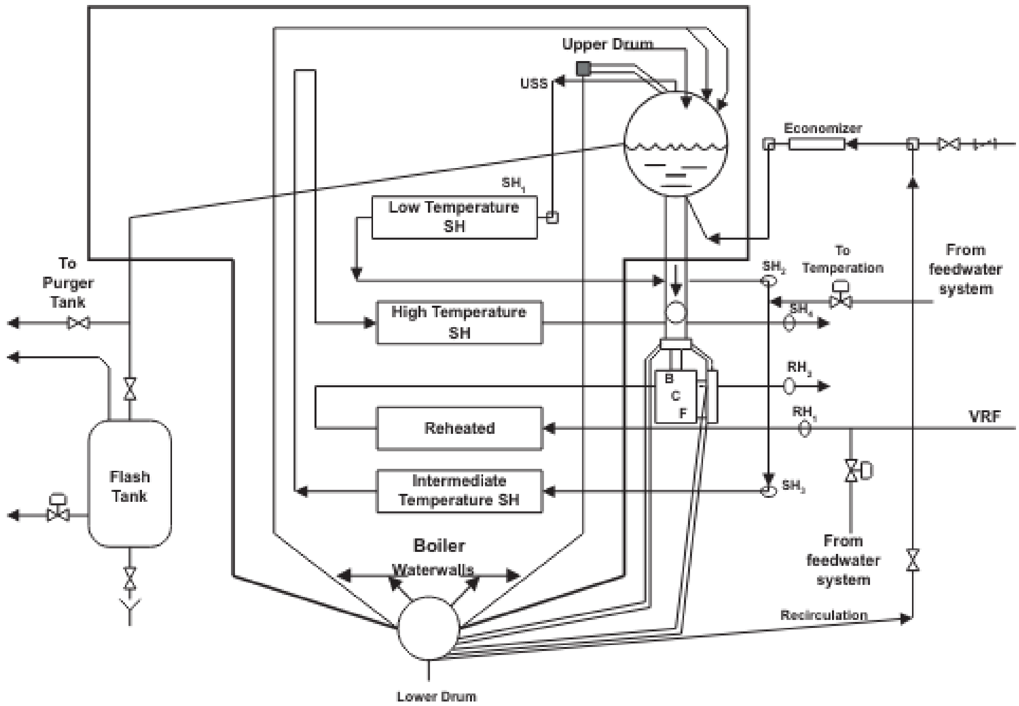


Figure 53. Steam Generator and Superheating System, (Jose Hernandez, 2008).

A Fault Diagnosis picture can be illustrated with below scheme showing the whole RNN pattern. The controller information is fed into the set points and inputs are transferred to the process and to the Neural Network. The Neural Network further supports the function of fault diagnosis which is provided in isolation along with neutral network. Please see below Figure 54. explaining the neural network scheme for measuring fault diagnosis.

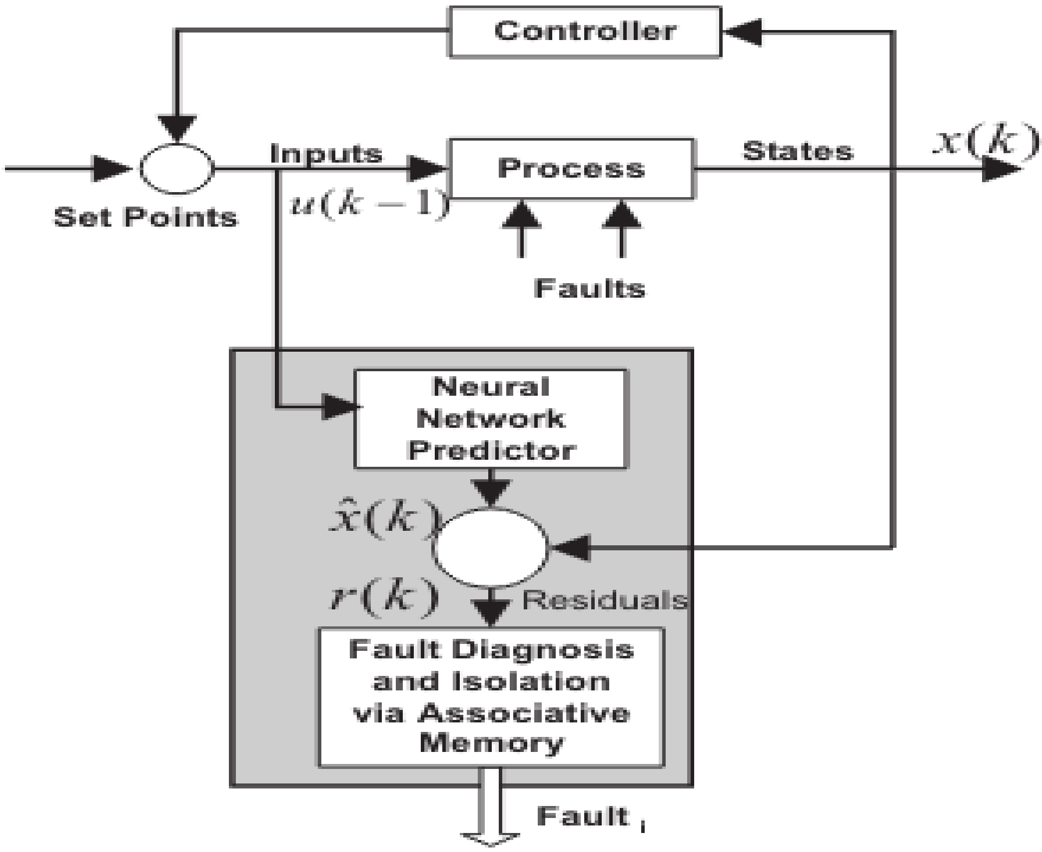


Figure 54. Neural Network-Based Scheme for Fault Diagnosis, (Jose Hernandez, 2008)

4.4 Machine Learning Algorithms

Machine learning algorithms can be categorized into 3 different models that are supervised learning, unsupervised learning, and Deep Learning. In supervised learning techniques Support Vector Machines (SVM), Random Forests, and Gradient Boosting Machines (GBM) are utilized to train a model on labelled data where we have a particular case available, with a label indicating whether a defect is present or not. In un-supervised learning methods, the labelled data is little, this includes techniques such as clustering (e.g., K-means) which can be used to identify patterns indicating the defects without requiring relative labels. Deep neural networks, including (CNNs) and (RNNs), automatically learn the features from the sensors, images and videos taken as sample or reference. There are some variants used in this specific model including Variants like YOLO (You Only Look Once) or SSD (Single Shot Multi-Box Detector) which are mainly beneficial in object detection.

A) Solar Panels Power Output With SVMR, GR & MLR Functions

Machine learning approach can be utilized in predicting the output power of PV panels. Refer below image showing machine learning approaches including support vector machine regression (SVMR), Gaussian regression (GR) and multi-linear regression (MLR) which were used for predicting the output power of solar PV panels. They are used to make a perfect model for the output measurement and fall under supervised learning category. SVMR serves for identifying the non-linearity in the data and thus generates a more helping model. In our case a Bayesian nonparametric method is used and helps in selecting the model at an appropriate level of complexity. MLR are used to establish relationships between a single dependent variable and more than one independent variable, Multiple Linear Regression. By comparing the values that were measured to the one predicted by each technique in our scheme can be shown in the below image. The most accurate of results can be predicted with MLR AI Algorithms. (Tripathi, 2022).
Please see below Figure 55. explaining the Machine Learning workflow model supported by various regression models.

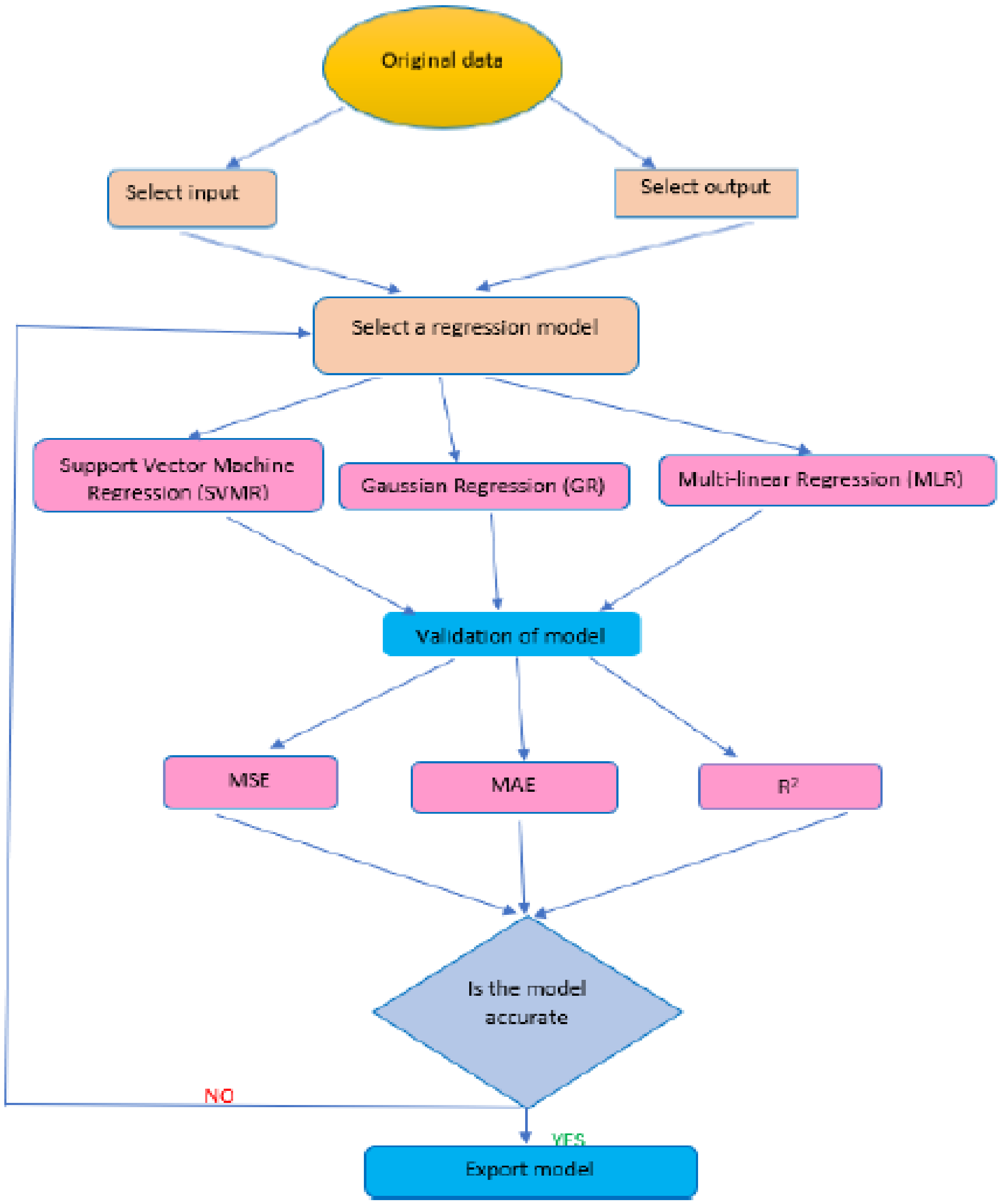
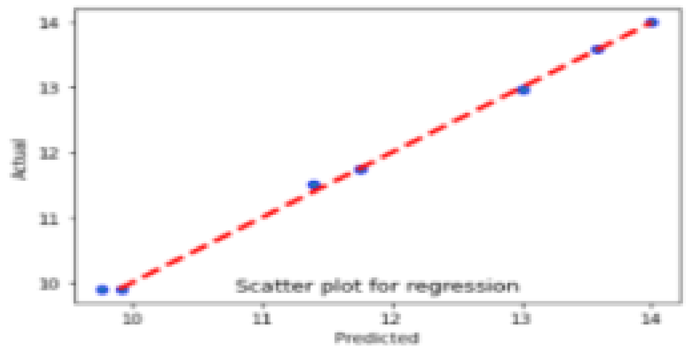
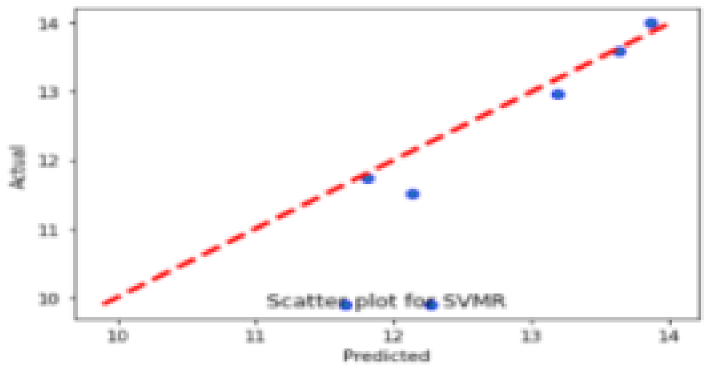


Figure 55. Machine Learning Workflow Model, (Tripathi, 2022)

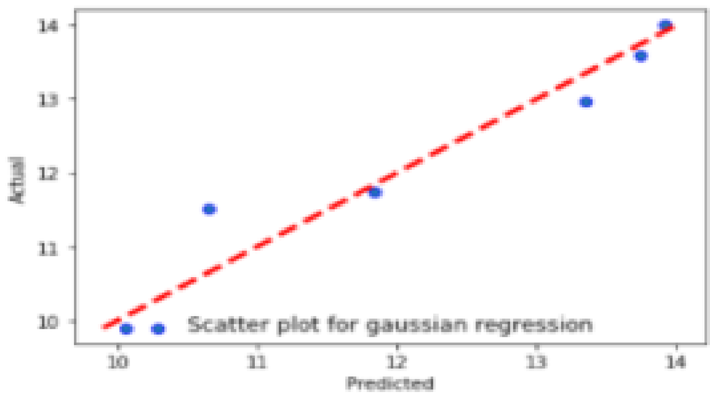
Please see below Figure 56. presenting output comparison between the actual and predicted values for various run machine learning algorithms.



Output power prediction of solar photovoltaic panel using MLR ML algorithms



Output power prediction of solar photovoltaic panel using SVMR ML algorithms



Output power prediction of solar photovoltaic panel using GR ML algorithms

Figure 56. Output Power Prediction of Solar Photovoltaic Panels by Various ML Algorithms, (Tripathi, 2022)

B) Wind Turbines Fault Detection Based on Support Vector Machine Functions

Wind turbines fault detection model can be executed by using SVM algorithms. The date set readings are taken from the SCADA signals from turbines. The sensors signals are taken from the turbine inner side. They train the signals which are downloaded and transferred to an excel file. Machine learning models is trained with the readings from the generator including generator speed, bearing temperature and stator windings. A high amount of data gathering is avoided as well to make sure over fittings is not happening. The data further needs to be labelled or in other words needs to be annoted. While annoting the data the readings classification needs to be inherited to the system. The readings may include data such as generators' speed, bearing temperature and other effective constraints.

The next step involves creating a testing dataset by making sure that it is in accordance with the training data set. A comparison between the true and predicted classes is required to define the differences. There should be two files for a testing dataset to perform this task. One with the true classified class and the other one without the classification. Next, the model's result from the predicted class is compared with the true class and accuracy is determined through calculation. The training set is used to train the model; in the meantime, the validation set is used to evaluate the model's performance while tuning the hyper parameters of the model. This data is used for more frequent evaluation and is used to update hyper parameters, such as the validation set affects the model indirectly. Numerous methods have been explored to achieve optimal accuracy in machine learning models employing SVM. Six distinct SVM models—linear, quadratic, cubic, fine Gaussian, medium Gaussian, and coarse Gaussian—have been the focal points. Each of these models underwent experimentation using three different validation techniques to compare the accuracy yielded by each model. Figure 57. shows each step of the network formed to carry out the fault detection. (Shahrulhisham, 2022).

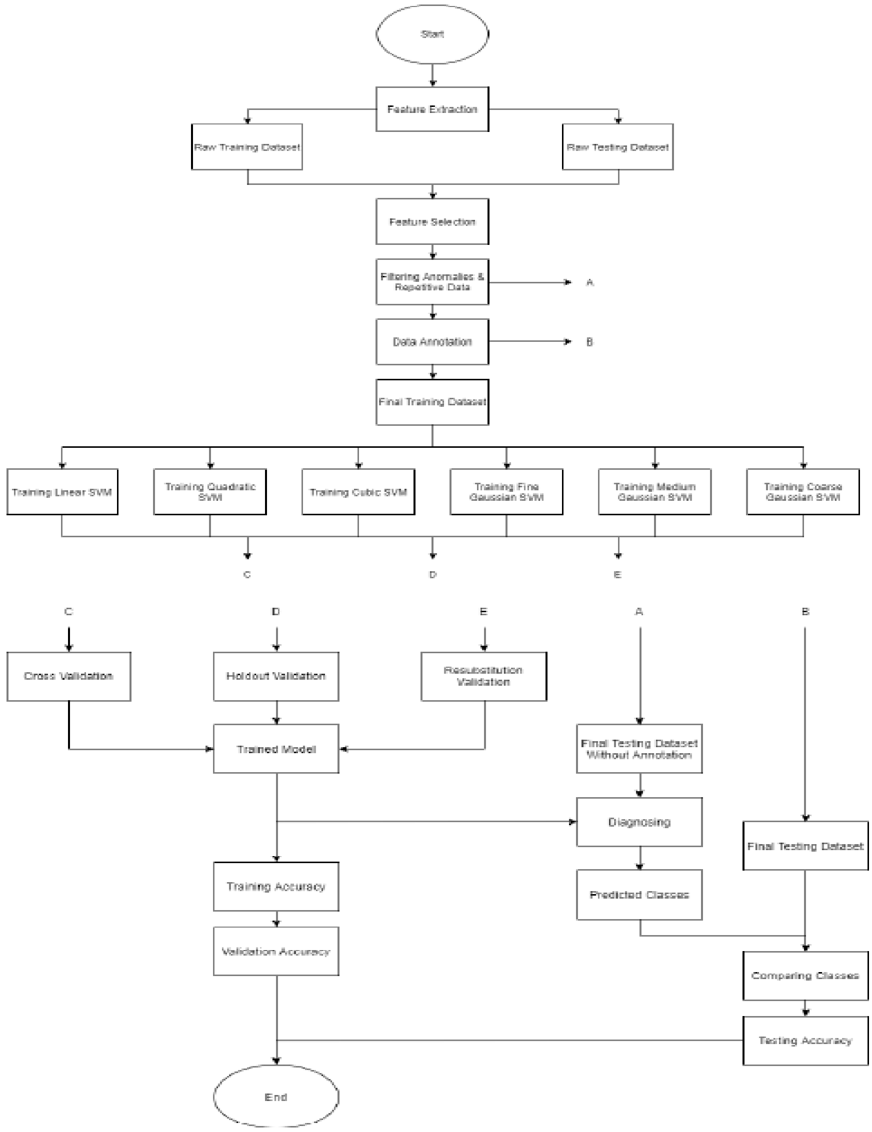


Figure 57. Summary of AI Functions Used with SVM, (Shahrulhisham, 2022).

C) Electrical Power Connections of Induction Machines by Machine Learning Method

Induction motors (IM), especially squirrel cage motors, are commonly used in Power generation of renewable energy power plants and due to their extensive utilization in the power-driven equipment, they are more prone to fault and wear. Most occurring failures are found in bearings and stator winding. Both failures are directly related to its continuous working. Simulations based data is utilized as the feature vector which is then fed to the supervised algorithm. In supervised machine learning approaches, every training data sample (Xin) is assigned a specific label (Yin), indicating its current health status. Consequently, interpreting the output predictions (Yout) of the machine learning model on new, unseen datasets becomes more straightforward. (David Gonzalez-Jimenez, 2021). Please see below Figure 58. specifying schematic diagram of supervised ML methodology.

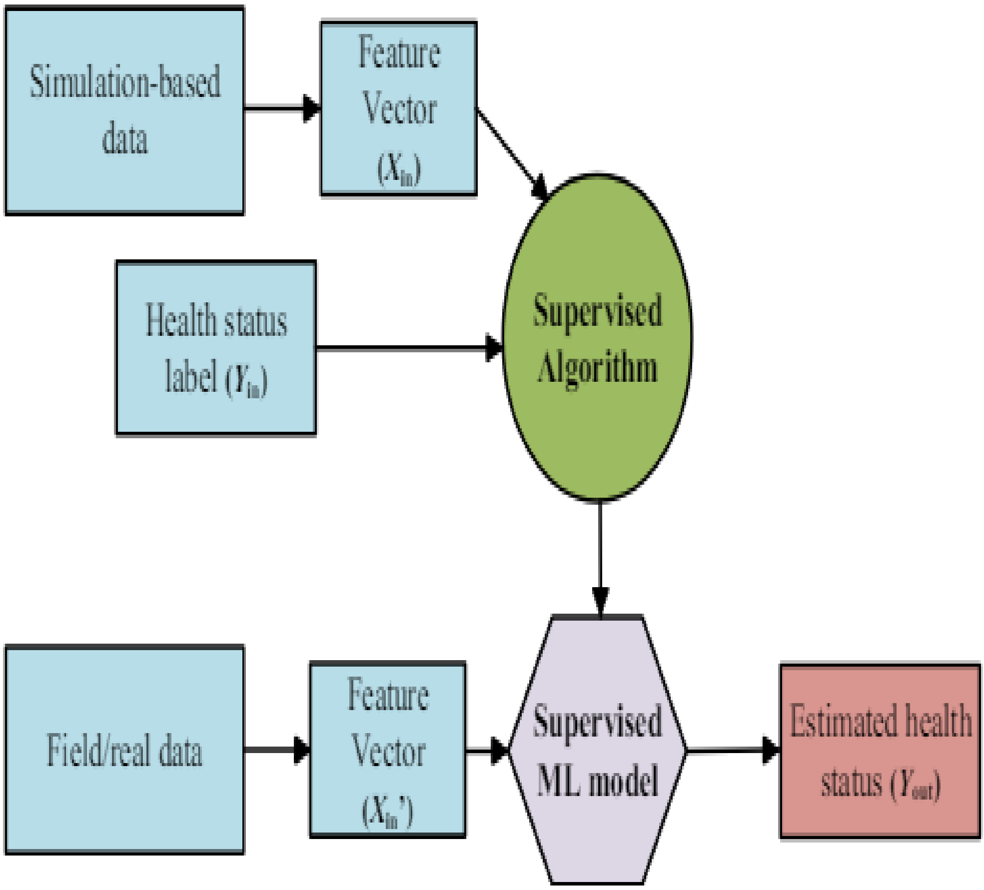


Figure 58. Schematic Diagram supervised ML methodology, (David Gonzalez-Jimenez, 2021)

A complete set-up for the training testing process of ML algorithms can be indicated with the below figure. Please see below Figure 59. presenting flow- chart of training and testing process utilized in supervised ML methodology.

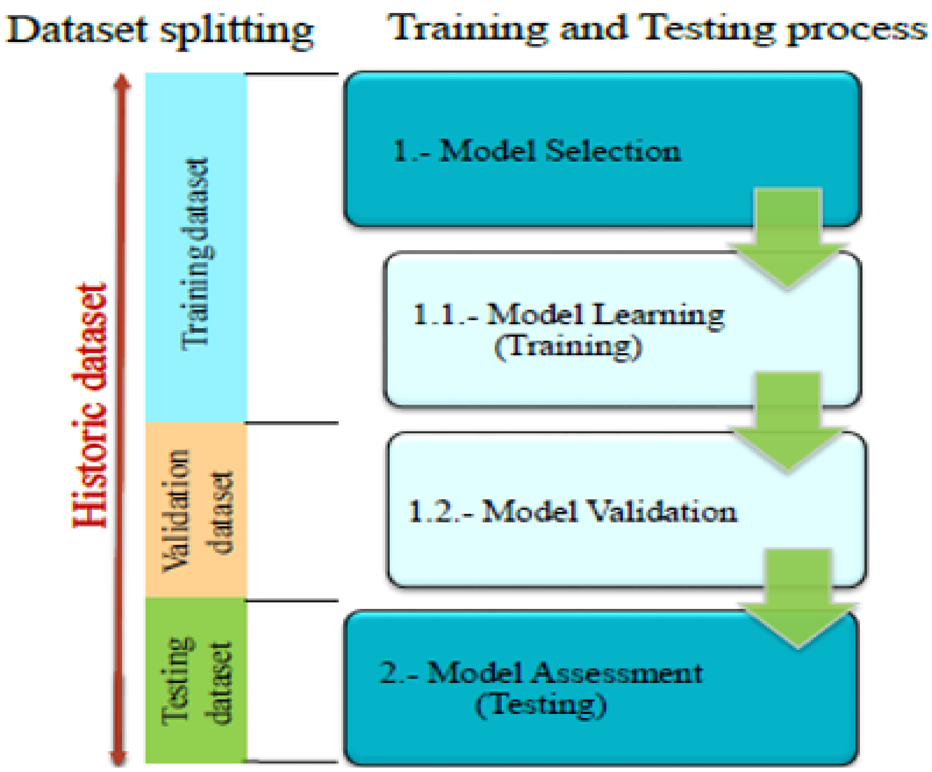


Figure 59. Schematic Diagram supervised ML methodology, (David Gonzalez-Jimenez, 2021)

4.5 Anomaly Detection Techniques

Anomaly detection techniques can be applied to various components and systems within renewable energy equipment to identify faulty conditions and deviations from the normal functioning and performance of the relative equipment. It can recognize the operating conditions and address the malfunctions in the running system. Likewise, other techniques, it can also be utilized in all mainstream renewable energy system projects. They can support in solar panels monitoring and maintenance by measuring the deviation in its performance. The altered values of power output, voltage, temperature, any kind of defects, cracks, condition deterioration can also be measured. It can support in wind turbines condition monitoring of internal working components as well as assist in measuring the visual condition from the outside including the condition of gearbox, blades, generator, and control system. In hydro-power system projects it can contribute to finding generator output that could indicate problems such as cavitations, sediment build-up, or mechanical wear. Anomaly detection can be applied to monitor the performance of wave and tidal energy devices, including mechanical components and power generation systems. Damages such as component wear and subsea cable damage can be assessed using this method. In geothermal power plants and Bio-Mass plants it can also be helpful by monitoring and measuring temperature, pressure, and fluid flow rates. Any out of the pattern variations in these parameters may signal issues such as reservoir depletion, scaling, or corrosion. It can also support in measuring combustion efficiency, fuel consumption rates, or emissions levels that indicate problems such as combustion chamber damage and air leakage. In energy storage systems it can help in monitoring the performance and health of energy storage components such as batteries and capacitors. Furthermore, it can also help in measuring the charging/discharging behaviour of the batteries.

A) Anomaly Detection in Hydraulic Accumulator Using Time Series Data

Hydraulic accumulators face extensive challenge and prone to deterioration and damage by continuous abnormal pulsating pressure which may occur by the malfunctioning of hydraulic systems. The depicted model is CNN encoding based structure supported by SVM and XGBoost algorithm model that distinguish normal and abnormal pulsating pressure. The CNN is a series of convolution operations, and the output calculation of neurons in the convolution layer is the same.

A combination of convolution operation in a Matrix with specific number is called kernel or filter and the interval applied itself is called stride**.** An auto encoder automatically extracts the nonlinear features. The auto encoder consists of a neural network, and the basic auto encoder consists of input, hidden, and output layers.

(Min-Ho Park, 2022).Please see below Figure 60. specifying the complete assembly of hydraulic Accumulator utilized as part of the equipment network.

Figure 60. Hydraulic Accumulator Model Assembly, (Min-Ho Park, 2022)

Please see below Figure 61. for CNN structure model, utilized for Anomaly detection in Hydraulic Accumulator.

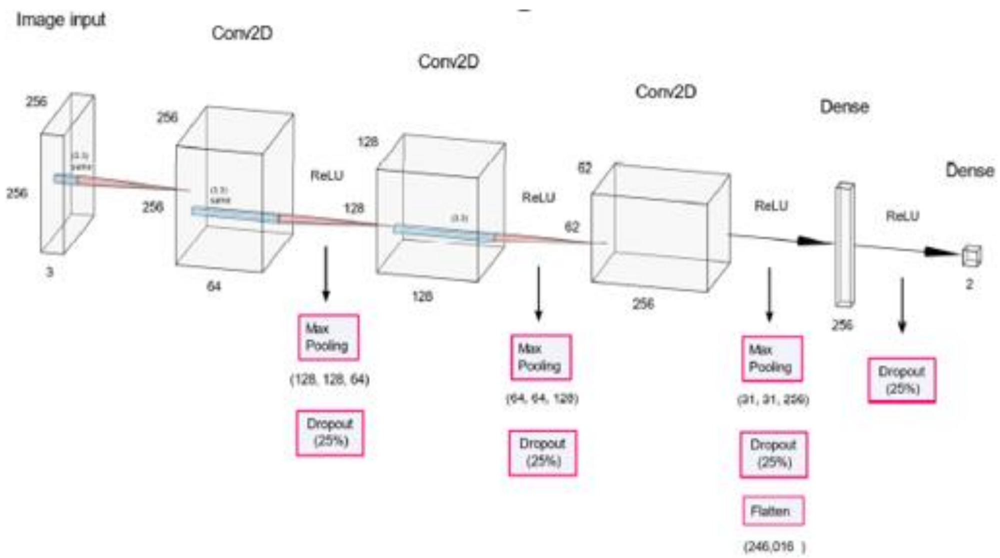


Figure 61. Representation of CNN Structure Assembly, (Min-Ho Park, 2022)

B) Anomaly Detection and Diagnosis in Sensors Signals in Li-Ion Using LSTM

An intelligent least short time memory (LSTM), a deep learning classification technique can be utilized to find existing anomalies in measurements dataset in Li-ion battery type. LSTM technique is an intelligent algorithm supported by data with better and accurate results which can support at approximately 80 % accuracy with zero performance losses. This helps in collecting the data directly from Li-ion battery sensors. Furthermore, it also contributes to performing the online fault scenarios and thus provides more accurate results. A long short-term memory (LSTM) neural network is a type of RNN which is used to work in three preceding steps. Initially by learning, then processing and finally classifying the sequential data. The input date is processed by looping over with respect to time steps and further updating the state of network. Below picture shows utilization of the LSTM neural network architectures that differs in the number of layers depending on the type of application. (Nicolae Tudoroiu, 2023).

Please see below Figure 62. part a & b. Part a show the LSTM Neural Network classification mode and part b shows the Regression mode. The LSTM neural network makes predictions based on the individual time steps of the sequence dataset.

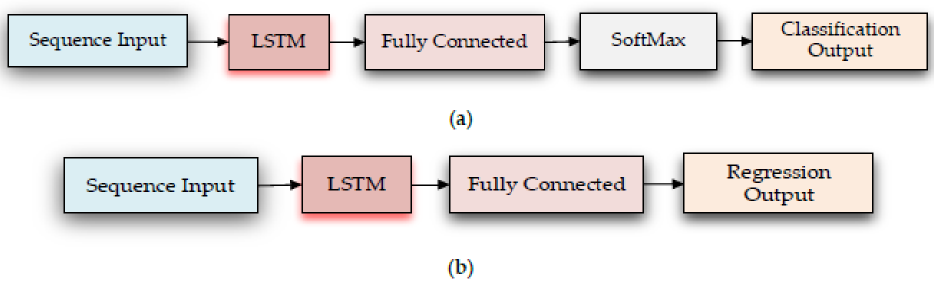


Figure 62. LSTM Neural Network Diagrams for Classification and Regression applications: (a) LSTM for classification; (b) LSTM for Regression, (Nicolae Tudoroiu, 2023)

D) Anomaly Detection in Industrial Electrical Equipment's using Unsupervised Method

Anomalies in electrical Industrial equipment can also be made by identifying irregularities in industrial machinery without supervision. It involves analysing electrical current data and additional parameters from the power grid. The framework combines Machine learning techniques with traditional analysis methods to enhance performance and efficiency. Additionally, it includes a method for examining the temporal behaviour of anomalies using Short-time Fourier transform, which enhances detection accuracy. It can utilize data clustering method which allows a dataset to be analysed. The data set further explores group objects into clusters. Clustering process can be carried out with original data of clusters as well as based on the time series model and further can be inherited to the system. After that Spectrogram analysis is performed using Short-Time Fourier Transform (STFT) to make the function act robustly. The spectrogram analysis uses the local thresholding of the spectral power density, which is the confirming step for the clustering algorithm and individually identifies the areas for anomalous points. STFT itself is not enough to detect time series without anomalies because one window with maximum spectral density power is always raised as anomalous by the algorithm. This is the reason K-means clustering is used to intensify the methodology. Same model that is used for STFT can be implemented with Silhouette and clustering method. (Marco Carratù, 2023). Please see below Figure 63. specifying the flowchart of methodology for Anomaly detection in Industrial Equipment.

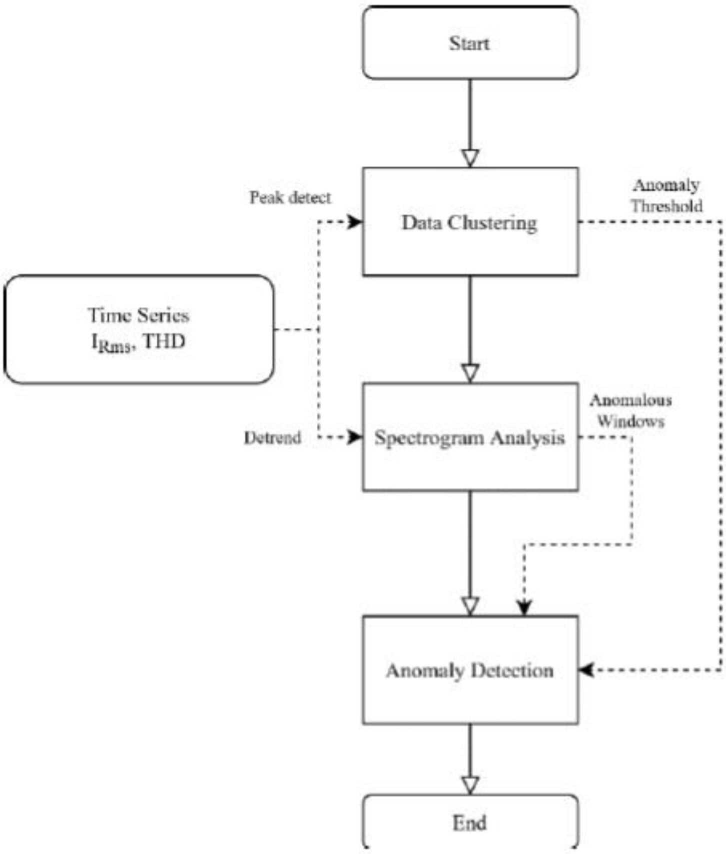


Figure 63. Flow Chart of Unsupervised Methodology for Industrial Electrical Equipment, (Marco Carratù, 2023)

4.6 Time Series Analysis

Time series analysis is based on a measurement technique which is used to examine and gather data points collected over a certain period. It employs sequential data points checked at time intervals equally placed at recurring intervals. Time series data often form the patterns that act as trends, which are cyclic and have irregular fluctuations, and the objective of time series analysis is to device a model from these patterns to make predictions, detect anomalies, and detect the abnormalities in the functioning of relative equipment and devices. It can also support in energy production measurement and optimization of the equipment.

A) Time Series Analysis for Predicting Hydroelectric Power Production

Hydro-electric power production can be predicted by the time series analysis. They predict the behaviour of hydro-electric system production by precipitation data from previous operations which can be utilized to compare the Box-Jenkins (ARIMA) and the Box-Tiao (ARIMAX) regression methods. It can assist in accurately predicting the monthly production values. In a forecasted model, there's a built-in function that calculates the future value of a predicted variable based on historical and pertinent data. The model's precision is gauged by comparing its predicted values to the actual ones. Training a forecast model involves adjusting its parameters to reduce this disparity using a known dataset with input and target values. Ideally, the forecasted model should generalize effectively to values beyond the training dataset. (Julio Barzola-Monteses, 2019)

Initially, the time series underwent a transformation to ensure that they are in the stationary condition. Moving along, the parameters of the series were estimated using correlogram functions, which were then processed with statistical testing. Subsequently, various models were estimated to identify the one that most precisely matched with the training data. The final agreed model then goes through validation by final analysis and hypothetical approach. (Julio Barzola-Monteses, 2019)

Stationary is verified before feeding into the suitable model. Identified models are estimated internally for the design criteria and then processed for validation where model’s accuracy is predicted by performing a residual analysis. After confirming the validation of both the ARIMA and ARIMAX models, it becomes feasible to forecast future time series values. Please see below Figure 64 showing the flow chart of time series analysis methodology used for predicting hydroelectric power production.

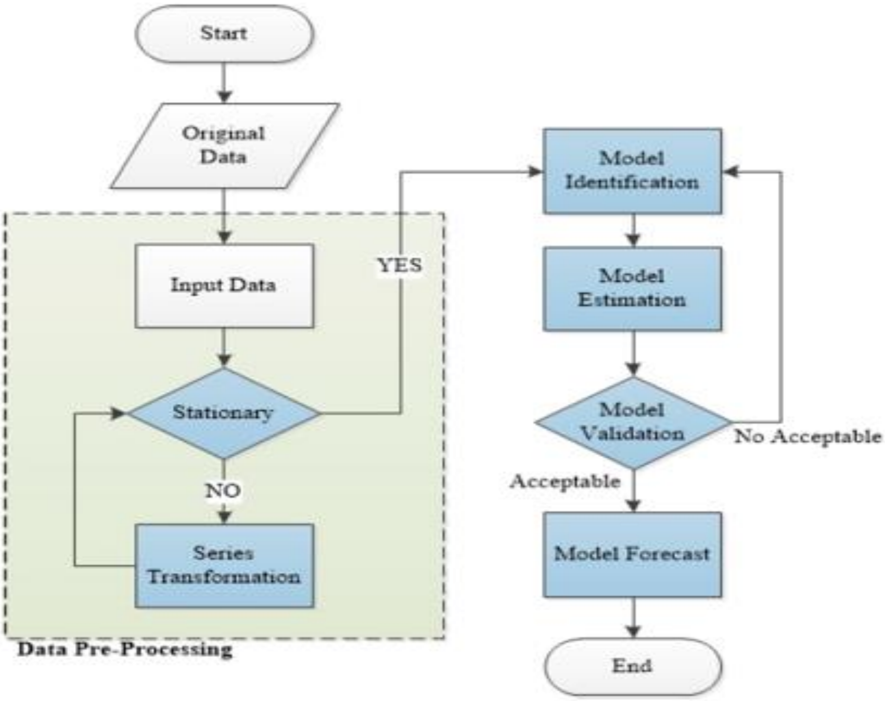


Figure 64. Flow Chart of Time Series Analysis Methodology, (Julio Barzola-Monteses, 2019)

B) Time Series Analysis for Measuring Wind Turbine Performance

SCADA data from various wind turbines can be used to forecast power generation by utilizing time series techniques. Time series analysis can make use of Functional Neural Networks (FNN) and Long Short-Term Memory (LSTM) as major techniques. A predictive accuracy can be achieved with this approach which can be used as trained model for final evaluation. This kind of model helps in measuring the performance of standalone models, governing precise power output predicted values. Similarly, the machine learning methods can identify deterioration in wind turbine. The deterioration and damages observed on the turbine blade and internal components directly effects the performance, helping to plan future inspection dates and time to keep the health of turbines in check. LSTM is a type of RNN architecture, particularly engineered to detect long-term dependencies in sequential data, making them best techniques for assessment of power output and its corresponding variables over time whereas FNN Functional Neural Networks is a branch of statistics that deals with data that work as functions or curves, not as numerical values. (Jana Backhus, 2024). Please see below Figure 65. showing a general architecture of functional neural network for measuring wind turbine performance.

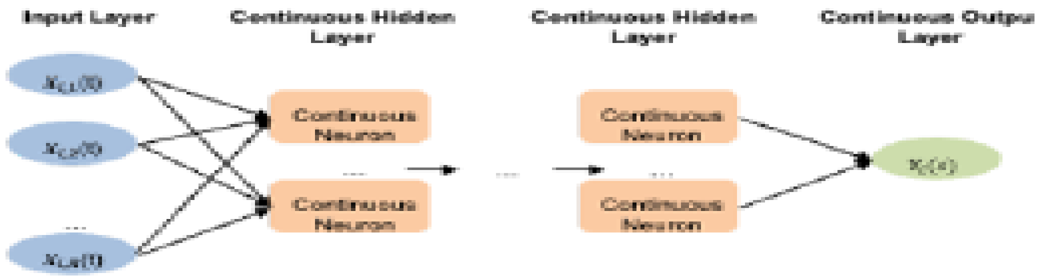


Figure 65. General Architecture of Functional Neural Network, (Jana Backhus, 2024)**.**

Prediction method model can be depicted in Figure 66. Data is initially processed from SCADA controlling system. It is then identified, segregated and after verification good data is fed into the ML training model which further sends the data into the Wind turbine Model. The values are measured with the new data provided separately into the wind turbine model. Power output prediction model for each wind turbine use "good" data timeline, and subsequently evaluates its performance on subsets of both "good" and "bad" data timelines. (Jana Backhus, 2024). Please see below Figure 66. showing workflow for wind turbine power output.

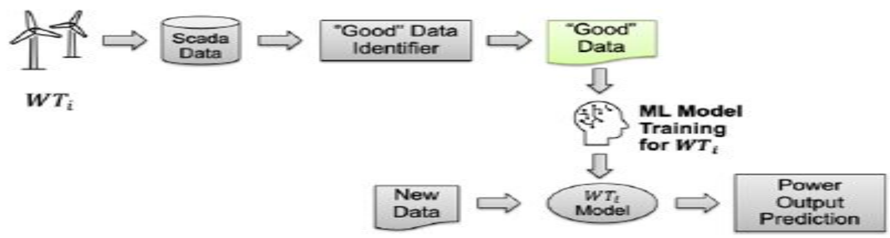


Figure 66. Workflow for Wind Turbine Power Output, (Jana Backhus, 2024)

4.7 Reinforcement Learning

Reinforcement learning (RL) is a machine learning technique where sequential decision is made by agents which are directly in contact with the environment to get the desired objectives. The agent may act as censoring system, a robot, a system with learned values. The learning of the agent is based on a procedure which maximizes the overall benefit it receives over the presented time. It includes trial and error method and receives feedback from environment in the form of rewards and accordingly updates the application procedure to induce better results and rewards.

A) Intelligence Operations for Cascaded Hydropower Reservoirs

Deep Reinforcement Learning is a kind of Reinforcement Learning method that helps in monitoring surveillance and Intelligence activities measurement for cascaded Hydro power reservoirs. It can utilize a computer system that learns how to manage a series of hydropower reservoirs better. By this, system predictions can be made about how much water will flow into the reservoirs. The DRL model is more efficient with respect to comparison models in terms of annual power output and system functionality. In the DRL, the deep Q network (DQN) works as the trigger agent for making the decisions. The DQN comprises of mainly 2 networks having same symmetry and purpose, typically termed as an action network (AN) and target network (TN), respectively. Observation of the state inputs is made by the agent including water levels and fluid inflow forecasts before the start of every step. DQN networks determine the action for functioning hydropower operation in the environment, allowing evaluation of the operation's reward and the states at the end of the time step. These steps coming at the end of states become the initial input for the next time step. Afterwards, the variables including actions, rewards and states are then stored in memory as knowledge samples. The agent utilizes these samples to train the weights of the A network, which helps in its performance and reliability with better decision-making capabilities by continuous learning from these samples. (Wei Xu, 2020)

Please see below Figure 67. showing DRL model learning framework for cascaded hydropower reservoirs.

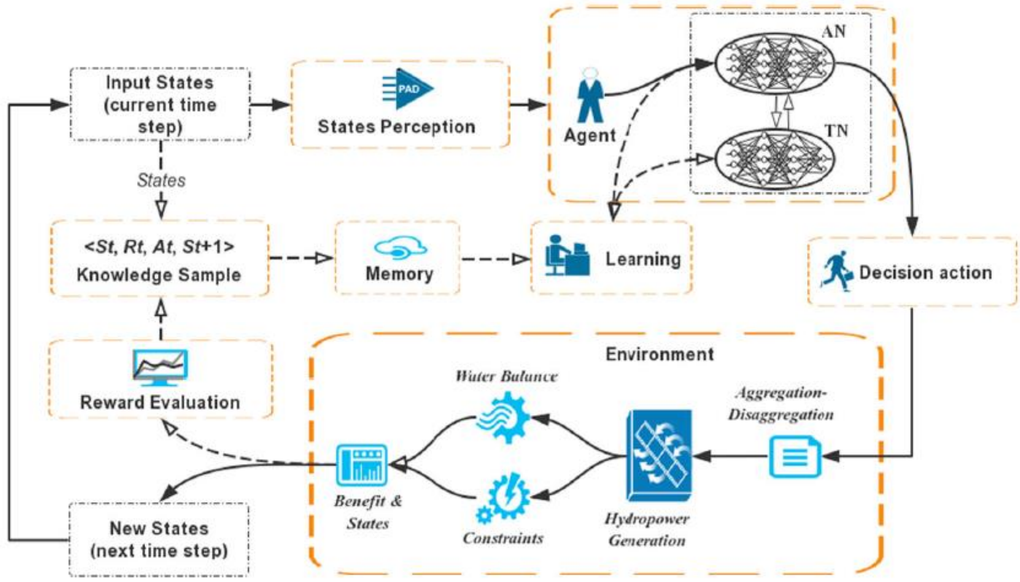


Figure 67. DRL Model Learning Framework for Cascaded Hydropower Reservoirs, (Wei Xu, 2020)

B) Inspection of Rusted Steel Surface by Deep reinforcement learning

A deep reinforcement learning (DRL) can be used to increase the efficiency of automated optical inspection system by using the adaptive image augmentation. During the process it minimizes the unpredictability issue observed in individual image augmentation methods. This approach uses a DRL algorithm, specifically DQN, which act as agent in our case, and used to anticipate the most appropriate augmentation method for every single image. Mathematical and computational pixel and features are gathered to construct states, while a DeepLab-v3+ model is used to confirm the augmented images and further provide rewards. DQN algorithm single out the optimal methods based on characteristics of the image and segmentation model result. A better segmentation performance is achieved in relation to the alternative semantic segmentation models. Refer below figure explaining the DRL method utilized with DQN model functions acting as agent, on the other hand the collection of images contributes as the Environment in our case. The agent and environment engage in repeated reciprocations exchanging signals comprising of the current state (st), fixed action (at), and resulting reward (rt). The Environment furnishes the DQN model with the state and reward, while the DQM model selects and performs actions within the Environment. These interactions occur in various steps. All along the proceedings, experience data is accumulated and further employed to train the agent which can line up the augmentation methods perfectly with the images. The agent-DQN Model can suitably augment a given image, hence maximizing the performance of the segmentation model with the help of an augmented image set (Shiyong Wang, 2023).

Please see below Figure 68 explaining the DRL-enabled adaptive image augmentation framework to identify rust formation on the steel surface.

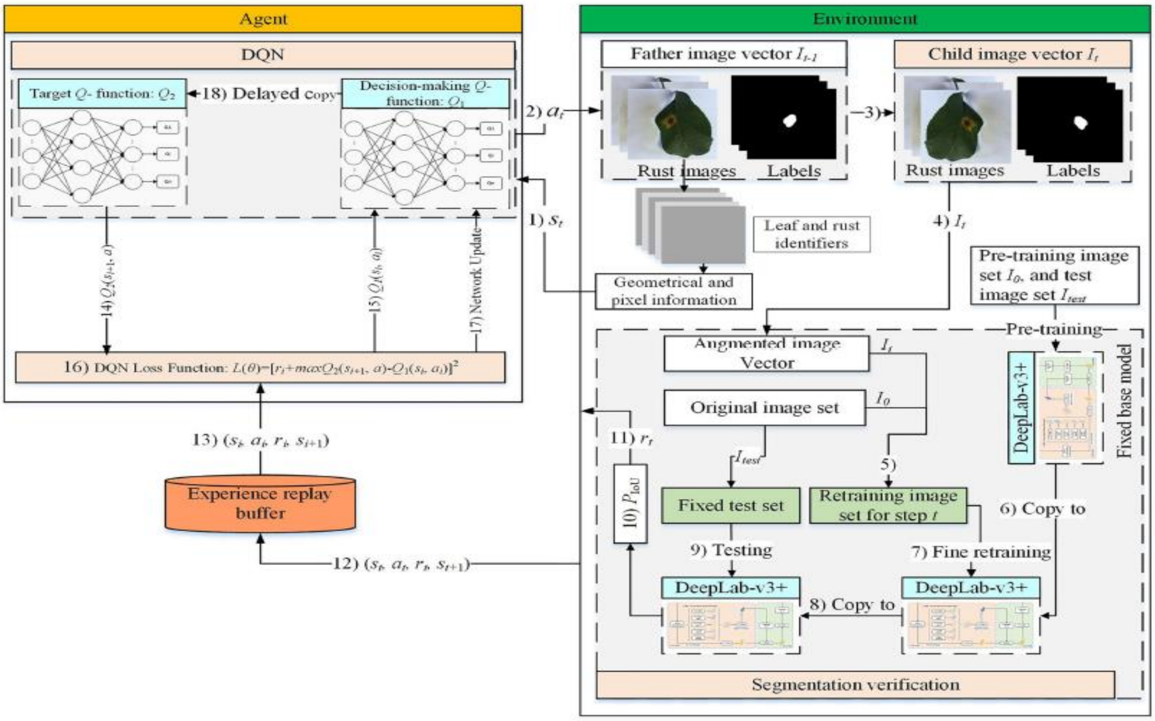


Figure 68. DRL-enabled adaptive image augmentation framework, (Shiyong Wang, 2023)

5 RESULTS OF LITERATURE REVIEW

A total of 63 study citations were utilized to address the compilation of thesis and those 63 were further sub divided into 6 separate subject themes of thesis including 4 renewable energy topics and 2 General study sections namely renewable energy and AI- Artificial Intelligence. Eighteen study references were used to explain general renewable energy subject. 19 articles were used to address general artificial intelligence portion. 9 articles were specifically used for explanation of AI role in wind energy projects including specific techniques and methods whereas hydropower and solar energy projects sector took 9 and 7 study references for addressing their literature review respectively. Only 1 article was referred that had reporting information for explaining the wind and solar energy sectors. Please see below table 7. explaining the filtration made in this thesis and the outcome specifying the number of articles to address artificial intelligence, renewable energy aspects and AI role in major sources of renewable energy.

Table 7. Summary of Citations Gathered for Literature Review

Serial No.	Thesis Subject Themes	Citations Gathered for Literature Review		
		Searched Citations	Citations After First Filter	Citations After Second Filter
1	General-Renewable Energy	97	33	18
2	AI-Artificial Intelligence	88	29	19
3	Wind Energy	78	24	9
4	Solar Energy	67	19	7
5	Hydropower Energy	53	16	9
6	Wind/Solar Energy	4	3	1
7	Total	387	124	63

Source: Own Exploration

Please see below Figure 69. showing graphical representation of literature review findings for addressing each source of renewable Energy and in general all AI sections and renewable energy sections.

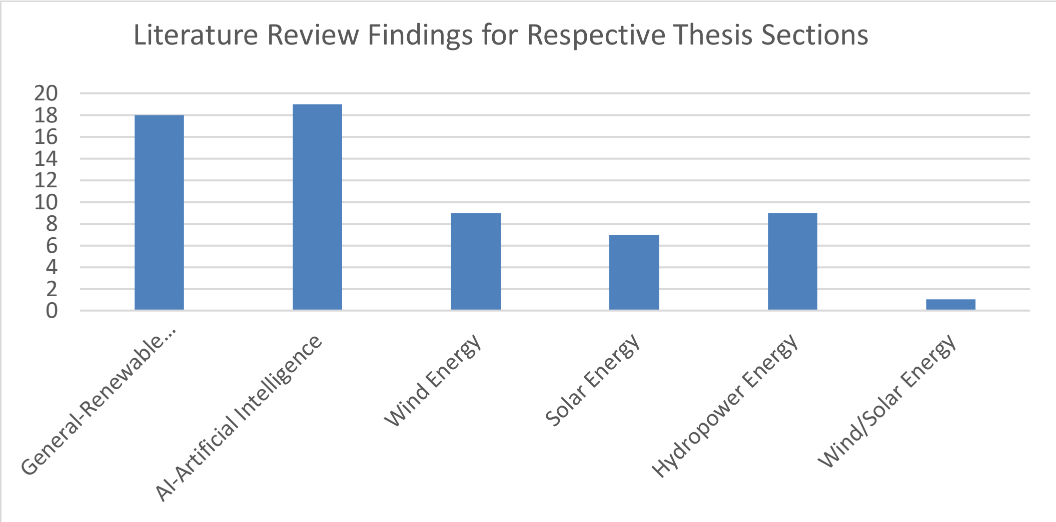


Figure 69. Literature Review Findings for Respective Thesis Sections.

Source: Own Elaboration

Study citations utilized for addressing the research topics included the thesis work and peer reviewed work by various researchers, online websites and organization profiles and reports and journals/articles published so far. Please see below table 8. explaining the reference and nature of each article with depiction of its utilization for compilation of this thesis.

Table 8. Summary of Literature Review Findings for Respective Thesis Sections

Serial No.	Reference ID	Reference Details	Renewable Energy/AI
1	Journal/Article	Adlen Kerboua, R. K. (2022). Recurrent neural network optimization for wind turbine condition prognosis.	Wind Energy
2	Online Website	Agency, I. I. (2024). Outlook for 2023 and 2024. Retrieved from IEA- International Energy Agency.	General-Renewable Energy
3	Journal/Article	Angga Wahyu Aditya, N. R. (2023). Web-based low–cost rooftop solar power plant for household application.	Solar Energy
4	Thesis Work	Araf, S. (2023). The Role of Artificial Intelligence in Marketing Project Management.	AI-Artificial Intelligence
5	Thesis Work	Basnet, A. (2022). Artificial Intelligence in Cyber Security.	AI-Artificial Intelligence
6	Thesis Work	Bogomolova, S. (2023). Artificial Intelligence and its impact on work in the field of logistics.	AI-Artificial Intelligence
7	Journal/Article	Boucher, P. (2020). Artificial intelligence: How does it work, why does it matter, and what can we do about it?	AI-Artificial Intelligence
8	Journal/Article	Carlos Cacciuttolo, D. C. (2024). Renewable Energy from Wind Farm Power Plants in Peru:	Wind Energy
9	Journal/Article	Chang Liu, M.-S. C.-C.-M. (2017). A Wind Power Plant with Thermal Energy Storage for Improving the Utilization of Wind Energy.	Wind Energy
10	Journal/Article	David Gonzalez-Jimenez, J. d.-O. (2021). Machine Learning-Based Fault Detection and Diagnosis of Faulty Power Connections of Induction Machines.	AI-Artificial Intelligence

11	Journal/Article	Deeb, A. (2019). Large-Scale PV Solar Power Plant & Energy Storage System.	Solar Energy
12	Journal/Article	Enas Taha Sayed, A. G. (2023). Renewable Energy and Energy Storage Systems.	General-Renewable Energy
13	Journal/Article	Evrencan Özcan, R. Y. (2019). Risk Based Maintenance in the Hydroelectric Power Plants	Hydro Power Energy
14	Thesis Work	Fahli, M. B. (2021). The Impact of Artificial Intelligence on the B2B Sales Funnel	AI-Artificial Intelligence
15	Journal/Article	Farrokh Aminifar, M. A. (2021). A review of power system protection and asset management with machine learning techniques.	AI-Artificial Intelligence
16	Journal/Article	Fausto Pedro García Márquez, A. P. (2021). A Comprehensive Review of Artificial Intelligence and Wind Energy.	Wind Energy
17	Journal/Article	Filipa S. Barros, P. A. (2024). Using Recurrent Neural Networks to improve initial conditions for a solar wind forecasting model.	Solar/Wind
18	Journal/Article	G N Uzakov, Z. E. (2024). Energy indicators of the micro-hydro power plant adjusted to outlet water flows from pump units.	Hydro Power Energy
19	Thesis Work	Gu, Y. (2020). Renewable Energy Integration in Distribution System with Artificial Intelligence.	General-Renewable Energy
20	Journal/Article	Hosam M. Saleh, A. I. (2023). The challenges of sustainable energy transition: A focus on renewable.	General-Renewable Energy
21	Thesis Work	Jalonen, J. (2023). Artificial Intelligence as a Part. Automation of Accounts Payable Processes.	AI-Artificial Intelligence
22	Journal/Article	Jana Backhus, A. R. (2024). Equipment Health Assessment: Time Series Analysis for Wind Turbine Performance.	Wind Energy
23	Journal/Article	Jingcheng, L. (2010). Application Of Solar Energy.	Solar Energy
24	Journal/Article	Jose A. Ruz-Hernandez, E. S. (2008). Fault Detection and Diagnosis for Fossil Electric Power Plants via Recurrent Neural Networks.	AI-Artificial Intelligence
25	Journal/Article	Julio Barzola-Monteses, M. M.-L.-A.-R. (2019). Time Series Analysis for Predicting Hydroelectric Power Production: The Ecuador Case.	Hydro Power Energy
26	Journal/Article	Kalogirou, S. A. (2005). Artificial Intelligence in Renewable Energy Applications in Buildings.	AI-Artificial Intelligence
27	Journal/Article	Latifa A. Yousef, H. Y.-M. (2023). Artificial Intelligence for Management of Variable Renewable.	AI-Artificial Intelligence
28	Journal/Article	Lei Kou, Y. L. (2022). Review on Monitoring, Operation and Maintenance of Smart.	General-Renewable Energy
29	Thesis Work	Lipsanen, O. (2019). Cooling with renewable energy.	General-Renewable Energy
30	Journal/Article	Liu, Y. Z. (2023). A Lightweight CNN for Wind Turbine Blade Defect Detection Based on Spectrograms.	Wind Energy
31	Journal/Article	M. Talaat, M. H. (2023). Artificial intelligence applications for microgrids integration and management of hybrid renewable energy sources.	AI-Artificial Intelligence
32	Journal/Article	M. Waqar Akram, G. (2019). CNN based automatic detection of photovoltaic cell defects in electroluminescence images.	Solar Energy
33	Journal/Article	MajidMemari, P. S. (2024). Review on the Advancements in Wind Turbine Blade Inspection: Integrating Drone and Deep Learning Technologies for Enhanced Defect Detection.	Wind Energy
34	Thesis Work	Manyonje, F. X. (2023). Automation And Optimization of Renewable Domestic Energy Production and Storage Using Electric Vehicles.	General-Renewable Energy
35	Journal/Article	Marco Carratù, V. G. (2023). A Novel Methodology for Unsupervised Anomaly Detection in Industrial Electrical Systems.	AI-Artificial Intelligence
36	Journal/Article	Min-Ho Park, S. C.-H.-W.-U.-H.-J. (2022). Anomaly Detection Based on Time Series Data of Hydraulic Accumulator.	Hydro Power Energy
37	Journal/Article	Mudhar A. Al-Obaidi, S. A. (2024). Integration of Renewable Energy Systems in Desalination.	General-Renewable Energy
38	Journal/Article	Nallapaneni Manoj Kumar, S. M. (2018). On the technologies empowering drones for intelligent monitoring of solar.	Solar Energy
39	Online Website	Nations, U. (2024). Climate Action. Retrieved from United Nations.	General-Renewable Energy
40	Thesis Work	Ndonku, N. E. (2022). The Transition of Fossil Fuel as a Source of Energy.	General-Renewable Energy
41	Journal/Article	Nicolae Tudoroiu, M. Z.-E. (2023). Investigations on Using Intelligent Learning Techniques for Anomaly Detection and Diagnosis	General-Renewable Energy
42	Journal/Article	Nura Garba, B. A. (2024). Renewable Energy Sources, Sustainability and Environmental Protection: A Review.	General-Renewable Energy
43	Thesis Work	Pozdnyakova, L. (2009). Promotion Of Electricity fromRenewabe Energy Sources in Finland	General-Renewable Energy
44	Journal/Article	Rajendra Prasad Ch., K. M. (2022). A review on hydro power plants and turbines.	Hydro Power Energy
45	Journal/Article	Report, G. S. (2023). Renewable Energy in Energy Demand. Retrieved from REN21.	General-Renewable Energy
46	Journal/Article	Saini, K. K. (2021). Application of Artificial Intelligence for the Optimization of Hydropower Energy Generation.	Hydro Power Energy
47	Journal/Article	Sang-Soo Baek, J. P. (2020). Prediction of Water Level and Water Quality Using a CNN-LSTM Combined Deep Learning Approach.	Hydro Power Energy
48	Journal/Article	Shahrulhisham, N. N. (2022). Application of Machine Learning Technique Using Support Vector Machine in Wind Turbine Fault Diagnosis.	Wind Energy
49	Thesis Work	Shanab, N. A. (2015). Mapping The Potential of Renewable.	General-Renewable Energy

50	Journal/Article	Shiyong Wang, A. K. (2023). Deep reinforcement learning enables adaptive-image augmentation for automated optical inspection of plant rust.	AI-Artificial Intelligence
51	Journal/Article	Sitaula, S. (2018). Techno-Economic Analysis of solar PV system for Tampere University of Applied Sciences	General-Renewable Energy
52	Journal/Article	Suja Cherukullapurath Mana, T. S. (2022). Automated fish detection and tracking system using pre-trained Mask R-CNN for Ecological biodiversity	General-Renewable Energy
53	Journal/Article	Sunil Kr. Jhaa, J. B. (2017). Renewable energy: Present research and future scope of Artificial Intelligence.	AI-Artificial Intelligence
54	Journal/Article	Syahril Ramadhan Saufi, Z. A. (2019). Challenges and Opportunities of Deep Learning Models for Machinery Fault Detection and Diagnosis: A Review.	AI-Artificial Intelligence
55	Journal/Article	Tanay Birişçi, D. K. (2023). Solar power plants in terms of landscape protection and repair: activities of local governments in Izmir.	Solar Energy
56	Journal/Article	Teja Kattenborn, J. L. (2021). Review on Convolutional Neural Networks (CNN) in vegetation remote sensing.	AI-Artificial Intelligence
57	Journal/Article	Tripathi, A. K. (2022). Output Power Prediction of Solar Photovoltaic Panel Using Machine Learning Approach.	Solar Energy
58	Journal/Article	Wei Xu, X. Z. (2020). Deep Reinforcement Learning for Cascaded Hydropower Reservoirs Considering Inflow Forecasts.	Hydro Power Energy
59	Journal/Article	Weizhen Fang, Y. S. (2021). Recognizing global dams from high-resolution remotely sensed images using convolutional neural networks.	Hydro Power Energy
60	Online Website	Wikipedia	AI-Artificial Intelligence
61	Journal/Article	Xue Zhou, Y. K. (2023). Sustainable Operation and Maintenance of Offshore Wind.	Wind Energy
62	Journal/Article	Zand, M. (2024). Technology and energy management with Renewable Energy aspects.	General-Renewable Energy
63	Journal/Article	Zhang, H. (2022). A Review of Convolutional Neural Network Development in Computer Vision.	AI-Artificial Intelligence

78 percent of the citations were from the journals/articles published related to the thesis topics. 17 percent of the references gathered were from the research work from various researchers who worked on the thesis topic previously whereas only 5 percent of the complete work was referred from online websites and organizational data available for different organizations. Please see below Figure 70 showing graphical representation of the whole gathered data in this respect.

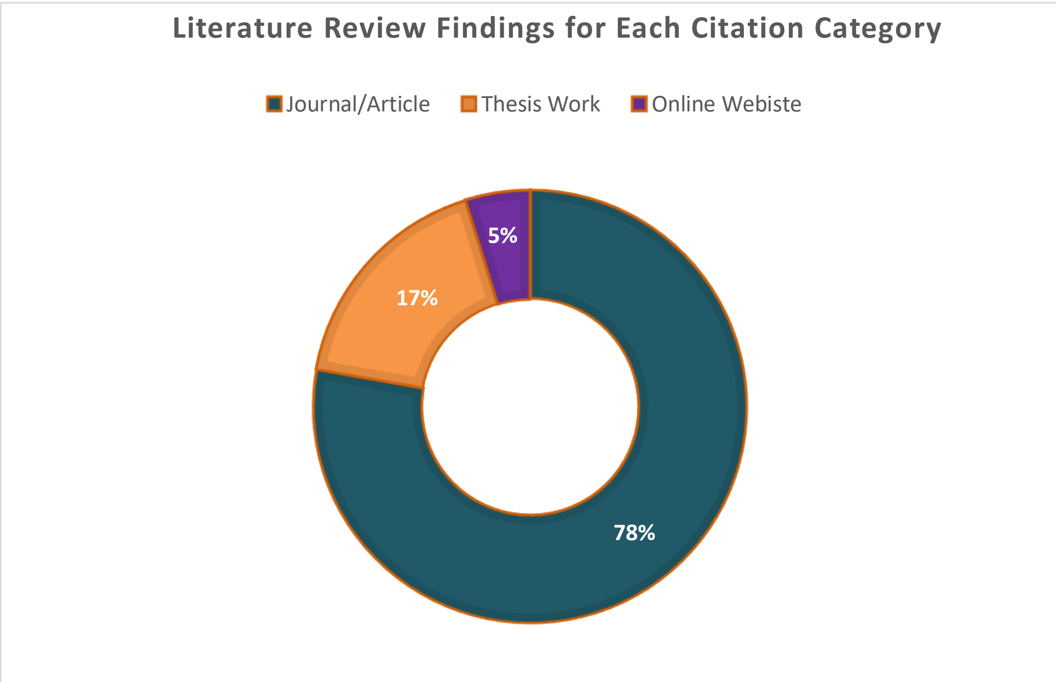


Figure 70. Literature Review Findings for Each Citation Category

Please see below table 9. explaining AI role in different phases of renewable energy projects related to solar energy.

Table 9. Solar Energy and Contribution of AI Methods and Techniques in Projects Phases

Renewable Energy/AI	Reference Details	AI Methods and Techniques	AI Role In Phases of Renewable Energy Projects
Solar Energy	Angga Wahyu Aditya, N. R. (2023).	General	Design and Construction
	Deeb, A. (2019).	General	Research and Development
	Jingcheng, L. (2010).	General	Design, Research and Development
	M. Waqar Akram, G. (2019).	Convolutional Neural Network	Inspection And Maintenance
	Nallapaneni Manoj Kumar, S. M. (2018).	Machine Learning (ML)	Inspection, Monitoring and Maintenance
	Tanay Birişçi, D. K. (2023).	General	Research and Development
	Tripathi, A. K. (2022).	Machine Learning {SVMR (Support Vector Machine Regression), MLR (Multi-Linear Regression), GR (Gaussian regression)}	Monitoring And Performance

Please see below table 10. explaining AI role in different phases of renewable energy projects related to wind energy.

Table 10. Wind Energy and Contribution of AI Methods and Techniques in Projects Phases

Renewable Energy/AI	Reference Details	AI Methods and Techniques	AI Role In Phases of Renewable Energy Projects
Wind Energy	Adlen Kerboua, R. K. (2022).	RNN (Recurrent Neural Networks)	Operations And Monitoring
	Carlos Cacciuttolo, D. C. (2024).	General	Research and Development
	Chang Liu, M.-S. C.-C.-M. (2017).	General	Operations And Performance
	Fausto Pedro García Márquez, A. P. (2021).	ANN (Artificial Neural Networks), SVM (Support Vector Machine), PSO (Particle Swarm Optimization), GA (Genetic Algorithms)	Inspection And Maintenance
	Jana Backhus, A. R. (2024).	Time Series Analysis	Monitoring And Performance
	Liu, Y. Z. (2023).	CNN (Convolutional Neural Network	Inspection, Monitoring and Maintenance

	MAJID MEMARI, P. S. (2024).	CNN (Convolutional Neural Network, YOLO (You Only Look Once), SVM (Support Vector Machine), SSD (Single Shot Multi Box Detector), LPSO (Levi-based Particle Swarm Optimization), Y SODA (Yolo Based Small Object Detection Approach)	Inspection, Monitoring and Maintenance
	Shahrulhisham, N. N. (2022).	SVM (Support Vector Machine), KNN k-Nearest Neighbors, ML (Machine Learning), Linear, Quadratic, Cubic, Fine Gaussian, Medium Gaussian, and Coarse Gaussian	Operations, Monitoring and Performance
	Xue Zhou, Y. K. (2023).	(VMD)Variational Mode Decomposition, CNN (Convolutional Neural Network, LSTM (Learning-Based Long Short-Term Memory)	Operations And Maintenance

Please see below table 11. explaining AI role in different phases of renewable energy projects related to hydro-power energy.

Table 11. Hydro-Power Energy and Contribution of AI Methods and Techniques in Projects Phases

Renewable Energy/AI	Reference Details	AI Methods and Techniques	AI Role In Phases of Renewable Energy Projects
Hydro Power Energy	Evrencan Özcan, R. Y. (2019).	General	Maintenance
	G N Uzakov, Z. E. (2024).	General	Operations And Performance
	Julio Barzola-Monteses, M. M.-L.-A.-R. (2019).	Time Series Analysis	Operations And Monitoring
	Min-Ho Park, S. C.-H.-W.-U.-H.-J. (2022).	Time Series Analysis, SVM (Support Vector Machine), CNN (Convolutional Neural Network), LSTM (Learning-Based Long Short-Term Memory)	Operations, Inspections and Monitoring
	Rajendra Prasad Ch., K. M. (2022).	General	Research and Development
	Saini, K. K. (2021).	ANN (Artificial Neural Networks), SVM (Support Vector Machine), CNN (Convolutional Neural Network), Fuzzy Logic, ANFIS (Adaptive neuro-fuzzy inference system), PSO (Particle Swarm Optimization), RMSE (Root Mean Square), MAPE (Mean Absolute Percentage Error) MARS (Multivariate adaptive regression splines) MFA (Modified firefly algorithm)	Operations And Maintenance
	Sang-Soo Baek, J. P. (2020).	CNN (Convolutional Neural Network), LSTM (Learning-Based Long Short-Term Memory)	Operation, Monitoring and Maintenance
	Wei Xu, X. Z. (2020).	DRL (Deep Reinforcement Learning), ANN (Artificial Neural Networks)	Operations And Monitoring
	Weizhen Fang, Y. S. (2021).	CNN (Convolutional Neural Network)	Operations And Monitoring

Please see below table 12. explaining AI role in different phases of renewable energy projects related to solar/wind energy.

Table 12. Solar/Wind Energy and Contribution of AI Methods and Techniques in Projects Phases

Renewable Energy/AI	Reference Details	AI Methods and Techniques	AI Role In Phases of Renewable Energy Projects
SOLAR/WIND ENERGY	Filipa S. Barros, P. A. (2024).	RNN (Recurrent Neural Networks)	Operation, Monitoring and Maintenance

Please see below table 13. explaining AI role in different phases of renewable energy projects related to all forms of renewable energy.

Table 13. Overall Renewable Energy and Contribution of AI Methods and Techniques in Projects Phases

Renewable Energy/AI	Reference Details	AI Methods and Techniques	AI Role In Phases of Renewable Energy Projects
GENERAL- RE	Agency, I. I. (2024).	General	Research and Development
	Enas Taha Sayed, A. G. (2023).	General	Research and Development
	Gu, Y. (2020).	DL (Deep Learning), , ML(Machine Learning), SVM(Support Vector Machine), CNN(Convolutional Neural Network), GR(Gaussian Restricted), RF (Random Forest)	Operations
	Hosam M. Saleh, A. I. (2023).	General	Research and Development
	Lei Kou, Y. L. (2022).	ANN (Artificial Neural Networks), SVM (Support Vector Machine), CNN (Convolutional Neural Network), LSTM (Learning-Based Long Short-Term Memory), Fuzzy Logic, RF (Random Forest), KNN k-Nearest Neighbors	Operation, Monitoring and Maintenance
	Lipsanen, O. (2019).	General	Research and Development
	Manyonje, F. X. (2023).	General	Operations
	Mudhar A. Al-Obaidi, S. A. (2024).	General	Operations
	Nations, U. (2024).	General	Research and Development
	Ndonku, N. E. (2022).	General	Research and Development
	Nicolae Tudoroiu, M. Z.-E. (2023).	DL (Deep Learning), ML (Machine Learning), LSTM (Learning-Based Long Short-Term Memory), RMSE (Root Mean Square Error)	Monitoring And Maintenance

	Nura Garba, B. A. (2024).	General	Research and Development
	POZDNYAKOVA, L. (2009).	General	Research and Development
	Report, G. S. (2023).	General	Operations, Research and Development
	Shanab, N. A. (2015).	General	Research and Development
	Sitaula, S. (2018).	General	Research and Development
	Suja Cherukullapurath Mana, T. S. (2022).	CNN (Convolutional Neural Network	Operations And Monitoring
	Zand, M. (2024).	General	Research and Development

Please see below table 14. explaining AI role in different phases of renewable energy projects related to all methods and techniques utilized for AI implementation.

Table 14. Artificial Intelligence and Contribution of AI Methods and Techniques in Projects Phases

Renewable Energy/AI	Reference Details	AI Methods and Techniques	AI Role In Phases of Renewable Energy Projects
AI-Artificial Intelligence	Araf, S. (2023).	General	Research and Development
	Basnet, A. (2022).	Machine Learning	Research and Development
	Bogomolova, S. (2023).	Machine Learning and Neural Networks	Research and Development
	Boucher, P. (2020).	ML (Machine Learning), ANN (Artificial Neural Networks), GAN Generative adversarial networks and Fuzzy Logics	Research and Development
	David Gonzalez-Jimenez, J. d.-O. (2021).	ML (Machine Learning), SL (Supervised Learning), SVM (Support Vector Machine), LR (Linear Regression), RF (Random Forest), KNN k-Nearest Neighbors	Monitoring And Maintenance
	Fahli, M. B. (2021).	DL (Deep Learning), NLP (Natural language Processing), ML (Machine Learning)	Research and Development
	Farrokh Aminifar, M. A. (2021).	ML (Machine Learning)	Operations And Maintenance
	Jalonen, J. (2023).	General	Research and Development
	Jose A. Ruz-Hernandez, E. S. (2008).	RNN (Recurrent Neural Networks)	Inspection, Monitoring and Maintenance
	KALOGIROU, S. A. (2005).	(ANNs)Artificial Neural Networks, (GA)Genetic Algorithms and Fuzzy Logic	Operations And Monitoring
	Latifa A. Yousef, H. Y.-M. (2023).	ML (Machine Learning)	Monitoring And Performance
	M. Talaat, M. H. (2023).	ML (Machine Learning), (ANNs)Artificial Neural Networks,	Operations And Maintenance
	Marco Carratù, V. G. (2023).	ML (Machine Learning)	Monitoring And Performance
	Shiyong Wang, A. K. (2023).	DRL (Deep Reinforcement Learning), ML (Machine Learning)	Inspection And Maintenance
	Sunil Kr. Jhaa, J. B. (2017).	General	Research and Development

	Syahril Ramadhan Saufi, Z. A. (2019).	DRL (Deep Reinforcement Learning), ANN (Artificial Neural Networks), SVM (Support Vector Machine), (ReLU), CNN (Convolutional Neural Network), GRBM (Gaussian restricted Boltzmann machine), LSTM (Learning-Based Long Short-Term Memory), RMSE (Root Mean Square Error)	Monitoring And Performance
	Teja Kattenborn, J. L. (2021).	CNN (Convolutional Neural Network	Operations And Maintenance
	Wikipedia	General	Research and Development
	Zhang, H. (2022).	CNN (Convolutional Neural Network	Research and Development

A total of 24 numbers of citations described the research and development aspect of the renewable energy projects however our major representation remained with the inspection, maintenance, monitoring and performance of the renewable energy projects. Mainly 6 articles presented operations and monitoring, 5 utilized for operations and maintenance, 5 employed for monitoring and performance of the renewable energy projects, 4 citations had inspection, monitoring and maintenance functions. Please see below Figure 71. showing graphical representation explaining the phases of the projects mentioned in the study references.

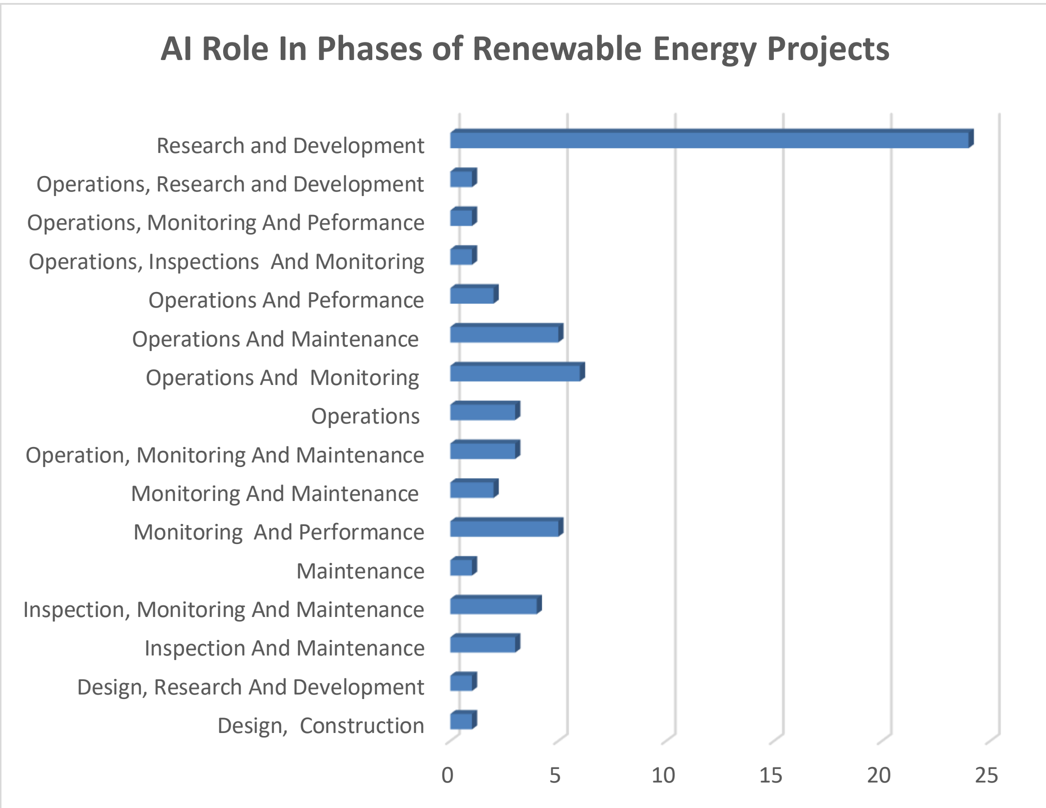


Figure 71. AI Role In Phases of Renewable Energy Projects

Percentage for each of the main AI methods and techniques used in the study references can be explained with below graphical representation. General Information articles comprise main part having 24 percentage of the citations reference following by ML (Machine Learning). After ML, CNN methods were referred in most references. Other notable AI techniques and methods that were extensively used include ANN, SVM, LSTM, DL, RNN and RL with less than 10 percentage of existence in all the literature references. The percentage value for each one of them can be presented in below figure. Please see below Figure 72 showing percentage of citations utilized for explaining commonly used AI Methods and Techniques employed in Renewable Energy projects.

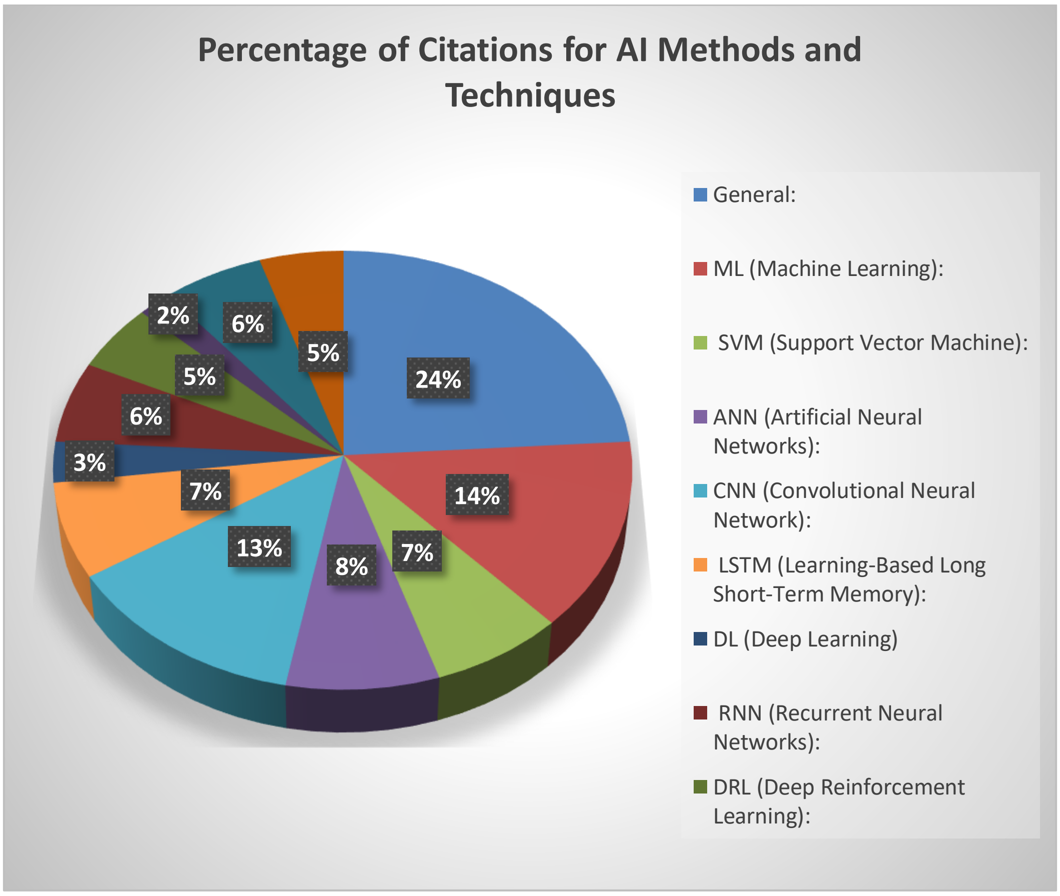


Figure 72. Percentage of Citations for AI Methods and Techniques

6 CONCLUSION

6.1 Theoretical Contribution

The literature review carried out from the study of 63 study references examines the application of artificial intelligence (AI) in renewable energy projects, related to General RE, Artificial Intelligence, solar, hydro, and wind energy. It demonstrates that AI significantly increased the sustainability and performance of renewable energy systems. Various AI techniques and methodologies, including machine learning, deep learning, and reinforcement learning, are utilized in different aspects of renewable energy projects. Machine learning is extensively used for tasks such as monitoring and maintenance. Techniques such as Support Vector Machines and Random Forests are employed to forecast problems before they happen. Deep learning, with the employment of AI methods such as CNN and ANN are effective for complex tasks such as image recognition during maintenance and inspection operations. Reinforcement learning optimizes the operation of energy systems and helps in forecasting the future inspection dates.

Different phases of renewable energy projects get the AI support, specifically including research and development to design, construction, operations, and maintenance. In research and development, AI supports innovation by maximizing the engineering and designs, by upgrading the system behaviours. During ongoing functions and process operations, AI provides monitoring and performance assessment in real-time to ensure smooth functioning. For inspections and maintenance, AI uses automated machinery and devices including drones, supporting precise and safe operations. Please refer to results section Tables 9 to 14 showing the explanation of AI methods and techniques for each study reference. It also includes the AI role defined for each project phase indicated in each citation utilized in this literature review. With a thorough literature review and study of the selected citations and references we can conclude by answering both the research questions.

RQ1: How can AI-supported inspection processes contribute to the overall sustainability and longevity of renewable energy system projects?

AI-assisted inspection methods can significantly enhance the durability and sustainability of renewable energy projects in numerous ways. AI algorithms can sift through vast data from sensors and other sources to detect potential problems in renewable energy systems (Nallapaneni Manoj Kumar, 2018). By catching issues early, such as equipment glitches or performance dips, prompt maintenance can prevent major failures and minimize downtime. AI can forecast maintenance needs based on accumulated performance data (Saini, 2021). This proactive approach prevents unexpected breakdowns, reduces the reliance on reactive fixes, and extends the lifespan of renewable energy infrastructure. Real-time data analysis by AI algorithms can fine-tune renewable energy systems for maximum output (Fausto Pedro, 2021).This optimization boosts efficiency enhances energy yields, and bolsters project sustainability. AI predicts patterns in resource availability, such as sunlight or wind, and adjusts system operations accordingly (Saini, 2021). By maximizing resource usage, renewable energy projects can operate more sustainably and cost-effectively in the long run.

AI evaluates various risks linked with renewable energy projects, like weather-related or equipment failure risks, and offers insights to mitigate them (Lei Kou, 2022). By proactively addressing potential risks, AI ensures the long-term viability and resilience of renewable energy systems. (Fausto Pedro, 2021) AI-driven analytics extract actionable insights from large datasets, empowering stakeholders to make informed choices regarding maintenance, upgrades, and investments. Leveraging data-driven processes allows renewable energy projects to adapt and optimize their operations for long-term sustainability.

RQ2: What are the most suitable AI algorithms or models for detecting defects in renewable energy equipment?

Various AI methods, such as computer vision, machine learning, anomaly detection, time series analysis, and reinforcement learning, present formidable solutions for finding and evaluating defects in renewable energy equipment. (Farrokh Aminifar, 2021). Computer vision methods use imagery and videos of solar panels, wind turbines, and hydroelectric infrastructure, helping in detection of prime defects and abnormalities such as cracks, damages, defects, wear in the equipment such as corrosion, and dimensional defect such as misalignments (Zhang, 2022).

Machine learning algorithms, especially supervised and unsupervised models, are effective in finding patterns indicative of deterioration in the machinery or reducing efficiency, helping in timely periodic inspection and maintenance (Tripathi, 2022). Anomaly detection techniques in combination with the sensors erected on the devices and instruments in the assembly of equipment, offer monitoring at the same time and early detection of unusual behaviour, further enhancing the risks of equipment breakdown and supporting system reliability (Min-Ho Park, 2022).

Various approaches used in time series analysis provide insights into equipment performance trends and pattern of deterioration over the passage of time, helping in the development and implementation of predictive maintenance strategies (Julio Barzola-Monteses, 2019). Reinforced learning methods are still new in the support of renewable energy projects however they have a great potential in optimizing control strategies for renewable energy systems, thus overall extending support in operational efficiency (Wei Xu, 2020).

6.2 Future Discussion and Ethical Considerations

The functions and performance measurement so far achieved with the help of AI aided techniques in renewable energy projects equipment is unbelievable; however, it can be optimised further by using combination of various techniques (All in one Hybrid models or with maximum efficiency potential). As discussed above, each technique and model are being utilized in a certain function monitoring and measurement; however, it does not quantify all the problems of whole system at one place and in one time monitoring capability. Recently there has been studies suggesting that work is still ongoing on these issues, and we have seen maximum tertiary hybrid models that have helped in maximizing the results. However, there still seems to be work done on automated system as one-time employed function to act as a system for a complete solution.

We initially targeted to cover all 5 major renewable energy sources and respective projects; nevertheless, it was difficult to cover all of them in this thesis. The Inclusion of geothermal and bio-mass energy system could have well and truly addressed our intention. Furthermore, we were only able to address the 5 major AI techniques utilized in renewable energy projects inspection and monitoring however there are several more techniques that are being employed in industry such as Natural Language processing, block chain technology, remote sensing and GIS, Fuzzy logic, and Bayesian Networks etc. All this can be added to our future armoury to address the complete renewable energy part.

6.3 Limitations to Study

We had limited work experience related to the renewable energy projects, and we were not specialists in this field. It required extended efforts to understand the entire concept of AI-based inspection and maintenance phenomenon. We consulted our various friends who had extensive work experience in this field to understand the complexities.

Another limitation to our literature review was the ever changing and evolving technology modifications and upgradation to the renewable energy projects equipment and devices. We noticed a lot of new AI variants are out in the market on which we could not find much literature. These recent changes are being modelled to be inserted in the inspection and maintenance procedure to enhance the results of AI based inspection procedure.

Furthermore, from the literature review we understood that for effective implementation of AI in renewable energy projects, we require its alignment with other engineering disciplines to optimize the end values and results of their functions. With a bit more management of engineering tools such as data science, engineering analytics and environment science we can maximize efficiency of AI inspection procedure.

REFERENCES

Adlen Kerboua, R. K. ((2022). Recurrent neural network optimization for wind turbine condition prognosis.

Agency, I. I. (2024). *Outlook for 2023 and 2024*. Retrieved from IEA- International Energy Agency: https://iea.blob.core.windows.net/assets/63c14514-6833-4cd8-ac53-f9918c2e4cd9/RenewableEnergyMarketUpdate_June2023.pdf

Angga Wahyu Aditya, N. R. (2023). Web-based low–cost rooftop solar power plant for household application. Surabaya, Indonesia.

Araf, S. (2023). The Role of Artificial Intelligence in Marketing Project Management. *A study of a data-driven approach to enhance marketing performance.* VAASA, Finland.

Basnet, A. (2022). Artifical Intelligence In Cyber Security.

Bogomolova, S. (2023). Artificial Intelligence and its impact on work in the field of logistics. Lahti, Finland.

Boucher, P. (2020). Artificial intelligence:How does it work, why does it matter, and what can we do about it? Brussels, European Union.

Carlos Cacciuttolo, D. C. (2024). Renewable Energy fromWind Farm Power Plants in Peru:. Peru, Chile.

Chang Liu, M.-S. C.-C.-M. (2017). A Wind Power Plant with Thermal Energy Storage for Improving the Utilization ofWind Energy. Shanghai, China.

David Gonzalez-Jimenez, J. d.-O. (2021). Machine Learning-Based Fault Detection and Diagnosis of Faulty Power Connections of Induction Machines.

Deeb, A. (2019). Large-Scale PV Solar Power Plant & Energy Storage System. Kuopio, Finland.

Enas Taha Sayed, A. G. (2023). Renewable Energy and Energy Storage Systems.

Evrencan Özcan, R. Y. (2019). Risk Based Maintenance in the Hydroelectric. Kirikkale, Turkey.

Fahli, M. B. (2021). The Impact of Artificial Intelligence. Helsinkni, Finland.

Farrokh Aminifar, M. A. (2021). A review of power system protection and asset management with machine learning techniques. Germany.

Fausto Pedro García Márquez, A. P. (2021). A Comprehensive Review of Artificial Intelligence and Wind Energy. Birmingham, UK.

Filipa S. Barros, P. A. (2024). Using Recurrent Neural Networks to improve initial conditions for a solar wind forecasting model.

G N Uzakov, Z. E. (2024). Energy indicators of the micro-hydro power plant adjusted to outlet water flows from pump units. Bukhara, Uzbekistan.

Gu, Y. (2020). Renewable Energy Integration in Distribution System with Artifificial. *A Dissertion*. Denver, USA.

Hosam M. Saleh, A. I. (2023). The challenges of sustainable energy transition: A focus on renewable. Cairo, Egypt.

Jalonen, J. (2023). Artificial Intelligence as a Part. *Automation of Accounts Payable Processes*. Tampere, Finland.

Jana Backhus, A. R. (2024). Equipment Health Assessment: Time Series Analysis for Wind Turbine Performance.

Jingcheng, L. (2010). Application of Solar Energy. Lappenraanta, Finlnad.

Jose A. Ruz-Hernandez, E. S. (2008). Fault Detection and Diagnosis for Fossil Electric Power Plants via Recurrent Neural Networks.

Julio Barzola-Monteses, M. M.-L.-A.-R. (2019). Time Series Analysis for Predicting Hydroelectric Power Production: The Ecuador Case.

Kalogirou, S. A. (2005). Artificial Intelligence in Renewable Energy Applications in Buildings.

Latifa A. Yousef, H. Y.-M. (2023). Artificial Intelligence for Management of Variable Renewable. 27.

Lei Kou, Y. L. (2022). Review on Monitoring, Operation and Maintenance of Smart. Jilin, China.

Lipsanen, O. (2019). Cooling with renewable energy. Mikkeli, Finland.

Liu, Y. Z. (2023). A Lightweight CNN for Wind Turbine Blade Defect Detection Based on Spectrograms.

M. Waqar Akram, G. ,. (2019). CNN based automatic detection of photovoltaic cell defects in electroluminescence images.

Majid Memari, P. S. (2024). Review on the Advancements in Wind Turbine Blade Inspection: Integrating Drone and Deep Learning Technologies for Enhanced Defect Detection.

Manyonje, F. X. (2023). Automation And Optimization Of Renewable Domestic Energy Production And Storage Using Electric Vehicles. Hämeenlinna, Finland.

Marco Carratù, V. G. (2023). A Novel Methodology for Unsupervised Anomaly Detection in Industrial Electrical Systems .

Min-Ho Park, S. C.-H.-W.-U.-H.-J. (2022). Anomaly Detection Based on Time Series Data of Hydraulic Accumulator.

Mudhar A. Al-Obaidi, S. A. (2024). Integration of Renewable Energy Systems in Desalination. Baghdad, Iraq.

Nallapaneni Manoj Kumar, S. M. (2018). On the technologies empowering drones for intelligent monitoring of solar. Tamil Nadu, India.

Nations, U. (2024). *Climate Acion*. Retrieved from United Nations: https://www.un.org/en/climatechange/raising-ambition/renewable-energy

Ndonku, N. E. (2022). The Transition Of Fossil Fuel As a Source Of Energy. *Environmental Chemistry and Technology*. Kokkola, Finland.

Nicolae Tudoroiu, M. Z.-E. (2023). Investigations on Using Intelligent Learning Techniques for Anomaly Detection and Diagnosis in Sensors Signals in Li-Ion Battery—Case Study.

Nura Garba, B. A. (2024). Renewable Energy Sources, Sustainability and Environmental Protection: A Review. Sokoto, Nigeria.

Pozdnyakova, L. (2009). Promotion Of Electricity From Renewable Energy Sources In Finland. Amsterdam, Netherlands.

Rajendra Prasad Ch., K. M. (2022). A review on hydro power plants and turbines. Warangal, India.

Report, G. S. (2023). *Renewable Energy In Energy Demand*. Retrieved from REN21.

Saini, K. K. (2021). Application of Artificial Intelligence for the Optimization of Hydropower Energy Generation. Roorkee, India.

Sang-Soo Baek, J. P. (2020). Prediction of Water Level and Water Quality Using a CNN-LSTM Combined Deep Learning Approach.

Shahrulhisham, N. N. (2022). Application of Machine Learning Technique Using Support Vector Machine in Wind Turbine Fault Diagnosis.

Shanab, N. A. (2015). Mapping The Potential Of Renewable. Helsinki, Finland.

Shiyong Wang, A. K. (2023). Deep reinforcement learning enables adaptive-image augmentation for automated optical inspection of plant rust.

Sitaula, S. (2018). Techno-Economic Analysis. Tampere, Finland.

Suja Cherukullapurath Mana, T. S. (2022). Automated fish detection and tracking system using.

Sunil Kr. Jhaa, J. B. (2017). Renewable energy: Present research and future scope of Artificial Intelligence. *Renewable and Sustainable Energy Reviews*.

Syahril Ramadhan Saufi, Z. A. (2019). Challenges and Opportunities of Deep Learning Models for Machinery Fault Detection and Diagnosis: A Review. Kuala lumpur, Malaysia.

Talaat, M. H. (2023). Artificial intelligence applications for microgrids integration and management of hybrid renewable energy sources.

Tanay Birişçi, D. K. (2023). Solar power plants in terms of landscape protection and repair: activities of local governments in Izmir. Izmir, Turkey.

Teja Kattenborn, J. L. (2021). Review on Convolutional Neural Networks (CNN) in vegetation remote sensing.

Tripathi, A. K. (2022). Output Power Prediction of Solar Photovoltaic Panel Using Machine Learning Approach.

Wei Xu, X. Z. (2020). Deep Reinforcement Learning for Cascaded Hydropower Reservoirs Considering Inflow Forecasts.

Weizhen Fang, Y. S. (2021). Recognizing global dams from high-resolution remotely sensed images using convolutional neural networks.

Wikipedia. (2024). https://en.wikipedia.org/wiki/Artificial_intelligence.

Xue Zhou, Y. K. (2023). Sustainable Operation and Maintenance of Smart Offshore Wind Farms. Guiyang, China.

Zand, M. (2024). Technology and energy management with Renewable Energy aspects. Tehran, Iran.

Zhang, H. (2022). A Review of Convolutional Neural Network Development in Computer Vision.