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with ESS for grid network stabilization**".
Case Study: Ntaruka hydropower plant

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DECLARATION

I, the undersigned, declare that this Project is my original work, and has not been presented for a degree at the University of Rwanda or any other universities. All sources of materials that will be used for the thesis work will have been fully acknowledged.

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A handwritten signature in blue ink, appearing to read 'Uwizerwa Jean Marie Vianney'.

Signature



APPROVAL

Submission Date: **1st December 2023**

This Thesis has been submitted for examination with my approval as a university advisor.

Dr. B. Bernard MUNYAZIKWIYE

Thesis Advisor

A handwritten signature in blue ink, appearing to read 'B. Bernard Munyazikwiye', written over a horizontal line.

Signature



DEDICATION

This work is truly dedicated to my beloved family, parents, and my cherished brothers and sisters whose unwavering support, boundless love, and enduring encouragement have been the cornerstone of my journey. Your sacrifices and guidance have shaped my aspirations and fueled my determination. I am forever grateful for your unwavering belief in me.



ACKNOWLEDGMENTS

In daily living, individuals encounter difficulties in reaching their goals. Remembering that we may face immense difficulties and roadblocks on the way to our success, we must never give up.

In light of the aforementioned, I take this wonderful occasion to acknowledge my supervisor **Dr. MUNYAZIKWIYE B. Bernard** for your invaluable advice in helping me attain this significant milestone. We are very grateful to the entire ACEESD personnel, especially the lecturers, for their sacrifices in providing us with correct and timely knowledge. My colleague, Engineer **Lars Kawaida MUGWANEZA**, is also greatly appreciated for his encouragement and assistance.

I frankly express gratitude to my coworkers and classmates for their facilitation of my academic endeavors. Gratefulness to REG and EDCL management for their assistance in obtaining key information about the energy sector and government projections about grid network stability, fossil fuel plant status, and electricity access.

Finally, I want to express my gratitude to UR, and REMA for their help in making this research feasible by offering financial assistance or scholarships under the National Adaptation Program (NAP) initiative financed by the Global Environment Facility (GEF) through the Least Developed Countries Fund (LDCF) and establishing a Long-Term Research Programme (LTRP) for Climate Change Adaptation (CCA) planning in Rwanda.

“May God bless all of you!”



ABSTRACT

This thesis aims to contribute to the shift to cleaner energy sources to improve grid stability in a northern network of Rwanda by exploring the design, modeling, and viability of integration of a 25MW Floating Solar system with 5MWh of Energy Storage System (ESS) that replaces the current 10MW fossil fuel-based generation at Mukungwa Hydropower Plant operated by Independent Power Producer (IPP) namely” SoEnergy Ltd” with a combination of renewable resources, ultimately fostering a more resilient and sustainable energy infrastructure that will create an ecosystem-based adaptation (EbA) at Ruhondo lake including URUGEZI Wetland. The floating solar PV system together with an existing 10.5MW Ntaruka hydropower station is intended to improve grid stability and reduce CO₂ emissions from fossil fuel plants.

The thesis addresses grid instability by designing and simulating floating photovoltaic modules connected to Energy Storage System (ESS), addressing voltage and frequency fluctuations caused by imbalanced energy demand.

This study enhances grid network stabilization by designing and simulating floating solar PV modules with ESS using advanced programs like Homer, MATLAB, PVsyst, and SolidWorks, focusing on design aspects.

In conclusion, this study proposes a comprehensive approach to enhance grid stability in the era of renewable energy, utilizing SolidWorks, Homer, MATLAB, and PVsyst to address design, energy storage, dynamic system behavior, and real-world performance modeling.

Keywords:

Renewable energy integration (REI); National grid instability; Modelling of floating Solar PV with ESS; Removing existing Fossil fuel gen sets.



ABBREVIATIONS & ACRONYMS

AC: Alternative Current

ACEESD: African Center of Excellence in Energy for Sustainable Development

BESS: Battery Energy Storage System

BMS: Battery Management System

CAD: Computer-Aided Design

CAE: Computer-Aided Engineering

CAPEX: Capital Expenditure

CST: College of Science and Technology

CO₂: Carbon Dioxide

DC: Direct Current

DoA: Days of Autonomy

DoD: Depth of Discharge

EbA: Ecosystem-based Adaptation

EDCL: Energy Development Corporation Limited

ESS: Energy Storage System

FEA: Finite Element Analysis

FRT: Fault-Ride-Through

GEF: Global Environment Facility

GHI: Global Horizontal Irradiance

Ha: Hectare

HPP: Hydro Power Plant

kW: kilo-Watt

kWh: kilo-Watt-Hour

LCOE: Levelized Cost of Energy

LDCF: Least Developed Countries Fund

LTRP: Long-Term Research Programme

IPP: Independent Power Producer

GMG: Green Mini-Grid



GoR: Government of Rwanda

GW: Giga Watts

IEA: International Energy Agency

MININFRA: Ministry of Infrastructures

MW : Megawatt

MWp : Megawatt peak

MWh : Megawatt-Hour

NAP: National Adaptation Program

NEP: National Electrification Plan

NPC: Net Present Value

OM: Operational and Maintenance

OPEX: Operational Expenditure

PID: Proportional Integral and Derivative Control

PLC: Programmable Logic Control

PSH: Peak Sun Hours

PCC: Point of Common Coupling

PV: Photo Voltaic

SPP: Solar Power Plant

SS: Substation

RE: Renewable Energy

RES: Rural Electrification Strategy

SPV: Solar Photo Voltaic

UR: University of Rwanda

UK: United Kingdom



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CHAPTER 1. INTRODUCTION

1.0. Background

Rwanda's electricity supply comprises both domestic generation and imported power from neighboring countries, in addition to contribute from regional shared power plants. The energy mix includes 48.9% from hydropower plants, 27% from thermal power plants (utilizing diesel and heavy fuel generators), 14% from methane gas, 7% from peat, and 5% from solar energy. The country's on-grid installed solar energy capacity stands at 12.08 MW. To enhance electricity access, households located beyond the planned national grid coverage are encouraged to adopt standalone solar photovoltaics (PVs) as cost-effective solution[1].

Currently, the total installed capacity in Rwanda augmented enormously from 76MW in 2010 to 238MW in 2021 according to REG report 2021 [1]. The percentage of households connected to the national grid witnessed a significant rise, escalating from 6% in 2009 to 61.0% by August 2022. Out of this, 47.0% are directly linked to the national grid, while 14.0% access electricity through off-grid systems as indicated by 05th Population and Housing Census done in August 2022 [1]. The Goal is promoting rural industrial development and productive use is expected to significantly increase the demand. REG needs to increase the supply capacity to meet the expected increase in demand. Electricity demand growth is expected to be 8% per year. To maintain sufficient capacity for supplying electricity, The GoR has set out clear targets for 556 MW of production where the share of Renewable energy (RE) will be 60% and universal access by 2024. [1] Rwanda's pursuit of clean and renewable energy sources has spawned creative solutions meant to fully utilize solar power's enormous potential.

Floating solar power generation is one of these technologies that has shown potential. It makes use of underutilized water bodies to support photovoltaic (PV) modules. Incorporating floating solar cells optimizes land use while posing new opportunities, especially when it comes to grid stability. By studying the design, simulation, and integration of floating solar PV modules with Energy Storage Systems (ESS) to improve grid network stabilization, this thesis aims at investigating these issues.

The use of floating solar cells for power generation is a paradigm change in the use of renewable energy. Scalability is limited by the fact that traditional solar arrays sometimes compete with urban or agricultural land use. On the other hand, innovative solutions such as floating solar arrays on lakes, reservoirs, and other water bodies offer a large resource without endangering terrestrial ecosystems. There are more and more pilot programs and large-scale implementations of this strategy taking place throughout the world.

There are additional factors to consider while designing floating solar PV modules than when designing terrestrial ones. It becomes crucial to consider elements like resilience, stability, and resistance to external stresses. Three-dimensional modeling software (SolidWorks) is used to generate strong designs that guarantee the longevity and dependability of the floating structures in addition to the best possible solar energy capture. This thesis examines the complexities of floating solar cell design as a fundamental component of the research since the efficiency of the modules directly affects total power generation.

The success of renewable energy, particularly solar systems, is widely credited to the strategic implementation of Energy Storage Systems (ESS). This approach has been instrumental in mitigating grid instability issues associated with the intermittent nature of solar energy production. Through optimized integration of ESS, the efficient storage and controlled release of surplus energy have been ensured, enhancing the overall resilience of the grid. Simulation tools like Homer pro have played a crucial role in facilitating this process.

Utilizing MATLAB facilitates the dynamic simulation of the entire system, encompassing tasks such as identifying optimal operating configurations and conducting in-depth analyses of power flow dynamics and system behavior across different scenarios. To ensure that floating solar cell electricity is seamlessly integrated into current grids, power distribution strategies are studied. This emphasizes the necessity for intelligent and adaptable systems that can accommodate the special qualities of solar energy.

Presently, Rwanda's electricity generation capacity stands at 332.6 MW across various power plants. In terms of generation technology distribution, thermal sources account for 51%. Hydro sources contribute 43.9%, and solar sources make 4.2% [\[2\]](#).

1.1. Problem Statement

Rwanda prioritizes sustainable energy mix development to address carbon emissions and electrical supply unpredictability. Currently, thermal and hydroelectric power plants dominate, causing shaky grid networks and carbon emissions. Improving energy infrastructure is crucial.

Rwanda's current energy paradigm requires a comprehensive strategy to address both carbon emissions and grid network reliability. Earlier, the government has taken action to install 10 x 1 MW oil-fired generator sets at Mukungwa Hydropower Plant to augment the national grid stability, especially in the northern ring network that starts from the existing Ntaruka HPP in Burera district to Rwinkwavu substation in Kayonza district of Eastern province. The project aims to enhance grid network stability and reduce electricity supply issues by integrating diverse energy sources, including oil-fired generator sets, for a sustainable future.

1.2. Research Objectives

1.2.1. Major Objective

The major objective of this research is to model and simulate a floating solar PV with ESS on Ruhondo Lake integrated with existing Ntaruka HPP as an alternative RE generation for an energy optimum solution to replace installed oil-fired gen sets at Mukungwa I HPP with aims to augment grid network stability and reduction of CO₂ emission.

1.2.2. The Specific Objectives

This study aims at achieving the below specific objectives:

- To obtain solar radiation information for Rwanda, especially in Burera District, and Ruhondo Lake
- To design a model for technical feasibility analysis
- To show information related to the cost-overview of the operation of the diesel plant including the impact on the environment as well as CO₂
- To compare operation cost for floating PV plant with the existing grid diesel generator sets

1.2.3. Research Questions

- How feasible is the technical integration of a floating solar plant with Energy Storage Systems on Ruhondo Lake?
- What are the economic implications of implementing this floating solar solution to replace diesel for grid stabilization at Ntaruka and Mukungwa I hydropower plants?

-
- How can ecosystem-based adaptation strategies be effectively employed to sustain the floating solar project and minimize environmental impact?

1.2.4. Research Justification

The urgent need to switch to robust and sustainable energy sources. Evaluating the technological viability of an Energy Storage Systems-equipped floating solar plant on Ruhondo Lake responds to the demand for novel renewable energy sources. Examining the financial ramifications of this approach satisfies the pressing need for reasonably priced substitutes for traditional grid stabilization techniques. Furthermore, looking into ecosystem-based adaption techniques guarantees the enduring sustainability of the proposed floating solar project aligns with global initiatives aimed at minimizing environmental impact. With the potential to greatly contribute to a more sustainable and resilient energy future, this research is essential for educating decision-makers about practical, environmentally friendly energy alternatives.

1.3. Scope of the study

The scope of this research is on modeling and simulating a floating solar photovoltaic system with an integrated ESS. The purpose of this system is to replace the currently employed diesel generators at the Ntaruka and Mukungwa 1 Hydropower Plants (HPP) to maintain stability in the northern ring grid. The scope includes a detailed analysis of the proposed transition's technological features, financial implications, and environmental implications. The purpose of the study is to give a thorough grasp of the viability and possible difficulties of applying this renewable energy solution to improve grid stability in the designated area.

1.4. Conceptual framework

Going through different and similar research, several approaches have been applied to deal with the target objective. This work has been conducted firstly through the identification of site for the project development, clearly defining the problems among the community living within the village, collecting relevant data for analysis, consulting related literature and identifying the gaps, using software to simulate the collected data and come up with findings that might be applicable to satisfy the population's needs in terms of electricity access facing out the issues encountered among the community.

Below is the summary of the research theoretical context:

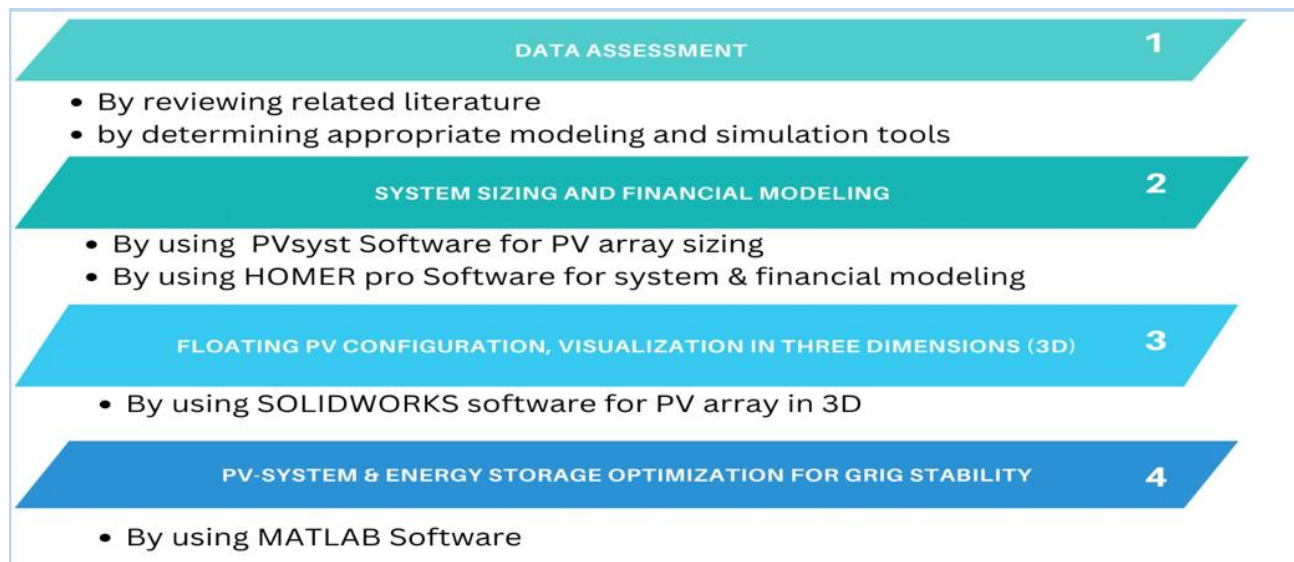


Figure 1: Conceptual framework of the research

1.5. Thesis organization

As per the title of the work “**Design and simulation of Floating Solar PV Modules with ESS for grid network stabilization**” highlights, this work was carried out systematically focusing on the designing and simulation of floating solar PV with Ess for grid network stability at the northern ring in north province and east of Rwanda. To develop the work, about five main chapters were covered as follow:

Chapter 1 covers the general introduction of the research work, clearly defining the contextual of the research, highlighting the existing problem, and identifying gaps, then comes up with the research objectives and their relevancy, and finally the expected outcomes of the work and methodology approach.

Chapter 2 summarizes the contents that were consulted from numerous literatures and some key terms that were used in the project development about designing solar mini-grid PV systems.

Chapter 3 defines the materials and approaches that were mainly utilized conduct research work, such as simulation tools that might be potential in developing this work, resources assessment, and approaches that might be useful to reach the set objectives. The assessment was based on both primary and secondary data. Estimation of AC primary daily load and energy forecasting requirement in four (4) years were presented in this thesis. Chapter 4 discusses the system design analysis of the different mini-grid solar PV components such as PV modules, battery banks, inverters, and accessories.

Chapter 5 consists of a general conclusion and recommendations about the thesis work.

1.6. Contribution and Significance of the Study

1.6.1. Contribution of the Study

The following are contributions of this research:

- i. Reliable electricity through grid stability,
- ii. Floating PV plant designed based on accurate data collected and precision tools utilized, thus the plant will operate more efficiently than ever,
- iii. Good design leads to a sustainable floating solar PV plant and requires little OM costs.
- iv. Proven feasibility of solar floating PV plants at Ntaruka HPP, which will replace the usage of gen set to stabilize the national grid in northern ring starting from Ntaruka HPP in Burera district to Rwinkwavu SS in Kayonza District
- v. Increased number of renewable energy usage hence Carbon emission reduction

1.6.2. Significance of the Study

The study's relevance stems from its potential to transform Ntaruka's energy landscape by tackling critical elements that impact grid stability. The attainment of dependable electricity via improved grid stability is an essential result, guaranteeing a continuous power supply to the area.

Additionally, the design of the floating PV plant assures optimal efficiency through the use of precise instruments and reliable data, which contributes to enhanced energy output.

The focus on Homer & PVsyst design promotes long-term economic viability by resulting in a floating PV plant that is sustainable and may have low operation and maintenance expenses. Significantly, the viability of solar floating photovoltaic plants at Ntaruka has been demonstrated, signifying a revolutionary departure from conventional generator sets and highlighting the possibilities for ecologically friendly and sustainable energy solutions.

The study's conclusions essentially have important ramifications for developing renewable energy practices and guaranteeing a consistent and sustainable power supply in Rwanda.

CHAPTER 2. LITERATURE REVIEW

2.0. Literature review

In this Chapter we are going to recognize and point out the review on previous research on floating solar systems with ESS by intensifying their findings:

In [3] The authors highlight the potential of FPV systems with ESS for renewable energy solutions but lack a detailed analysis of cost-effectiveness and potential obstacles in transitioning from conventional power sources to FPV systems. Addressing these gaps is crucial for informed decision-making on FPV as a cost-reflective alternative.

In [4] The authors emphasize the advantages of FSPV, including land use reduction and water evaporation mitigation, while analyzing its technical performance, energy production, and grid stability. The research lacks a comprehensive analysis of the operational costs of the FSPV system, hindering a comprehensive understanding of its economic viability compared to existing oil-fired power plants. The closing of this gap is crucial for making informed decisions about the economic feasibility of FSPV as a replacement for oil-fired power plants.

In [5] The authors delve into the technical intricacies of ESS, encompassing various storage technologies and control strategies employed for seamless integration with solar PV systems. The analysis highlights the benefits of combining ESS with solar PV, including improved grid stabilization, efficiency, and reliability. However, the research lacks a comprehensive exploration of operational costs compared to existing oil-fired power plants, which is crucial for a comprehensive evaluation of solar PV with ESS combinations.

In [6] The authors explore technical aspects of floating solar photovoltaic (FSPV) systems, including module types and installation methods. It evaluates energy production and grid stability, and explores battery energy storage benefits. However, there's a gap in examining operational costs compared to existing oil-fired power plants reserved for energy stability and energy supply dependency.

This research in [7] The authors conduct a thorough examination of the system's performance, assessing both energy output and grid stability. The paper delves into the technical and discusses the selection of modules and batteries. Additionally, the advantages of utilizing battery-powered FSPV systems for

enhancing grid stability, including improved system reliability and efficiency, are explored. However, a notable gap in the study is the absence of a dedicated analysis of the operational costs. Addressing this gap is crucial for a comprehensive evaluation of the economic viability of replacing conventional power sources with FSPV systems.

This study in [8] The authors sought to determine whether a floating photovoltaic system could be installed at Ntaruka HPP reservoir to reduce water evaporation, increase Solar PV cell efficiency, and keep land for other uses.

However, a gap in the study lies in the absence of consideration for designing a system without overlooking grid stability, not considering the challenges of an expensive power evacuation line, and neglecting the integration of renewable energy into the existing hydropower plant as floating solar PV seems like designed in island mode system. Furthermore, the study lacks analysis regarding the required energy and type of storage that can be applied in the context of designing the floating system.

In [9] The authors investigate the impact of wetlands degradation on water resources management in Rwanda, with a specific focus on the Rugezi Marsh case While it sheds light on the negative impact of wetlands degradation, including its implications for water resources, the study falls short in providing proposed measures to protect the ecosystem. Additionally, there is a notable gap in the paper concerning the integration of renewable energy to support the Ntaruka Hydropower Plant (HPP).

The growth of solar energy has progressed slowly throughout Africa, with the continent adding about 4 GW of new solar PV capacity between 2010 and 2018. [10] Challenges including low institutional capacity within government agencies, low scale and competitiveness, high transaction costs, and the perceived high risk associated with solar projects are to blame for this slow growth, which is especially evident in sub-Saharan Africa. These difficulties highlight the more general systemic problems that need to be resolved to hasten the adoption of sustainable energy solutions and stabilize the national grid network as Rwanda struggles with its energy transition. The solar irradiation in Rwanda is good enough whereby the peak sun time per day is expected to be 5 hours, even in the rainy seasons, and the average solar potential is 4.5 kWh/m²/day. [11]



Figure 2: Mukungwa 1 HPP power house



Figure 3: 10 x 1MW oil-fired plant operated by IPP “So-Energy Ltd” at Mukungwa 1 HPP

Trend of total energy losses in Network

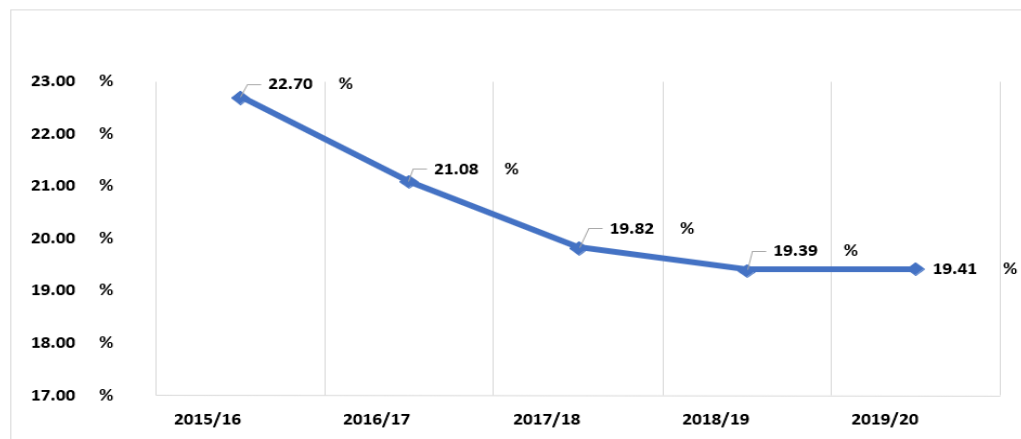


Figure 4: Performance of the distribution line in national grid network (RURA report, 2015-2020)

Performance on the distribution network Vs SAIDI and SAIFI				
Year	2018/2019	2019/2020	2020/2021	2021/2022
System Average Interruption Duration Index (SAIDI - Hours/Year)	25.6	17.2	18	18.59
System Average Interruption Frequency Index (SAIFI - Times/Year)	49	37	44.4	45.67

Table 1: SAIDI and SAIFI in national grid network (RURA report, 2018-2022)

There was a significant improvement from 49 times/year in 2018/2019 to 37 times/year in 2019/2020, indicating a reduction in the average frequency of interruptions, and network performance (Figure 4). However, in the subsequent years, there was a slight increase, reaching 45.67 times/year in 2021/2022. Overall, monitoring these indices provides valuable insights into the reliability and performance of the

distribution network indicating instability caused by the increase of demand and applying oil-fired gen sets at Mukungwa I HPP to compensate for energy required in peak time over the specified four-year period. (Table 1)

Electricity generation (kWh)					
Year	2018	2019	2020	2021	2022
Capacity	kWh	kWh	kWh	kWh	kWh
TOTAL	10,609,761	38,628,822	14,544,100	39,244,400	41,333,980
Fuel consumption (Liters/Tones)					
Year	2018	2019	2020	2021	2022
Capacity	Liters	Liters	Liters	Liters	Liters
TOTAL (Liters)	4,243,904	1,545,1529	5,817,640	15,697,760	16,533,592
TOTAL (Tones)	4243.904	15451.53	5817.64	15697.76	16533.59
Estimation Fuel Cost (USD\$ 1.26/L)	5,347,319 USD\$	19,468,927 USD\$	7,330,226 USD\$	19,779,178 USD\$	20,832,326 USD\$
OPEX (10% of Fuel cost); USD\$	534,732	1,946,893	733,023	1,977,918	2,083,233

Table 2: Electrical generation and Fuel consumption for Gen-Sets (10MW) owned by So Energy Ltd at Mukungwa HPP (RURA report, 2018-2022) / Cost of Fuel is USD\$ 1.26/Liter (RURA, Tariff by 2023)

Analyzing the system Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) data between 2018 and 2022 offers valuable insights into the performance of the distribution network, shedding light on the dynamics of electricity generation and fuel consumption during those years. When considering fuel consumption in tons, there is a proportional increase, with the total fuel consumption in mentioned years. This aligns with the increased electricity generation capacity and indicates the system's reliance on fuel-powered generation. The decrease in SAIDI suggests an improvement in the distribution network's reliability, potentially indicating enhanced infrastructure or better maintenance practices.

The corresponding rise in fuel consumption emphasizes the need for sustainable practices and alternative energy sources to mitigate environmental impacts associated with increased reliance on fossil fuels.

In conclusion, the combined analysis of SAIDI, SAIFI, electricity generation, and fuel consumption provides a comprehensive overview of the distribution network's performance and its associated energy generation dynamics over the specified five-year period. (Table 2)

To assess the floating solar PV power plant capacity with ESS that will be added to Ntaruka HPP and replace the Diesel Generator sets by not only considering capital expenditures but also environmental considerations. Moreover, various studies on floating Solar PV systems have been undertaken, to address issues associated with ground-mounted solar installations in Rwanda. The design of a floating solar PV system is intended to mitigate concerns such as water evaporation, while also highlighting the advantages of employing floating photovoltaic systems [12]. The global photovoltaic (PV) energy market is experiencing rapid growth, and countries, including Rwanda, are encountering challenges related to limited space, especially in densely populated urban areas. Apart from the scarcity of land, other issues include concerns about water evaporation and the suboptimal effectiveness of land-based PV installations [13].

In general, this literature offers valuable perspectives on the technical, economic, and environmental facets of integrating floating solar PV modules with ESS for stabilizing grid networks. Ntaruka HPP case study exemplifies the practical implications, both positive and challenging, associated with this renewable energy approach. As awareness of climate change and the imperative to reduce greenhouse gas emissions grows, renewable energy solutions have garnered increased attention. Among these solutions, the utilization of floating solar PV modules with ESS for grid network stabilization is a relatively novel concept that is gaining momentum, attributed to its diverse advantages [14].

The adoption of RES has witnessed substantial growth and is anticipated to accelerate in the coming years. The incorporation of RES into grid networks offers dual advantages like reducing carbon footprint and minimizing grid losses. Nevertheless, the inherent unpredictability and intermittency of RES can lead to substantial disruptions, posing challenges in maintaining the balance between load and generation on the grid [14, 15, 16]. The widespread use of PV and wind-producing facilities also leads to other issues, such as harmonic distortions and voltage fluctuations [17]. As the penetration of RES increases, the periodic fluctuations in RES power output can impose additional stress on conventional generating units, necessitating efforts to maintain voltage and frequency within acceptable limits [18]. Additionally, a rise in RES penetration lowers the system's accessible inertia, which raises the requirement for more spinning reserves and ultimately results in additional expenses.

Many nations currently have mandatory grid regulations that take into account unforeseen circumstances in order to manage variations and guarantee dependable renewable energy operation within the permitted operating range, hence reducing the negative effects of RES on the grid [19]. The limitations of the grid codes include those related to dispatchability, voltage and frequency regulation, fault-ride-through (FRT)

capacity, ramp-rate, and more. A few nations, like Germany [20], Italy [21], and the UK [22], have already instituted financial penalties for RES farms that fail to keep the output power schedule that was agreed upon.

BESS is capable of controlling the flow of both active and reactive power and storing energy. autonomously at the PCC and offers a range of services as seen in Figure.5.

Transient frequency stability is one of the potential BESS services. Transmission congestion management, peak shaving [23], increased dependability [24], dispatchability [25], ramp rate control [26], and output power leveling [27].

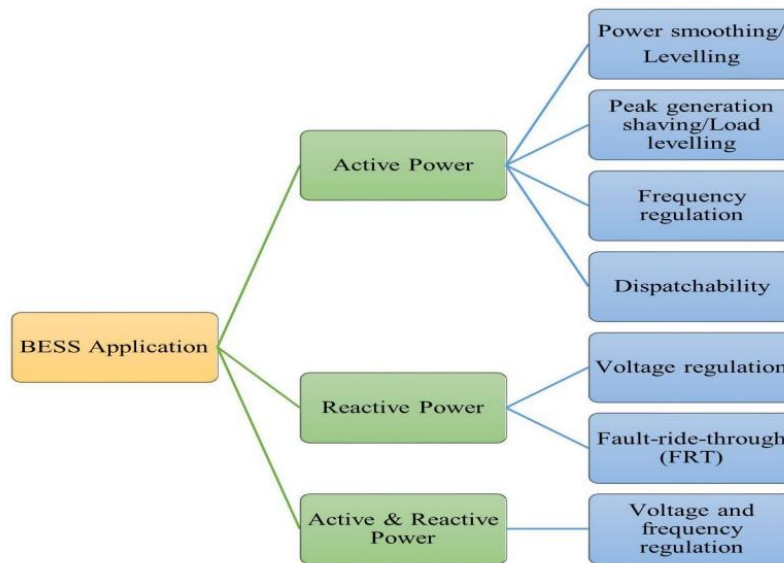


Figure 5: Typical BESS applications in renewable energy integrated system [23-27]

2.1. System Energy Storage Technologies

The characteristics of system energy storage technology depend on factors such as the storage type, operational time frame (both short-term and long-term), power and energy ratings, as well as specific applications [28].

2.1.1. System Storage Technologies General Consideration

The Time duration of operation, power and energy ratings, and the intended applications are key considerations in determining the characteristics of energy storage technology [29].

It is feasible to store the available energy for use at a later time in a variety of energy forms, such as Mechanical, magnetic, and electrical components represent different types of technologies, and these can be summarized as follows[30]:

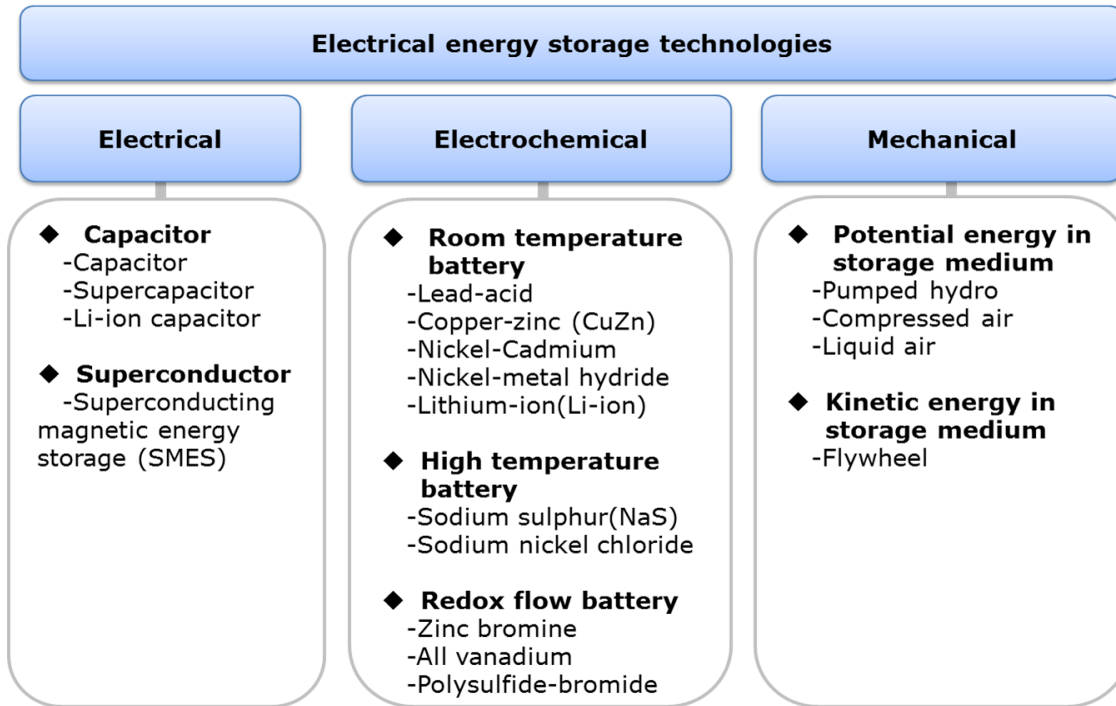


Figure 6: Classification of Energy Storage Technology

2.1.2. System Operating Time Frame, Power and Energy Rating

The ESS have been used in the power business for over 150 years. Research into the application of numerous highly promising storage technologies to large-scale power systems is still underway, despite their advanced state. Energy storage methods can be categorized based on their durability of application, as illustrated in Figure 6.

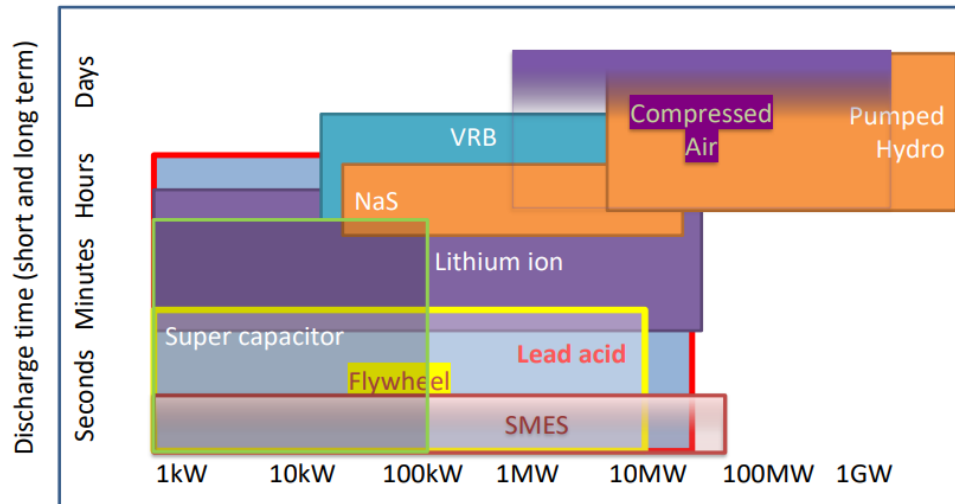


Figure 7: Energy storage technologies capability- operating time frame [30]:

Various ESS are accessible in MWh, as depicted in Figure 7. But in the pursuit of better power and energy ratings, mechanical storage devices continue to lead the way. More extensive battery storage installations than ever before are planned thanks to recent technological advancements in battery technologies.

2.1.3. Batteries and BESS Technology

The ESS technology has used over a century. In power system application, however, only secondary or rechargeable batteries are recommended. Because of their capacity to offer operational flexibility, quick reaction times, lower cost per kWh, and scientific advancements in contemporary battery technologies, battery technologies are becoming more and more common in power system applications [31]. In power systems, batteries are frequently utilized at all voltage levels [32]. Applications of them can provide benefits to the environment and operational flexibility. However, owing of their limited power capacity and energy density, battery storage devices are not commonly used on a big scale. However, there is now more interest in the use of batteries in large-scale power systems due to recent advancements in battery technology, particularly with regard to lithium-ion batteries.

2.1.4. BESS Connection Diagrams

The voltage level at which a BESS is meant to be attached mostly determines its basic construction. Battery banks, which are essentially parallel, and a DC/AC conversion system are common components of a BESS construction. Perhaps a transformer is required. in order, if BESS is intended to be, converted from the Voltage output level to national grid voltage parameters. Frequently, BESS takes in and transports electricity to and from the grid, necessitating the use of a bidirectional voltage source. current-source converter [33], converter (VSC) [34], with its selection primarily based on the BESS's objective in that specific case study.

Fig. 8 displays common BESS-PV combinations. Every setup has benefits and drawbacks of its own. The cost of the system will rise in the instance of Fig.8 (a) due to the additional DC/AC converter. Furthermore, because BESS connected directly to the PCC, an additional circuit breaker protection system is needed, which raises the system's overall cost. The primary benefit, though, is that BESS may be controlled like a stand-alone grid storage system. Because it enables the battery voltage to be raised to a high DC-link voltage, the central DC-DC INV with BESS in Fig. 8 (b) offers the flexibility to be coupled with several DC link voltage levels. Fig. 8 (c)' s block diagram does away with the requirement for a DC-DC converter.

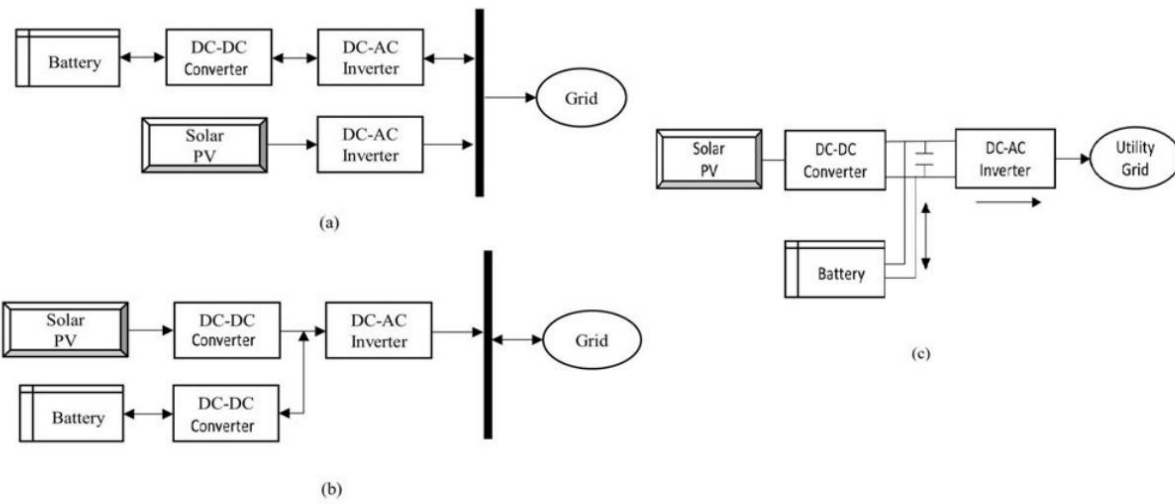


Figure 8: BESS in a PV-BESS energy system; (a) PV/BESS to single converter (b) BESS to common DC side through DC/DC converter (c) Direct BESS connection to DC side[33], [34]

2.1.5. Peak Generation / Load Shaving

The peak generation and peak load demand rarely align in commercial, residential, and industrial settings. During periods of high energy production, a BESS can store surplus energy for later use during peak demand periods. Furthermore, during off-peak times when electricity costs are lower, the battery can be charged from the grid at a more economical rate. The installation of BESS for peak demand smoothing facilitates the optimal utilization of available generation [35]. BESS can significantly reduce the grid network's power flows [36] and facilitate the use of extra energy stored during the day to support peak load demand in the evening. The battery charging/discharging rate is changed in response to the actual SOC with the intended SOC level [37], and with the least amount of cost and power loss [38]. A customer-owned BESS can achieve sufficient peak reduction even when the peak load demand in a feeder is not equal to the peak demand across the utility when there is sufficient battery capacity available [39].

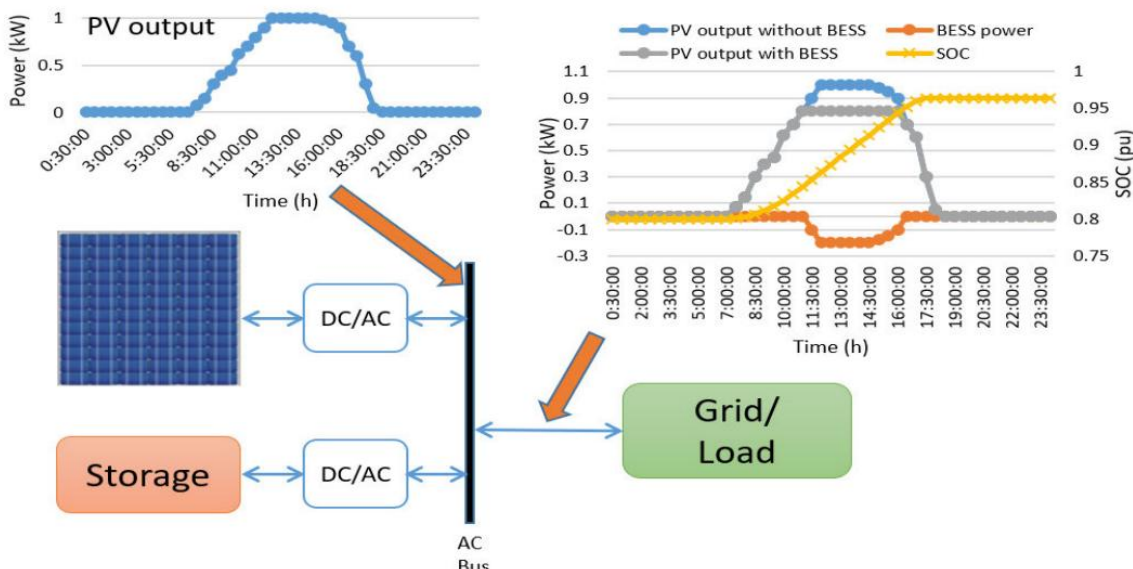


Figure 9: PV peak generation shaving with BESS [40]

An illustration of a standard BESS process for peak generation shaving is provided in **Figure 9**. BESS can support the lowering of peak load demand by storing extra PV energy during the day for use at night. Demand peak-cutting is essential to lowering a particular peak power consumption point in commercial, industrial, and residential buildings that might lead to extra expenses for consumers. Users' electricity bills can be greatly reduced by implementing BESS [40]. In a deregulated and competitive power distribution system, the peak energy price could not be much higher than the regulated price, which could affect the battery storage system's economic advantage [40].

2.1.6. Voltage Regulation

The Variable renewable energy sources need to adhere to stringent voltage regulation guidelines in order to guarantee that nominal voltage stays within the working limit. Battery storage responds quickly to voltage sags or surges, maintaining a steady voltage source in the power system and charging or discharging the battery accordingly. Power flows backward into the network as a result of a voltage surge that occurs when PV peaks in production and there are minimal to no load demands [41]. Many strategies have been put up to counteract the negative effects of significant photovoltaic penetration in low-voltage distribution networks [42]. One option is to curb PV production, but doing so will minimize the financial gain by reducing the maximum usage of PV generation capacity [43].

The installation of a voltage regulator [44], transformer tap adjustment [45], and PV converter reactive power compensation [46] are other options that have been implemented. Although grid strengthening is more expensive, it might be an additional way to lower feeder losses [47]. As seen in Figure 10 By using BESS to consume excess PV energy during peak generation, PV's impact on the grid's voltage rise can be minimized. Depending on the requirements of the network, BESS can be designed to either consume extra energy or regulate reactive power to change grid voltage within the allowed range.

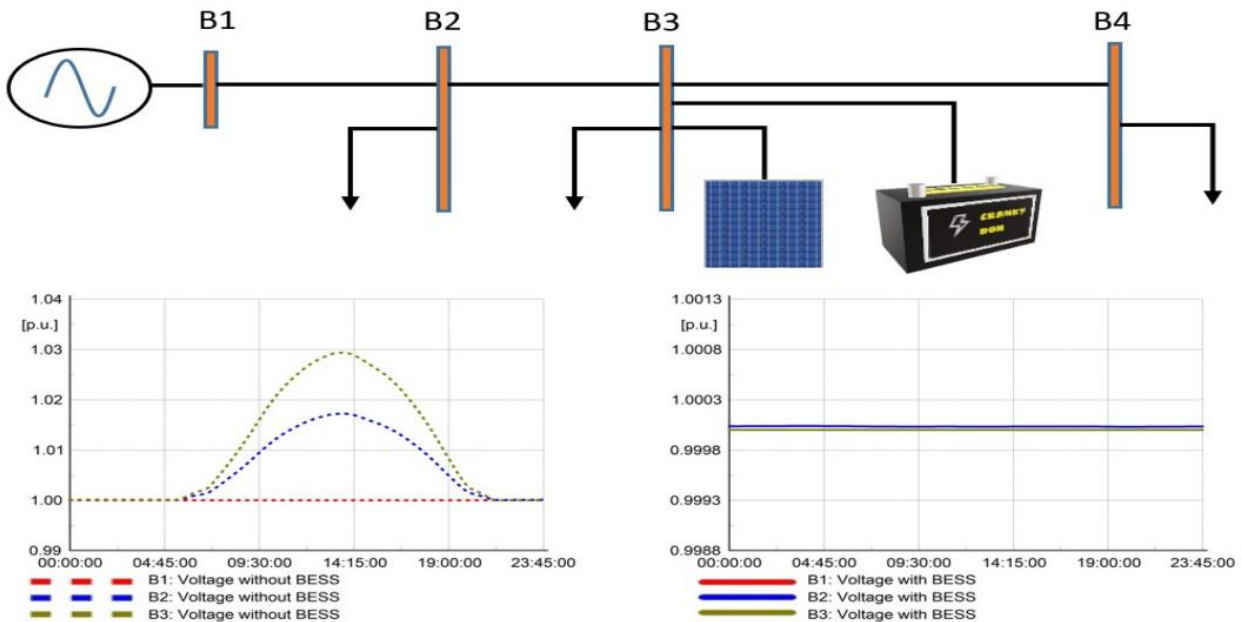


Figure 10: Voltage control system in solar PV integrated with BESS [41]

An essential function of battery storage systems is to manage voltage spike or drop that occurs during The existence of either peak PV generation or peak load demand [48]. Local droop approach [49], PCC voltage monitoring [50], and measurements from distributed controllers [51] can all be used to control battery charging and discharging[52, 53], and supporting increasing PV penetration while keeping acceptable voltage limits [54] are all possible with battery storage systems. Voltage regulation can be provided by BESS active power [55] or by setting superiority to BESS' reactive power along with BESS' active power [56, 57].

In conclusion, the literature review provides a comprehensive understanding of research on floating solar PV systems with energy storage, highlighting potential benefits like reliability and environmental impact reduction. It also highlights challenges in integrating renewable energy, emphasizing the need for comprehensive solutions.

The literature review offers significant insights into the developing topic of energy storage systems (ESS) integration with floating solar photovoltaic (FPV) systems for grid stabilization. However, there is a noticeable gap in the specific context of Rwanda's energy transition, where issues like sub-Saharan Africa's slow adoption of solar energy and not mentioning the negative effects of relying on diesel power plants for grid stability and energy demand matching, the inability to control hydropower and ESS in the event of peak hours, the reduction of needless battery capacity, and the lower cost of installed solar power plants remain. This study not only considers the technical and economic aspects but also emphasizes the broader goal of stabilizing the national grid and replacing an existing 10MW oil-fired plant. By doing so, this research aims to provide a comprehensive solution that aligns with Rwanda's sustainable energy goals, utilizing the abundant solar potential.

CHAPTER 3. RESEARCH METHODOLOGY AND MATERIALS

3.0. Introduction

To perform any renewable energy project, to properly analyze the effective performance of the designed system, the deep assessment may need suitable conditions to be met such as site description, needful technologies, system investigation, and operative performance influence. This research aims are Design and simulation of Floating Solar PV Modules with ESS for grid network stabilization from Ruhondo District. Each step used to design such a system will be discussed in this report.

To achieve the research specific objectives, different tools such as SOLIDWORKS, MATLAB, HOMER & Also PVsyst and ArcGIS. A set of questionnaires were used for gathering the required information including solar radiation, daily energy requirements by end-users, grid status even more others daters concern.

The design of the green solar PV mini-grid Design and simulation of Floating Solar PV Modules with ESS for grid network stabilization was accomplished through the use of MATLAB, Homer, SolidWorks and PVsyst simulation software.

Homer

Homer is a model that is used in optimization and simplifying the activity of power system evaluation designs in various use. Configuration of the PV plant can be made by using the Homer software tool. It is possible when utilizing this software to select different components of the designed system. The core goal of this research is to investigate a green PV plant that can provide stable and reliable electricity at a minimal cost compared to the other energy provision systems. The tool will help to determine how the designed system interrelates with end-use requirements according to the expediency and potentiality of energy in the load region where the system is modeled for.

Simulation

The Homer simulating tool consists of different components, resources, loads, and system constraints. The performance of enormous system configurations is simulated through the calculation of energy balance per hour. The tool will help Simulate a long-term operation of the system with accurate sensitivity. Homer can hold a considerable simulation than other similar tools. Therefore, it is my preference among other simulation tools.

MATLAB Simulink

A graphical platform for modeling, simulating, and evaluating multidomain dynamical systems is offered by MATLAB Simulink, an extension of MATLAB. It offers a block-diagram interface where users can represent system components as blocks and connect them to model complex interactions. Simulink is extensively used for dynamic system simulations, control system design, and signal processing applications. Its library of predefined blocks covers a wide range of domains, including mathematics, control systems, electrical circuits, and more. Simulink allows users to simulate the behavior of their systems over time, making it a powerful tool for developing and testing control algorithms, communication systems, and other dynamic processes in engineering and research

PVsys

PVsys is a specialist software application intended for photovoltaic (PV) system modeling and simulation. For the design, optimization, and performance analysis of solar power systems, it is extensively utilized in the solar energy sector. To simulate energy production of a solar PV system over time, users can input site specific data into PVsys, such as geographic location, climate conditions, and system components. Its features, which offer insightful information for the design and improvement of solar installations, include financial evaluations, energy yield forecasts, and shading analyses. For engineers and solar industry experts involved in PV system design and assessment, PVsys is a vital tool.

SolidWorks

SolidWorks is a software program for CAD and CAE that is used to create 3D models and simulations. With tools for assembly building, parametric modeling, and finite element analysis (FEA), it offers a complete platform for product design and development. The product development process is expedited by SolidWorks, which gives engineers and designers the ability to envision and test their concepts in a virtual environment. With its extensive skills in mechanical design, sheet metal design, and simulation, it is a vital tool in manufacturing and mechanical engineering, among other fields.

3.1. Floating Solar PV 3D model with SOLIDWORKS

The solar PV is positioned atop in an environment with seawater. The solar PV Module angled T with respect to the horizon, while the unit itself is flat. The location's latitude angle I equals the optimal tilt angle in theory. It is necessary to choose this tilt angle between the conditions of wind speed and solar PV. The force of wind expressed F_w given by below formula:

$$F_w = 0.5 \rho V^2 A$$

where ρ is the air density, which at roughly 25 degrees is believed to be 1.18 kg/m³. The solar PV's effective area, A_e , depends on the direction of the wind. As $A_e = A_s \sin \theta$, whereas A_s is the solar panel's area as shown in Figure. 11, is the estimated effective area due to the tiling angle.

But wind speed isn't always horizontal, thus the estimation above provides an empirical method; as a result, the safety tilted angle is:

$$0 \leq \theta \leq \phi.$$

According to experimental findings, the tilt angle should be lowered to prevent damage to the solar panel from strong winds, gusts, or typhoons.

$$\theta \leq \phi/2.$$

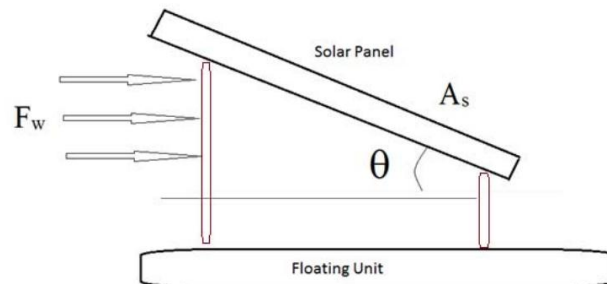


Figure 11: Angle between solar PV and Floating mounting structure

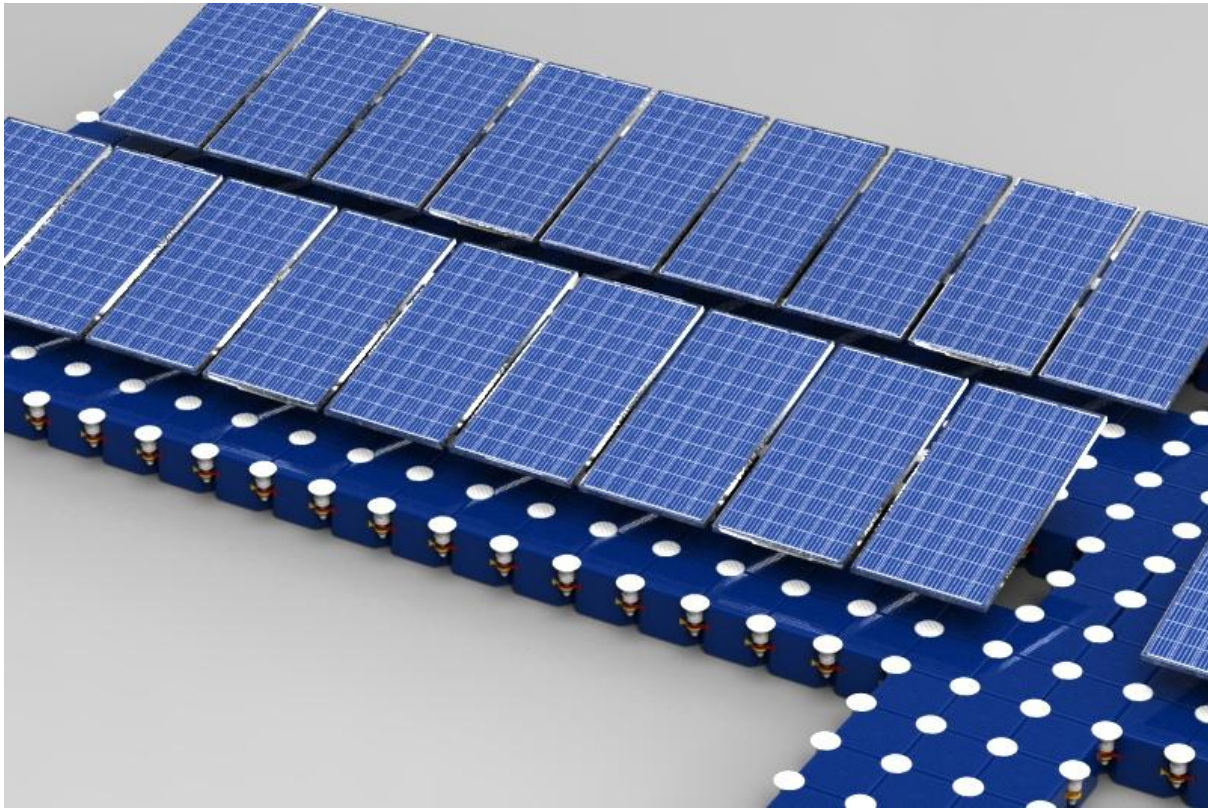


Figure 12: actual configuration of floating solar PV using SOLIDWORKS

3.2. Floating solar PV model by MATLAB

A MATLAB model that integrates hydropower and solar PV modules in a grid system, improved by an intelligent battery management system (BMS). This project's primary goal is to integrate a PID control system made especially for the BMS. During the charging and discharging stages, this system is crucial for monitoring and managing the linked battery's voltage and current. The objective is to increase grid stability by ensuring precise control and management of the battery's characteristics over its working cycles.

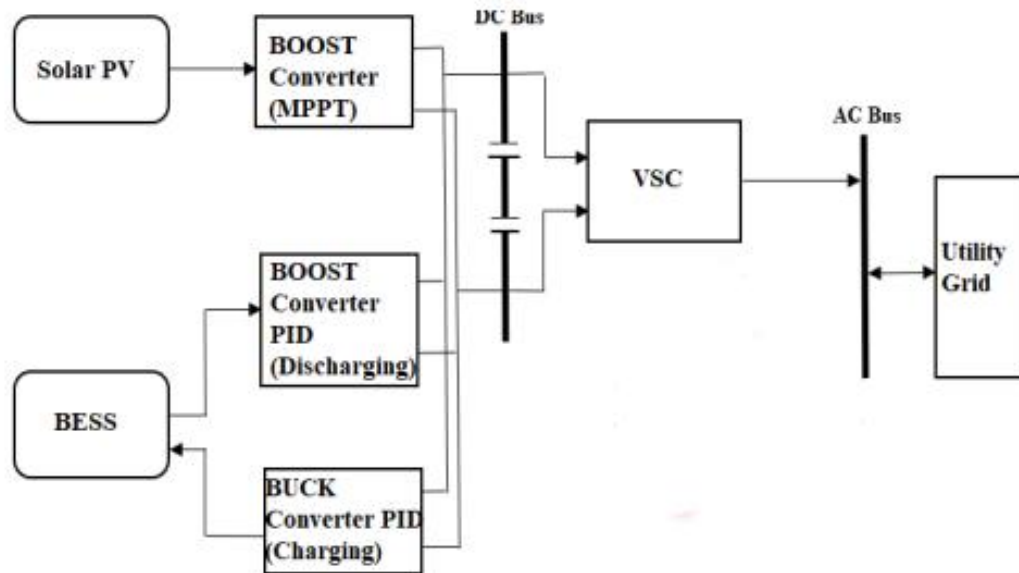


Figure 13: BESS and solar PV structure

Figure 13. illustrates the proposed system, which includes PV arrays, a DC-DC boost converter with MPPT, a VSC as a DC/AC inverter, a lithium-ion-based BESS, a DC/DC buck converter with a PID-based charge controller, a DC/DC boost converter with a PID-based discharge controller, and a three-phase load. The PV arrays and BESS are connected to the AC Bus via a DC/DC converter and a DC/AC voltage source controlling inverter.

The Homer Pro floating solar PV system uses photovoltaic modules, floating structures, inverters, and a ESS to optimize energy consumption and efficiency. The system offers an applied and reasonable way to shift to clean energy because it is built with the local climate and environmental factors in attention. Grid stability is supported by the system’s resilience

Schematic

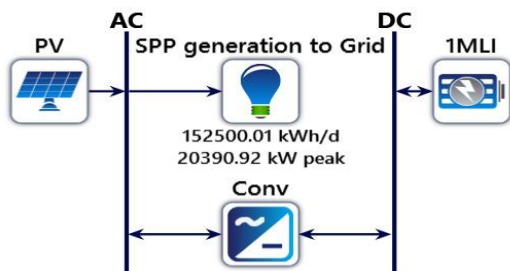


Figure 14: Simple schematic design for floating Solar system

3.3. Site data collection, data analysis, assessment (General)

3.3.1. Site description

The geographical location of the study area of floating solar PV is at Longitude 29.749212 and Latitude -1.478597, which are located near the Ntaruka HPP on Ruhondo lake and are found in Northern Province of Rwanda, Burera District, Kinoni Sector, and Ntaruka Cell.

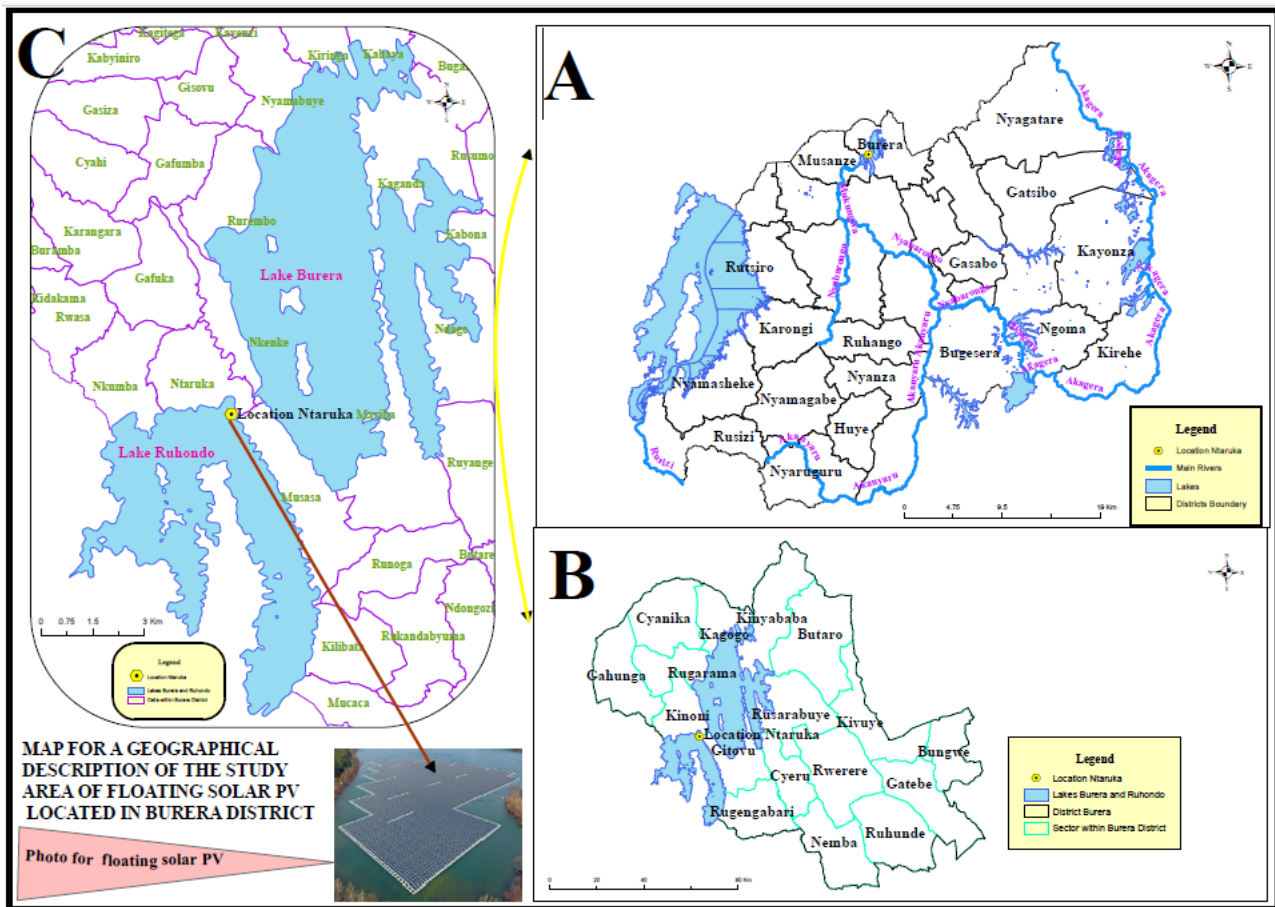


Figure 15: A, B, and C Maps of Rwanda, Burera District, Ruhondo lake locating Floating solar out stream of Ntaruka HPP [Burera, Rwanda Administration Maps, 2023, NISR]

This floating solar power plant is going to be located downstream of the Ntaruka HPP’s powerhouse. Ruhondo is one of the two lakes formed by the volcanic activity of the Sabyinyo Volcanic Mountain, which erupted and cooled, spitting lava over a river valley. A land mass of one kilometer divides Lake Ruhondo from Lake Burera. The northern regions of Rwanda, where lakes Ruhondo and Burera are situated, are adjacent to Uganda. Burera, Musanze, and Gakenke are the three districts that Lake Ruhondo crosses.

At its southwest end, Lake Burera provides Lake Ruhondo with water. Its approximate area is 2800 hectares. Water from several streams' feeds Lake Ruhondo, which empties into the Mukungwa River, a tributary of the Nyabarongo River, to the southwest. Ruhondo and Lake Burera are separated by a 1 Km long land mass.



Figure 16: Satellite view of the village showing site location with existing Ntaruka HPP, Ruhondo and Burera lakes

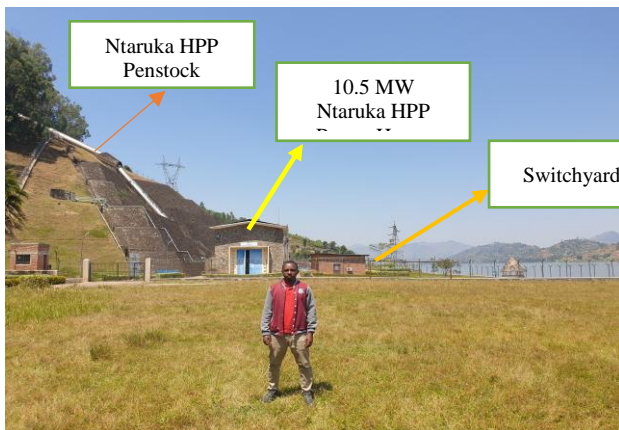


Figure 17: Ntaruka 1 HPP power house

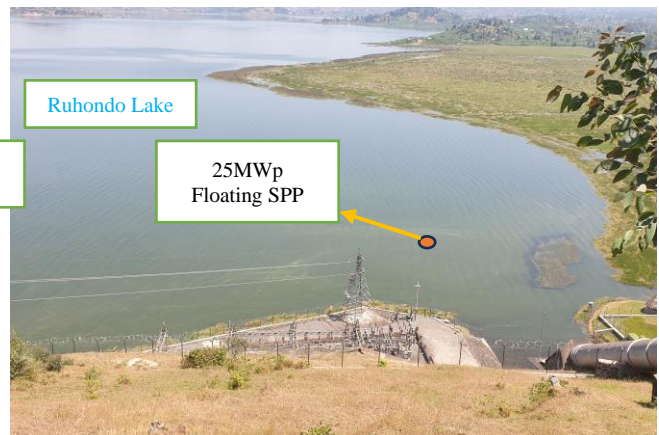


Figure 18: Ruhondo Lake where Solar PV Floating Plant will be located

3.3.2. Rugezi Wetland Degradation, Impacts on Ntaruka HPP, Ecosystem-Based Adaptation (ebA) Approach in Restoration, with Integration of Floating Solar PV

This comprehensive study investigates the temporal dynamics of Rugezi Wetland degradation, its consequences on the Ntaruka Hydropower, and the application of ecosystem-based adaptation (ebA) principles in the restoration process. Additionally, the research explores the incorporation of a floating solar photovoltaic (PV) system to enhance sustainability and resilience. Through before-and-after comparisons, the study assesses the effectiveness of ebA in bolstering ecosystem resilience and supporting the operational recovery of Ntaruka Hydropower, with a focus on the impact of the integrated floating solar PV. By comprehensively examining the degradation, restoration, and operational recovery of Rugezi Wetland and Ntaruka Hydropower, this research offers a nuanced thoughtful of the profits of ecosystem-based adaptation and the integration of renewable energy solutions in fostering resilient and sustainable energy ecosystems.

Section	Key Findings / Principles / Strategies / Impacts / Lessons
Background	People began cultivating in the Rugezi for primarily two reasons: population pressure and upland deterioration. Rugezi satisfies two vulnerability criteria: one related to biodiversity and the other to hydrology, in addition to its agricultural role. The two main HPP facilities in Rwanda are Mukungwa HPP, which is located downstream from Lake Ruhondo, and Ntaruka HPP, which is located between Lake Burera and Lake Ruhondo. The stream discharge from the Rugezi wetland is necessary for these stations to function. Rugezi is also home to a greater variety of bird species. Rugezi is badly degraded since it has lost a significant amount of its ecological, hydrological, and energy supply functions, claim (Sylvère Hategekimana ¹ , 2008).
Wetland Degradation and Hydropower Consequences	<ul style="list-style-type: none"> • Wetland degradation impacts water quality and quantity • Reducing hydropower efficiency • Loss of biodiversity in degraded wetlands adversely affects ecosystem services
Ecosystem-Based Adaptation (ebA) Principles	<ul style="list-style-type: none"> • Biodiversity conservation involves restoring native plant species in Rugezi Wetland • Ecosystem resilience through natural barriers and habitat restoration

	<ul style="list-style-type: none"> • Sustainable resource management includes integrating renewable energy such as floating solar PV
Intervention Strategies	<ul style="list-style-type: none"> • Rugezi Wetland restoration with ebA involves habitat restoration and natural barriers • Ntaruka Hydropower rehabilitation includes technical upgrades and operational enhancements
Degradation of Rugezi Wetland and Impact on Ntaruka Hydropower	<ul style="list-style-type: none"> • Historical context outlines the timeline of degradation and effects on Ntaruka Hydropower • Causes of degradation include agriculture runoff and deforestation with corresponding impacts on the wetland and hydropower • Consequences for Ntaruka Hydropower involve reduced efficiency and environmental compliance issues with mitigation strategies
Restoration Interventions with Ecosystem-Based Adaptation	<ul style="list-style-type: none"> • Rugezi Wetland restoration focuses on habitat restoration and natural barriers • Ntaruka Hydropower rehabilitation includes technical upgrades, adaptive management, and habitat protection • Integration of Floating Solar PV brings benefits such as renewable energy generation, reduced water evaporation, and positive impacts on biodiversity and hydropower efficiency.
Comparative Analysis	<ul style="list-style-type: none"> • Before-and-after restoration compares parameters like ecological health and operational performance • Impact of Floating Solar PV includes aspects like wetland conservation and enhanced hydropower synergy.
Challenges and Lessons Learned	<ul style="list-style-type: none"> • Challenges faced during restoration include funding constraints and community resistance with corresponding mitigation strategies • Lessons for future wetland-hydropower management emphasize community involvement, adaptive management, and the incorporation of ecosystem-based adaptation for project resilience and sustainability

Table 3: Rugezi Degradation, Impacts on Ntaruka HPP, ebA) approach in its restoration by integrating Floating Solar PV with existing HPP

3.4. Component sizing

The component sizing calculations for a solar power system are outlined in the provided equations. Let's dissect the parts and explain how the sizes of a grid-tie floating solar system with a 25 MWp capacity and a 5 MWh integrated battery storage system relate to each other. These characteristics are among system design parameters that was based on MATLAB, Homer Pro, and PVsyst Software during optimization of the actual system needed to replace a 10 MW diesel thermal power plant for grid stabilization.

$$P_{array} = \frac{E \times n}{PSH \times H_{Tilt}} \dots \dots \dots (3.1)$$

Whereby:

- **P_{varray}**: Power output of PV array in kWp
- **E**: Daily Average energy consumption in kWh/day
- **PSH**: Peak sun Hour solar irradiance 1000W/m² at STC
- **H_{Tilt}**: tilt angle specified occurs at Peak Average solar radiation
- **n**: PV array sizing coefficient

The ratio of the designated system voltage to the voltage **V** of the solar PV module at STC was used to estimate the number of solar PV modules in series at STC.

$$N_s = \frac{V_{System}}{V_{module}} \dots \dots \dots (3.2)$$

Whereby:

- **N_s**: is the number of PV modules to be connected in series
- **V_s**: the system voltage
- **V_{Module}**: voltage per PV module

The ratio of the power produced by the solar PV array to the number of solar PV modules in series and the power loss by the solar PV module was used to determine the number of solar PV modules in parallel.

$$N_p = \frac{P_{array}}{N_s \times P_{module}} \dots \dots \dots (3.3)$$

Whereby:

- N_P : Number of solar PV modules in parallel
- M_{Module} : Power generated by PV module

Thus, it was obvious that multiplying solar PV modules in series and parallel would produce the entire solar PV Modules needed to be connected to meet the required plant capacity.

$$N_T = N_S \times N_P \dots \dots \dots (3.4)$$

Whereby:

- N_T : total number of PV modules for solar power plant

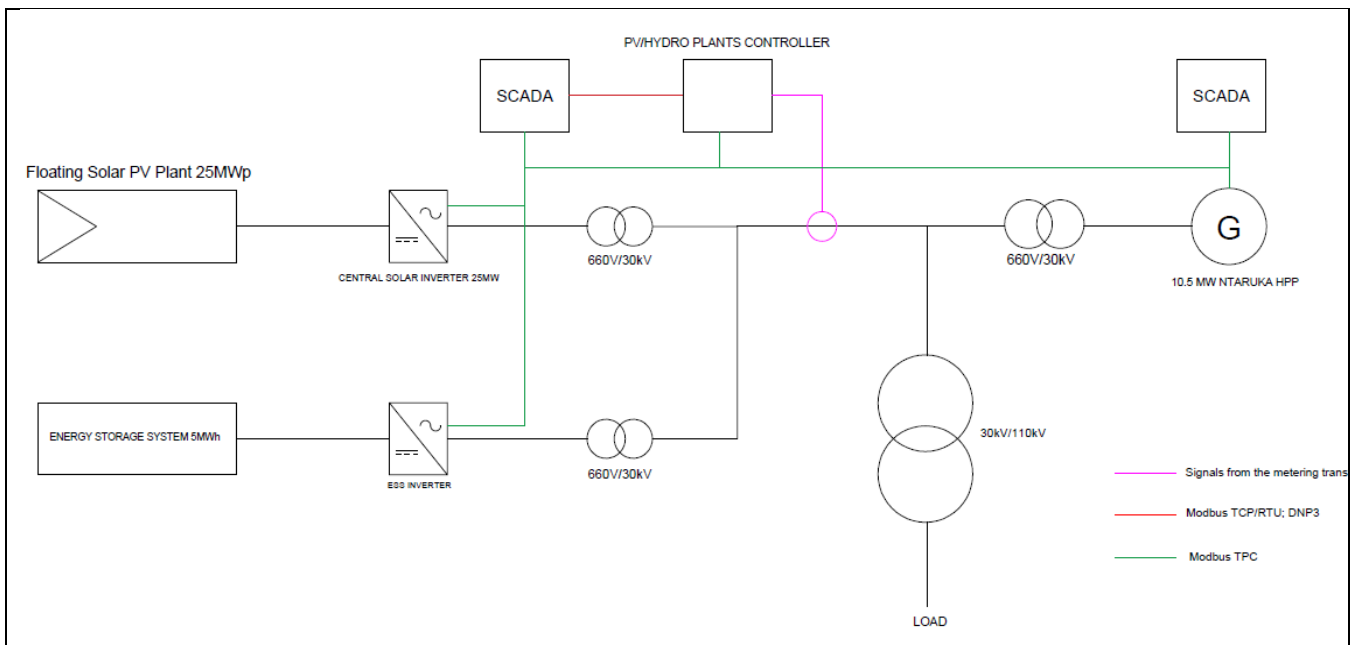


Figure 19: SLD for 25MWp with ESS integrated with existing 10.5MW Ntaruka HPP

CHAPTER 4. RESULTS AND DISCUSSION

4.1. PVSYST software design results

Energy yield calculations are performed with PVsyst software and result is presented in Table 4. Energy Estimation:

		Unit	25,000kWp
Input data	GHI	kWh/m ² /year	2059.6
	GI	kWh/m ² /year	2,058.4
	Ambient Temperature	°C	22.93
	Azimuth	Deg	0
	Peak Power	MWp	24.5
	Total Rated Power AC	MW	23.4
	Number of PV Module	No.	37,038
	Number of PV string	No.	74
Loss factors	Soiling	[%]	0
	Wiring Ohmic	[%]	0.1
	Serie Diode	[%]	0.1
	(LID) Light Induced Degradation	[%]	0.1
	Module Quality	[%]	-0.8
	Module Mismatch	[%]	1
	String Mismatch	[%]	0.1
	AC Wire Loss Inverter to Transformer	[%]	0.8
	External Transformer Iron	[%]	0.1
	External Transformer Resistive	[%]	1
Results	Net Energy	MWh/year	41.5
	Performance Ratio	[%]	80.64
Area	Planned areas for PV	m ²	145,980

Table 4: Project Results summary

25MWp Floating SPP

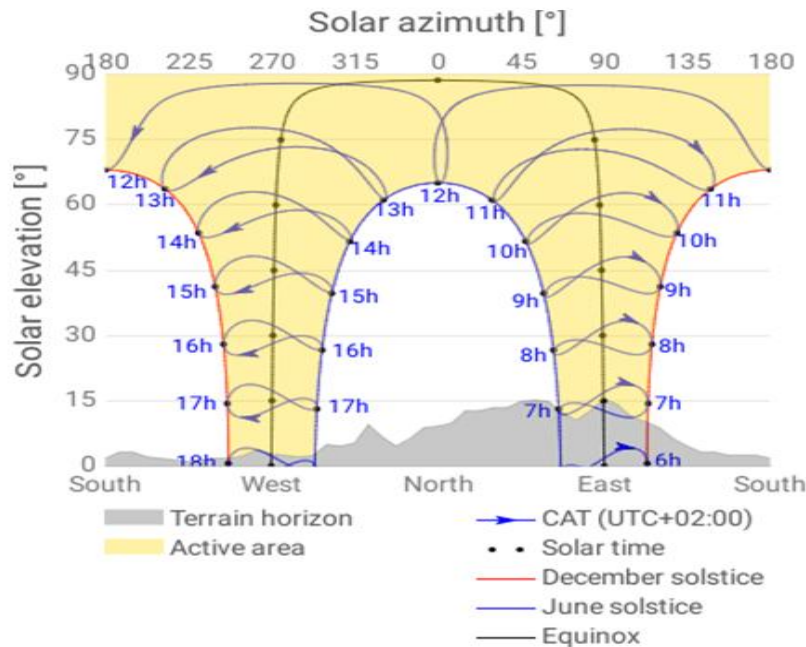


Figure 20: Shading Analysis by PVsyst

The plant sizing and simulation were done by the software module PVsyst which is the industry standard for sizing of utility-scale plants. The basic parameters of the 25MWp installation are shown in the Table 4 above. With the parameters chosen, the area covered is about 162.360m² not including walkways, inverter spaces, and transformer stations.

The PVsyst results show an annual energy production of about 41.496 MWh/year with a performance ratio of 80.6%.

4.2. HOMER software results

The solar irradiance data provided by HOMER Pro presented in Table 4 offers a comprehensive overview of the solar energy potential for each month, allowing for accurate modeling and analysis of a solar power brief in the description of the key parameters:

A dimensionless index represents the clarity of the atmosphere. A higher clearness index, 0.487 indicates clearer skies with less atmospheric interference.

The average daily global horizontal irradiance for the entire year indicates the overall solar energy potential resulting by 4.87 kWh/m²/Day.

The average ambient temperature, 20.41°C for the entire year, influences the efficiency of solar panels cooled by water.

The average wind speed, 2.57 m/s for the entire year, impacts the local climate conditions and potential cooling effects on solar panels.

This data is essential for designing and optimizing solar power systems, helping to estimate energy production, assess system performance, and make informed decisions about system sizing and configuration based on local climatic conditions.

Month	Clearness Index	GHI daily (kWh/m ² /Day)	Temperature (°C)	Wind speed(m/s)
Jan	0.480	4.900	19.730	2.570
Feb	0.493	5.170	20.580	2.710
March	0.478	5.030	20.140	2.400
Apr	0.487	4.930	19.710	2.350
May	0.504	4.800	20.790	2.740
Jun	0.526	4.810	21.300	3.290
Jul	0.528	4.900	21.480	2.990
Aug	0.501	4.920	22.030	2.860
Sept	0.485	5.000	21.350	2.510
Oct	0.450	4.690	19.630	2.240
Nov	0.454	4.640	19.010	2.080
Dec	0.491	4.639	19.009	2.078
Annual Av.		4.87	20.41	2.57
Annual Average (kWh/m²/Day)			4.87	
Solar Resources in Ruhondo Lake on planned area of Solar PV Floating System. Source: NASA Database and Solar Energy Database				

Table 5: Annual Average (kWh/m²/Day) for the site

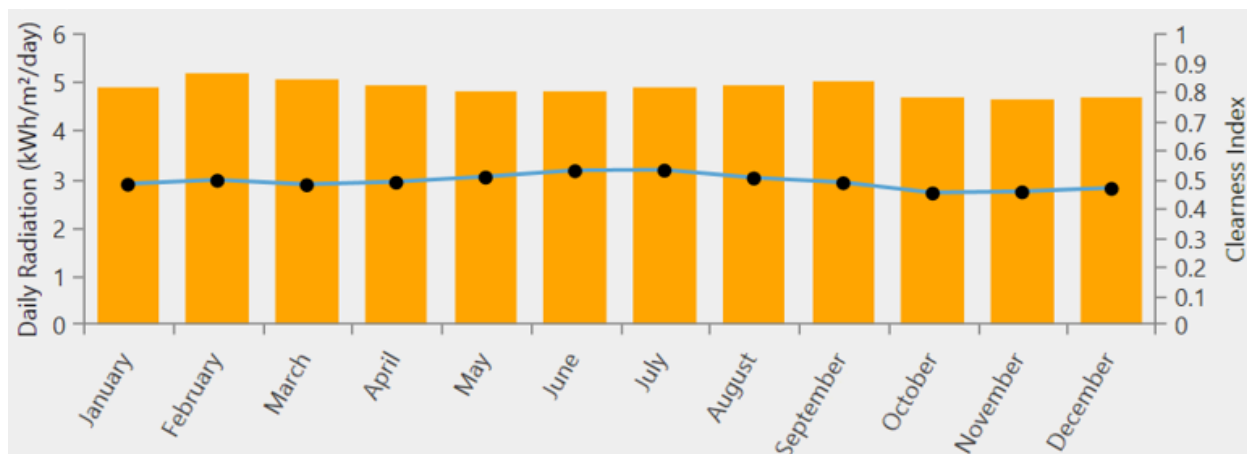


Figure 21: Solar Resources in Ruhondo Lake on planned area of Solar PV Floating System

The data on solar irradiation that was gathered from Ruhondo Lake in the region set aside for the proposed Solar PV Floating System is shown in Figure 20. With the help of this vital information, the floating solar

panels may be positioned and designed in the best possible way to maximize energy capture and the overall performance of the solar photovoltaic system. The graphic is a useful resource for learning more about the location's solar potential.

Component	Name	Size	Unit
PV	Generic flat plate PV	25,000	kW
Storage	Generic 1MWh Li-Ion	15	strings
System converter	Generic large, free converter	25,000	kW
Dispatch strategy	HOMER Cycle Charging		

Table 6: Floating solar PV System Architecture

Table 5 outlines the key components and specifications of the Floating Solar PV System. Generic flat plate modules are used to generate renewable energy in the 25,000kW installed capacity Floating Solar PV System. For energy storage, 15 strings of 1MWh Li-Ion batteries are included. The system converter makes energy conversion and distribution easier with its 25,000kW capacity. Energy storage utilization is maximized with the HOMER Cycle Charging technique.

This schematic design in Figure 21, created using HOMER Pro software, illustrates the key components and their interconnections in a floating solar system. The figure provides a clear visualization of the solar panels mounted on the water surface, connected to a generic large, free converter with a capacity of 25,000 kW. Additionally, the design incorporates 15 strings of generic 1MWh Li-Ion batteries for energy storage. The simplicity of the schematic enhances understanding, making it an invaluable tool for systems in the implementation and optimization of floating solar PV projects.

Electrical Summary

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	33,113,082	100
Total	33,113,082	100

Table 7: Floating solar PV System Production Summary

Consumption Summary

Component	Consumption (kWh/yr)	Percent
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AC Primary Load	27,615,350	100
DC Primary Load	0	0
Total	27,615,350	100

Table 8: Floating solar PV System consumption Summary

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	20,246	kW
PV Penetration	59.5	%
Hours of Operation	4,380	hrs/yr
Levelized Cost	0.0880	\$/kWh

Table 9: Floating solar PV electrical Summary

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	25,000	kW
Mean Output	3,780	kW
Mean Output	90,721	kWh/d
Capacity Factor	15.1	%
Total Production	33,113,082	kWh/yr

Table 10: Floating solar PV statistics

ESS, Storage: Generic 1MWh Li-Ion

Generic 1MWh Li-Ion Properties

Quantity	Value	Units
Batteries	15.0	qty.
String Size	1.00	batteries
Strings in Parallel	15.0	Strings
Bus Voltage	600	V

Table 11: ESS, Storage: Generic 1MWh Li-Ion

Generic 1MWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	\$/kWh
Energy In	3,384,640	kWh/yr
Energy Out	3,057,560	kWh/yr
Storage Depletion	12,000	kWh/yr
Losses	339,080	kWh/yr
Annual Throughput	3,222,952	kWh/yr

Table 12: ESS, Storage results

Generic 1MWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	1.89	Day
Storage Wear Cost	0	\$/kWh
Nominal Capacity	15,000	kWh
Usable Nominal Capacity	12,000	kWh
Lifetime Throughput	45,000,000	kWh
Expected Life	14.0	Yr

Table 13: ESS, Storage statistics

Converter: Generic large, free converter

Generic large, free converter Electrical Summary

Quantity	Value	Units
Hours of Operation	1,201	hrs/yr
Energy Out	2,904,682	kWh/yr
Energy In	3,057,560	kWh/yr
Losses	152,878	kWh/yr

Table 14: Converter electrical summary

Generic large, free converter Statistics

Quantity	Value	Units
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Capacity	25,000	kW
Mean Output	332	kW
Minimum Output	0	kW
Maximum Output	10,815	kW
Capacity Factor	1.33	%

Table 15: Converter statistics

The dispatch strategy employed in this system architecture in Table 5 follows the HOMER Cycle Charging method. This strategy optimizes the charging and discharging cycles of the storage system to enhance the overall efficiency and reliability of the hybrid energy system.

This system architecture is designed to integrate solar power generation, energy storage, and efficient conversion for optimal performance in Table 6, Table 7, Table 8, Table 9, Table 10, Table 11, and Table 12, Table 13, and Table 14. The dispatch strategy ensures intelligent management of the energy flow, maximizing the utilization of renewable resources and minimizing reliance on non-renewable sources. The use of lithium-ion batteries in the storage system reflects a contemporary and widely adopted technology for energy storage in renewable energy systems. The overall goal is to enhance grid stability and reduce dependence on conventional energy sources, contributing to a more sustainable and resilient power infrastructure.

The solar photovoltaic (PV) component is the primary contributor to electricity generation, producing 33,113,082 kWh per year. It constitutes 100% of the total electrical output, indicating a reliance on solar energy for the system's power generation.

The AC primary load represents the total electricity consumed by the system. In this case, it amounts to 27,615,350 kWh per year, constituting 100% of the total consumption. This load is typically associated with the demand for electricity within the system.

The absence of a DC primary load indicates that there is currently no direct current load in the system. This could imply that all direct current generated is efficiently converted to alternating current for consumption or storage.

This data provides a snapshot of the system's electrical balance. It serves as valuable information for system optimization, suggesting adjustments to better align production with consumption.

4.3. Simulation Results and discussion

This study's use of MATLAB produced thorough and informative results, especially when it came to the dynamic modeling and analysis of the suggested floating solar PV system. The complex interactions inside the system were successfully represented thanks to the Simulink extension, enabling a thorough analysis of its behavior across time. Finding the best operating configurations was made easier by the simulation findings, which offered a solid understanding of the system's responsiveness to changing circumstances. The ability to integrate many components was made possible by MATLAB's adaptability, which also made it easier to analyze the intricate relationships and dependencies that exist inside the floating PV plant and its connection to the grid.

Figure 22. The MATLAB results provide a detailed insight into the performance parameters of the integrated renewable energy system, consisting of a 25MWp Floating Solar PV array with a 5MWh Energy Storage System (ESS). This system is intelligently designed to complement the existing 10.5MW Hydropower Plant and strategically replace the 10MW Diesel Power Plant, contributing to national grid stability.

Input Voltage from PV Array (V_{pv}); the results show the voltage supplied by the 25MWp Floating Solar PV array, indicating the efficiency. The values are critical for understanding the electrical characteristics of the PV system and ensuring optimal power generation.

Input Current for PV Array (I_{pv}); this parameter represents the current flowing through the PV array. Monitoring I_{pv} is essential for assessing the real-time performance of the solar panels, aiding in identifying any issues such as shading or module malfunctions that may impact overall efficiency.

Power Output for PV Array (MWp); the power output from the 25MWp Floating Solar PV array is a crucial metric indicating the actual electricity generated. This result is pivotal in evaluating the system's capacity to meet energy demands and contribute to the overall power supply to the grid.

Vac and Iac Similar to Grid Parameters (Network Stability); the alternating current (Vac) and current (Iac) parameters representing grid conditions are of paramount importance. These results demonstrate the synchronization and compatibility of the integrated system with the national grid, ensuring stability and reliable energy contribution.

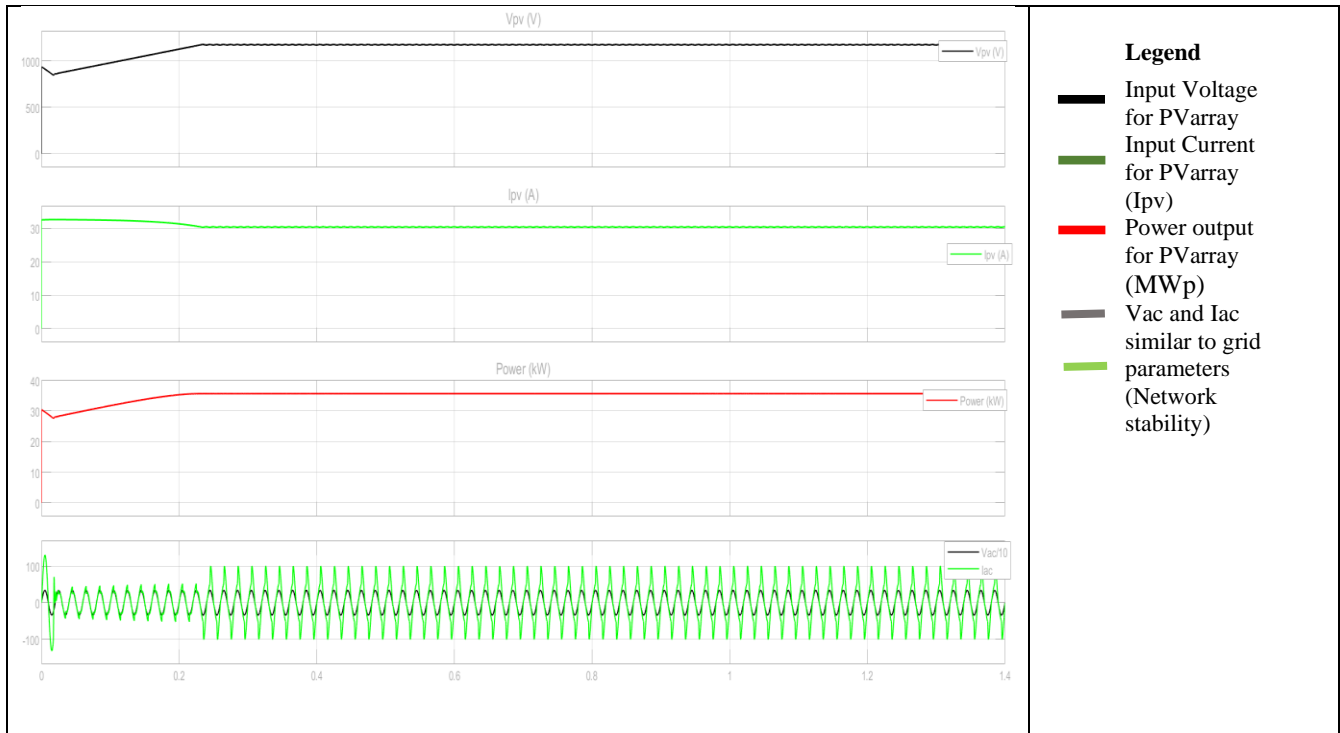


Figure 22: Network stability the simulation result from MATLAB

For the purpose of national grid stabilization, the proposed 25MWp Floating solar integrated with the existing 10.5MW Ntaruka HPP replaces 10MW oil-fired gen sets. The figures provided show simulations from HOMER Pro for a photovoltaic (PV) system, including the PV array, inverter (INV), and lithium-ion batteries.

The figure illustrates the simulation of available GHI in kilowatts per square meter (kW/m²). The related PV power output in kilowatts is shown, indicating the energy generated by the photovoltaic array in response to the solar irradiance.

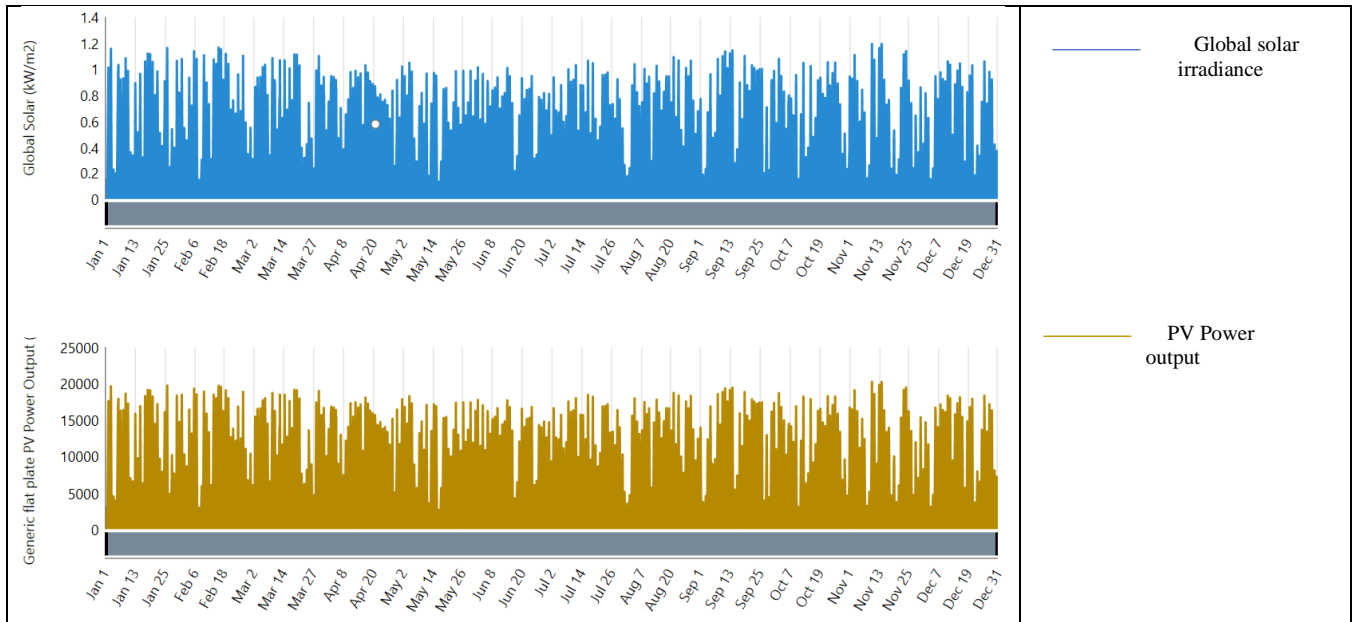


Figure 23: simulation of available GHI (kW/m^2) and its related PV Power output (kW)

This simulation displays the power output of the inverter in kilowatts. The main inverter rated 25MW will be embedded with a transformer to evacuate the generated power into the national grid.

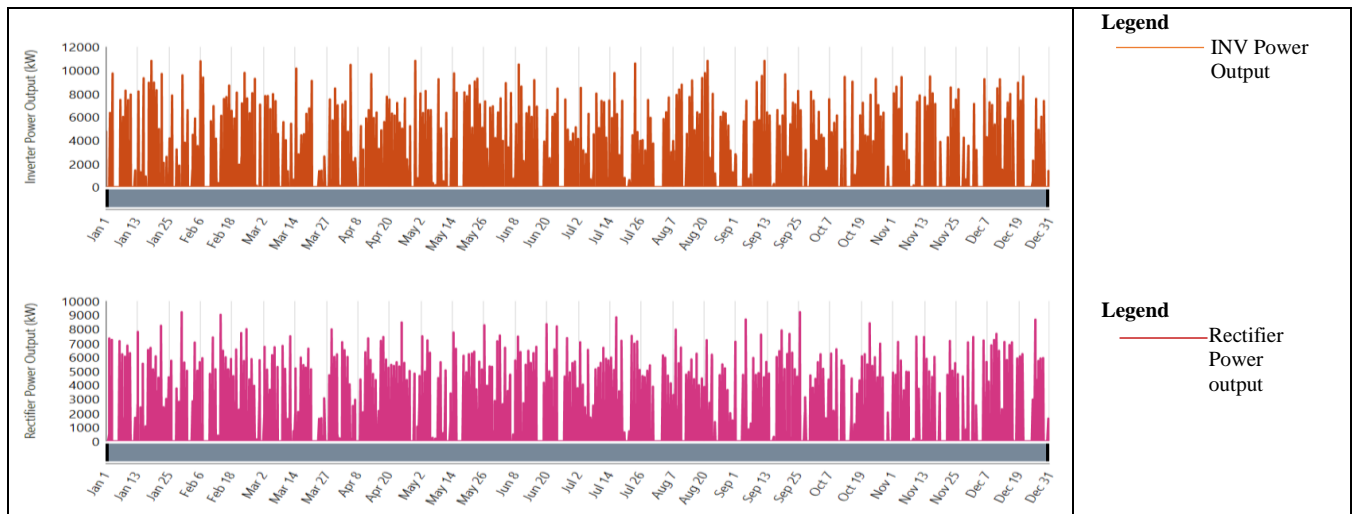


Figure 24: simulation of INV power output (kW)

The power provided to charge the Li-ion batteries is represented by the simulation's input power in kilowatts. The power output from the batteries when they are discharging to supply energy is shown in this section of the figure. The Li-ion batteries' state of charge is shown, indicating the amount of energy they can hold at any one time.

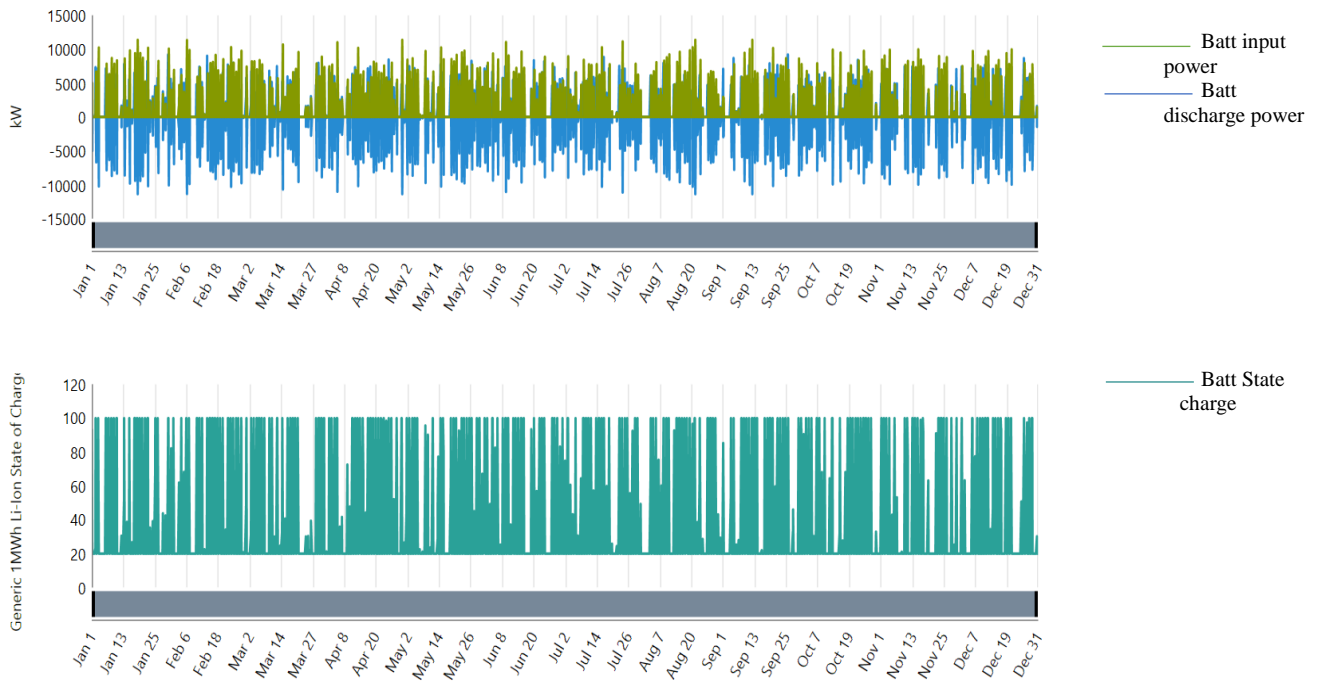


Figure 25: simulation of Li-ion batteries input power (kW), and Li-ion batteries discharge power and its state charge

The collective perspective offered by these simulations offers a thorough understanding of the operation and interactions of the PV system. To comprehend the general behavior of the system and optimize its operation, it is essential to study the figures as they provide information on the efficiency of the PV array in converting solar irradiance into power, the output of the inverter, and the dynamics of charging and discharging the Li-ion batteries.

4.4. Economic Analysis

Cost Summary

Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1MWh Li-Ion	\$375,000	\$116,348	\$0.00	\$0.00	\$0.00	\$491,348
Generic flat plate PV	\$37.5M	\$155,130	\$0.00	\$0.00	\$0.00	\$37.7M
Generic large, free converter	\$4.00M	\$129,275	\$0.00	\$0.00	\$0.00	\$4.13M
Other	\$115,000	\$5.55M	\$0.00	\$0.00	\$0.00	\$5.67M
System	\$42.0M	\$5.96M	\$0.00	\$0.00	\$0.00	\$47.9M

Table 16: capital cost of project

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1MWh Li-Ion	\$29,008	\$9,000	\$0.00	\$0.00	\$0.00	\$38,008
Generic flat plate PV	\$2.90M	\$12,000	\$0.00	\$0.00	\$0.00	\$2.91M
Generic large, free converter	\$309,418	\$10,000	\$0.00	\$0.00	\$0.00	\$319,418
Other	\$8,896	\$429,700	\$0.00	\$0.00	\$0.00	\$438,596
System	\$3.25M	\$460,700	\$0.00	\$0.00	\$0.00	\$3.71M

Table 17: Annualized costs

Economic Analysis Summary Table

for floating Solar PV with ESS:

Category	Total Cost (\$)	Cashflow (\$)
Capital	\$47,945,710.00	(\$42,000,000.00)
Operating	\$2,120,505.00	(\$460,700.00)
Total Annualized	\$50,066,215.00	(\$42,460,700.00)

Table 18: Economic analysis summary

Description

Table 17 illustrates the economic analysis provides a comprehensive overview of the costs associated with the renewable energy system components. The total net present cost (NPC) for the entire system is \$47,945,710.00, encompassing capital, operating, replacement, salvage, and resource costs. The cash flow analysis shows the financial flow over time, indicating the investment costs and returns associated with the project.

The capital investment for the entire system is \$42,000,000.00; Annual operating costs total \$460,700.00, contributing to the overall economic performance of the system. The annualized costs, including capital and operating expenses, amount to \$50,066,215.00. The NPC, representing the present value of all costs over the project's lifetime, is \$47,945,710.00.

The LCOE is calculated at \$0.134 per kilowatt-hour, providing a measure of the per-unit cost of electricity generated by the system.

This economic analysis aids in assessing the financial viability and competitiveness of the renewable energy project, offering valuable insights for decision-making and further optimization.

4.5. Operational Cost Comparison of 25 MWp Floating SPP with ESS and Existing 10x1MW Diesel Power Plant

Items	25 Floating SPP with ESS	Existing 10MW Diesel
CAPEX	USD \$47,945,710	Not compared
Energy generated per Annum	33,113,082kWh	41,333,980kWh (consumption 2022 year)
LCOE	USD\$ 0.134	USD\$ 0.34 (Incl. GoR subsidy)
OPEX per Annum	USD\$ 4,437,153	USD\$ 14,053,553
Total OPEX in 25 years (PPA)	USD\$ 110,928,825	USD\$ 351,338,830

Table 19: Comparison of 25 MWp Floating SPP with ESS and Existing 10x1MW Diesel Power Plan

Table 18 provides a comprehensive comparison between the operational aspects of a 25 MWp Floating Solar Power Plant (SPP) with an Energy Storage System (ESS) and an existing 10x1MW Diesel Power Plant. The Floating SPP with ESS boasts a capital expenditure (CAPEX) of USD 47,945,710. Annually, the Floating SPP generates 33,113,082 kWh, whereas the existing Diesel Power Plant consumes 41,333,980 kWh in the year 2022. The Levelized Cost of Electricity (LCOE) for the Floating SPP is



significantly lower at USD 0.134 compared to the Diesel Power Plant's LCOE of USD 0.34 (inclusive of the Government of Rwanda subsidy). The annual operational expenditure (OPEX) for the Floating SPP is USD 4,437,153, notably lower than the existing Diesel Power Plant's OPEX of USD 14,053,553. Over 25 years, the total Operational Expenditure under the Power Purchase Agreement (PPA) for the Floating SPP is USD 110,928,825, demonstrating economic efficiency compared to the existing Diesel Power Plant's USD 351,338,830. This analysis underscores the financial and operational advantages of adopting a Floating SPP with ESS, highlighting its potential for sustainable energy generation and cost-effectiveness in comparison to traditional diesel power plants.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

This master's thesis presents a comprehensive and innovative approach to addressing grid instability in a northern network of Rwanda. The proposed solution involves replacing a 10MW fossil fuel-based generation at the Mukungwa HPP with a 25MW Floating Solar system integrated with 5MWh of Energy Storage System (ESS). Through a multidisciplinary approach, utilizing tools like SolidWorks, Homer, MATLAB, and PVsyst, the study focuses on designing, modeling, and simulating the floating solar PV modules coupled with ESS to improve grid stability.

The economic analysis underscores the financial feasibility of the renewable energy project, with a total net present cost (NPC) of \$47,945,710.00 and a levelized cost of electricity (LCOE) at \$0.134 per kilowatt-hour. These figures, coupled with detailed cash flow and cost breakdowns, provide a robust foundation for decision-making, emphasizing the economic viability of transitioning from fossil fuels to a cleaner energy system. Overall, this research contributes not only to the academic understanding of grid stability but also offers practical insights for implementing sustainable energy solutions that align with environmental conservation and economic prudence in the Rwandan context.

The Floating SPP with ESS has a lower LCOE (USD \$0.134 per kWh) compared to the existing Diesel Power Plant (USD 0.34 per kWh).

The annual OPEX for the Floating SPP with ESS is significantly lower than that of the existing Diesel Power Plant. Over 25 years (PPA), the total OPEX for the Floating SPP with ESS is considerably lower than that of the existing Diesel Power Plant.

These conclusions suggest that the Floating SPP with ESS is a more cost-effective and sustainable option with a positive environmental impact compared to the existing Diesel Power Plant.

All energy stakeholders are urgently encouraged to support implementation of the proposed 25 MWp Floating Solar Power Plant (SPP) with Energy Storage System (ESS). This project not only exhibits a positive impact on the environment but also demonstrates cost-effectiveness. There is a significant opportunity to increase the share of renewable energy in the energy mix to meet national installed capacity, as this floating SPP only covers 1.434 Ha of the 2800 Ha of Ruhondo Lake.

To optimize its contribution to the national renewable energy goals, future research endeavors have to concentrate on expanding the floating solar power plant's coverage to encompass a greater area of Ruhondo Lake. Furthermore, there is a recommendation to investigate the feasibility of incorporating an eco-tourism park at Ruhondo Wetland and conservation of Urugezi wetland.

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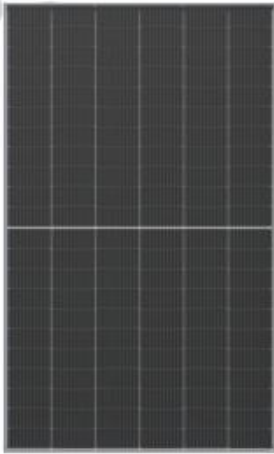
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APPENDICES

ANNEX 1. PV MODULE DATASHEET









Ultra X Plus

HALF-CELL MONOFACIAL MODULE
TYPE: STPXXXS - D66/Wmh

655-675W **21.7%**
POWER OUTPUT MAX EFFICIENCY

-  **High module conversion efficiency**
Module efficiency up to 21.7% achieved through advanced cell technology and manufacturing process
-  **Low risk of hidden cracks**
The fine non-destructive cell cutting process avoids the damage of cutting surface effectively and reduces the risk of hidden cracks and hot spots on modules
-  **Withstand harsh environments**
Reliable quality that makes module resistant even to high temperatures, salt water and ammonia
-  **Extended wind and snow load tests**
Module certified to withstand extreme wind (2400 Pascal) and snow loads (5400 Pascal)*

ISO 14001 Environment Management System

ISO 45001 Occupational Health and Safety

ISO 9001 Quality Management System

SA 8000 Social Responsibility Standards





IEC TS 62941 Guideline for Module Design



IEC 61701 Salt-mist certification

IEC 62716 ammonia certification

IEC 60068-2-68 Dust and Sand

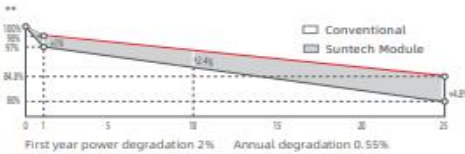
IEC 61730-2 (UL790) fire class C

25 years of linear warranty

12 years of product warranty



** Please refer to Suntech Standard Module Installation Manual for details.
*** WEEE only for EU member states.
**** Suntech reserves the right to the final.

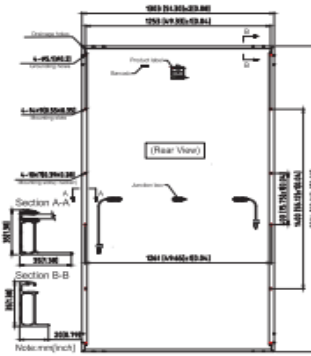


Ultra X STPXXXS - D66/Wmh 655-675W

Mechanical Characteristics

Solar Cell	Monocrystalline silicon 210 mm
No. of Cells	132 (6 × 22)
Dimensions	2384 × 1303 × 35 mm (93.9 × 51.3 × 1.4 inches)
Weight	33.5 kgs (73.9 lbs.)
Front Glass	3.2 mm (0.126 inches) fully tempered glass
Output Cables	4.0 mm ² , (-) 350 mm (+) 160 mm in length or customized length
Junction Box	IP68 rated (3 bypass diodes)
Operating Module Temperature	-40 °C to +85 °C
Maximum System Voltage	1500 V DC (IEC)
Connectors	STP-XC4
Maximum Series Fuse Rating	30 A
Power Tolerance	0/+5 W
Frame	Anodized aluminum alloy frame
Packing Configuration	31 Pieces per pallet 558 Pieces per container /40'HC 1325×1120×2510 1072.5kg

For tracker installation, please turn to Suntech for mechanical load information.



Electrical Characteristics

Module Type	STP675S-D66/Wmh		STP670S-D66/Wmh		STP665S-D66/Wmh		STP660S-D66/Wmh		STP655S-D66/Wmh	
	STC	NMOT	STC	NMOT	STC	NMOT	STC	NMOT	STC	NMOT
Maximum Power (Pmax/W)	675	510.9	670	507.5	665	503.7	660	499.9	655	496.1
Optimum Operating Voltage (Vmp/V)	38.65	36.2	38.45	36.0	38.25	35.8	38.05	35.6	37.85	35.4
Optimum Operating Current (Imp/A)	17.46	14.13	17.43	14.11	17.39	14.07	17.35	14.04	17.31	14.00
Open Circuit Voltage (Voc/V)	46.65	44.0	46.45	43.8	46.25	43.6	46.05	43.4	45.85	43.2
Short Circuit Current (Isc/A)	18.46	14.89	18.43	14.87	18.39	14.84	18.35	14.80	18.31	14.77
Module Efficiency (%)	21.7		21.6		21.4		21.2		21.1	

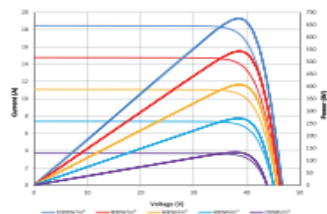
STC: Irradiance 1000 W/m², module temperature 25 °C, AM1.5; NMOT: Irradiance 800 W/m², ambient temperature 30 °C, AM1.5, wind speed 1 m/s; Tolerance of Pmax is within +/- 2%.

Temperature Characteristics

Nominal Module Operating Temperature (NMOT)	42 ± 2 °C
Temperature Coefficient of Pmax	-0.34%/°C
Temperature Coefficient of Voc	-0.26%/°C
Temperature Coefficient of Isc	+0.050%/°C

Information on how to install and operate this product is available in the installation instruction. All values indicated in this data sheet are subject to change without prior announcement. The specifications may vary slightly. All specifications are in accordance with standard EN 50380. Color differences of the modules relative to the figures as well as discolorations of/in the modules which do not impair their proper functioning are possible and do not constitute a deviation from the specification.

Graphs Current-Voltage & Power-Voltage Curve (675W)



Information bar



ANEX 2. BATTERY DATASHEET

WECO **ESS**

INDUSTRIAL ⚡ HIGHVOLTAGE



Lithium Energy
Storage System

14K3



INDUSTRIAL  HIGH VOLTAGE



5U- HV MODULE RACK	19'' 5U RACK
Module Application	Series Connection High Voltage
Usable Energy (kWh)	14,3
Standard C-Rate	0.5C
Max C - Rate	1C
Cell Capacity (Ah)	280
Max Output Power (kW)	14.3Kw
Peak Output Power (kW)	28.6kW
Min/ Max Modules in Serial Connection	4 -17
Module Voltage Range (Vdc)	48-57.6
String Voltage (Vdc)	192-979.2
Dimension (mm) WxHxL	L445x235x810
Net Weight (Kg)	90.1
Depth of Discharge	97.8%
Protection Class	IP30
Charging Temp. (°C)	-10 +50
Discharg. Temp. (°C)	-20 + 57
Storage Temp. (°C)	-20 +60
Design Life	10 Year (25°C)/7000 Cycles
Standard Usage (STC conditions)	90% DoD 0.5C @ 25°C
Branching	10 Towers (2431 kWh)
Communication	Ethernet, CAN, RS485, RS232 (WiFi, Bluetooth Opt)

ANNEX 3. INVERTER DATASHEET

Grid Tied Central Inverters

HIVERTER NP201i Series

250 kW to 2500 kW

HITACHI
Inspire the Next



kW Scale Central Inverter



MW Scale Central Inverter

With over 3 GW installations in India, Hitachi Grid Tied Central Inverters are among the best available Grid Tied Solar Inverters which is suitable for multi megawatt and utility-scale PV power plants. It is a critical balance of system (BOS) component in a solar photovoltaic system. It converts DC Power generated by the Photovoltaic (Solar) array to AC Power that is fed to the Utility Power Grid System.

This highly acclaimed Hitachi Solar Inverters are being developed at Sanand based manufacturing facility near Ahmedabad in India based on the contemporary technology of Hitachi Ltd, Japan, ably supporting Government of India's 'Make in India' initiative. It has been thoughtfully designed keeping all the critical parameters and challenges faced by project developers in terms of better grid compliance & most importantly CAPEX Vs. YIELD factor.

With reactive power control, 3 Level IGBT technology and wider MPPT range, Hitachi solar inverters deliver considerably maximum power generation. Its compact design and lower weight offers ease of installation, repair & maintenance. Its large touch screen display collects the real-time data and provides fault detection diagnostics; ensure faster retrieval of Information for corrective action. It is also suitable for high ambient temperature.

Product Range

- kW Scale: 250 kW, 500 kW, 630 kW, 670 kW, 715 kW
- MW Scale: 1 MW, 1.25 MW, 1.34 MW, 1.43 MW, 2.5 MW

Highlights

3 Level PWM Inverter technology resulting in reduction of losses, low harmonic output current (< 3%) & improved efficiency	Low current harmonic distortion
Reactive power control (night time)	Lowest auxiliary consumption
Suitable for handling DC overloading capacity up to 140%	Rated power @ 0.95 pt at 50°C
Widest MPPT range	Provision of air circuit breaker at o/p at each MW scale inverter
Variable output AC voltage suitable for retrofitting jobs.	2.5 MW containerized solution

ANNEX 4: PROJECT RISK AND ENVIRONMENTAL IMPACT ASSESSMENTS

Project Risk Assessment

Risk Category	Potential Risks	Likelihood	Impact	Mitigation Measures
Technical	Solar panel malfunction, Inverter failure	Moderate	High	Regular maintenance, real-time monitoring
Environmental	Adverse weather conditions affecting solar performance	Moderate	Medium	Advanced weather forecasting, energy storage integration
Regulatory	Changes in energy policies, permitting delays	Low	High	Continuous engagement with regulatory bodies, staying informed about policy changes
Financial	Fluctuations in energy prices, budget overruns	Moderate	Medium	Robust financial modeling, cost contingency planning, long-term power purchase agreements
Project Management	Delays in construction, supply chain disruptions	Moderate	High	Detailed project planning, diversified supply chain, contingency schedules
Social	Local community resistance, land use conflicts	Low	Medium	Stakeholder engagement, community outreach programs

Environmental Impact Assessment

Environmental Aspect	Potential Impacts	Mitigation Measures
Biodiversity	Disruption of aquatic ecosystems, impact on fish habitats	Floating solar design to allow sunlight penetration, ecological studies, and habitat restoration
Water Quality	Changes in water temperature and quality due to shading	Monitoring water quality, implementing water management strategies
Land Use	Utilization of water surface, potential conflicts	Floating solar minimizes land use, engaging with local communities for land use planning
Greenhouse Gas Emissions	Reduction in emissions due to replacing oil-fired generators	Regular emission monitoring, reporting, and verification
Visual Impact	Changes in landscape aesthetics	Landscaping, visual screening, and community consultation
Decommissioning	End-of-life disposal of solar panels	Developing a recycling plan, adhering to environmental regulations

