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(Research Article)

Optimization Generation Planning using RFR GWO under harsh environment via microgrid for TARS Turkish Antarctica Research Station

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Abstract

Transitioning from the fossil-gasoline energy era to renewable electricity generation and electricity garage in remote places has the capacity to reduce both carbon emissions and costs. A techno-monetary evaluation for the implementation of a hybrid renewable energy device on the South Pole in Antarctica at the Turkish Antarctica Research Station, which currently hosts several high-electricity physics experiments with nontrivial electricity demands. RFR embedded GWO gives iterations in terms of sizing, placement, allocations, and cost. The IEEE 30 bus radial system network reduces power line losses. A tailored model for using sun photovoltaics, wind turbine generators, lithium-ion electricity storage, and long-duration energy garage at this web page is explored in extraordinary combinations with and without traditional diesel energy generation. We find that the least-price machine consists of all 3 strength technology resources and lithium-ion power storage. For instance, regular-country load of one hundred seventy kW, this hybrid device reduces diesel intake by way of 95% compared to an all-diesel configuration. Over the direction of a 15-12 months analysis length, the reduced diesel usage results in a net savings of $57M, with a time to pay back of approximately years. All the eventualities modeled display that the transition to renewables is fairly price-effective under the specific economics and constraints of this extremely far-off site.

Keywords: RFR Random Forest Regression; GWO Grey Wolf Optimizer; Li-ion Lithium-ion; IEEE Institutes of Electrical and Electronics Engineering

1. Introduction

Renewable power sources coupled with power garage are permitting a global transition away from fossil gasoline mills, decreasing the related greenhouse gas emissions. As renewable technologies have matured over the past decade, the energy generated has emerge as more and more dependable and low-cost. Adoption of renewable strength has extended with decarbonization projects in many countries, for example over ninety% clean electricity through 2035 in the US, or maybe 'Carbon net zero' and 'internet 0 world Initiative' at the global stage (Ardani et al., 2035; S. Babinec et al., 2024; *Net Zero by 2050 – Analysis - IEA*, 2021). the use of locally-to be had renewable power resources in faraway areas may be mainly impactful as transportation of gas to those places can be each complicated and costly, and a transition to renewables can lessen these fees along with the greenhouse gasoline emissions. Antarctic studies stations are some of the maximum remote centers in the world, depending generally on fossil gas to generate power with high reliability. inside the case of the South Pole, the deliver of fossil fuel is in particular highly-priced because of the complicated transportation logistics required for its delivery. A transition to power technology that uses the nearby sun and wind

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resources has the capability to lessen each the bad monetary and environmental influences. The Protocol on Environmental protection within the Antarctic Treaty specially notes that "The safety of the Antarctic environment...will be essential concerns in the making plans and behavior of all sports in the Antarctic Treaty place" (Protocol on Environmental Protection to the Antarctic Treaty (1991)). however, the extreme environment and logistical constraints of Antarctica pose singular challenges inside the implementation and operation of renewable generation. two precise limitations for sun installations are the aid availability and snow accumulation. For wind mills, challenges center around the acute variety of climate situations and the associated mechanical stresses. a few progress towards decarbonization of the Antarctic has been made with more than one stations incorporating renewable assets to supply a fragment in their power (*COMNAP*, 1998; Lucci et al., 2022). If the technical challenges may be resolved, then extensive opportunities exist for similarly adoption of renewable assets. Renewable strength hybrid systems in Antarctica are tailor-made to the specific traits of each web page because key elements inclusive of terrain and climate vary widely across the continent. as an example, Belgium's Princess Elisabeth Station employs each wind turbines and sun panels to generate a a hundred% renewable power supply (132 kW).

Renewable energy on the South Pole encompass specially designed rotors and blades to withstand the web site's wide variety of wind speeds (Lucci et al., 2022; Running on Renewable Energies - Princess Elisabeth Antarctica Research Station). New Zealand's Scott Base and the usa' McMurdo Station proportion the Ross Island Wind Farm, a 990 kW set up of three wind generators imparting tens of percentage of the overall strength utilized by the two stations, even as the Black Island Communications Station has used wind, solar and diesel engines to offer power (Samasiuk, 2012). The Australian Casey Station has installed 30 kW of solar panels that supply ~10% of the yearly electricity intake (*First Australian Solar Farm in Antarctica Opens at Casey Research Station – Australian Antarctic Program (News 2019)*, n.d.). numerous agencies have also accomplished renewable energy feasibility studies for other stations throughout the continent (Boccaletti et al., 2014; Bockelmann et al., 2022; de Christo et al., 2016; Olivier et al., 2008). The Amundsen Scott South Pole Station is a usa studies station that operates yr-spherical to support on-going clinical experiments covering a huge range of disciplines from astrophysics and geophysics to atmospheric and weather sciences. positioned on the geographic South Pole, this station reviews excessive temperatures with a lowest recorded temperature of-82 ∘ C. electrical energy for each the station and experiments are presently furnished totally with the aid of diesel generators. opinions of the technical and economic feasibility of each photovoltaic (PV) panels Babinec et al. (2023) and wind mills I. Baring-Gould et al. (2005) have been formerly performed for the South Pole. PV panels have been installed on a building for over 400 days (such as both austral summer time and winter) and the output strength monitored. No structural degradation turned into determined at the stop of this era and the output electricity relied on each the angle of the sun and the general visibility due to cloud cover or blowing snow. For wind technology, a preceding economic evaluation indicated the possibility of extensive financial savings compared to diesel gasoline no matter the tremendously low wind speeds on the South Pole (I. Baring-Gould et al., 2005). each of these studies help the capacity of renewable energy generation at this extraordinarily far off website. The price of renewable strength technology and garage have dramatically reduced at the same time as reliability has advanced due to the fact that those studies have been performed (Way et al., 2022). parent 1 indicates the reduction in price for distinctive renewable technologies over the last decade (Dorr & Seba, 2020; Ramasamy et al., 2021; Stehly et al., 2019; Wiser et al., 2021). The economic case for using renewables and garage at the South Pole is therefore even more potent now.

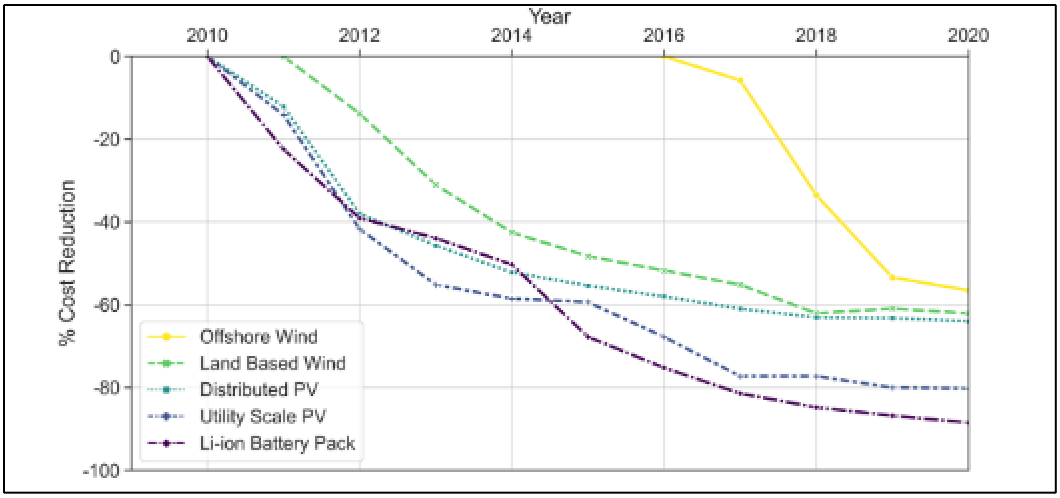


Figure 1 Summary of the cost reduction in renewable technologies over the past decade (Dorr & Seba, 2020; Ramasamy et al., 2021; Stehly et al., 2019; Wiser et al., 2021)

In this work, we gift an up to date feasibility analysis for a South Pole hybrid renewable energy system the use of solar and wind energy generation in combination with electricity garage. A price optimization of strength generation, consisting of current fossil gas mills, is done. section 2 introduces the renewable technology and details how weather facts measured on the South Pole helps modeling of both sun- and wind-generated electricity. energy garage is also delivered, including both mature lithium-ion batteries in addition to emerging technologies for longer intervals no longer economically addressed with lithium-ion. an in depth cost analysis of all technologies is offered in section 3, consisting of South Pole specific charges which include delivery and labor. The resource and fee facts are used to calculate most desirable device configurations under numerous unique eventualities. discussion of the optimization consequences is supplied in section 4, consisting of evaluation of the sensitivity to input assumptions. phase 5 summarizes the findings and discusses a route for technical development of the renewable-primarily based hybrid gadget.

1.1. Modeling Renewable Resources for the South Pole

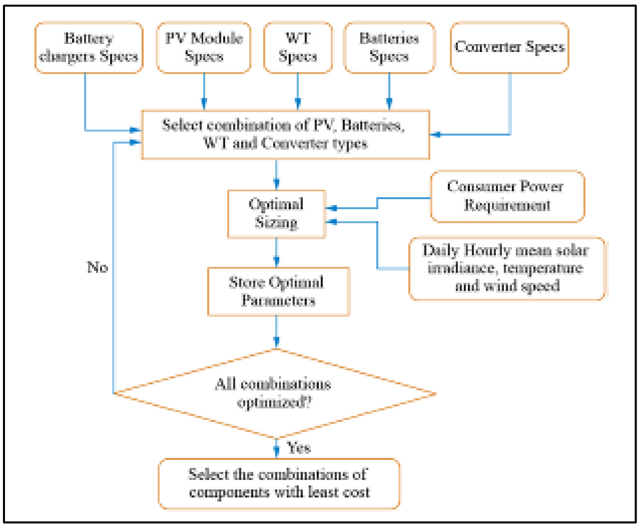


Figure 2 Flow chart optimization

The implementation of renewable energy technology at the South Poles it must account for the unique environmental conditions in addition to constraints imposed by the suite of scientific experiments. The maximum fundamental requirement is the capability of the gadget to survive the extreme South Pole winter, regardless of whether or not it's far in an operational or standby state. The common annual temperature is about-50 ◦ C with a record low temperature is-82 ◦ C, nicely under the endorsed temperature ranges of most business off-the-shelf renewable generation system. additional environmental situations consist of nearly zero relative humidity, an annual snow accumulation of approximately 20 cm Langer et al. (2023), and the thick Antarctic ice sheet that effects in a loss of strong ground. those environmental constraints are crucial factors of the sun and wind generation identification and resource modeling discussed within the following section.

1.2. Solar Resource Modeling

1.2.1. Solar radiation

The design includes bays of six vertical mounted PV modules, with five bays per row separated by two meters, and eight rows per section. The array depicted represents an 180 kW system, which is the optimized size for the least-cost hybrid system discussed in subsequent sections. Shading shown corresponds to February 20th, 2 PM GMT-12:00. Sun position, along with current day path line, annual hourly analemma, and solar path area are also depicted. Sun irradiance for an array of vertical, bifacial PV panels is modeled the use of the NREL open-supply bifacial radiance ray tracing device. This ray tracing tool can examine complex situations, inclusive of tracker-detail shading (Ayala Pelaez & Deline, 2020). a completely unique solar array is designed to adapt to the unconventional sun availability on the South Pole. To seize the solar radiation during each 24-hour revolution of the solar around the horizon the panels are organized into four subarrays orientated in a North-South-East-West configuration as proven in parent 2. Modules are grouped into bays within every row at a height of 0.6m above grade and a vertical orientation to decrease snow accumulation. NOAA information of sixteen Renewable strength on the South Pole from 2016, a mean yr in terms of weather, is used to calculate the irradiance on an hourly cadence. The simulated irradiance is then combined with PV panel electric parameters and the strength generation overall performance of the array is decided using the PV lib implementation of the single-diode version (F. Holmgren et al., 2018). A Longi 72HBD-380M monocrystalline bifacial module with 0.7 bifaciality become decided on as an example module due to its appropriate reliability beneath NREL research Urrejola Elías, (2020) and location as a top performer on the PV Evolution Labs PV Module Reliability Scorecard 2. determine three shows the full output of an instance one hundred kW-DC solar array as a characteristic of time.

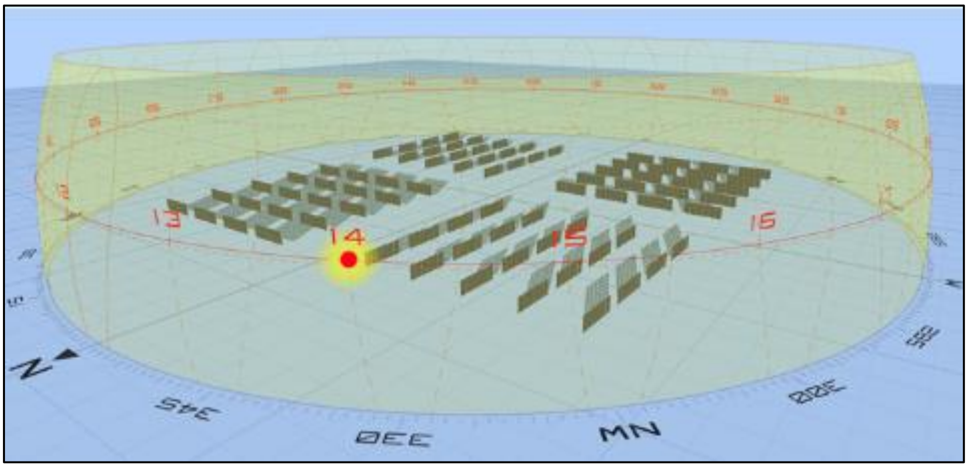


Figure 3 Diagram of a four-directional bifacial PV array.

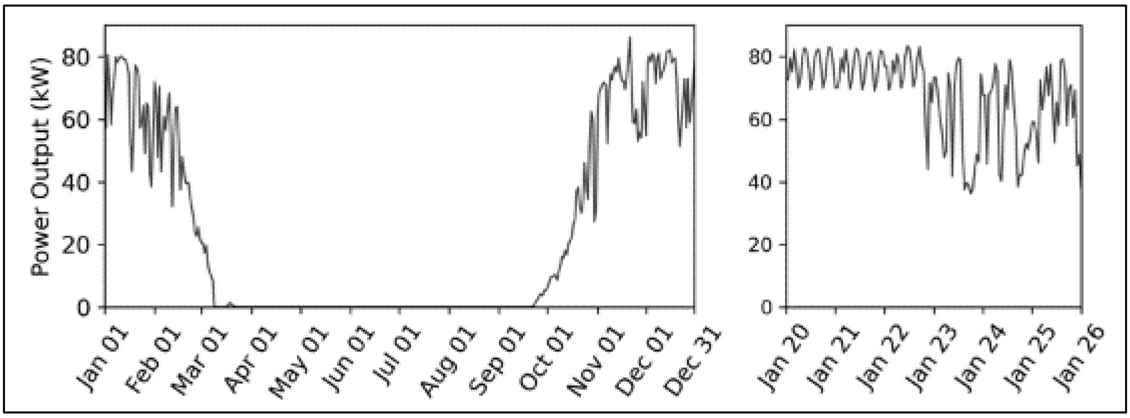


Figure 4 (Left) Daily average of estimated energy production of PV modules in the vertical array configuration for an example size of 100 kW-DC over one year.

The model uses weather data from 2016. (Right) Hourly energy production profile for six days; showing variability due to both the intrinsic array configuration and clouds several versions at the array configuration are modeled to explore the sensitivity to the unique layout. initially, an array of horizontally oriented panels (i.e., parallel to the ground) changed into taken into consideration. sun output is more consistent in this case than the vertical orthogonal array. however, the low sun attitude relative to the panel face ordinary resulted in considerably lower output in keeping with unit area. Coupled with the truth that a horizontal orientation could be extra liable to snow accumulation, this configuration became quick eliminated from attention. For the vertical array configuration, versions on module orientation, spacing between bays of modules, and spacing among rows within the array are explored. An array tilted by way of 30 tiers from vertical is also simulated for contrast. figure 4 shows the ensuing general annual irradiance for every variation. As anticipated, increasing the separation between rows reduces self-shading and barely increases cumulative irradiance. The difference in energy production between these different configurations is marginal, aside from the tilted panels, which has significantly reduced cumulative irradiance. The configuration with vertical, portrait-orientated panels is selected as the baseline for the remainder of this have a look at. each bay agencies together six modules with rows which can be separated with eight meter pitch. The power manufacturing as a function of time for this configuration serves as an input to the co-optimization defined in section three.

Wind power has been used significantly in remoted arctic environments, commonly working together with diesel pushed mills (B. Anderson et al., 2023; P. I. Baring-Gould et al., 2009; de Witt et al., 2021; Holdmann et al., 2022). Wind turbines are increasingly utilized in those locations due to the excessive electricity density compared to sun strength and the ability to offer 12 months-spherical electricity technology. As formerly stated, wind turbines were used appreciably in Antarctica, but simplest small mills have been established at the South Pole, ordinarily to energy smaller studies tasks or as a part of short-time period demonstration initiatives. For electricity structures at the scale of 100 kWor greater, large turbines are required. on this evaluation, we use a a hundred kW turbine which balances turbine length, for transportation and logistics reasons, and reasonable energy output. Wind speed information is accrued by means of the NOAA South Pole Observatory; however, this records has a dimension peak of 10 meters above ground level and extrapolation need to be finished to decide the capacity for wind electricity. For this evaluation, wind pace at the 10-meter peak in conjunction with the temperature and stress measurements from 2003 are used at a measurement c program language period of 1 minute (I. Baring-Gould et al., 2005) (Riihimaki, L et al. (2023): Basic and Other Measurements of Radiation at Station South Pole (1992-01 et Seq). one after the other, common monthly reporting of wind speed records from February 2008 to June of 2009 from the NOAA meteorology to were at a height of 30 meters is used to assess winds hear,

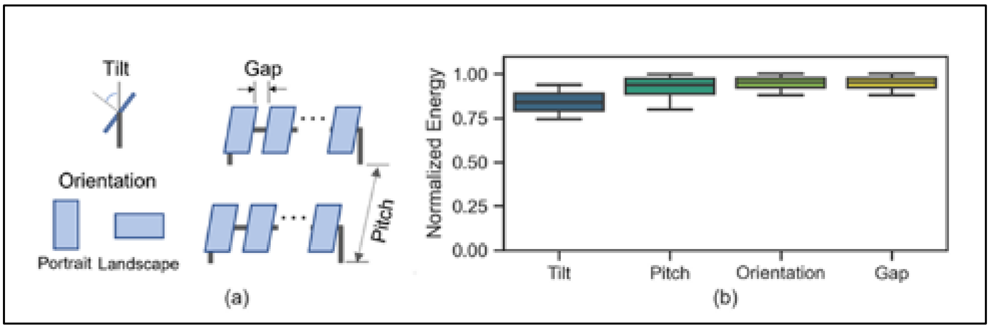


Figure 5 (a) Conceptual diagram of the array parameters explored. (b) assessment of the normalized every year energy manufacturing performance among variations in array parameters.

The baseline state of affairs carried forward includes portrait oriented vertical panels with a 0.6-meter floor clearance. Panels are grouped into bays of six modules with 8-meter pitch between bays.

All configurations display similar results, apart from tilt angle wherein power manufacturing decreases slightly which describes how the wind pace changes with distance faraway from the earth's surface. the usage of the Windographer3 software program, the only minute records is transformed into an estimated hourly common wind turbine energy output for a Northern strength machine NPS 100C-244. This 95 kW Arctic wind turbine has a 24.four-meter rotor diameter and a 30-meter hub height. This specific turbine changed into to begin with designed for excessive bloodless climate packages such as the South Pole5, but different similar mills should additionally be assessed in future analysis (S. J. Babinec et al., 2023; Lynch et al., 2004). further to the supply of the wind resource, an important consideration for wind energy at the South Pole is the operational temperature restriction. The turbine considered in this evaluation operates to-forty ◦ C, beneath which the turbine shuts down. but, initial tests imply turbine operation right down to-70 ◦ C is technically possible. For the wind useful resource estimation, the wind turbine is believed to be offline whilst the temperature is beneath-70 ◦ C, resulting in no electricity manufacturing at some point of those time periods. The ensuing expectation of strength produced by a unmarried turbine for the conditions of the evaluation year is proven in figure 6. while this aid profile is consultant, additional atmospheric measurements at a peak of at the least 30 meters above ground level might allow additional refinement and confidence.

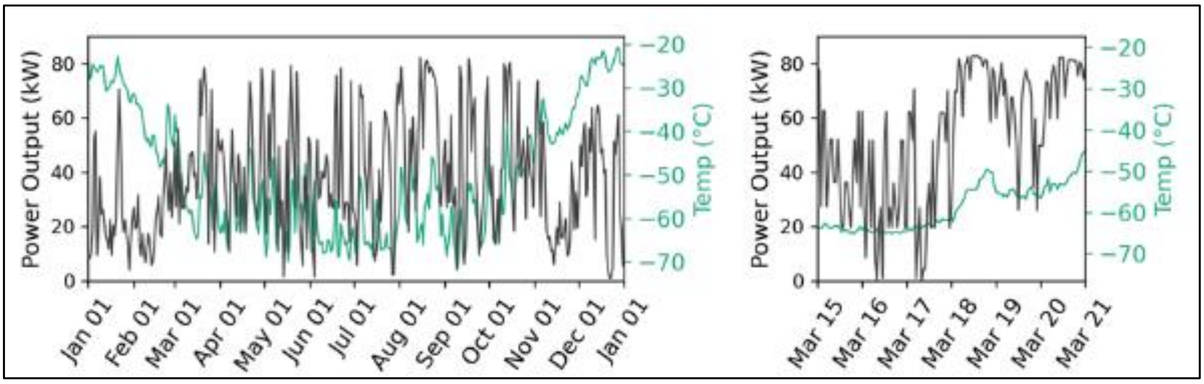


Figure 6 (Left) Daily average of estimated power output for an NPS 100C-24 wind turbine installed at the South Pole on a 30-meter tower (grey). The daily average temperature is shown in teal. The model uses wind speed data from 2003 and the turbine is assumed to have a-70 ∘ C lower limit on operating temperature. (Right) Hourly average estimated power output for a six day period with temperature overplotted.

There are numerous demanding situations for working turbines at the South Pole: transportation and construction logistics, intense cold weather operation,and developing a appropriate turbine foundation. generator s of the 100 kW length are generally designed to ship within a C130 transport aircraft and to be installed with minimum additional equipment, potentially including the use of tilt-up towers. This is the case for the NPS 100C-24 turbine considered in this analysis. Turbine operation in very cold climates has been researched extensively Davis et al. (2014) and requires consideration of materials, including metallurgy and lubricants, component heating, and unique operating conditions in these environments. The latter includes both specialized safety requirements and potential operational limits during extreme weather events.

TurbinedeploymentattheSouthPolerequiresspecialdevelopmentforthefoundationassolidgroundfortraditional tower footings is not available due to the thick Antarctic ice sheet. Development of an ice-based foundation would be required. Although not documented in the literature, ice foundations have been used for smaller turbines installed at the Summit Station in Greenland and at least twice at the South Pole. In all three cases a modified guyed tower foundation is used, similar in concept to the tall meteorological towers installed at the South Pole. Ice-based foundations are also used for the elevated station building Blaisdell George (2011) as well as other buildings on-site, including the South Pole Telescope (Carlstrom et al., 2011). In these designs the weight of the turbine and tower is dispersed to not exceed the load bearing weight of the ice and dead man anchors for the guy wires address the overturning moment of the tower. Towers of the height and weight proposed in this research have yet to be demonstrated, however, the engineering principles are well-understood.

Strength storage electricity garage (ES) is fundamental to enabling deep decarbonization via electrified transportation and renewable electricity generation. The evolution of present day energy garage is basically driven thru its function in electric motors (EV), which now have fee and overall performance which might be enough for mass adoption after many years of battery studies and development. nowadays, lithium-ion (Li-ion) is the single dominant ES generation with production this is scaling globally to satisfy this hastily developing demand (Buchanan & Stacy, 2022). ES is the primary method to deal with variability in solar and wind renewable resources due to its ease of implementation. stationary storage these days is served with simply to be had Li-ion batteries primarily based on designs that were to begin with targeted on EVs. These serve as a natural starting point for the evolving stationary markets but are not gold standard in numerous elements. One example is the flammability risk. even as always essential, it's far of paramount importance for stationary applications in which deployment sizes are usually several orders of magnitude larger than an EV p.c. and consequently can bring about full-size terrible consequences. desk bound protection these days is insured with more than one gadget factors to prevent such activities. answers to the lengthy-term intention of nonflammable/reduced flammability versions of Li-ion are now emerging; one choice became recognized within the path of this analysis and ought to stay below attention inside the destiny. As the percentage of renewable technology will increase in huge grids, both the amount (kWh) and sort of ES needed to stability the useful resource variability adjustments. while the hours of to be had energy (length) to ensure system reliability surpasses 10 hours, the storage necessities enter a regime referred to as lengthy-period energy storage (LDES) (Albertus et al., 2020). The less costly price of energy storage also decreases appreciably with increasing period. presently, maximum technology are not able to fulfill LDES value necessities. Li-ion isn't always projected to be fee powerful for LDES even as its cost maintains to drop due to economies of scale for EV mass adoption. The LDES cost requirements create a tremendous technology gap that could be a extremely good project for near-total renewable era situations, which draws international attention. for example, the usa branch of strength (DOE) has an earthshot initiative to increase LDES technologies for a centered price reduction of ninety% relative to Li-ion. in the context of the analysis supplied right here, Li-ion can be taken into consideration as 'brief duration' power storage. it's far the dominant generation today but is not the singular lengthy-term answer. A summary of the generalized tradeoffs among Li-ion and LDES is supplied in desk 1. The usual value proposition and design criteria derived from the energy storage cost and performance framework do no longer at once translate to the South Pole analysis provided here, but the era maturity and marketplace focus without delay impacts the provision of options. Li-ion fee and overall performance projections are without problems available, as an example from the DOE annual record used on this analysis (Freeman & Agar, 2024). LDES emerging technology aren't currently characterised with a dependable comparable annual compendium. As such, the LDES data considered right here is gathered using strategies(Hammad, et al., 2025). First, cost and performance values are acquired from distinctive discussions with precise LDES groups which are in early huge-scale deployments and as a result can provide projections for the following 5-10 years. 2d, DOE earth shot value targets are used as a guide to fashionable aspirational values (Spitsen, 2020). Projected values from the companies were as compared to the DOE target and in some cases found to be approximately consistent. The statistics from these groups are consequently used for 2 instances of the gadget-huge optimization described inside the following segment. total EScostisacombinationofup-frontcapitalcostandtheshippingcosttotheSouthPolesite.Thelatterdepends at the electricity density (in Wh/kg) of the ES generation. there's a big disparity nowadays in electricity density for Li-ion and LDES technologies. Li-ion was first of all developed for purchaser electronics and transportation wherein excessive electricity.

density is seriously critical while LDES is optimized for decrease fee however no longer for electricity density (Hammad, Fauzi, et al., 2025; Ullah et al., 2025). Li-ion typically has better energy density compared to LDES and consequently significantly decreases total weight and next shipping value. An extra discussion of those cost influences can be determined in section 3.2. Due to those considerations, we compare both short- and long-period strategies to energy garage in this analysis.

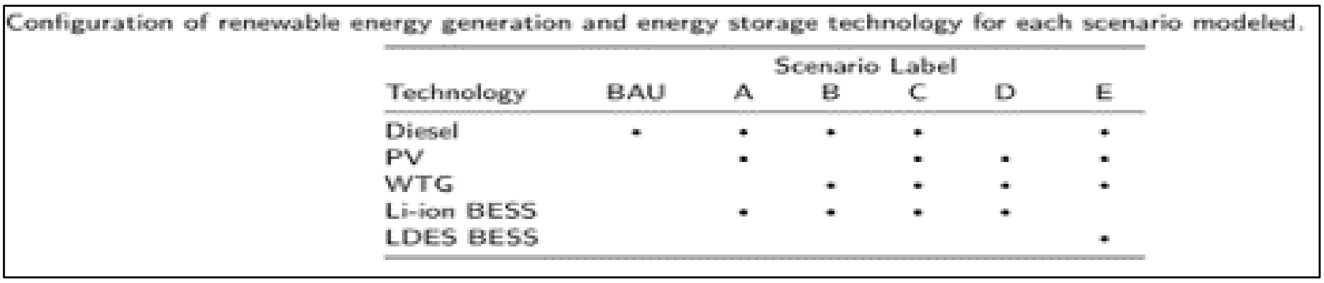
2. Optimization of the Hybrid machine the use of REopt

TheREopt™ techno-economic decision support platform is used to analyze alternatives for a South Pole hybrid energy device (K. H. Anderson et al., 2017). REopt's improvement has spanned over 15 years, evolving from its inception as a spreadsheet model to a complicated, open-source, combined-integer linear application accessible as an API or via an internet-based user interface. REopt identifies the optimal blend of renewable electricity, traditional technology, and strength garage technology to satisfy objectives of value, financial savings, resilience, emissions reductions, and energy performance. REopt generates the least-cost alternatives for serving a diagnosed load based on prices and performance of technology estimations for the South Pole. The technologies taken into consideration on this evaluation consist of diesel strength, solar photovoltaics (PV), wind turbine mills (WTG), and each short- and long-period power battery power garage systems (BESS). The South Pole version has one-hour time steps for an unmarried 12 months of load, wind, and solar assets. PV, WTG, and BESS generation sizes and the hourly device dispatch are optimized to limit total lifecycle prices. In this evaluation, a fifteen-year monetary evaluation duration is used. charges and financial savings taking place inside the analysis length are discounted using popular monetary standards to determine existence-cycle price and net gift value, described because the lifetime financial savings in comparison to an all-diesel case, for every scenario. An easy payback duration is likewise calculated. subsequently, key outputs on averted diesel fuel intake and emissions are generated.

2.1. Assessment of situations

Acost-benefit analysis for a couple of configurations of renewable era is carried out. To create a baseline for contrast, REopt is first run assuming all strength is supplied through a current significant diesel plant. numerous one-of-a-kind mixtures of both generation and garage technologies are explored inclusive of configurations with and without the use of diesel fuel. desk 2 defines the mix of technologies for each of the scenarios modeled. All scenarios are compared to the business-as-usual (BAU) case in which energy is handiest provided with the aid of an present diesel energy plant.

Table 1 Configuration of renewable energy generation and energy storage technology for each scenario modeled



Configuration of renewable energy generation and energy storage technology for each scenario modeled.

	Scenario Label					
Technology	BAU	A	B	C	D	E
Diesel	•	•	•	•		•
PV		•		•	•	•
WTG			•	•	•	•
Li-ion BESS		•	•	•	•	
LDES BESS						•

RenewableenergyandBESSscenariosthatincludedieselgenerationarealsomodeledwithandwithoutconstraints on total diesel consumption to inform cost-benefit considerations of achieving higher shares of renewable energy contribution above the least-cost solution. Additionally, sensitivity to diesel fuel cost, diesel plant fuel economy, and LDES performance and cost assumptions are evaluated. These sensitivities are further discussed in Section 4.1.

2.2. System-wide Assumptions

A steady-kingdom power call for of one hundred seventy kW is modeled across a complete yr. This stage is a consultant example that is decided on based totally on the anticipated load from a destiny massive scientific test planned for the South Pole station6. The renewable power era profiles for sun and wind defined in section 2 are enter into the techno-financial optimization. The technical performance and charges of all generation alternatives also are entered into REopt. Key prices and economic parameters for this evaluation are included in table 3. costs consist of the total hooked up value estimates and on-going maintenance value estimates to assure the systems will operate reliably after commissioning. PV and Li-ion BESS charges are based totally on price models that inform NREL's Annual generation Baseline (Ramasamy et al., 2022). those are bottoms-up fashions that incorporate all major gadget and installation components for a given structure. Parameters consist of (but are not limited to) device price, set up time and labor charge estimates, overhead, contingency, income, and sales tax. every parameter changed into reviewed for the South Pole precise context with key modifications made to labor rates and intervals, development charges, profit, and introduced transportation price. WTG capital cost is one by one envisioned based on a NPS100C-24 version.

charges for all renewable technology encompass the anticipated procurement and overall installation fees based on assumed hard work quotes and hours. hard work hours for both PV and Li-ion BESS are doubled in comparison to a North American preferred to adjust for South Pole conditions. set up fee estimates for the WTG are primarily based on initial turbine basis concepts, modeled on what was used for the McMurdo Station wind generators, which include shipping for pre cast turbine footings and extended installation timelines. As with PV and Li-ion BESS, a massive price premium is delivered to account for deployment on the South Pole consisting of delivery, additional installation charges, and expanded labor rates and hours. a further premium is also delivered to traditional annual operations and renovation prices, including extended gadget monitoring which might be required at one of these regions (Hammad, et al., 2025; Hammad, et al., 2025). LDES overall set up costs are advanced via consulting with industry to estimate fee at 'factory gate' and then getting into those procurement prices into the identical bottom-up version used for PV and Li-ion formerly mentioned. even though the LDES power garage procurement fees are predicted to be considerably decrease than Li-ion battery packs, while balance of system expenses, along with strength electronics, engineering, shipping to the South Pole, and installation exertions are included, their total hooked up costs are similar. eventually, the price of diesel energy technology is restricted to the value of the gas, which is kind of envisioned based on a2012cost Samasiuk (2012) and subsequent inflation costs to extrapolate to 2023. gas economy is based totally on evaluation of supplier catalogs for diesel engine-generators and assessment of faraway strength machine performance in rural Alaskan communities7.

general mounted prices additionally consist of South Pole delivery charges primarily based on envisioned weights of the equipment. The contribution of delivery to the South Pole to the entire hooked up price is massive. table four breaks out the shipping charges from procurement and set up assuming $19.eight/kg for delivery to the South Pole web site, that's kind of predicted the usage of popular inflation factors and fee from previous monetary analysis of cargo transportation (H. Lever James, 2011). The incremental transport costs for BESS power electronics are assumed to be captured within the strength storage capacity (kWh) transport costs.

Table 2 Cost estimates and system wide details breakdown

Cost Estimates and System-Wide Details Breakdown			
Parameter	**Value**	**Annual Maintenance Cost**	**Additional Factors**
Power Demand	162.1 KW		Constant Load Profile
Energy Demand per Day	1404.4 KWh		
PV Cost	2400 US $ /kW (Installation)	43 US $/kW -DC	0.5 % Annual degradation
Wind Turbine Cost	5000 US$/kW (Installation)	230 US $/kW	
Battery BESS Li- Ion Cost	9645 US $/kW (Installation) + 807 US $/kWh (Installation)		97.5% RTE, DC-DC 96% Inverter and Rectifier efficiencies 20% minimum state-of-charge
Battery BESS LDES Cost	5230 US $/kW (Installation)+ 780 US $/kWh (Installation)		55% RTE, DC-DC 96% Inverter and Rectifier efficiencies 10% minimum state-of-charge
Analysis Period	20 Years		
Discount Rate	3%		
Inflation Rate	2.50%		Non Fuel maintenance
Diesel Fuel Cost	42 US $/gallon (delivered)		2.7% Annual Escalation Rate
Diesel Plant Fuel Economy	12 kWh/gallon		Marginal Fuel Economy
Total Fuel Required for 162.1 kW per day	117 Gallons		

For additional context of the economic environment, the levelized costs of energy(LCOE)for diesel generated electricity, PV, and wind power are shown in Table5. LCOE is a common cost metric to allow comparison across technology options. Levelized cost calculations generally include the total installed costs, maintenance costs, annual production, and useful life of the asset. However, the LCOE for diesel generation shown in Table5 is based on the fuel costs alone. It does not include any incremental investment that might be needed for additional diesel generation capacity nor non-fuel generator operations and maintenance costs. The LCOEs for South Pole demonstrate how expensive electricity currently is the re-due to the high costs for diesel fuel and thus the economic impetus for integrating PV and wind power. The economic model shows the value of integrating BESS to facilitate greater shares of PV and wind to off set the more expensive diesel generation. Integrating, BESS will also provide additional critical services in a power system that this model does not consider,

Table 3 Summary of levelized cost of energy for each generation technology

S. No.	**Technology**	**Levelized cost of Energy($/kWh)**
1	Diesel generation, fuel only	$4.08
2	PV	$0.24
3	Wind	$0.35

including, among others, ramp rate management of variable renewable energy, operating reserve to cover resource uncertainty, short circuit contribution for system protection devices, and improved power quality.

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3. Results of REopt Analysis

For each scenario enumerated in segment three.1 REopt optimizes the era sizes needed to meet the input load over the route of the yr for the least price. parent 6 shows an instance dispatch model that meets the specified load as a function of time for scenario C. The impact of the polar longitude is without a doubt seen in the PV generated strength present at some stage in the austral summer season months that then diminishes as the sun sets under the horizon. WTG power is to be had all through the year, however BESS or diesel generated electricity is needed for durations of diminished wind. the lowest panel of figure 7 shows the curtailed electricity of the gadget. this is excess power that could be generated further to that dispatched to the electrical load or used to recharge the BESS. For the purpose of this evaluation no monetary value is given to curtailed energy.

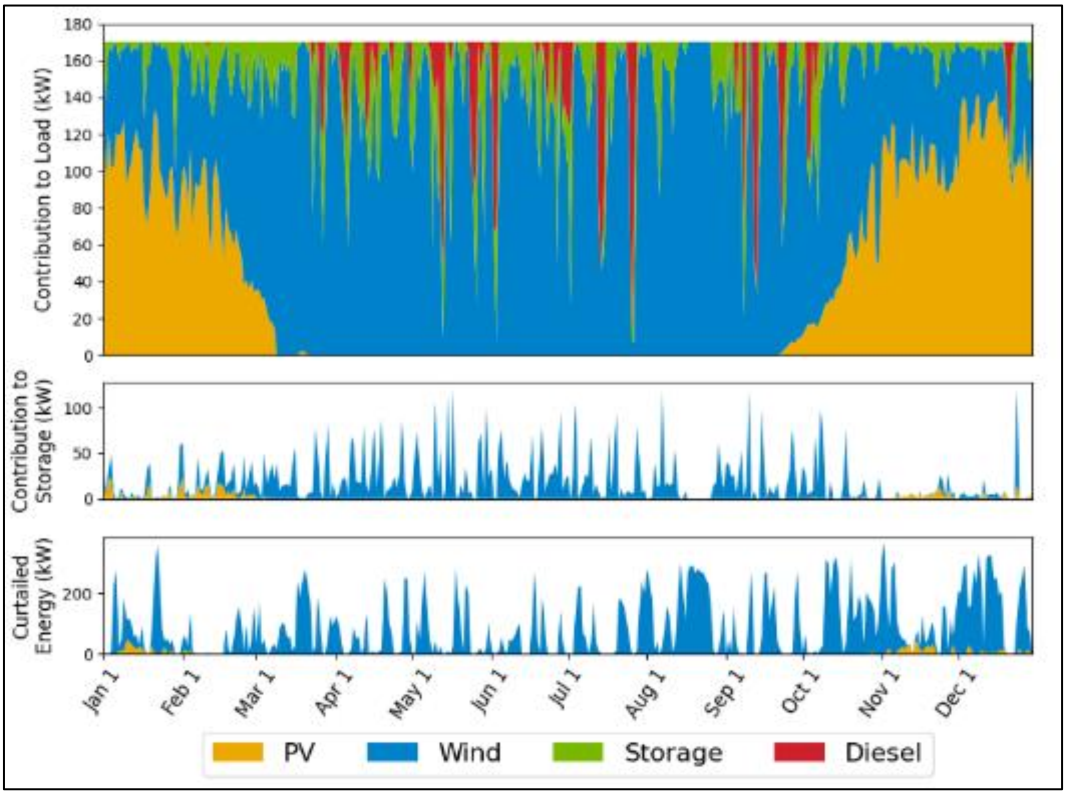


Figure 7 (Top) Dispatch plot showing the contribution to the load over a year for scenario C with diesel, solar PV, wind, and BESS/Li-Ion. (Middle) Contribution of solar PV and wind to charging the BESS. (Bottom) Curtailed energy that could be generated based on the available resources in this scenario.

Important is the scenario results that HOMER generated for the optimal generation expansion planning using microgrid under harsh environments as per coordinates

Table 4 Scenarios -Renewable Energy optimized results

	Diesel BAU	**Diesel PV, Li-ion A**	**Diesel, Wind, Li-ion B**	**Diesel, PV, Wind, Li-ion C**	**PV, Wind, Li-ion D**	**Diesel, PV, Wind, LDES E**
Life-cycle cost ($M, discounted)	$72.9	$47.7	$18.8	$14.9	$19.4	$15.9
Net present value ($M)	-	$25.8	$54.1	$57.9	$53.5	$57.1
Capital expenditure	-	$3.9	$10.8	$9.8	$17.4	$8.9
Simple payback (years)	-	1.9	2.5	2.2		
PV system size (kW-DC)	-	690	-	180	125	210
Wind system size (kW)	-	-	710	590	600	590
BESS power (kW)	-	70	210	190	190	210
BESS energy (kWh)	-	127	3310	3,469	12,670	2220
Hours of storage	-	2.9	16.7	18.8	70.2	10.9
Annual fuel consumption (gallons)	125000	76,700	9600	5660	2	8600
Fuel reduction	0	43%	92%	96%	100%	93%
Annual avoided CO2 (metric tons)	0	540	1176	1220	11280	1180

Outcome results from modeling all technology configurations are presented in desk 6 and Figure8. The baseline BAU configuration with out integrating renewable electricity and energy storage is envisioned to require 124,000 gallons of gas per 12 months to meet the 170kW electric electricity requirement. Over a 15-yearperiod, the BAU gasoline fees are envisioned. To be $60 to $73 Min gift fee terms. those are the benchmark parameters in opposition to which renewable electricity and electricity storage scenarios are as compared and are shown inside the first column of Table6.Analysisresultsindicatethat the all-diesel, BAU scenario, has the best lifestyles-cycle fee. All architecture alternatives with renewable electricity reduce existence-cycle costs below BAU and therefore bring about nice internet gift values. The excessive price of diesel gas is riding high penetration of renewable electricity in mixture with BESS and effects in envisioned payback durations of two to 4 years. Techno-financial fashions are a useful first step identifying era options, indicating capability capacities, and for generating estimates of excessive-degree expenses and blessings.

The least-price state of affairs proven in Table6 is scenario C. scenario C consists of 180kW-DC of PV, a total of six one hundred kW wind turbines (rounding up the model result of 570kW), and 180kW/3, 400kWh Li-ion BESS integrated with the prevailing diesel gadget. It has a internet gift value exceeding $57M. The$10 M preliminary investment reduces diesel energy consumption by 96 percent and has an approximately 2-years implement payback. scenario A simplest lets in PV for renewable electricity generation. solar radiation is at a very low degree of completely unavailable for a massive fraction of the 12 months, therefore, entire replacement of diesel era with simplest PV is not possible. aside from WTG reduces internet gift value by way of 56% under the nice option, state of affairs C, however it's miles nonetheless a fantastically cost-effective alternative with a net gift fee of $25M. The state of affairs A PV machine is nearly 4 instances larger than state of affairs C, at 683kW-DC.

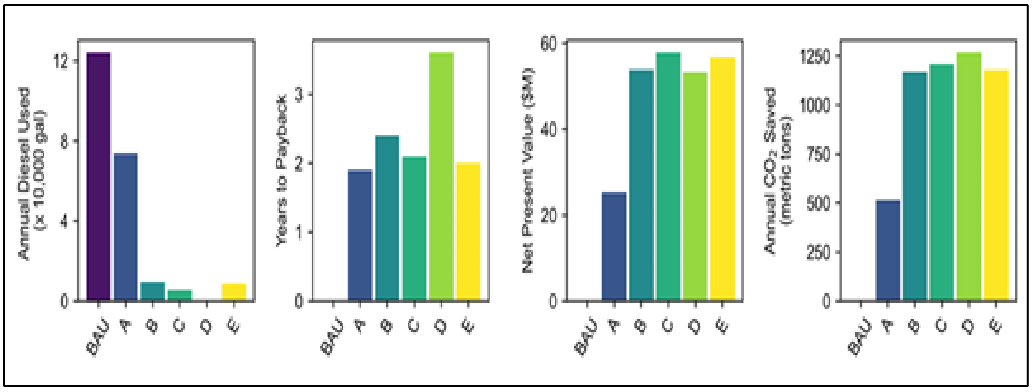


Figure 8 Comparison of optimization results between the scenarios

A, with the exception of an strength technology generation from the least-price choice reduces the net-gift cost. however, a WTG-BESS diesel hybrid device is drastically nearer in overall advantage to the least-cost scenario C with an NPV of $54M and fuel savings of 92% because wind-generated energy is to be had year spherical.

state of affairs D shows an assessment of how the optimization outcomes alternate if diesel-generated energy is not allowed, i.e. the machine is completely renewable with PV, WTG and Li-Ion BESS. To take away diesel gasoline usage, the version barely adjusts the PV and WTG sizing relative to the case in which diesel is authorized. but, this state of affairs provides notably large BESS energy potential of 12,six hundred kWh, more than 3.five× the capability of a device with diesel power (situation C).

The preliminary capital investment of $17.4M is the best of the investment situations, usually due to the bigger BESS.

The machine remains fairly fee-effective with an NPV of $53M, approximately 8% much less than that of the machine with diesel. this may be taken into consideration the incremental value to increasing the reduction in gas intake from 96% to a hundred%, and keeping off an additional fifty seven metric lots of CO2 emissions yearly. Sooner or later, situation E captures the projected fees and blessings of the use of LDES rather than Li-ion BESS. The outcomes throughout all situations, except for A, fashion towards longer period energy garage motivating inclusion of

LDES in this scenario. As showninTable4, LDES capital cost is about 55% the value of Li-ion earlier than delivery ($370 as opposed to $680/kWh, respectively) however is assumed to weigh a issue of 3 more than Li-ion on a in keeping with kWh foundation.

Given the high expenses of shipping to the South Pole, LDES total set up costs are barely better than Li-ion BESS.

Combined with the lower assumed round-trip energy storage efficiency (shown in Table2) LDES has reduced economic advantage relative to Li-ion. The value most efficient LDES solution is a smaller strength garage system than Li-ion (2,210 kWh as opposed to three,410 kWh) in scenario C and has a marginally decrease NPV. therefore, the low RTE and strength density of LDES currently outweigh the notably decrease buy rate in comparison to Li-ion. As mentioned in phase 2.3, LDES is an rising technology and ongoing assessment of the techno-monetary performance is warranted because it matures.

4. Sensitivity to Assumptions

Numerous different situations had been explored with REopt to discover the sensitivity of the outcomes to input assumptions and constraints on the renewable machine. Of specific importance are the assumptions on fee of fuel at the South Pole as well as the gasoline economic system of diesel power technology. additional scenarios are explored, first with value of introduced diesel gas reduced to $30/gallon (scenario C1) and second with each decreased fuel value and increased gas financial system of 14.6 kWh/gallon for displaced diesel technology (state of affairs C2) (Mason, 2007). In both eventualities, the renewable technology system consists of PV, WTG, and Li-ion BESS.

With decrease value gasoline and greater green diesel technology, there is nonetheless sturdy motivation for integrating renewable generation at the South Pole. outcomes for those alternative scenarios are given in table 7 and a assessment shown in discern 8. In scenario C1 and C2, the sizes of the PV and wind plants do not exchange extensively. alternatively, the Li-ion BESS energy capability is decreased via approximately a thing of two. easy payback instances continue to be less than 3 years and the annual fuel savings exceeds ninety%. at the same time as the NPV does decrease with greater conservative fuel assumptions as expected, the financial savings is still massive at >$30M. Another sensitivity explored is the sizing of the PV machine, which is sort of a factor of 4 large in situation A as compared to state of affairs C pushed by means of periods of low sun useful resource availability. To this give up, an artificial constraint is imposed to simplest include the austral summer time months among November 1 to Jan 31, while the sun is farther above the horizon. A hybrid gadget with PV and diesel electricity generation and Li-ion BESS is modeled underneath this constraint,

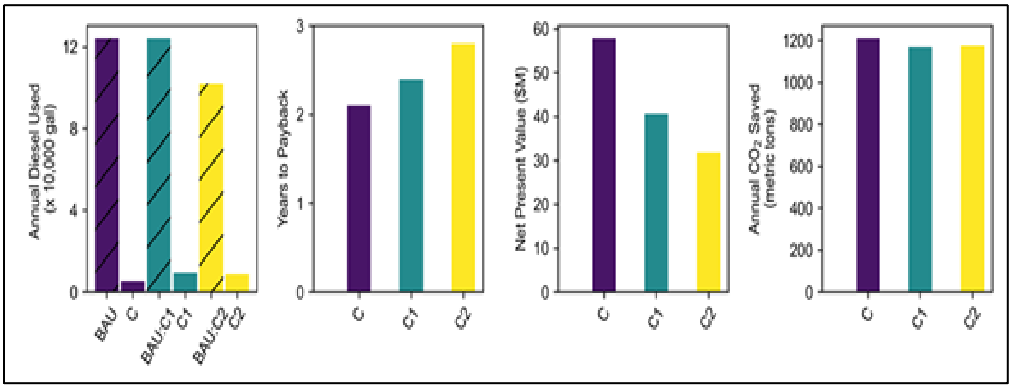


Figure 9 Comparison to results for a hybrid renewable system with PV, WTG, Li-ion BESS (scenario C) in combination with diesel generation under different input assumptions on fuel cost and the economy. Scenario C1 corresponds to a lower fuel cost and scenario C2 includes both lower fuel cost and increased fuel economy.

Table 5 Comparison of REopt results for variations in fuel cost and economy

S. No.		**Diesel, PV** **C**	**Wind** **C1**	**Li-ion BESS** **C2**
1	Net present value ($M)	$59.8	$40.6	$31.9
2	Capital expenditure ($M)	$10.7	$7.8	$7.5
3	Simple payback (years)	2.1	2.3	2.8
4	PV system size (kw-DC)	180	190	200
5	Wind system size (kW)	570	530	500
6	BESS power (kW)	182	162	142
7	BESS energy (kWh)	3512	1821	1570
8	Hours of storage	19	11.7	11.4
9	Annual fee consumption (gallons)	5700	9400	8800
10	Fuel reduction	96%	92%	92%
11	Annual avoided CO2 (metric tons)	1210	1174	1184

ensuing in a PV machine size of 350 kW and a 30 kWh BESS. A 2d model is then generated with the era sizes fixed at these values but calculating the electricity generated over the overall year. This smaller gadget will reduce diesel intake by 36% (compared to 41 percent in scenario A), with a capital cost of $1.9M and an NPV of $23.8M. This result suggests that a majority of the gain from a hybrid system with PV simplest renewable era may be reaped from a smaller machine with a lower capital fee.

Eventually, the sensitivity to the price of LDES is taken into consideration by way of modeling a futuristic case where the LDES strength value is reduced with the aid of ~60% in comparison to situation E. The power density is also assumed to be a component of nine times denser. As referred to in segment three.2, the full installed price for LDES is dominated through stability of the machine and delivery prices. Beneath these assumptions, the optimized model is a system with PV and WTG sizes just like state of affairs E. The dimensions of the LDES system increases appreciably, each in power and strength potential, although really highly lowering the diesel consumption handiest by using an extra 2.6% and barely growing NPV. This state of affairs is economically very similar to the more conservative LDES instance suggesting that the machine optimization is dominated usual with the aid of the energy technology additives The IEEE 30-bus radial distribution system is a widely recognized benchmark test network used in power system research to evaluate load flow analysis, optimization techniques, and distributed generation integration. The system consists of 30 interconnected buses arranged in a radial topology, which closely resembles practical distribution networks where power flows from a single source toward multiple load points. Due to its moderate size and well-documented electrical parameters, the IEEE 30-bus system provides a reliable platform for testing new algorithms under realistic operating conditions. It includes multiple feeders, load buses, and branch connections, enabling detailed assessment of voltage profiles, power losses, and system stability.

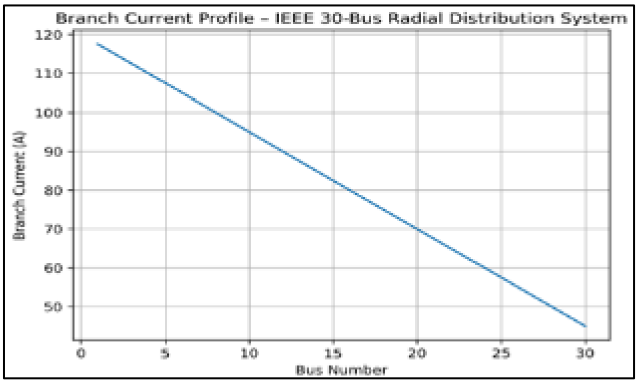


Figure 10 IEEE 30 bus radial distribution network currents

In this research, the IEEE 30-bus radial distribution network is employed to validate the performance of the proposed Random Forest Regression embedded Grey Wolf Optimizer (RFR–GWO) framework. The predicted renewable generation and optimized resource allocations are integrated into the system to perform backward–forward sweep load flow analysis. This allows accurate evaluation of bus voltage magnitudes, branch currents, and total system power losses under uncertainty-aware operating scenarios. Using a standard IEEE test system ensures that the effectiveness of the proposed optimization approach can be compared with existing methods in the literature, thereby strengthening the credibility and reproducibility of the results.

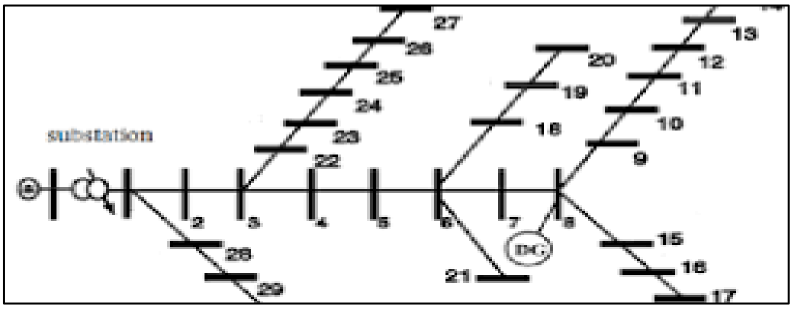


Figure 11 Standard IEEE 30 bus radial distribution network

4.1. RFR embedded Grey Wolf Optimizer

The Random Forest Regression embedded Grey Wolf Optimizer (RFR–GWO) is a hybrid intelligent optimization framework that integrates machine learning–based prediction with metaheuristic search for improved decision-making under uncertainty. In this approach, Random Forest Regression is first used to model and forecast stochastic renewable energy parameters such as solar irradiance and wind speed, providing accurate estimates of future power generation. These predicted outputs are then embedded into the Grey Wolf Optimization algorithm, where they guide the search for optimal system configurations, such as sizing and allocation of solar panels, wind turbines, and battery energy storage. By combining the predictive strength of RFR with the exploration and exploitation capabilities of GWO, the framework enhances convergence speed, solution accuracy, and robustness, making it particularly suitable for renewable microgrid planning in highly uncertain and harsh environments such as Antarctica.

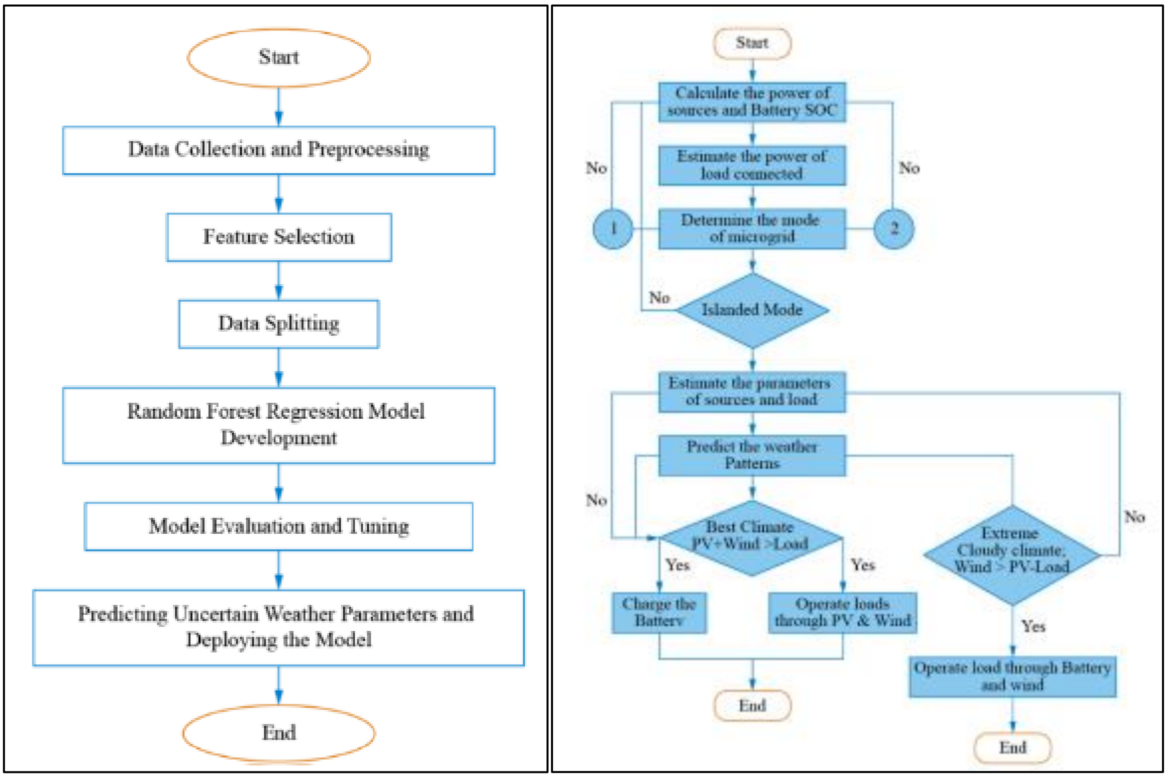


Figure 12 Random Forest Regression flow chart for weather prediction of solar pv and wind turbines

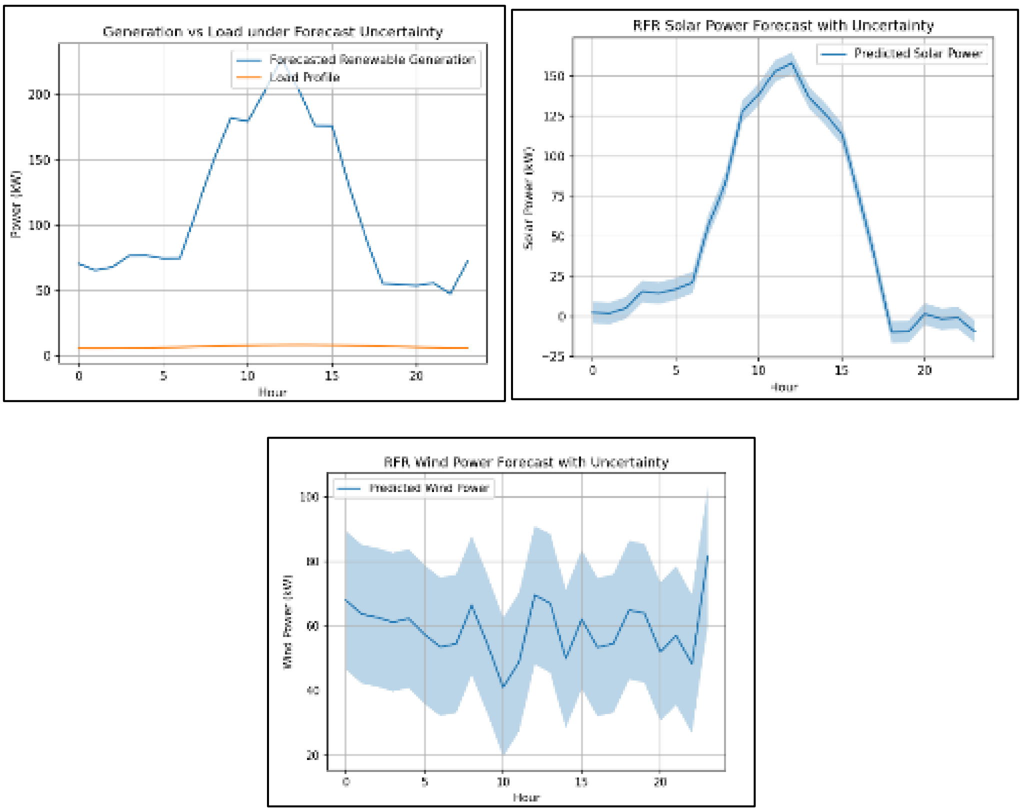


Figure 13 Predicted Wind Solar through RFR

In fig 11. Renewable energy is forecasted against load profile, predicting wind solar through RFR. Solar power increases in the mid 6-18 hours are at peak.

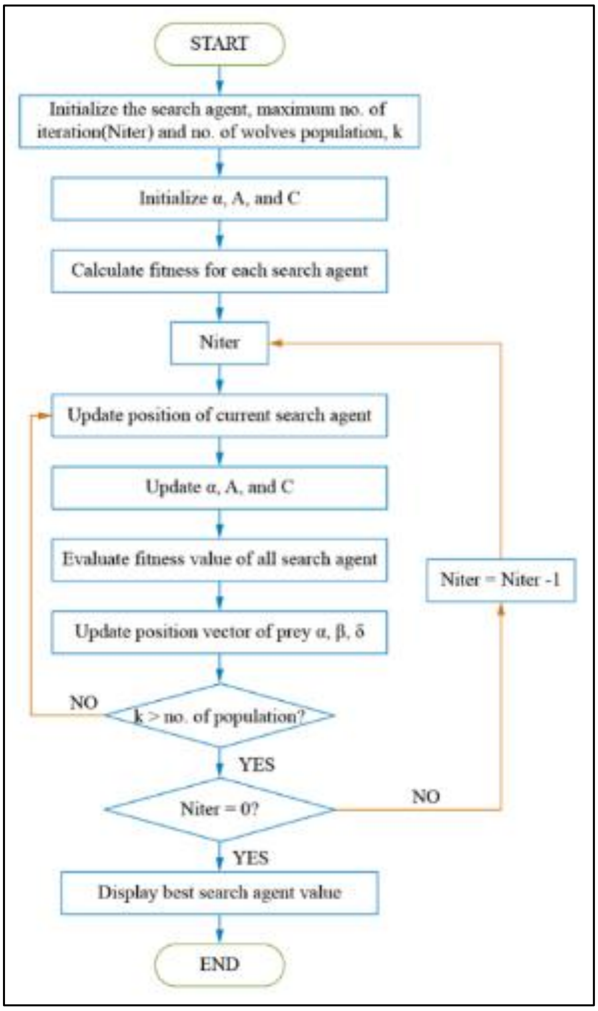
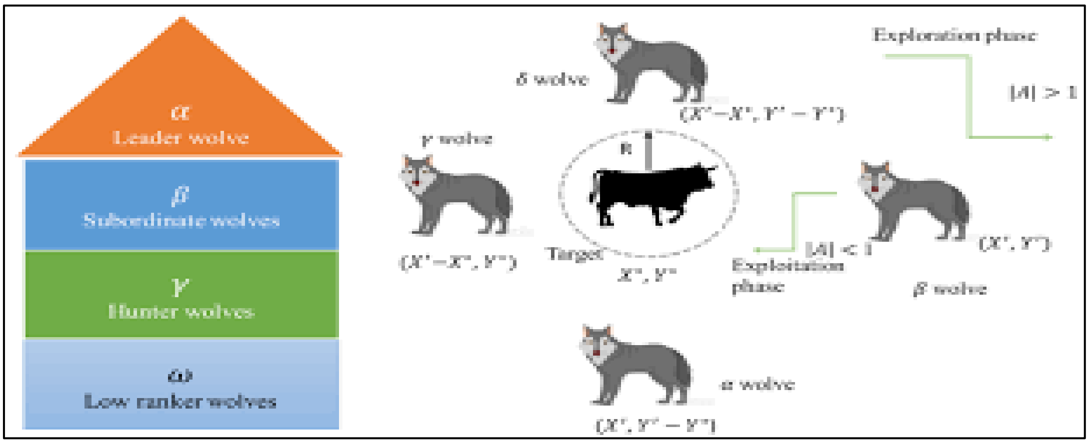


Figure 14 Process flow of GWO



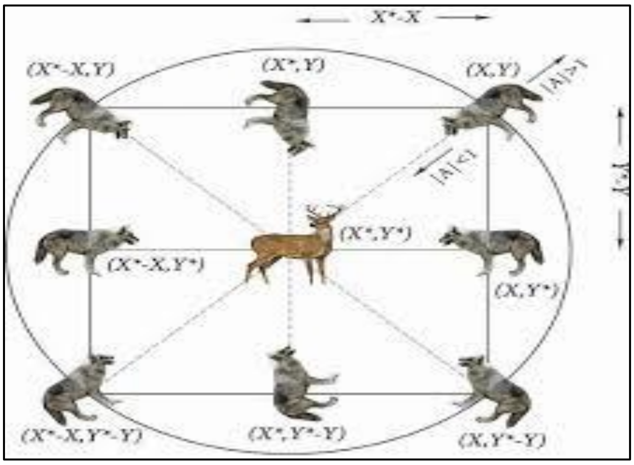


Figure 15 Grey Wolf Optimizer Algorithm positioning iterations for solar wind bees

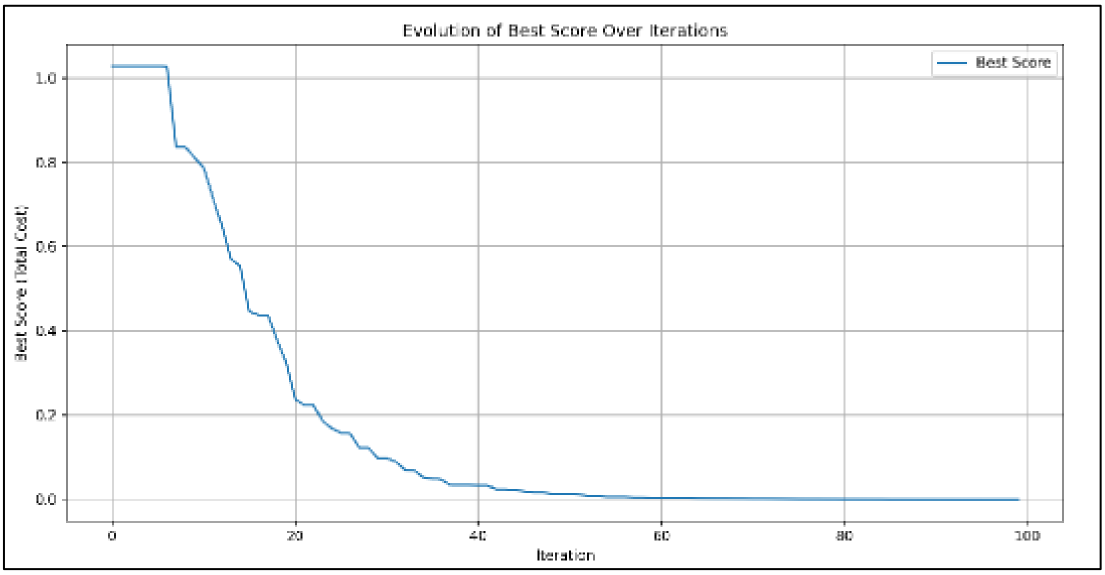


Figure 16 Optimized results GWO best score iterations 100

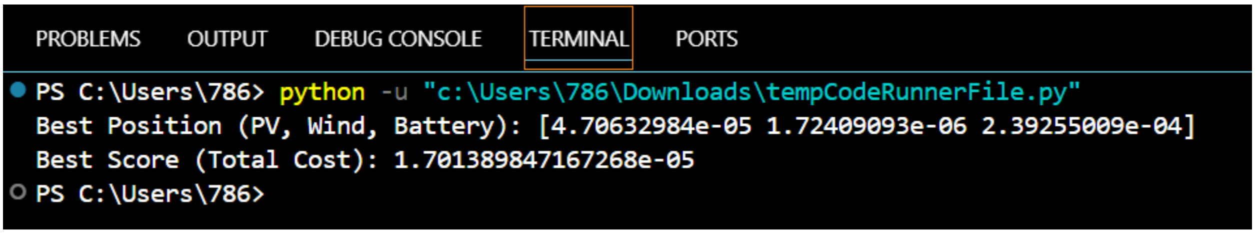
Sizing, allocation, power and cost optimization is achieved through GWO best score iterations in 100. It converges towards optimized results.

4.1.1. RFR GWO Pseudocode:

- Initialize population of wolves Xi (i = 1…N) randomly within [LB, UB]
- Initialize Alpha, Beta, Delta wolves with best three fitness values
- Set Alpha_score, Beta_score, Delta_score = ∞

```
FOR iteration = 1 to T DO

   4.1 Evaluate fitness of each wolf Xi using Objective Function

   4.2 Update Alpha, Beta, Delta:

      IF fitness < Alpha_score

         Delta ← Beta

         Beta ← Alpha
```

```
            Alpha ← Xi
        ELSE IF fitness < Beta_score
            Delta ← Beta
            Beta  ← Xi
        ELSE IF fitness < Delta_score
            Delta ← Xi
    4.3 Compute adaptive control parameter:
        adj = Fuzzy_Adjustment(iteration, T)
        a = 2 − 2 × adj
    4.4 FOR each wolf Xi DO
        Generate random vectors r1, r2
        Compute:
            A1 = 2a r1 − a
            C1 = 2 r2
            D_alpha = |C1 × Alpha − Xi|
            X1 = Alpha − A1 × D_alpha
        Repeat similarly for Beta and Delta:
            X2 based on Beta
            X3 based on Delta
        Update wolf position:
            Xi = (X1 + X2 + X3) / 3
        Enforce boundary limits:
            Xi = clip(Xi, LB, UB)
    4.5 Store best fitness and position for convergence analysis
5. END FOR
6. Return Alpha (best solution) and Alpha_score (minimum cost)
```



```
PS C:\Users\786> python -u "c:\Users\786\Downloads\tempCodeRunnerFile.py"
Best Position (PV, Wind, Battery): [4.70632984e-05 1.72409093e-06 2.39255009e-04]
Best Score (Total Cost): 1.701389847167268e-05
PS C:\Users\786>
```

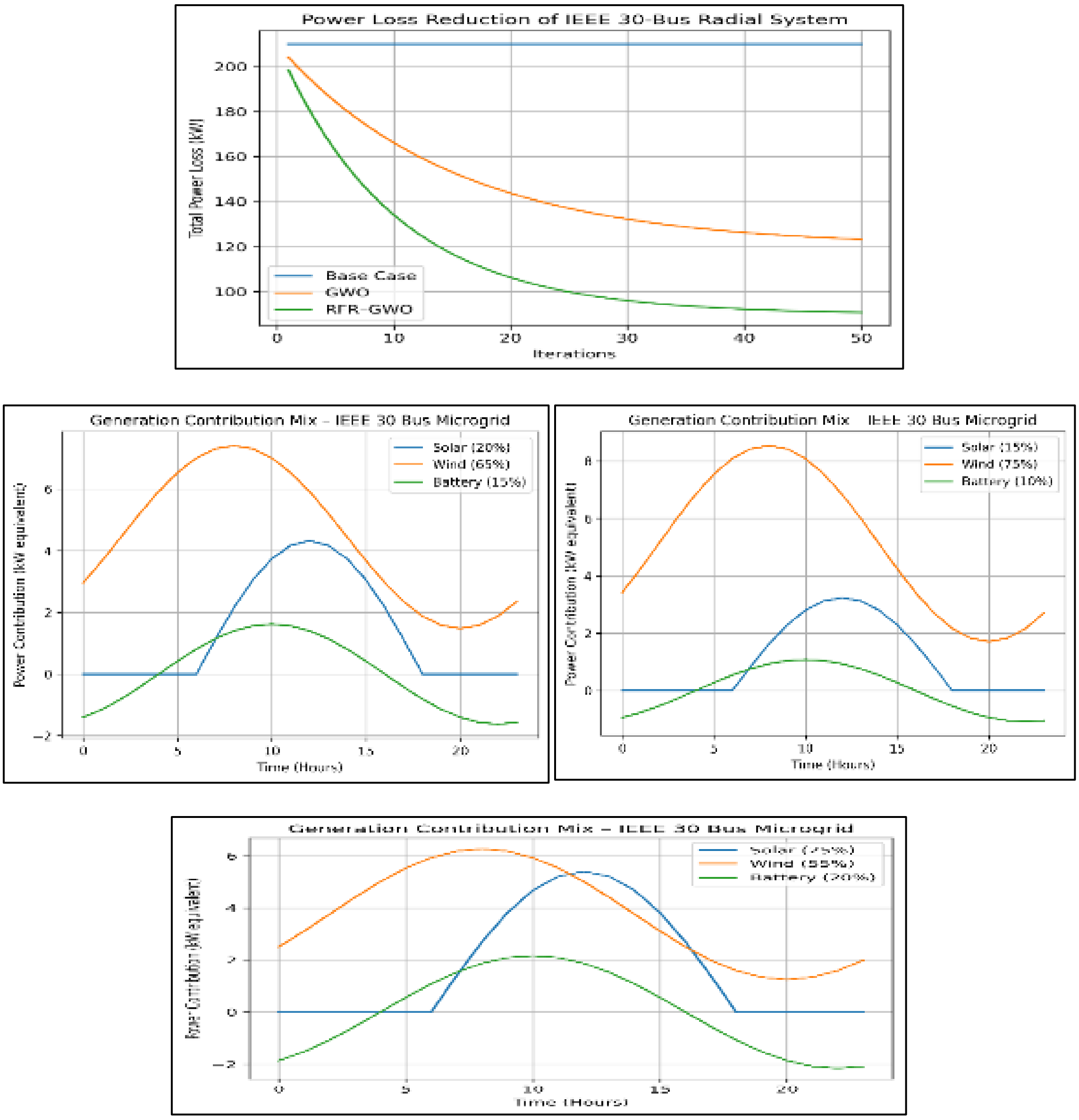


Figure 17 IEEE 30 bus radial power losses Solar Wind Battery Iterations Random Forest Regression embedded Grey Wolf Optimizer

Powre loses are reduced as in the base case power losses are more but with the help of RFR GWO and GWO power loses are reduced as shown in fig 15. Solar wind battery energy storage shows its power contribution.

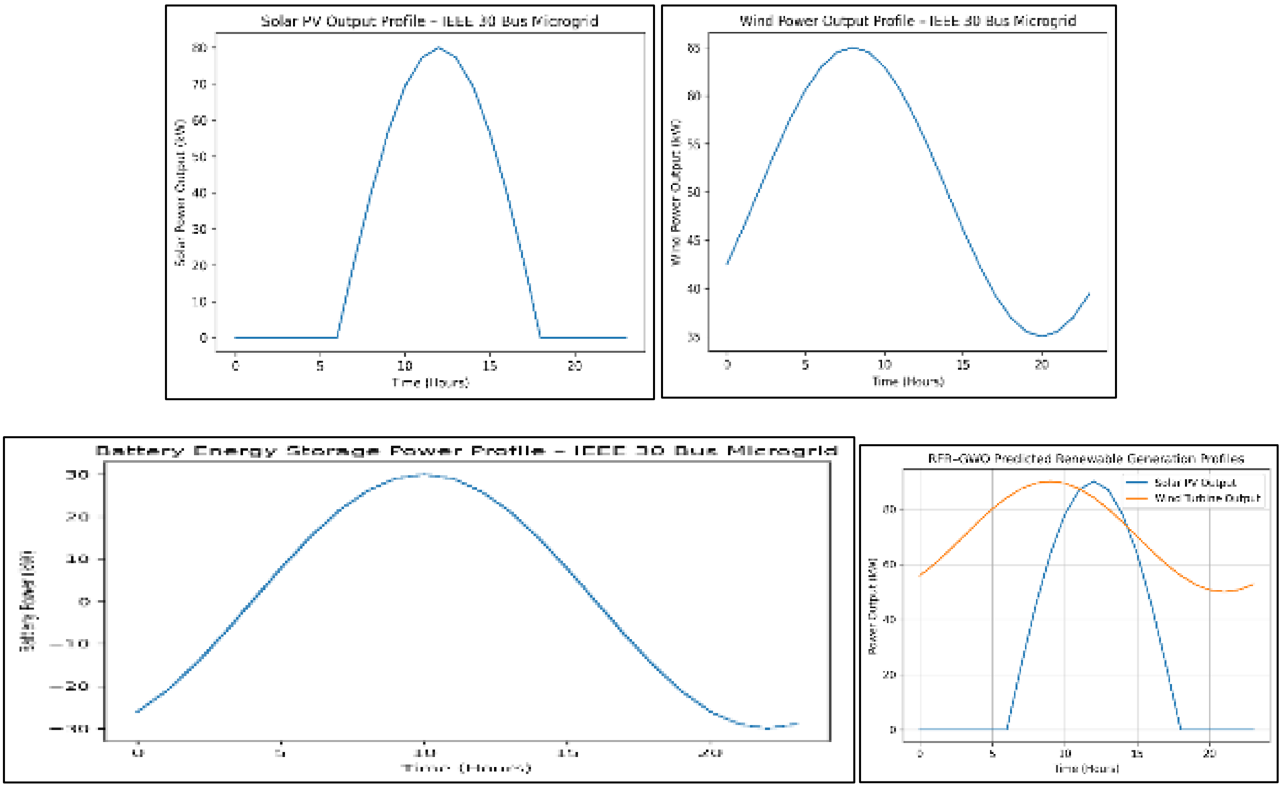


Figure 18 Predictive power output RFR GWO

Optimized Power output after RFR GWO : Predicted Solar Wind Battery Energy

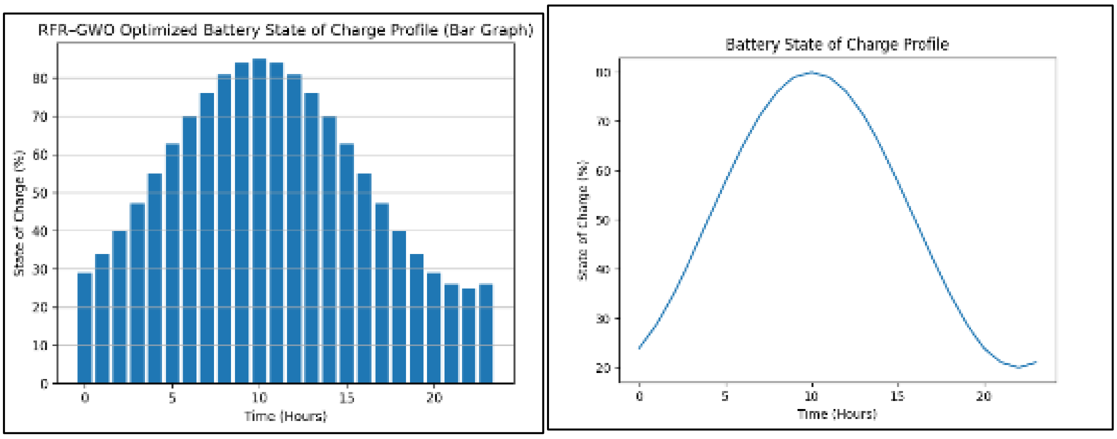


Figure 19 Predicted Battery State of Charge RFR GWO

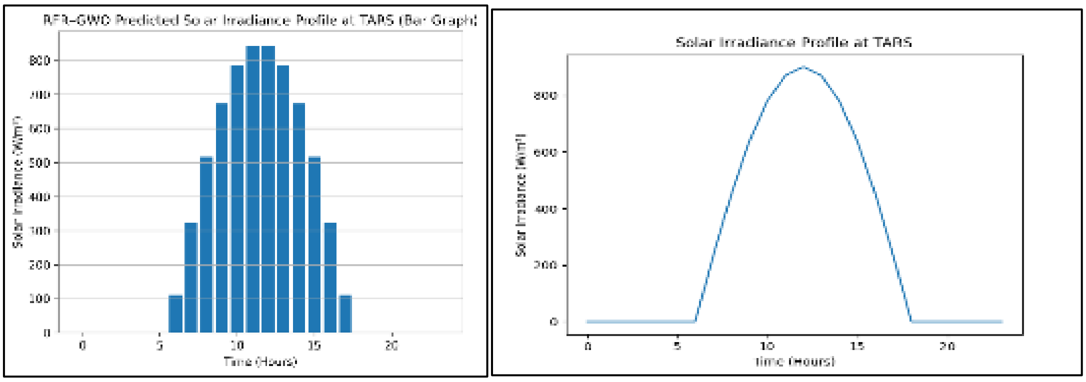


Figure 20 Predicted Solar irradiance W/m2

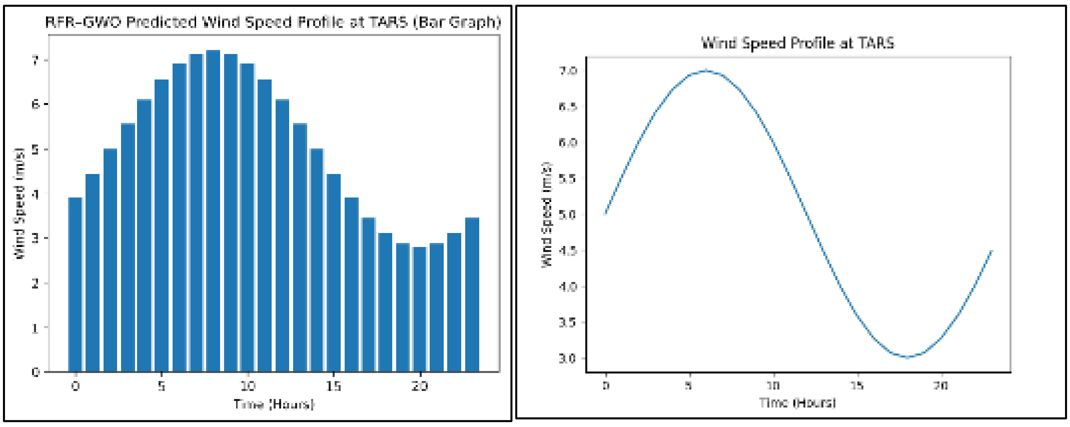


Figure 21 Predicted Wind speed RFR GWO m/s

Fig 18 and 19 shows the predicted solar irradiance and wind speed at TARS. Solar irradiance is more between 6-17 hours per day rising to 800 W/m^2

Wind speed is distributed as 4m/s to 7 m/s from 0-8 hours. Then it settles down to 3 m/s between 18-22 hours. In fig 17, state of charge is more between 10-15 hours mostly providing 80% of power of the battery.

5. Conclusions

Renewable strength on the South Pole on this paintings we present a feasibility evaluation for renewable electricity era on the South Pole. distinct sun and wind resource profiles for 12 months are generated the usage of on-site meteorological records. A techno-economic optimization is carried out using those profiles in addition to quite tailored economic inputs, modeling the least-fee method to generate one hundred seventy kW of electrical power for a period of 15 years. Same is achieved for Turkish Antarctica Station and Saudi Arabia's future research station. A hybrid renewable machine inclusive of PV sun panels, wind turbine turbines, a Li-ion electricity storage gadget included with an current diesel machine is capable of lessen diesel gas consumption by way of 95% ensuing in a internet gift price of $57M. this type of system would require an initial capital investment of $9.7M dollars with a simple payback length of two.1 years. several additional eventualities are modeled, with results ranging from forty%-a hundred% diesel gas reduction and the associated decarbonization. In all situations, renewable strength technology is extraordinarily fee powerful. Realizing these advantages calls for addressing numerous key technical demanding situations within the on-website online implementation of renewable strength era in the South Pole surroundings. destiny work will focus on relevant engineering trends for every element. The PV machine modeled here assumes the panels are hooked up as a standalone array as opposed to hooked up on a constructing. Windblown snow creates drifts round buildings and different structures established at the snow on the South Pole (Allen et al., 2022). A approach for snow waft prevention and maintenance could be required to preserve the panels absolutely operational and to reduce the overall effect of drifts on the website. one of the essential complications of Li-ion energy storage is its flammable nature. at the same time as now not a unique challenge for the South Pole, fire has amplified results at such a remote site. for the duration of the path of this take a look at, rising non-flammable Li-ion storage era was identified and going ahead should be preferentially evaluated to satisfy the garage needs. moreover, persisted tracking of already recognized as well as nascent LDES technologies should arise.

Several elements of wind turbine implementation require improvement. As cited in segment 2.2 the anticipated strength technology profile for a wind turbine can be improved through collection of additional wind data at a top of 30 meters above the ground. A greater entire wind aid assessment may also encompass combining this new information with an research of long-time period traits in the existing meteorological data. Wind generators also have the capability to produce electromagnetic interference (EMI) (Winkel & Jessner, 2018). The South Pole Station consists of the radio-quiet dark sector, which hosts medical experiments that are EMI touchy (*Measure 2-Annex A • Management Plan for Antarctic Specially Managed Area No. 5 AMUNDSEN-SCOTT SOUTH POLE STATION, SOUTH POLE*, 2017). A detailed assessment of EMI from a turbine ought to be completed and a subsequent mitigation plan along with location on website online or turbine modifications might be essential. Moreover, a fundamental assumption of the wind useful resource modeling is operation down to a decrease temperature limit of-70 ∘ C.

The turbine diagnosed right here was firstly designed to meet that goal but is handiest currently assured to a temperature of-40 ∘ C. The turbine will want to be evaluated for change and operation on the necessary lower temperatures demonstrated. Eventually, the muse design for the turbine would require improvement to decide the viability of a compacted snow foundation. A devoted campaign of engineering development has the potential to address the technical challenges noted here, which could pave the manner for renewable power sources and strength storage to end up an critical a part of decarbonized electricity era on the South Pole.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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