Whitepaper

High Penetration Renewables for Mines – a Business Case for >85% Renewable Share

Renewable hybrid energy solutions: Decarbonising mines, cost reduction and energy security

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Executive Summary

Can renewables account for a 100% renewable energy production at an off-grid mine with 24/7 operations? This white paper explores two sides of this question. A case study by Dornier Suntrace analyses on a high level the potential to combine PV and wind energy generation to reach high shares of renewable energy in the power mix for off-grid mines.

Provided there is suitable solar and wind resource available at such off-grid location for a captive power generation, it shows a high potential for renewable energy to be not only a decarbonization, but even more a cost reduction measure to increase the profitability of a mine.

Wind and PV generation combined with a 4 h Battery energy storage can achieve >85% of renewable electricity share as annual average with an amortization period of below 6 years.

During a period of several months, the renewable resource is sufficient for a continuous zero-engine operation, reducing the fossil-based electricity generation to less than 15%, focusing on the night operation during low resource seasonal periods. It creates a stunning scenario for off-grid mines, and indicates that such analysis should be made for every off-grid location that has a sufficient remaining life of mine to harvest the benefits. The result may be different based on the location specific solar and wind resource as well as other site-specific factors.

There are many benefits that a renewable energy system will provide additionally: more energy autonomy with less fuel trucking risks, reduced CO2 footprint (no cost benefits for future carbon tax included in the assessment)

Once a power plant is operational, wind and solar powers' high variability imposes an additional challenge. Therefore, wind and solar power production forecasts play an essential role in adapting the daily operational schemes to the actual weather conditions, leading to an increased wind and PV performance. Reuniwatt explains state-of-the-art short-term forecasting technologies for wind and solar power production, and how these forecasts can be matched up and combined with the load forecasts by the Energy Management System (EMS) help to ensure system reliability at all times. Finally, we answer a range of Frequently Asked Questions (FAQ) in the last section of the white paper, providing answers to some questions regarding the decarbonisation of mines, based on the webinar "Renewable hybrid energy solutions: Decarbonising mines, cost reduction and energy security".

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Introduction to the Dornier Case Study

The following white paper delves into a comprehensive assessment of renewable energy integration for remote mining operations in Western Africa. The primary focus is on evaluating the feasibility and economic viability of transitioning from traditional fossil fuel-based power generation to a hybrid system that incorporates solar and wind energy sources alongside energy storage solutions. Mining operations in remote regions often face logistical challenges, including high fuel costs and carbon emissions associated with diesel or heavy fuel oil (HFO) power generation. As the world shifts towards sustainable and environmentally friendly energy sources, it becomes imperative for such operations to explore innovative ways to maximise its carbon emissions, preferably alongside a reduction of operational costs and thus upgrading to a more sustainable and economically viable operation.

Within the cases study, multiple system configurations are explored, each with the aim to optimize energy generation considering mine load and economic efficiency. Key performance metrics, including amortization periods, return on investment (ROI), and renewable energy contributions, are scrutinized to provide a comprehensive assessment of the economic feasibility of renewable integration.

This case study shall provide mining companies, stakeholders, and policymakers with valuable insights into the potential benefits and challenges associated with transitioning to a high share of renewable energy. By assessing the economic rationale behind these transitions, the study underscores the critical role of renewable energy in enhancing both the environmental sustainability and long-term economic viability of remote mining operations.

In-house Modelling: One step *AHEAD*

Dornier-Suntrace's in-house tool *AHEAD (Advanced Hybrid Energy Allocation & Dispatch)* operates within a python based scientific framework, allowing us the capacity to meticulously simulate a diverse array of energy scenarios. Specifically engineered for both off-grid hybrid systems and grid-connected, it accommodates an intricate combination of solar, PV, wind and battery which can be further extended to several renewable energy sources. It also includes the simulation of fossil or existing power supply, be it HFO- or Diesel-fired engines, gas fired power plants or from the connection to an electricity grid.

Through its computational prowess, it aptly determines the optimal dispatch of renewable resources while concurrently reducing carbon emissions. A remarkable feature is its time granularity, allowing simulations down to 1-minute intervals, complemented by multi-year projections that encapsulate the entirety of a project's lifecycle. System dimensions are tailored to the load requisites of each situation. The tool's adaptability extends to dispatch strategies, which can be customized and user-defined to align with unique preferences. Intricately intertwined is an inbuilt financial model that computes key metrics such as LCOE, IRR, NPV, and ROI, enabling a comprehensive amortization analysis.

Figure 1 Salient features of AHEAD simulation tool

The tool's optimization capability discerns configurations with the lowest generation costs, providing an empirical basis for decisions that bridge economics and strategy. As shown in the below image, the tool can visually represent renewable generation in relation to load, illustrating critical insights of the hybrid dispatch.

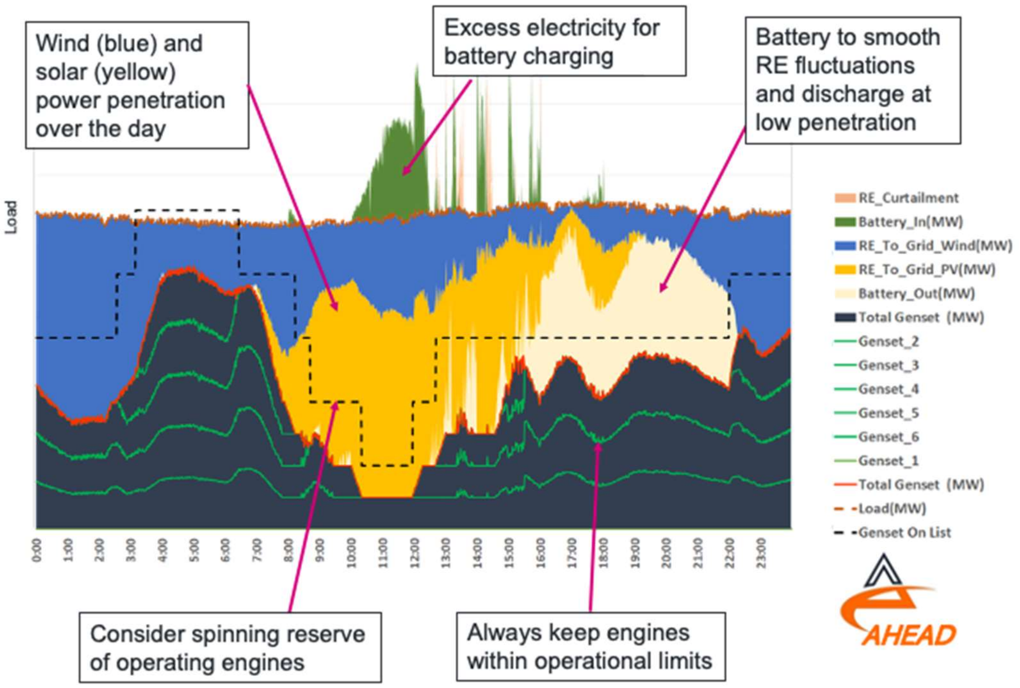

Figure 2 Exemplary plot for the energy distribution of a hybrid system with solar, wind, BESS and fossil fuel fired gensets.

Case Study Analysis

Assumptions for Wind and Solar Resource

For the case study, a mine at a location in Western Africa, operating independently off-grid using heavy fuel oil (HFO) for power generation is chosen. The mine operates continuously 24/7 throughout the year. The study is using a mine load ranging between 20-40 MW, however it is normalized for the sake of this analysis. This load curve also accounts for regular maintenance by anticipating typical load reductions. The renewable landscape features favourable solar conditions, boasting an annual solar irradiance of approximately 2000 kWh/m². Additionally, the region exhibits a consistent wind resource with speeds averaging 7-8 m/s. Figure 3 shows the solar and wind resources used for the study.

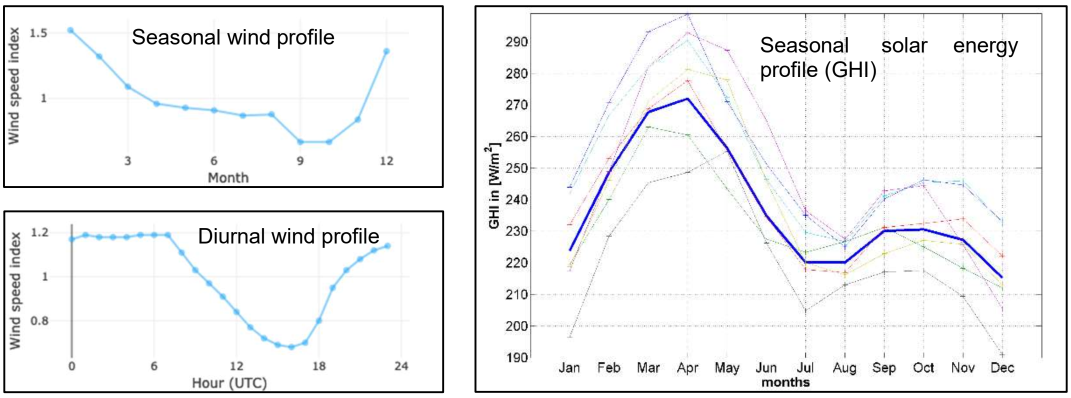

Figure 3 Wind and solar profile used for the scope of the study.

Notably, the months from December to March show robust to high wind potential, while the April till November has a relatively lower wind potential. Wind-energy during night complements the daytime solar production nicely. A harmonious solar-wind synergy compensates for the gaps and complements each other during most seasons. Employing state-of the art renewable technologies, the solar infrastructure involves single axis tracked photovoltaic (PV) systems equipped with bifacial modules. Simultaneously, wind energy harnesses the power of robust standard turbines, each capable of generating 4-5 MW. The main aim of the study is centred around achieving a substantial renewable energy contribution at a competitive cost. Latest economic assumptions from the internal updated databank are used.

Case 1: Solar-Only - up to 35% annual renewable share:

In this scenario, we focused on maximizing solar energy during daylight hours. A small battery was utilized to manage fluctuations in solar output without engaging in load shifting. A battery acts as spinning reserve and safety buffer to allow engine start-up for sudden solar output drops, ensuring uninterrupted production. Figure 4 – Case 1 shows exemplary days, where the solar output is similar throughout the year, allowing a full solar penetration during sunny days.

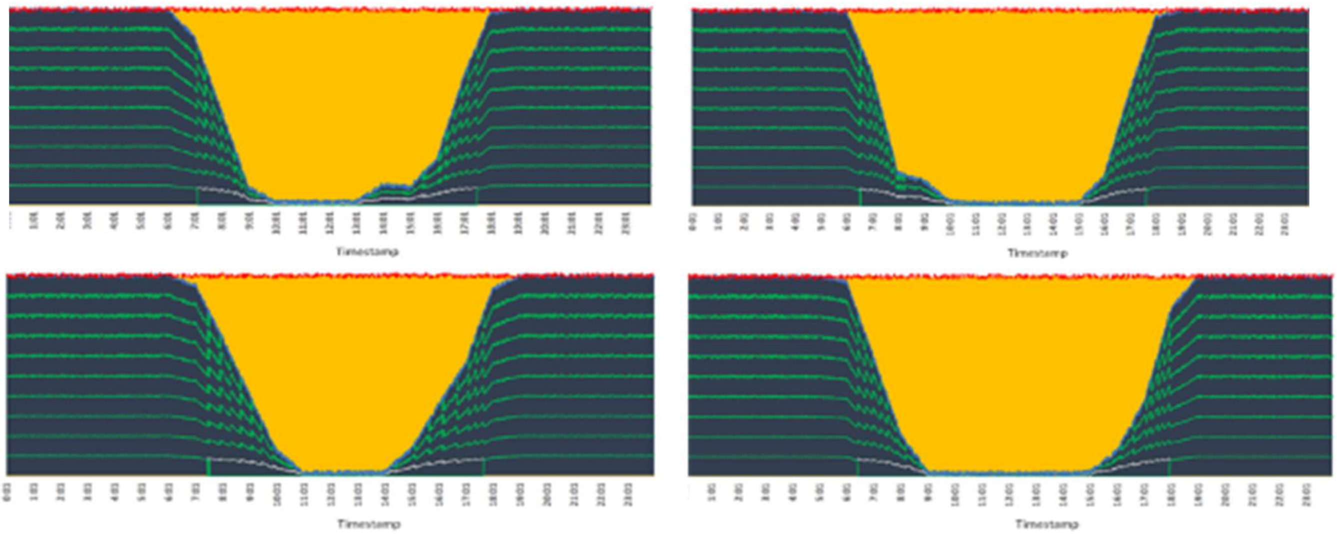

Figure 4: Case 1, daily generation results for sample days (Feb 09, Jun 02, Oct. 03, Oct. 11)

35% renewable energy contribution can be achieved over the year with 150% of the mine's load in terms of PV capacity installed and a battery with capacity for one hour.

Figure 5 shows the annual distribution of the system in Case 1 as daily average values, with solar penetration (yellow) and HFO production with light brown. The dips in the load represent the maintenance intervals for the operations of the mine. A very low amount of PV energy is curtailed in this case.

PV (MWdc)	Wind (MW)	BESS POWER (MW)	BESS ENERGY (MWh)	RE Fraction (%)	RE Curtailed	Total PV Production	PV to Mine	Total Wind Production	Wind to Mine	PV & Wind to Battery	Battery to mine	Total Engine Production
150%	0%	100%	1,0	35%	0,7%	35%	34%	0,0%	0,0%	0,1%	0,1%	65%

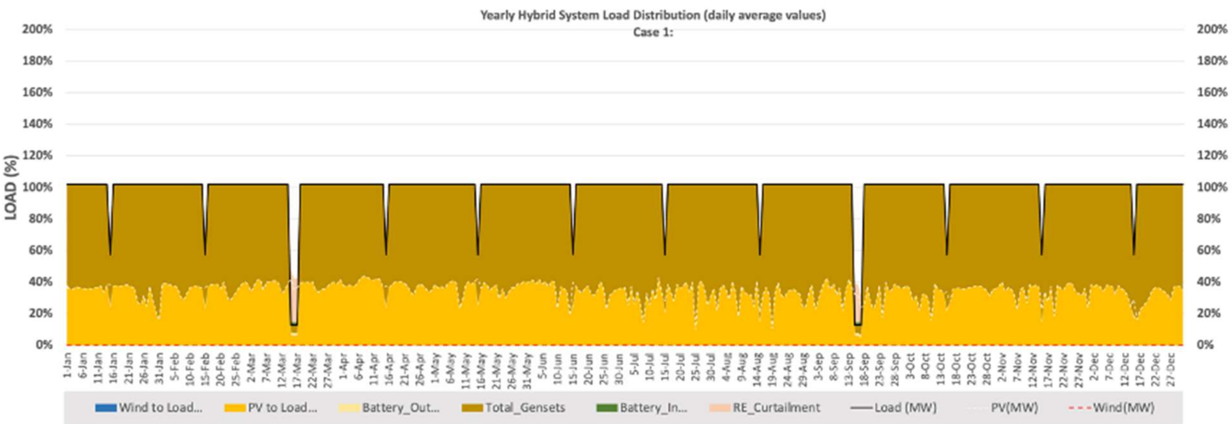

Figure 5: Case 1, annual power generation distribution, daily average contribution of solar and fossil.

Case 2: Solar and Wind Integration without BESS reaches >70% renewable share:

Case 2 is adding wind generation to complement the solar generation of Case 1. Figure 6 shows on exemplary days that wind can have a significant if not dominating influence (Feb. & Jun.) with excess renewable generation, but a rather marginal contribution during other periods (Oct.) still requiring engine operation throughout the night.

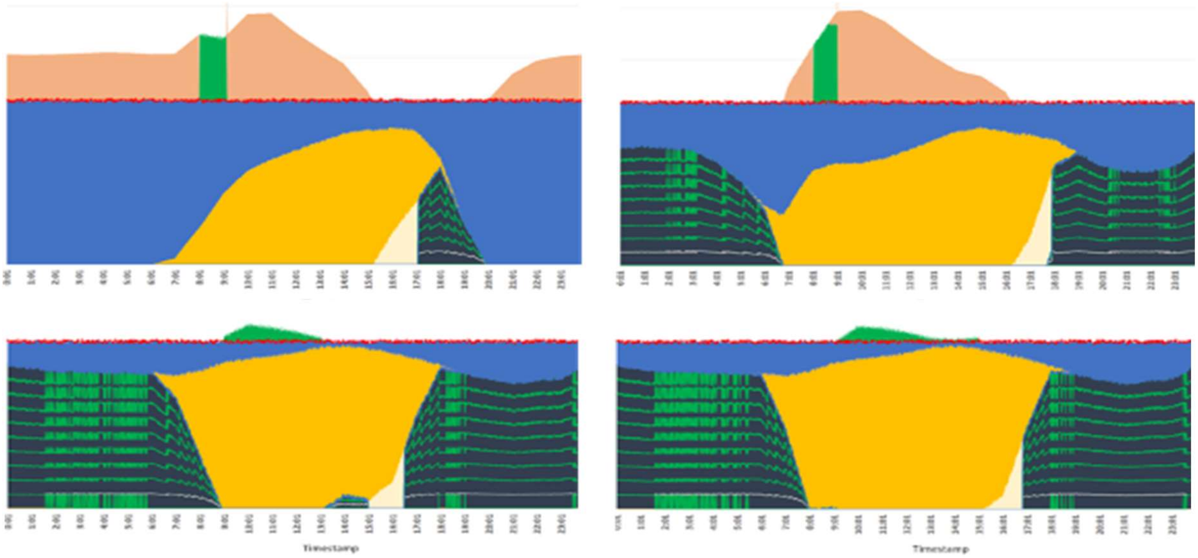

Figure 6: Case 2, daily generation results for sample days (Feb 09, Jun 02, Oct. 03, Oct. 11)

73% of renewable energy share can be achieved by adding Wind to the Solar generation, assuming both PV and Wind have an installed capacity of 150% of the mine load. Effectively, the fossil fired generation transitions from back-bone to a back-stopping power generation role.

Figure 7 shows the annual energy distribution for this case. This configuration already yielded a significant 73% renewable energy share, even without an optimized Battery for some load shifting. However, it's important to note that there were periods of excess energy (shown in peach color) during the day in winter months, while during other periods, the engines are still required during certain hours to meet the mine's energy demands.

PV (MWdc)	Wind (MW)	BESS POWER (MW)	BESS ENERGY (MWh)	RE Fraction (%)	RE Curtailed	Total PV Production	PV to Mine	Total Wind Production	Wind to Mine	PV & Wind to Battery	Battery to mine	Total Engine Production
150%	150%	100%	1,0	73%	14%	35%	28%	51%	42%	1,7%	1,4%	27%

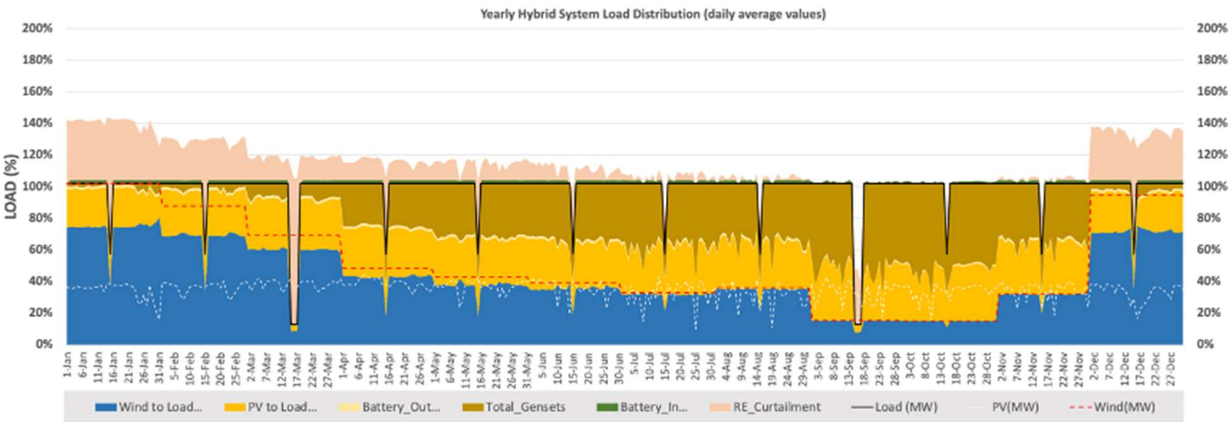

Figure 7: Case 2, annual power generation distribution, daily average contribution of solar and fossil.

Cases 3 & 4: Wind & PV and Battery for Load Shifting:

In Case 3 & 4, additional PV and Wind generation capacity and a larger energy storage (Case 3: 3 hours, Case 4: 4hours) have been integrated. PV and Wind generation has been increased to different levels to evaluate the seasonal use of the battery and charging/discharging depending on which technology provides more excess. Solar would provide the cheaper source of electricity, while wind contributes a higher capacity factor. In these cases, the battery facilitates a substantial amount of load shifting, however it cannot compensate for the seasonal reduction in wind resource. The results for Case 3 and Case 4 are quite similar, so that only the graphs for Case 4 are shown below.

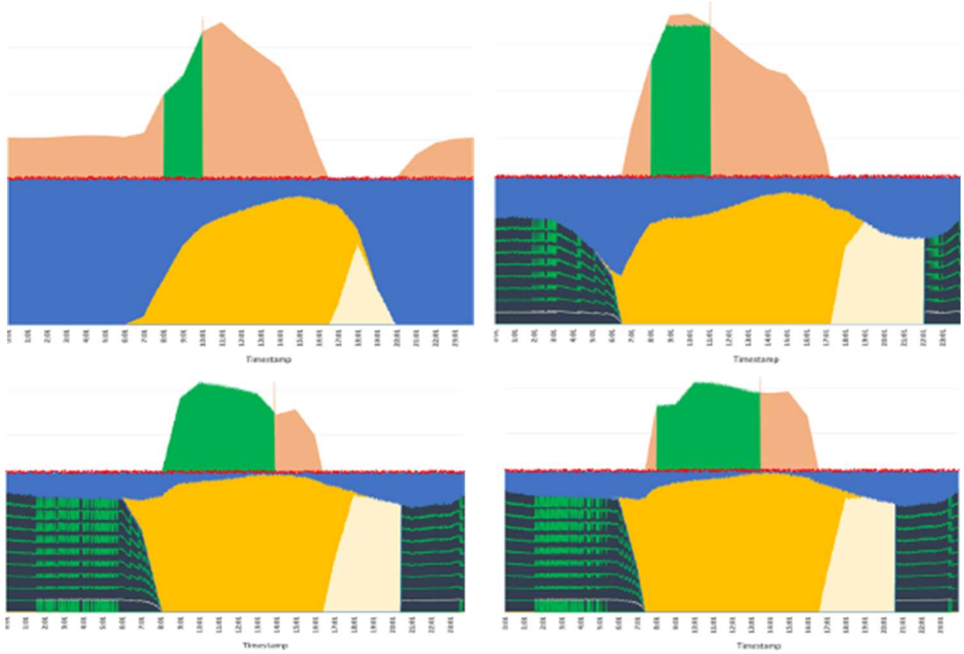

Figure 8: Case 4, daily generation results for sample days (Feb 09, Jun 02, Oct. 03, Oct. 11)

Based on Case 4, Figure 8 shows the daily generation for the same for days as in cases 1 and 2. In February, the battery can cover all OV and Wind gaps and allows a 24/7 operation based on renewable power. In June and October days, engine operation is required during the night to compensate specifically for low wind generation. The battery's operation is represented by green (charging) and light yellow (discharging) segments.

Case #	PV (MWdc)	Wind (MW)	BESS POWER (MW)	BESS ENERGY (MWh)	RE Fraction (%)	RE Curtailed	Total PV Production	PV to Mine	Total Wind Production	Wind to Mine	PV & Wind to Battery	Battery to mine	Total Engine Production
Case 3	230%	150%	100%	3,0	82%	22%	54%	33%	51%	40%	9,8%	8,6%	18%
Case 4	180%	200%	100%	4,0	87%	26%	43%	29%	71%	49%	9,2%	8,0%	13%

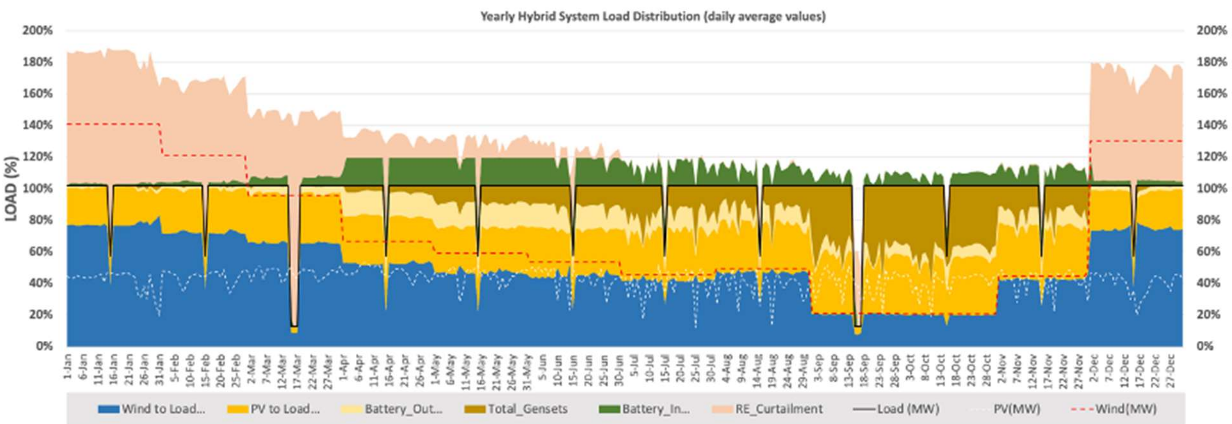

Figure 9: Case 4, annual power generation distribution, daily average contribution of solar and fossil.

Figure 9 shows that as result, the contribution of fossil fuel fires engines to the power mix (light brown color) diminishes to only 13% in Case 4. With a four-hour battery and the additional PV & Wind capacity, a renewable energy share of 87% is achieved.

The seasonal graph also shows that during the Winter period, a large excess of renewable energy remains unused (curtailed), while during the summer and autumn periods, the engine operation is still required. This mainly owed to the low wind during these Months, that requires engine operation through the night.

There are options to achieve these additional 13% with renewable energy as well, but this has not been examined in greater detail. Further scaling of wind, PV and Battery would result in a significant increase generation cost. The same would apply to potential use of the excess energy in winter by generating a green hydrogen-based fuel and store this for the low wind periods. It would be more beneficial to monitor the technology and cost evolution in the coming years and conduct a re-assessment based on future cost and technology options.

Economic Results and Conclusions

As we delve into the realm of economic considerations, the study's focal point shifts towards a comparative analysis. To facilitate these assessments, a standardization per megawatt of mine load has been employed. While acknowledging that direct scalability of figures might not be seamless, this approach provides a foundational benchmark for further analysis. Figure 10 shows the cash flow for the four cases. The commercial assumptions are based on 2022 CAPEX levels and a fossil fuel price for HFO at US$ 0.7 per liter, which is a rather low and thus conservative level.

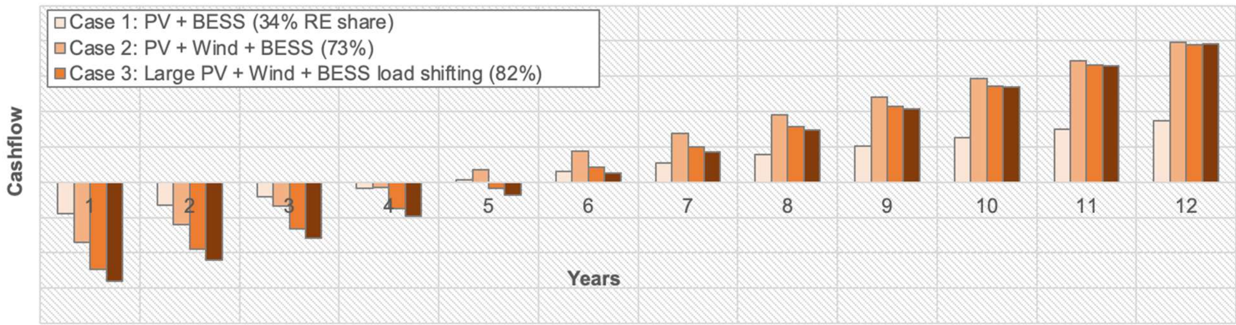

Figure 10 Cash flow for the various assessed cases

Table 1 illustrates the summary of the study results for the cases assessed. Notably, within this framework, the solar-oriented scenario yields an intriguing 35% return on investment, accompanied by a relatively brief 5.3-year amortization period, only calculated against fossil fuel savings. However, the pinnacle of interest lies in the combined wind and solar scenario, wherein an even swifter 4.5-year amortization period is achieved, primarily driven by the substantial fuel savings achieved by adding the wind power generation. When adding the Battery storage, the related cost are stretching the amortization period again towards 5-6 years, which still is an incredible business case for the renewable generation.

The curtailed electricity during periods where the supply exceeds the demand and the battery is fully charged, is considered as lost and does not contribute to the benefits of the economic assessment. It remains as an unused potential. Still the renewable business case is highly profitable, and amortization is short.

Table 1 Summary of the study results

Case	PV Capacity	Wind Capacity	BESS POWER	BESS ENERGY (hours)	Initial Capital Mio US$/MW Mine Load	Energy from RE	Energy from Engine	Nominal Amortization Period (Years)	Average Fuel Saving (Mio liter)	Year 1 Savings (Mio US$/MW Mine Load
	per MW Mine Load				per MW Mine Load				per MW Mine Load	
1	150%	0%	100%	1,0	$2,50	**35%**	65%	**5,3**	0,62	$0,48
2	150%	150%	100%	1,0	$4,50	**73%**	27%	**4,5**	1,33	$1,00
3	230%	150%	100%	3,0	$5,90	**82%**	18%	**5,3**	1,49	$1,12
4	180%	200%	100%	4,0	$6,80	**87%**	13%	**5,8**	1,58	$1,18

The CAPEX levels are normalized towards the load of the mine, not the generation capacity. As example for a mine with 20MW in case 1 a PV system of 30MW (150%) with a 20MWh Battery would be installed at a CAPEX of 20MW x 2.5 mUS$ = 50 mUS$. Please note these CAPEX are only indicative (+/-30%) and will be different based on market development and mine site. Also the sizing of PV, Wind and Battery should be evaluated specifically for each mine site. In case 1, the solar would contribute 35% of electricity and thus would result in fuel savings of 20 x 0.48 mUS$ =9.6 mUS$ per year. These fuel savings are considered as “revenue” for the amortization of the renewable investment.

Regarding case 2, it should be noted, that this is only used in to analyze the impact of the additional wind generation in comparison to case 1, mainly boosting the renewable share. From an operational perspective, the battery would not be optimally sized and thus a different concept would eventually be determined as optimal solution.

The annual fuel savings are culminating in a tangible demonstration through the staircase graph in Figure 10, where accruing savings grow with each passing year. Even within a scenario where wind energy isn't maximized during the year, creating excess energy, such as case 4, the payback period remains below six years.

The conclusion emphasizes a compelling message: For an off-grid operations heavily relying on diesel or heavy fuel oil (HFO), the exploration of diverse renewable resources is not merely a strategic choice; it stands as an economic imperative. The business case for renewable integration stands evident. While there's a substantial capital commitment during the initial construction phase, operating costs remain marginal in the long run.

Various funding schemes and market players can offer avenues for financial support. In essence, for a 12-year mine life, an amortization period of 5.8 years establishes a robust economic rationale. For operations spanning 20 years or more, embracing renewable energy seems a wise decision from an economic standpoint. Neglecting to undertake a thorough study to analyze these possibilities could potentially overlook an expensive opportunity to enhance product pricing. By minimizing all-in sustaining costs, renewable energy stands as an avenue for improving the overall economic viability of mining operations. This conclusion forms a rallying call for detailed scrutiny and consideration of renewable integration, a fact that holds the promise of not just sustainability, but economic growth within the mining sector.

Outlook & Recommendations

This case study did not include the scenarios of electrification of the mine operations, such as electric vehicle fleets and other means to reduce the CO2 emissions. Also a potential use of the excess electricity available during the winter months has not yet been analysed further. Both remain options to be looked at when planning a larger renewable energy project at a mine site.

1. **Carbon Taxes:** the cases have not included any cost for carbon emissions; thus any carbon tax would significantly improve the renewable business case, or alternatively, the renewable can be considered a hedge against carbon tax as well fossil fuel cost increase.
2. **Intermittency of Renewable Sources:** Solar and wind energy sources are inherently intermittent, meaning their output can fluctuate with weather conditions. Ensuring a stable power supply to meet the continuous energy demands of a mining operation requires a careful analysis of the energy storage and back-up power generation.
3. **Energy Storage:** To mitigate the intermittency issue, energy storage systems like batteries are the go-to solution. Selecting the appropriate type, capacity, and technology for energy storage is a key aspect. Future market developments, specifically the expected cost reduction, will open up larger energy storage applications at economic levels.
4. **Scalability:** Mining operations may have varying energy demands based on production levels. Ensuring that the renewable energy system can scale to match these varying demands is important.
5. **Initial Capital Costs:** The upfront capital investment for setting up a renewable energy plant can be substantial. Securing the necessary funding and justifying the initial costs is a key element of a successful renewable case.
6. **Grid Integration:** Integrating renewable energy systems with existing grid infrastructure, or creating an entirely new microgrid for the mine, requires careful planning and engineering to ensure reliability and stability.
7. **Resource Assessment:** Conducting a detailed assessment of the available solar and wind resources at the mine site is crucial. Inaccurate assessments can lead to under- or overestimate the generation and thus lead to a potential mismatch in renewable power generation.
8. **Operational and Maintenance Costs:** While renewable energy systems typically have lower operating costs compared to fossil fuel generators, ensuring proper maintenance is important, specifically in remote locations.
9. **Energy Demand Variability:** Mining operations can have highly variable energy demands due to equipment usage and production fluctuations. Matching this variability with a reliable renewable energy supply needs to be considered in the feasibility stage.
10. **Environmental and Regulatory Compliance:** Complying with environmental regulations and securing permits for renewable energy projects is required, and specifically for wind energy will be more complex.
11. **Technical Expertise:** Developing and maintaining a renewable energy system requires some expertise that would need to be acquired by the mine.
12. **Return on Investment (ROI):** Demonstrating a favorable ROI within a reasonable timeframe is critical for gaining support for renewable energy projects. Proving economic viability only against the official life of mine may be challenging, especially if the remaining life of mine is limited. However, in view of very likely expansion of operations, this perspective may need to be factored into the investment case and the decision.
13. **Backup Power:** Ensuring reliable backup power, such as diesel generators, during periods of low renewable energy production is essential to avoid interruptions in mining operations.
14. **Heritage:** The renewable project can be transferred and connected to the national grid after the shutdown of a mine and can continue provide a sustainable contribution to the host countries energy system.

It is highly recommended to address these aspects thorough planning, technical expertise, and often collaboration with renewable energy experts and financing institutions. Each mining operation is unique, and addressing these challenges effectively requires a tailored approach that considers specific site conditions and operational requirements.

Energy security with Reuniwatt's wind and solar power forecasts

Once a power plant is operational, forecasts play an essential role in adapting daily operational schemes to the actual weather conditions and renewables performance. An Energy Management System (EMS) will be used to set a production schedule several hours in advance. Moreover, the control settings applied to the power plant and the battery storage can be adjusted short-term, for example every 15 minutes, to adapt their response to the expected differences between the forecast and the actual conditions. The combination of wind and solar forecasts and advanced energy management tools enables real-time control decisions that respect the technical and commercial constraints of the plant while anticipating their implications for the rest of the day. Reuniwatt's wind and solar forecasts will be matched up with the load forecasts by the EMS, to ensure system reliability at all times.

These decisions are based on weather forecasting, which allows to anticipate the solar and wind resources available. These forecasts, combined with numerical models, make it possible to predict the behaviour of the mine's hybrid system in order to maximise performance at several levels, minimising the amount of solar energy curtailment, optimizing the spinning reserve and battery charging cycles, and maintaining the batteries at appropriate charge states.

The role of renewable production forecasts in hybrid systems

As presented in Case 3 and Case 4 by Dornier Suntrace on page 11, even when combining solar with wind, the respective mining site with 24/7 operations might still require additional generators and cannot fully rely on renewable power generation in the given constellations. However, it is in the financial and environmental interest of the mine's operators to use the maximum share of renewable energy they can, and keep the *spinning reserve* on the minimum level required, reducing fuel consumption while making sure they can meet their electricity demand at any time and avoid blackouts, preventing gensets from overloading and reducing genset ramps while managing battery charge cycles.

Due to the inherent variability of wind and solar power generations, intra-hour production forecasts, possibly in combination with intraday forecasts, are the best solution for planning Heavy Fuel Oil (HFO) generators' dispatch schedule.

In Case 3, the battery can provide electricity for up to 3 hours, and up to 4 hours in case 4. However, sudden changes in generation will occur for both wind and solar power:

- Cloud movements can result in sudden ramp up and down events of solar power production of >80% in extreme cases.
- Successive fluctuation of wind speed makes it difficult to figure out how much electricity will be generated.
- Strong winds can require wind turbines to be stalled, resulting in a complete stop of the wind power production.

Forecasting expected wind and solar power output for the next hours in advance allows to get the right number of gensets running and to start additional engines in time, therefore optimising battery utilisation. On the following pages we will present state-of-the-art wind and solar power forecasting technologies.

What is a Spinning Reserve?
Spinning reserve refers to the amount of power generating capacity that is available to the power grid and ready to be deployed within a short notice period, typically in a matter of seconds to minutes, to compensate for sudden changes in electricity demand and/or unexpected outages of other power generation sources. Spinning reserve is typically provided by power plants that are kept running at less than full capacity, allowing them to ramp up their power output quickly when needed. The term "*spinning*" refers to the fact that these generators are already spinning and synchronised with the power grid, so they can be quickly brought online to meet unexpected demand. Having sufficient spinning reserve is essential for maintaining the stability and reliability of the microgrid, and is an important aspect of energy security planning.

Solar power production forecasting

Off-grid mines in particular can benefit from cheap solar and wind energy to cover their energy needs. However, the variability of solar irradiance can lead to challenges in the planning and use of solar power. Mainly, the accurate anticipation of solar power ramp events results in less frequent starts/stops of gensets and makes it possible to reduce the number of online gensets during daytime compared to a baseline control strategy without forecasting. The reduced number of gensets needed to ensure a stable power supply translates into an increased mean load applied to the gensets (an increase of about 10%[1]), resulting in higher fuel economy thanks to a more efficient load redistribution on the gensets.

To overcome these challenges, solar power forecasting for off-grid systems is ever more important. Reuniwatt offers solar power forecasts for different time horizons:

- Day-ahead (Reuniwatt's **DayCast**™ solution) - up to several days ahead. This method is not detailed in this white paper. Is it is commonly required for an optimized management of utility-scale grid-connected power plants, as well as by transmission system operators and many local grid codes.
- Intra-day (Reuniwatt's **HourCast**™ solution) - from 10 to 15 minutes up to 6 hours ahead. This time-horizon is ideal in combination with the batteries shown in cases 3 and 4, in order to optimise charge cycles and plan ahead.
- Intra-hour (Reuniwatt's **InstaCast**™ solution) - from 1 minute up to 30 minutes ahead. This solution allows plant operators to anticipate sudden power drops in PV power production using a sky camera installed on-site.

The accuracy of the forecasts is site-dependent and relies on a number of variables: the local climate, the concerned time-horizon, as well as the metric used. In-situ measurements offer high temporal resolution, but require a careful calibration and maintenance of the instruments to ensure high data quality.

HourCast™ for solar plants

Reuniwatt's proprietary method for providing intra-day solar forecasts (from 10 to 15 minutes ahead up to 6 hours ahead) is based on the most efficient methods of converting satellite imagery into solar radiation maps. The use of images originating from five or more satellites enables a global coverage.

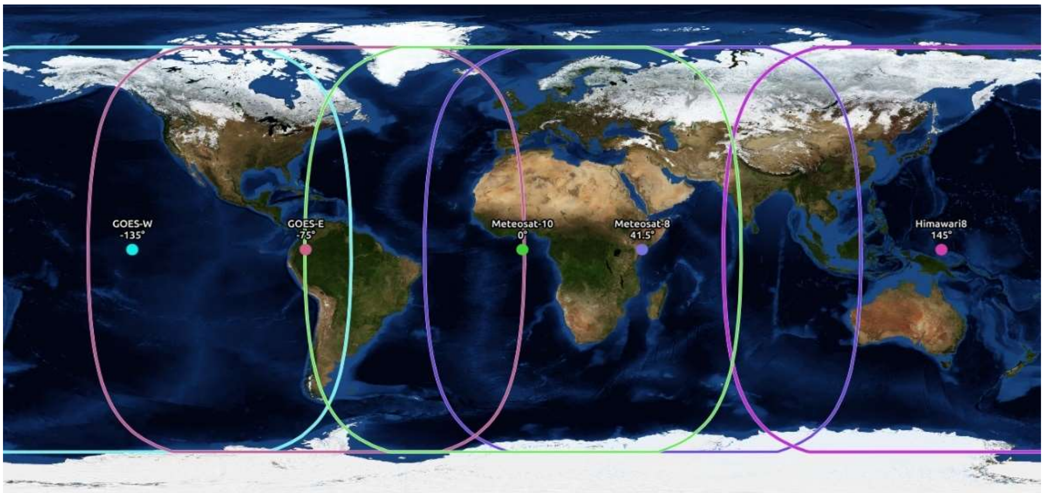

Figure 11: Global coverage of HourCast™ is ensured through 5 geostationary meteorological satellites.

The first step consists in converting two successive satellite images into a cloudiness map. In the following step, the movement of clouds between two images is derived from cloud maps by analysing the optical flow,

[1] Boudreault L-E. et al. (2020). Driving the Unknown Towards Fuel Economy With a Sky-Imager in a Hybrid PV-Diesel System. PVSEC.

transformed into a vector field of the clouds' movements. This field is then applied on an image taken at T_0, extrapolating it to predict the various cloud maps for up to T_0 + 6 hours. The solar irradiance forecast is obtained by combining these extrapolated maps with the corresponding irradiation. The illustration below represents an overview of this process:

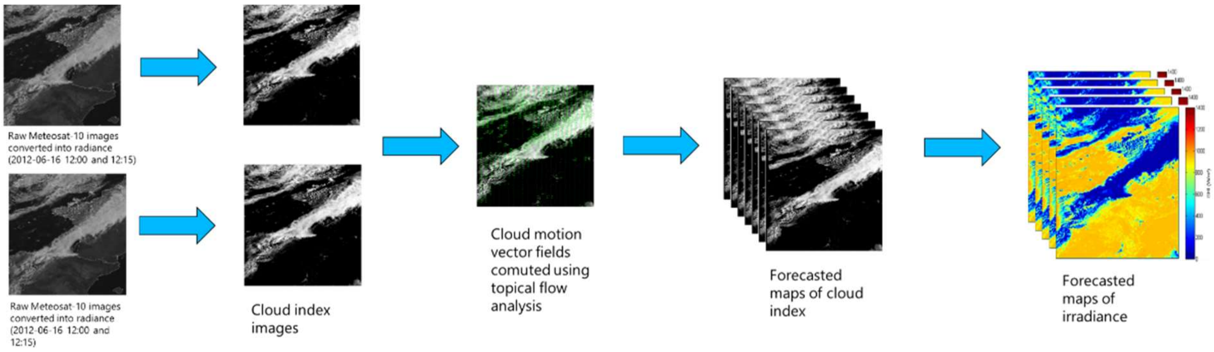

Figure 12 Forecasting method of Reuniwatt using satellite images.

InstaCast™

Reuniwatt's intra-hour forecasting technology **InstaCast**™ is used to provide solar forecasts to smooth down-ramp events, to optimise the use of battery storage assets, and to ensure grid compliance, optimise grid injection and provide grid-ancillary services of utility-scale solar projects. Intra-hour forecasts are based on image processing technologies, and provide very high-resolution intra-hour solar forecasts, with rapid forecast updates. This solution exploits images acquired by sky cameras every 30 seconds to provide forecasts of irradiance (Global Horizontal Irradiance – GHI) and/or power production. Using a cloud motion vector algorithm, the software is able to track the clouds' evolutions, and calculate their movements relative to the Sun's position.

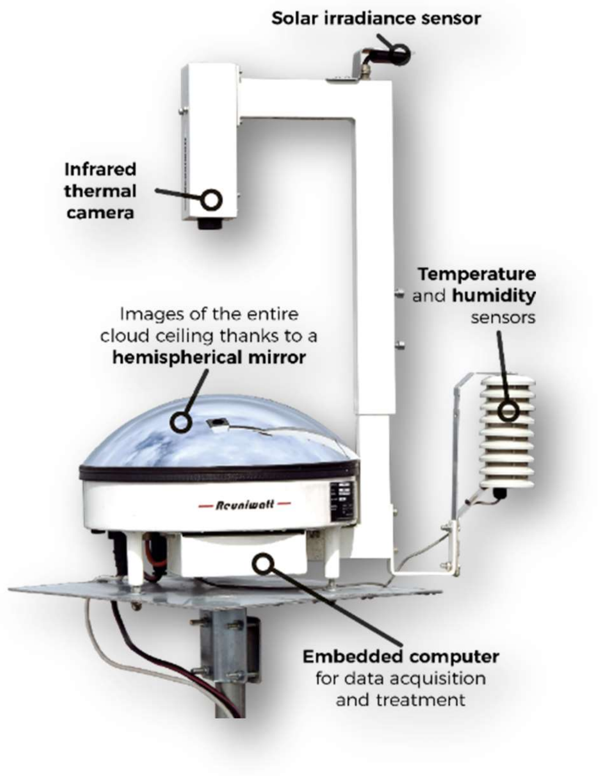

Figure 13 (left): InstaCast™ forecasts are derived using one of Reuniwatt's all-sky imagers (Sky InSight™).

InstaCast™ services are of specific interest for off-grid mines: intra-hour forecasts can be used to optimise the energy fluxes between a solar plant, a storage system, the grid and/or a diesel genset. All-sky imagers installed on-site are essential to ensure a smooth supply-and-demand balance in a grid with a substantial renewables' share, while avoiding unnecessary curtailment of solar power.

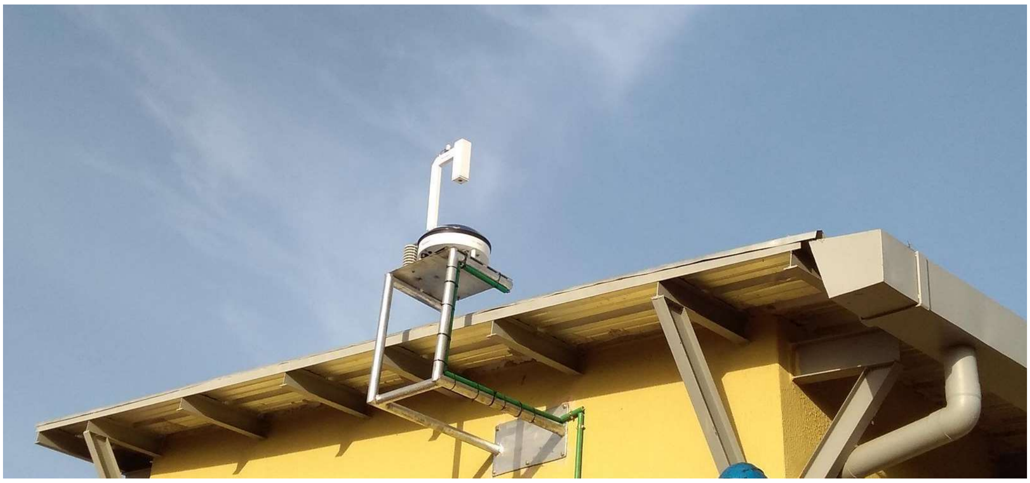

Figure 14: Sky InSight™ installed on-site at an off-grid mine in Western Africa.

Once a solar hybrid plant is installed and operational, using forecasts becomes an essential tool to optimise the injection of solar energy into the mini-grid. Anticipating the ramp events at a time-horizon of 30 minutes offers the flexibility to operate the plant as efficiently as possible. Including intra-hour forecasts will reduce the overall fuel consumption of the system while reducing the potential number of blackouts observed[2]. Mainly, the accurate anticipation of solar power ramp events results in less frequent starts/stops of gensets and makes it possible to reduce the number of online gensets during daytime compared to a baseline control strategy without forecasting. The reduced number of gensets needed to ensure a stable power supply translates into an increased mean load applied to the gensets (an increase of about 10%[3]), resulting in higher fuel economy thanks to a more efficient load redistribution on the gensets. All settings will be site-specific and customised during the implementation process, based on the metrics selected, and supported by the EMS provider. The criteria for a sudden drop in power production can be adapted according to the client's expectations.

[2] Liandrat O. et al. (2018) Sky-imager forecasting for improved management of a hybrid photovoltaic-diesel system. *International Hybrid Power Plants & Systems*.

[3] Boudreault L-E. et al. (2020). Driving the Unknown Towards Fuel Economy With a Sky-Imager in a Hybrid PV-Diesel System. PVSEC.

Wind power production forecasting

While satellites provide frequent and global observations of clouds from space and are therefore useful for solar forecasting, satellite-based observations of the wind at altitudes of around 100 m above the ground do not exist. Therefore, numerical weather prediction (NWP) models must be used to produce hour-scale intra-day wind forecasts. Reuniwatt retrieves, stores, and processes the raw forecasts of a dozen NWP models. These models are operated by national weather agencies around the world and provide forecasts for any location on the globe. Meteorological observations from weather stations, satellites, radars etc. are constantly being used to update these models and their forecasts. This enables us to capture and predict the state of the atmosphere including the wind field in different heights as accurately as possible.

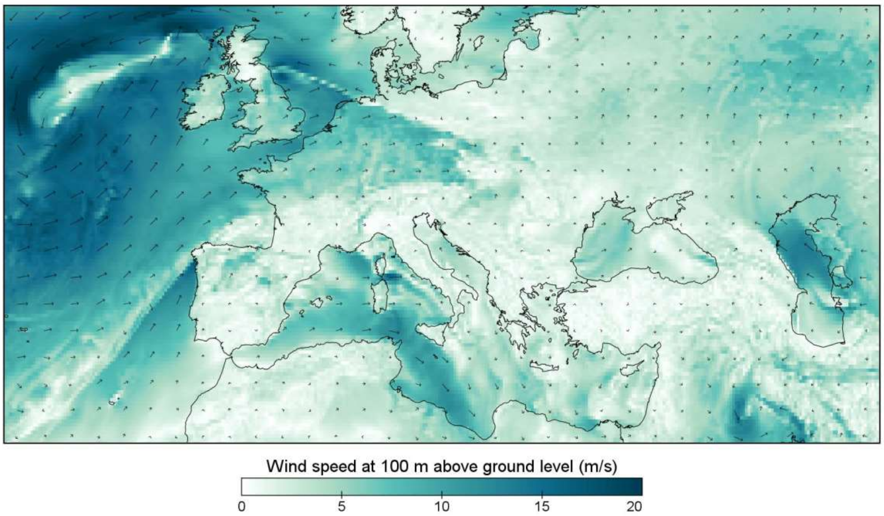

Figure 15: NWP-model based simulation of wind speed at 100 m above the ground.

To optimise the hour-scale wind power forecasts, we use various machine learning methods. These methods use first guess forecasts from NWP models in combination with actual production data (SCADA data) of all wind turbines. Therefore, intra-day wind power forecasts from 30 minutes up to 6 hours ahead require SCADA data. These forecasts are calculated based upon the latest available data, in particular near real-time on-site power production measurements.

Reuniwatt's HourCast™ Wind forecasts use real-time production data in combination with machine-learning (blue curve), while DayCast™ Wind forecasts rely solely on NWP models (red curve).

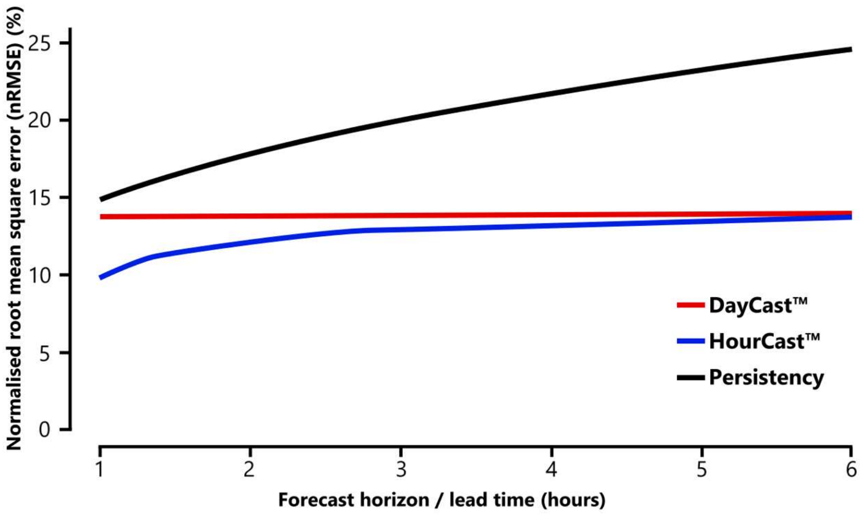

Figure 16: Using local measurements and machine-learning, HourCast™ Wind achieves a forecast improvement compared to DayCast™ Wind, which only relies on NWP models

A deterministic wind power conversion process allows to convert the wind speed and direction into power from the first day of operations. This process is based on a physical model that uses standard power curves of the wind turbines. Due to the difference between standard and realistic power curves, the deterministic power conversion can be switched to statistical power conversion to improve the forecast quality after a couple of months, which takes historical production data into account.

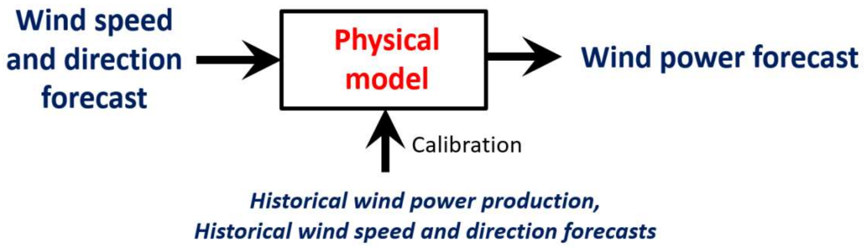

Figure 17: Wind power conversion process

Using forecasts in the operational phase

Once a hybrid plant is installed and operational, using forecasts becomes an essential tool to optimise the injection of wind and solar power into the mini-grid. Anticipating the ramp events at a time-horizon of 30 minutes offers the flexibility to operate the plant as efficiently as possible. The addition of wind and solar forecasts will reduce the overall fuel consumption of the system while reducing the potential number of blackouts observed[4].

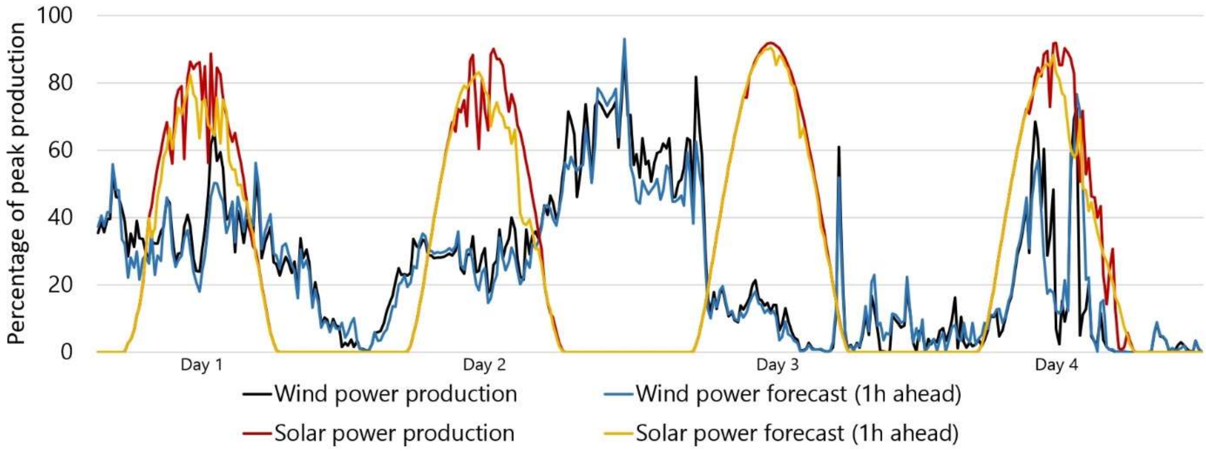

Figure 18: One hour ahead forecasts of wind and solar power production for a hybrid power plant.

The use of our sky cameras within hybrid projects with a large share of solar capacity in particular, will allow to trim down the additional over-spinning reserve, and to optimise the number of gensets ignited at all times in order to avoid blackouts. The reduced number of gensets needed to ensure a stable power supply translates into an increased mean load applied to the gensets, resulting in higher fuel economy thanks to a more efficient load redistribution on the gensets. A reliable internet connection is preferable. Nevertheless, in case a smooth bandwidth cannot be guaranteed, a fully-autonomous offline mode can be implemented for solar forecasts, in order to ensure the local availability of the forecasts. Forecast outputs can be communicated to the plant’s control system using the Modbus TCP/IP protocol.

All settings are site-specific and customised during the implementation process, based on the operators/ owner’s expectations and supported by the EMS provider and the solar forecaster. The alarm for a sudden

[4] Liandrat O. et al. (2018) Sky-imager forecasting for improved management of a hybrid photovoltaic-diesel system. *International Hybrid Power Plants & Systems*.

drop in power production can be based on more or less sensitive criteria, according to the client's expectations.

Using backtests in the early planning phase

To get a glimpse of the expected forecasting accuracy on a specific site, it is possible to put in place a so-called "***backtest***" (or "*hindcast*"). Backtests can be integrated in simulations during the detailed design phase and help with sizing the plant and batteries, and will take about a month. In addition, backtests can be fed into the EMS and/or the control system to fine-tune the decision-making processes in relations to weather conditions. The probabilities of "ramps events" (sudden drops ("ramp-down") or increases ("ramp-up") in the solar power output due to cloud movements) can be integrated in backtests, with the supply of one or many percentiles (P1 to P99).

Conclusions

Short-term wind and solar power forecasts within hybrid plants are an indispensable tool to optimise the use of available power sources while reducing costs. The implementation of short-term wind and solar power forecasts makes it possible to:

- Increase the integration of renewable production
- Reduce the amount of diesel/HFO used on site
- Better manage a battery's cycles
- Anticipate upcoming ramp rate events
- Avoid blackout situations
- Avoid having a constant HFO/diesel genset backup running, especially when unnecessary
- Prevent unnecessary starts/stops of the gensets
- Incorporate local input in the hybrid system

Wind and solar power forecasting leads to improved energy security and higher savings.

Frequently Asked Questions

Q. Is there still a strong case for low penetration at grid-connected sites?

A. Dornier Suntrace: Yes, definitely. Especially since energy costs have gone up everywhere, the “hedging” effect of energy cost by using solar energy has become very visible. If you had a solar plant already, you may have saved significant amounts of money against the cost increase in tariff. Also, as solar is the technology providing the lowest cost of electricity, there is usually also a business case against a grid tariff.

Q. How long do you take to do the analysis for the implementation of a hybrid project?

A. Dornier Suntrace: We usually start with a high-level analysis, which is normally completed in 6-10 weeks. It addresses all relevant aspects, such as the mine’s demand profile, solar & wind resources, technology selection, economic analyses and an optimization of the best sizing, the use of storage, etc. It provides all the necessary information to make a conscious decision on the available options and to identify the way to implement the project. There is a very similar approach for off-grid or grid-connected projects, but it addresses the different nature of the business case and the technical requirements.

Q. What is the lower limit of the battery discharge?

A. Dornier Suntrace: This depends on the type of battery used, and the application and use case. The specific data can be found with the respective suppliers. In the case of a battery connected to mining operations, the function of the battery is to provide safety to cover for a sudden load drop at the solar plant, and also for delayed ramping up of engines. Accordingly, the battery is not fully discharged or charged during operation based on this use case.

Q. Battery storage capacity seems to be the biggest challenge with solar power generation. How is the research in this area going?

A. Dornier Suntrace: Battery storage itself is not a big challenge, but the cost of battery storage is to some extent. Battery research is going into multiple directions, on one side to achieve a higher energy density, as required for mobile applications (EV, phones, etc.) and also for higher reliability, which may be more important for grid-scale storage. We expect that in the future, the cost of battery storage will come down a lot, and this will enable lower cost case for solar and storage with high penetration RE.

Q. Did you already receive feedback on the savings resulting from forecasts?

A. Reuniwatt: Every project is different, and the savings strongly depend on the size of the plant as well as on the number of gensets. However, as explained earlier, forecasts help reduce the consumption of diesel/oil on site by thousands of litres every year. Our analyses show that for a ~4MWp plant with a 30% PV penetration, the overall effect of the forecasts is to reduce the consumption of diesel by nearly 40 000 litres, the commercial equivalent of saving between USD 35 000/year and USD 60 000/year when considering a fuel price ranging from USD 0.9/litre to USD 1.5/litre (this represents a diesel operational expenditure reduction of about USD 0.1-0.2/kWh for such a project). The payback period for our sky cameras is less than 3 years.

Abbreviations

BESS	Battery Energy Storage System
EMS	Energy Management System
FAQ	Frequently Asked Questions
GHI	Global Horizontal Irradiance
HFO	Heavy Fuel Oil
LCOE	Levelized Cost of Energy
MLR	Multiple Linear Regression
NWP	Numerical Weather Prediction
SCADA	Supervisory Control and Data Acquisition