Hybrid Power

MAN Energy Solutions
Future in the making

Powering the future of remote areas

Author

MSc
Michael Raila
MAN Energy Solutions SE,
Germany

+49 821 322 6851
michael.raila@man-es.com

List of abbreviations

BESS	Battery energy storage system
CAPEX	Capital expenditure
CO_2	Carbon dioxide
EU ETS	European Emissions Trading System
HFO	Heavy fuel oil
IRR	Interest rate of return
LCOE	Levelized cost of electricity
NPV	Net present value
OPEX	Operational expenditure
PPA	Power purchase agreement
PV	Photovoltaic
RES	Renewable energy sources
RPA	Renewable purchase agreement
WACC	Weighted average cost of captial

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Executive summary

Electricity demand is set to increase and is expected to double by 2050. To combat the threats of climate change and limit global warming to 1.5°C, major nations of the world have committed to decarbonization. As a result of the increasing importance of carbon-neutral power production as well as the decreasing costs of renewable energy sources (RES), global energy systems are starting to transform.

Adding high shares of RES to the energy system results in a more decentralized, weather-dependent and thus barely controllable energy supply. This uncontrollability leads to a transformation from a demand-side-driven towards a supply-side-driven energy system.

Consequently, there is a need for a power system that consists of RES, cost-effective energy storage, e.g. a battery energy storage system (BESS), and controllable thermal generation, known as hybrid power plants.

The market for hybrid power systems has recently started to gain momentum. As initial hybrid projects such as Bonaire (Caribbean), El Hierro (Canary Islands) and Syama (African Gold Mine) show, these solutions can pave the way towards 100% renewable energy generation and provide a cost-effective power supply, even today if the resources are vital.

This paper presents two use cases for hybrid power systems based on real project data. The first use case considers the integration of RES and storage systems into existing infrastructure, as is the case on many small islands, which aim to develop climate-neutral power generation and reduce external dependencies.

The second use case describes building up new decentral power systems in rural areas using the example of mining projects. The major challenges involved in electrifying mines are high transportation costs and the absence of a transmission grid.

Both use cases show that hybridization supports reliable and cost-effective power generation, as:

- The integration of RES increases the CAPEX, but lowers the OPEX and LCOE.
- Hybridization can lower the OPEX of existing thermal plants to 60%.
- The LCOE can be reduced by almost 30%.
- For island applications, hybridization is necessary to provide affordable power generation.
- The integration of BESS replaces backup gensets and provides power reserves.
- The integration of RES serves as insurance against increasing fuel prices and transportation costs.
- Hybrid systems will pay off after four to nine years with an interest rate on return (IRR) of between 11% and 21%[1].
- With regard to the integration of BESS, the influence on the cost structure depends on the load profile:
- For base-load applications, storage systems do not influence the LCOE, or the CAPEX and OPEX
- With regard to flexible loads, the integration of BESS immediately pays off, as a result of replacing backup engines (n+1).
- For island applications, a BESS lowers the CAPEX to 75% in comparison to an engine-only design.

Furthermore, hybridization does not only influence the cost structure; it also supports decarbonization of the energy sector:

- Hybridization allows shares of 20% to >50% RES.
- Fuel consumption can be reduced by more than 30%.
- Emission reductions of more than 30% are possible, which the uncertainty surrounding future emission costs.

As those projects show, hybrid systems are already a feasible and economically viable solution that also considers environmental aspects while combining state-of-the-art-technologies.

It goes without saying that hybrid concepts are not effective in a broad scope, but instead are useful in many isolated power systems and rural areas of emerging markets.

In many cases, hybridization is the only commercially viable way to maximize RES penetration, while ensuring security of supply.

Market development of hybrid power solutions

The history of hybrid and renewable power generation

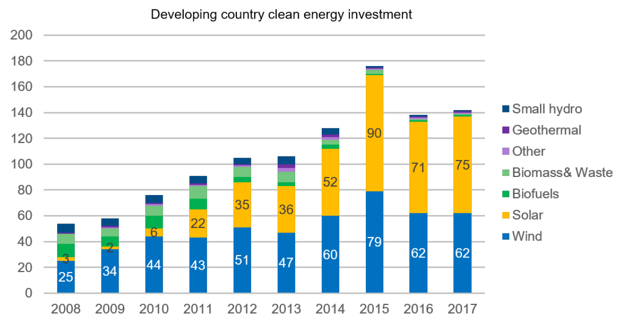
In the 1980s, the first hybrid wind-diesel power plants were built. Back then, the hybrid approach was applied predominantly in remote areas in order to avoid high transportation costs and using RES as insurance against increasing fuel prices through reduced fuel consumption (Hunter and Elliot 1994).

However, 40 years ago hybrid concepts were not widespread due to the high investment costs of the redundant design and storage systems (e.g. flywheels and lead-acid batteries). Additionally, a lack of economically viable technologies for other RES such as PV hampered the integration of renewables into power systems. Thus, hybridization was only applied in regions with constant wind penetration.

Since the 2000s, a massive transformation of power systems has been apparent. As a result of the technological improvement and the economic development of RES technologies, the energy sector started to turn towards renewable power generation with reduced fuel dependency and fewer CO_2 emissions.

Over the last 20 years, the annual capacity increases of RES have seen a ten-fold increase from 16GW to 170GW (IRENA 2018). While at the beginning of the 2000s, investment in RES was mainly undertaken in the world's wealthiest countries, the dropping capital costs of RES technologies, increasing costs of thermal power plants and constantly increasing electricity demand in developing nations marked a turnaround within the last decade (BloombergNEF 2018).

In 2017, the large majority of the world's RES capacity was built in developing countries (BloombergNEF 2018). Furthermore, the technical challenges of RES integration, the economic development of different energy sources, as well as the social and political demand for cost-effective and carbon-neutral power generation, supported the hybridization of power systems.



Graphic 1: Source: BloombergNEF. Note: Includes 100 non-OECD nations, plus Chile, Mexico and Turkey.

Status quo of renewable and hybrid power generation

Technical aspects

With regard to the technological side, the integration of renewable energy sources is a major challenge for today's power generation and grid infrastructure. While conventional power generation is controllable and can easily be adapted to the demand, RES strongly depend on weather conditions and are therefore uncontrollable and sometimes even unpredictable.

One effective way to integrate RES is to set up decentral power grids, where power supply and demand are geographically linked. In this case, hybrid power generation is necessary to increase spinning reserve and compensate for the absence of a tranmission grid connection, or a limited one. Those hybrid power plants consist of fuel-fired generators, RES and storage systems like batteries or flywheels. While the thermal generation provides stable power generation, the ESS can be used as reserve capacity to optimize the engine's operation.

Furthermore, thermal power generators need to consider economic and environmental aspects. Thus, high-efficiency and modular sizeable engines are essential in order to reduce costs and emissions, which is also in line with the economic and social perspectives of the future energy system.

Economic aspects

With regard to the economic point of view, a divergence between fossil and renewable power generation is apparent today.

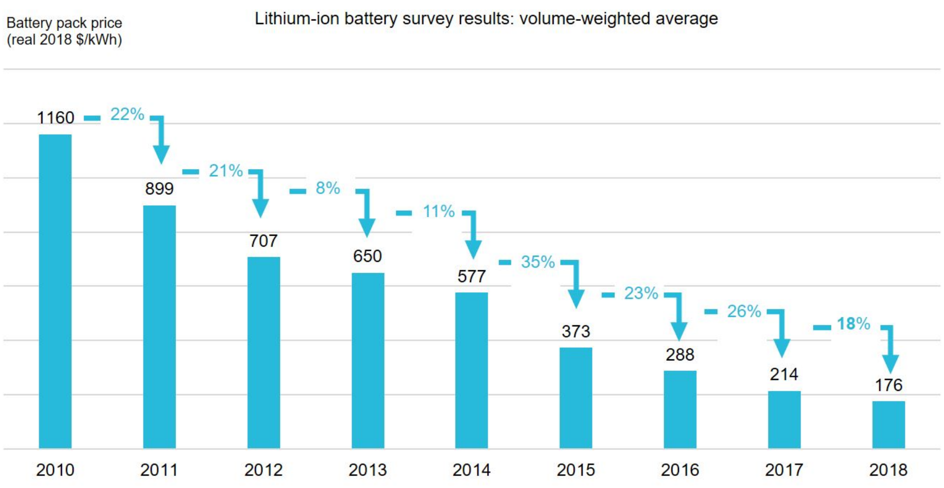
Within the last decade, PV module prices have decreased by 90% and system prices have dropped by around 80%. Today, all over Europe PV is already cheaper than the average electricity spot market price (Vartiainen et al. 2019).

In contrast, thermal power plants show constant or even increasing LCOE as a function of increasing fuel prices, high transportation costs and approaches to pricing CO_2 emissions such as the European Emissions Trading System (EU ETS).

The transformation of power systems and the divergence of the LCOE of renewable and thermal power generation led to changes in the merit order but also in the power purchase agreement (PPA) structures. While thermal power plants were used to provide the base load, they now tend to be used as peaking capacity, when generation of intermittent RES is not sufficient. Thus, the profitability of conventional power generators is decreasing.

Recent studies show that within the next few years, RES will outperform conventional power generation when it comes to cost (McKinsey 2019).

In addition, the technological and economic development of battery storage systems is accelerating this trend. Within the last few years, the cost of storage systems remarkably decreased and the cost of battery systems is expected to fall by 50-66% by 2030 (IRENA 2017) due to mass production and second life use of electric vehicles' batteries (Casals et al. 2019).



Graphic 2: Source: BloombergNEF.

In addition, the intermittency of RES and the increasing need for balancing leads to high redispatch costs or calls for additional investment in the transmission grid, resulting in higher energy costs for the end consumer. Germany for example, faces annual network and system security costs of about €1.4 bn (Bundesnetzagentur 2018), due to lacking transmission network capacities.

Therefore, centralized power systems are expected to undertake massive transmission grid investments in order to effectively integrate RES, while reducing external dependencies. Hybridization and decentralization address this point. The increased number of mixed assets within decentralized hybrid power systems offers high potential for optimizing the power systems' reliability and reducing energy costs through intelligent dispatch without additional transmission grid investments.

Social aspects

Energy demand is expected to double by 2050 (McKinsey 2019). Within the last century, technological innovations turned electricity into a key resource, and the availability and affordability of electricity serve as the basis for satisfying fundamental human needs, such as nutrition, education, healthcare, and social services.

However, many developing countries and rural areas are still confronted with an absence of electricity (Shyu 2014). As projects like Palau's "Armonia" power system show (ENGIE EPS), decentralized hybrid power generation can provide reliable and affordable power generation all over the world.

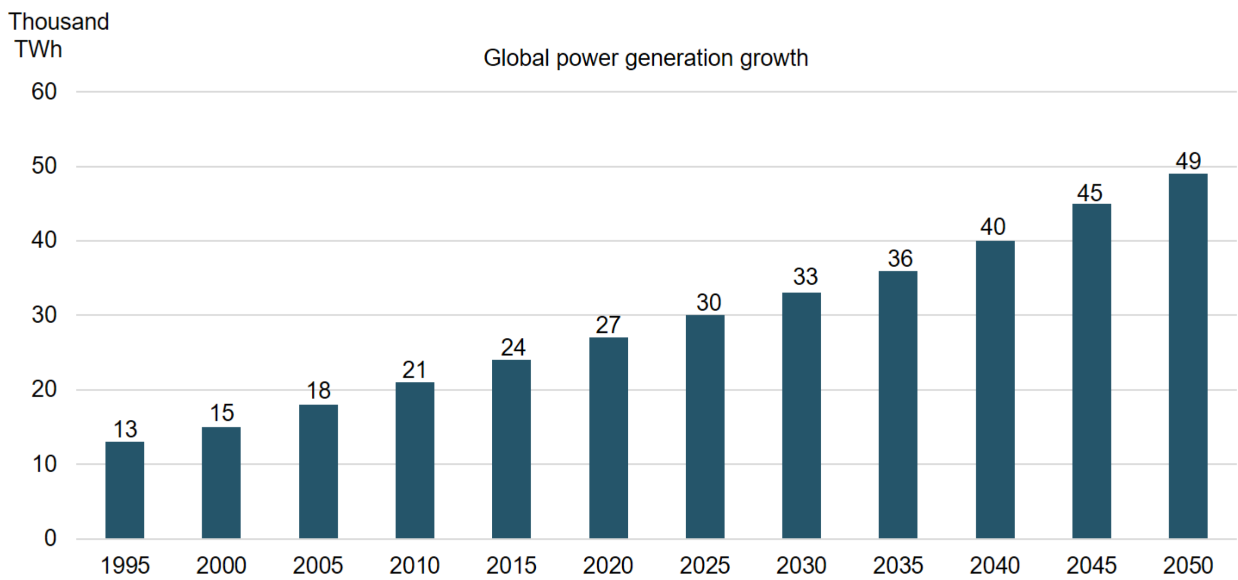
Furthermore, an awareness of the issues of climate change and sustainability is gaining global importance. Eco-conscious societies demand a reliable power supply with the highest possible shares of RES. The hybrid systems of Bonaire and El Hierro showed that hybridization could build the bridge towards systems with high shares of RES.

Political aspects

In line with the social demand for sustainability, policymakers from all over the world signed the Paris Agreement in 2015 to limit global warming to 1.5°C. They committed to decarbonization and introduced national as well as international legislation that promotes hybrid power systems and the integration of RES.

Such legislation aims to reduce emissions through either pricing them, as with the European EU ETS, or by penalizing investments in power plants that do not consider RES, as is the case with renewable purchase agreements (RPA). On the other hand, many countries have introduced subsidies for RES and high-efficiency plants to promote renewable power generation.

The following SWOT analysis illustrates the strengths and weaknesses as well as opportunities and threats of hybrid power generation. Furthermore, it is possible to identify the techno-economic capabilities of a state-of-the-art hybrid system.



Graphic 3: Source: Energy Insights by McKinsey: Global Energy Perspective 2019: Reference Case

SWOT analysis for hybrid power generation

Strengths	Weaknesses
– Integration of RES and battery storage systems reduces operational costs, fuel consumption and CO_2 emissions of the overall plant – Reduced dependency and insurance against increasing fuel prices (incl. transportation) and potential emission costs – Security of supply, due to combination of RES, battery storage systems and highly flexible engine power plants – Battery storage systems make it possible to maximize RES penetration and compensate for fluctuations	– Redundant design results in higher CAPEX due to additional investments for RES and storage – High complexity (planning and operation) due to integration of various hardware components demands additional efforts for interface and stakeholder management – Intelligent control systems and dispatch algorithms are key to the overall performance and economic efficiency – Profitability of integrating RES depends to a large extent on location and resources – Intensive decision-making support tools for planning and design optimization of hybrid power plants
Opportunities	**Threats**
– Access to attractive project financing and avoidance of additional renewable purchase obligations (RPO) in specific countries – Support of RES integration with limited or even no transmission grid investments – Transition from coal- or liquid-fuel-based power generation to RES and flexible gas generation – Reduced LCOE make it possible to maximize profit – Hybridization of existing conventional systems possible with low investment costs – Engine power plants can be operated with synthetic fuels and enable a energy system based on 100% RES	– Profitability depends on availability of subsidies, fuel savings and cost development of OPEX – Weak supporting schemes (e.g. special PPAs for hybrid systems) – Unsatisfactory performance due to lack of interface management and IT infrastructure – Uncertainty about cost development of battery storage systems and their impact on the environment – Uncertainty about technology development of different storage systems

Table 1: SWOT analysis for hybrid power generation

Hybrid power in islanded power systems

Islanded power systems

A typical application of hybrid power solutions is small isolated islanded power systems. On small islands with a population of up to 100,000 inhabitants, the main economic activities are in the primary sector and tourism, which, in addition to residential activities, mostly define the energy demand (Neves et al. 2014).

The self-supply of electricity is a major challenge. The lack of a grid connection and limited access to fossil fuels and their high import costs result in high external dependencies and increasing energy prices (Godina et al. 2015). To reduce external dependencies, small islands aim to exploit their local natural resources.

Hence, the integration of RES is taking on crucial importance for social, economic and environmental development. Therefore, many islanded power systems have transformed from diesel-based power generation to RES (Neves et al. 2014).

However, the integration of RES into small power systems can be more difficult due to low system inertia, grid topology and the geographical concentration of RES (Marrero Quevedo et al. 2018). As a result, the isolation demands a larger reserve capacity and accurate dimensioning of the power system in order to ensure a reliable power supply (Neves et al. 2014).

To address these challenges and increase the availability and reliability of power, a hybrid approach can be chosen. As the cases of El Hierro and Bonaire show, the integration of RES and storage systems complementing thermal power plants can build the bridge towards systems with high shares of renewable power generation.

The example of a small Indonesian island

In the following, the cost structure of different hybrid designs will be described, using an Indonesian island as an example. We consider an islanded region with around 12,500 inhabitants, with an average load of 3.4MW and a peak of 4.6MW.

As the island is located near the equator within the Indonesian archipelago, solar irradiance is very constant throughout the year. Thus, PV production offers high potential, and its penetration can be increased by adding a BESS. Over the last few years, thermal diesel-fired power plants supplied the inhabitants with electricity.

Hence, we will analyze the following design specifications.

Specification	Thermal generation	PV	Battery
Engine only	3*2.8MW MAN 9L27/38 gensets	Not included	Not included
Engine + battery	2*2.8MW MAN 9L27/38 gensets	Not included	1MWh with 2.8MW converter
Engine + PV	3*2.8MW MAN 9L27/38 gensets	6.5MW	Not included
Engine + battery + PV	2*2.8MW MAN 9L27/38 gensets	6.5MW	1MWh with 2.8MW converter

Table 2: Design specifications of islanded power systems

The thermal generation consists of two heavy-fuel-oil-fired (HFO) MAN 9L27/38 gensets with a BESS or an additional genset as backup. The fuel price is $0.58/liter (transportation costs included), which is assumed to be constantly increasing by 1% p.a.

We consider a weighted average cost of capital (WACC) of 10% and a project lifetime of 20 years. Furthermore, we assume that electricity is sold for a 20-year PPA of $0.17/kWh that has the same annual increase rate as the fuel price.

At the end of the project, the engines can be sold at the salvage value (i.e. the product of replacement cost and the relative remaining machine lifetime). The optimization of the given designs leads to the following results

Specification	LCOE ($ct/kWh)	OPEX ($/a)	CAPEX ($)	Fuel consumption (l/a)	Emissions (t/a)	RES share
Engine only	17.88	3.8 million	12.9 million	6.3 million	18.9 million	0
Engine + battery	16.37	4.0 million	9.5 million	6.2 million	18.6 million	0
Engine + PV	15.85	3.1 million	17.1 million	4.7 million	14.2 million	26%
Engine + battery + PV	14.98	2.9 million	15.8 million	4.5 million	13.5 million	27%

Table 3: Optimization results of islanded power systems

If we consider a non-hybrid design specification with only thermal power generation, the annual OPEX amounts to $3.8 million and the CAPEX is at $12.9 million. This results in a LCOE of $17.88ct/kWh. As the LCOE is higher than the PPA at the beginning of the project, the project might not be economically viable.

Therefore, a hybrid solution is necessary in order to reduce costs and to achieve affordable power generation. Taking “Engine only” as the benchmark, the costs of power generation are as outlined below. As the subsequent table shows, hybridization is able to reduce the LCOE by at least 8% and leads to economically viable power generation.

Specification	LCOE	OPEX	CAPEX	Fuel consumption & emissions
Engine only	100%	100%	100%	100%
Engine + battery	92%	106%	74%	98%
Engine + PV	89%	81%	133%	75%
Engine + battery + PV	84%	78%	122%	71%

Table 4: Cost and emission savings through hybridization in islanded power systems

As the integration of BESS is able to replace one thermal genset, the CAPEX can be reduced by around 25%. As a result, the investment pays off after almost nine years. Even if the OPEX slightly increases due to cell replacement, the LCOE can be lowered to $16.36ct/kWh. Hence, the NPV increases to $7.6 million and the IRR amounts to 15.1%.

Complementing thermal generation by PV, RES shares of around 26% are possible. The additional investment in PV modules increases the overall CAPEX by around 30%. The payback is reached after ten and a half years. How-ever, the OPEX can be decreased by around 35% due to reduced fuel consumption. Overall, the LCOE decreases to less than $0.16/kWh and the NPV amounts to $10.2 million. Furthermore, the project shows an IRR of 20.3%.

If we consider a fully hybrid system with thermal generation, PV and BESS, the share of RES can be increased to 27%, while the LCOE is below $0.15/kWh. As the emissions and fuel consumption decrease by around 30%, the OPEX can be reduced to 78%. In addition, the combination of BESS and PV lowers the CAPEX increase to 22%. The system will pay off after almost nine years and the NPV can be increased to around $13 million with an IRR of 15.3%.

Hybrid power in remote power systems

Power generation at mining facilities

As minerals in easily accessible places are getting fully exploited and the demand for metals and minerals is constantly increasing, mining operations are moving to more and more remote areas (Paraszczak and Fytas 2012). Like islanded power systems, remote areas all around the world, such as mines, face the challenges of availability, reliability and affordability of electricity supply, as there is no access to the transmission grid and transportation costs are very high.

Building up a mine from scratch includes expanding or constructing new infrastructure, which demands high amounts of energy. Thus, mining companies aim to establish their own stable power generation first, in order to reduce the rental costs of gensets or to avoid high electricity prices and the high cost of transmission grid investments. Although the electricity demand increases over time, the modular character of hybrid power systems makes it possible to increase power generation easily through adding new components to the system and adapting power generation to the demand (Mitra et al. 2008).

While the cost of wind and solar energy has fallen by more than 60% since 2014, renewables have become a key asset of mines all around the world in order to lower their energy bills (Millian Lombrana and Stillings 2018). Especially in areas with constant solar irradiation or constant wind speeds, RES provide the first stage of power generation. They are later complemented by thermal power generation and additional storage solutions, to ensure high overall power system availability during commercial operation. With the aim of minimizing the LCOE and achieving maximum RES penetration, thermal power plants need to be highly flexible and efficient in part load.

In addition, due to a limited project lifetime from five up to forty years, depending on reserves and economic factors (Paraszczak and Fytas 2012), early payoff of the power system is important. Therefore, the economic optimization of the hybrid power plant's design and operation is indispensable in order to ensure an affordable power supply.

The example of a mining project in Madagascar

In the following, we analyze a mining project located in the southwest of Madagascar. We consider a mine in 24/7 operation, with a constant electricity demand of around 9MW. As the load increases over time, mining projects are built up incrementally, thus thermal generation is provided through HFO-fired small-bore gensets.

Furthermore, the location is subject to high solar penetration that allows the integration of high shares of PV.

Therefore, the following design specifications for power generation are possible and will be further analyzed.

Specification	Thermal generation	PV	Battery
Engine only	7*1.8MW MAN 9L21/31S gensets	Not included	Not included
Engine + battery	7*1.8MW MAN 9L21/31S gensets	Not included	0.8MWh with 1.8MW converter
Engine + PV	7*1.8MW MAN 9L21/31S gensets	18MW	Not included
Engine + battery + PV	7*1.8MW MAN 9L21/31S gensets	17MW	0.8MWh with 1.8MW converter

Table 5: Design specifications for power systems of mining projects

Every design specification includes thermal generation, which is provided by six MAN 9L21/31S engines with a BESS or an additional engine as backup capacity. We assume a fuel price of $0.58/kWh, which is constantly increasing by 1% p.a.

We consider a project lifetime of 20 years and a WACC of 10%. At the end of the project, the engines can be sold at the salvage value (i.e. product of replacement cost and relative remaining machine lifetime).

The electricity can be sold for a 20-year PPA with a price of $0.15/kWh. The optimization of the different design specifications leads to the following results.

Specification	LCOE ($ct/kWh)	OPEX ($/a)	CAPEX ($)	Fuel consumption (l/a)	Emissions (t/a)	RES share
Engine only	14.75	10.6 million	4.7 million	4.1 million	49.0 million	0
Engine + battery	14.73	10.6 million	4.7 million	4.1 million	48.9 million	0
Engine + PV	12.49	7.3 million	22.1 million	2.6 million	33.0 million	33%
Engine + battery + PV	12.45	7.4 million	21.2 million	2.6 million	33.3 million	32%

Table 6: Optimization results of mining projects' power systems

If we consider a conventional design specification, the LCOE amounts to almost 14.75$ct/kWh with CAPEX of $4.7 million. The project results in an NPV of $2 million, an IRR of 11.4% and a payback time of 4.9 years.

Taking the engine-only specification as the benchmark, the relative costs and emissions of the different specifications are as outlined below:

Specification	LCOE	OPEX	CAPEX	Fuel consumption & emissions
Engine only	100%	100%	100%	100%
Engine + battery	100%	100%	100%	100%
Engine + PV	85%	69%	472%	67%
Engine + battery + PV	84%	69%	451%	68%

Table 7: Cost and emission savings through hybridization of mining facilities

The results show that the integration of PV reduces the LCOE by around 15%. Even if PV is linked to high CAPEX, the OPEX reductions of around 30% are able to reduce the overall costs. Therefore, hybridization enables emission reductions and RES shares of 30% without facing LCOE increases. Because of the high CAPEX, the payback time increases to 6.7 years. However, the “Engine + PV” specification has an NPV of around $20.2 million, with an IRR of 17.7%.

Complementing thermal generation by PV and BESS replaces one engine and reduces the optimal amount of PV power. As a result, the CAPEX as well as the LCOE decrease compared to the “Engine + PV” specification, which reduces the payback time to 6.4 years. Thus, the project’s NPV increases by an additional 2% compared to the “Engine + PV” system while the IRR amounts to 18.4%.

Through choosing a system of thermal generation and BESS, it is possible to replace one engine. However, the integration of BESS does not influence the cost structure, as the BESS CAPEX and OPEX do not remarkably differ from the engines’ CAPEX and OPEX. However, a slight reduction in emissions, CAPEX and fuel consumption is apparent (Table 6), which reduces the payback time to 4.8 years. In addition, the NPV increases by 4% with respect to the “Engine only” specification. The IRR amounts to 18.4%.

Therefore, the mining case shows that hybridization of base-load power generation needs to include RES such as PV in order to influence the cost structure and reduce emissions with respect to an “Engine only solution”.

Assumptions made

General assumptions

Project lifetime	20 years
Discount rate	10%
Inflation rate	3%
WACC	10%
Fuel price (HFO)	$0.58/liter
Fuel price increase	1% per year

Battery

Type	Li-ion
CAPEX	$452/kWh
OPEX	$305/year
Converter CAPEX	$172/kW
Converter OPEX	$11/kW
Converter efficiency	98%
Degradation limit	25%
Replacment cost	$286/kWh

PV

CAPEX	$970/kW
OPEX	$10.5/kW*year

MAN 9L 27/38

CAPEX	$4.3 million
OPEX	$14/operating hour
Minimum load	25%
Minimum runtime	30 min

MAN 9L 21/31S

CAPEX	$0.7 million
OPEX	$9/operating hour
Minimum load	25%
Minimum runtime	30 min

Bibliography

[1] BloombergNEF (2018): Emerging Markets Outlook 2018.

[2] Bundesnetzagentur (2018): Quartalsbericht zu Netz- und Systemsicherheitsmaßnahmen. Gesamtjahr und Viertes Quartal 2017 [German Federal Network Agency (2018): Quarterly report on network and system security measures. Whole year and Quarter 4 2017]. Edited by Bundesnetzagentur.

[3] Casals, Lluc Canals; Amante García, Beatriz; Canal, Camille (2019): Second life batteries lifespan. Rest of useful life and environmental analysis. In *Journal of environmental management* 232, pp. 354–363. DOI: 10.1016/j.jenvman.2018.11.046.

[4] ENGIE EPS: The Republic of Palau and ENGIE EPS launch ARMONIA: the largest microgrid in the world to pioneer access to affordable and reliable clean energy. Available online at https://engie-eps.com/news/2018/10/12/the-republic-of-palau-and-engie-eps-launch-armonia-the-largest-microgrid-in-the-world-to-pioneer-access-to-affordable-and-reliable-clean-energy/.

[5] Godina, R.; Rodrigues, E. M. G.; Matias, J. C. O.; Catalão, J. P. S. (2015): Sustainable Energy System of El Hierro Island.

[6] Hunter, Ray; Elliot, George (Eds.) (1994): Wind-Diesel Systems. A guide to the technology and its implementation. Cambridge: Cambridge University Press.

[7] IRENA (2017): Electricity Storage and Renewables: Costs and Markets to 2030.

[8] IRENA (2018): Renewable Power Generation Costs in 2017.

[9] Marrero Quevedo, Augustín; Medina Domínguez, Elías J.; de León Izquier, Jesús M.; Corujo de León, Rubén; Santos Arozarena, Pablo; Gil Moreno, Juan et al. (Eds.) (2018): Gorona del Viento Wind-Hydro Power Plant. 3rd International Hybrid Power Systems Workshop. Tenerife, Spain, May 8 - 9, 2018.

[10] McKinsey (2019): Global Energy Perspective 2019: Reference Case.

[11] Millian Lombrana, Laura; Stillings, Jamey (2018): These Massive Renewable Energy Projects Are Powering Chilean Mines. A surge in solar, geothermal, and wind development is helping to wean the industry off imported fossil fuels. Edited by Bloomberg Businessweek. Available online at https://www.bloomberg.com/news/features/2018-08-07/these-massive-renewable-energy-projects-are-powering-chilean-mines.

[12] Mitra, Indradip; Degner, Thomas; Braun, Martin (2008): Distributed Generation and Microgrids for Small Island Electrification in Developing Countries: A Review. In *SESI Journal*.

[13] Neves, Diana; Silva, Carlos A.; Connors, Stephen (2014): Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies. In *Renewable and Sustainable Energy Reviews* 31, pp. 935–946. DOI: 10.1016/j.rser.2013.12.047.

[14] Paraszczak, J.; Fytas, K. (2012): Renewable energy sources – a promising opportunity for remote mine sites? In *REPQJ*, pp. 251–256. DOI: 10.24084/repqj10.288.

[15] Shyu, Chian-Woei (2014): Ensuring access to electricity and minimum basic electricity needs as a goal for the post-MDG development agenda after 2015. In *Energy for Sustainable Development* 19, pp. 29–38. DOI: 10.1016/j.esd.2013.11.005.

[16] Vartiainen, Eero; Masson, Gaëtan; Breyer, Christian; Moser, David; Román Medina, Eduardo (2019): Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. In *Prog Photovolt Res Appl* 364 (6443), p. 836. DOI: 10.1002/pip.3189.

MAN Energy Solutions
86224 Augsburg, Germany
P + 49 821 322-0
F + 49 821 322-3382
info@man-es.com
www.man-es.com