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Techno-economic Analysis of Battery Energy Storage for Reducing Fossil Fuel Use in Sub-Saharan Africa

Transforming Energy Access

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Transforming Energy Access (TEA) is a research and innovation platform supporting the technologies, business models and skills needed to enable an inclusive clean energy transition

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Abbreviations

Abbreviation	Meaning
B/C ratio	Benefits/Costs ratio
BAU	Business As Usual
BESS	Battery Energy Storage System
BMS	Battery Management System
BSDG	Black Start Diesel Generator
CAPEX	Capital Expenditures (investment costs)
CCGT	Combined Cycle Gas Turbine
DG	Diesel Generator
EMS	Energy Management System
ESS	Energy Storage System
FFG	Fossil-Fuel Generator
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
HV	High Voltage
IDB	International Development Bank
IPP	Independent Power Producer
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
MV	Medium Voltage
NPV	Net Present Value
OCGT	Open Cycle Gas Turbine
OHL	Overhead Line
OPEX	Operational Expenditures
PCS	Power Conditioning System (converter, “battery inverter”)
PPA	Power Purchase Agreement
PPP	Public Private Partnership
SA	South Africa
SSA	Sub-Saharan Africa
WACC	Weighted Average Cost of Capital

1 EXECUTIVE SUMMARY

1.1 Project Background

Despite the considerable potential provided by an abundance of natural resources, sub-Saharan Africa (SSA) remains one of the most under-developed regions in the World. Only 35-40% of the population has access to affordable and reliable electricity, a prerequisite for economic and social development. One out of every two people born between now and 2040 will be in Africa. Providing the energy required to meet their needs and ensure that they can enjoy access to basic services from health to education presents challenges at many levels.

Transforming Energy Access (TEA) is funded by UK aid from the UK government. TEA is a research and innovation platform supporting the technologies, business models and skills needed to enable an inclusive clean energy transition. Through this program the Faraday Institution has received funding to research new battery technologies and conduct relevant techno-economic and related studies into battery-based solutions that have the potential to replace fossil-fuel powered generators and increase the uptake of cheaper, cleaner and more reliable energy in Overseas Development Assistance (ODA)-eligible countries.

Replacing generators and smoothing energy supply in areas of SSA where the national grid is unreliable or non-existent presents a significant market opportunity. Around 12-17 billion USD is spent on back-up generation every year in Nigeria alone and 9% of all the electricity consumed across SSA is supplied by generators. The rapidly falling costs of battery storage technology and supporting equipment such as PV panels makes the business case for their deployment more attractive each year. Per capita energy consumption is anticipated to more than double by 2040 and demand from industrial and service sector actors more than triple. This constitutes a significant opportunity for private sector providers of equipment locally and internationally.

The benefits extend beyond those directly servicing this demand. Improving the quality of energy access and smoothing intermittent supply has significant advantages for industries faced with idle machines because of grid downtime. Installing decentralised energy storage facilities at the utility and commercial scale also supports national interests by easing the burden on stressed infrastructure.

Perhaps most important are the human benefits. Diesel and petrol generators produce smog (NO_x, SO_x), Particulate Matter (especially $PM_{2.5}$), Ozone (O_3), CO emissions and noise pollution which directly harm human health. Burning fossil fuels also releases significant carbon dioxide into the atmosphere which exacerbates the problems of global warming and it is the global poor, most of whom are in SSA, that are disproportionately affected. The IFC estimates that replacing 25 million diesel and petrol generators in developing countries (excluding China) with energy storage technologies could save up to 100 million tonnes of CO_2 emissions per year.

Battery storage technologies can keep hospitals and schools delivering essential services as well as keeping factory floors humming and economies productively active. They can also enable off-grid energy delivery models like mini-grids that are the most affordable way of providing power to 111 million of the 238 million unelectrified households across sub-Saharan Africa.

This study, commissioned by the Faraday Institution, explores how novel energy storage technologies can be viable and competitive in SSA, offering alternative solutions for resilience and grid independence, enabling the integration of more utility-scale renewables and bringing electricity and opportunity to the least developed corners of the continent.

1.2 Project General Approach

The assessment of how battery energy storage can reduce fossil fuel use in Sub-Saharan Africa is based on:

1) An assessment of the current value chains, market structure and local conditions for fossil fuel generators, as well as what the value chain for battery energy storage solutions could look like and also a review of the main business cases or market sectors where energy storage could be competitive

2) the development of a techno-economic model that allows these main business cases (as well as other business cases) to be studied in detail and provide insights into when certain applications become commercially viable.

The value chain assessments and business cases are split between small-scale (up to five MW capacity) and utility-scale applications (approximately from ten to one hundred MW capacity), as these have very different dynamics and economics. The following five main business cases are assessed in this study:

- Business Case A: Mini Grid (small scale)
- Business Case B: Captive and Behind-the-Meter Applications (small scale)
- Business Case C: Off-Grid Industrial Facilities (utility-scale)
- Business Case D: Avoided T&D Expansion (utility-scale)
- Business Case E: Hybrid Solar and Wind Plants (utility-scale).

The model contains costs and performance forecasts for future years, allowing the user to assess how a certain business case could develop over time and determine by what year it may become feasible.

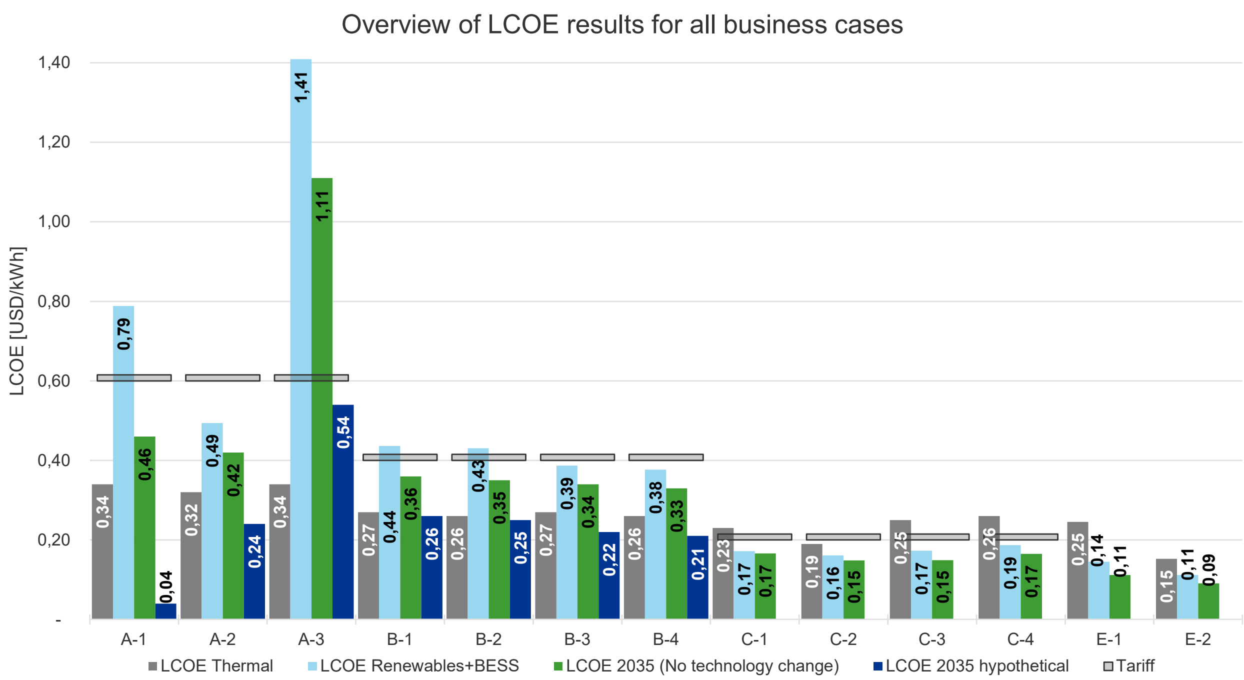
1.3 Current Opportunities for BESS to Displace Fossil Fuel Generators

The current opportunities for BESS replacing FFGs are driven by:

- The high cost of fuel
- The high opportunity cost due to unreliable electricity supply
- Weak, unreliable, or non-existent main power grids
- The availability of BESS in the local market at competitive costs
- Government or IDB support for implementing BESS and renewables projects.

The first three points are significant for many regions in SSA. BESS availability and support schemes are improving but are still lacking in many SSA countries. Figure 1 shows the LCOE results for all the business cases developed in the techno-economic model, and how these LCOEs change as the cost of battery technology decreases and other actions are implemented. The horizontal bars represent the tariffs (generally) applicable to these business cases (A-1, A-2, A-3, B-1 etc.) and the vertical columns the LCOE of the power supply systems.

The LCOE Thermal column presumes diesel or gas only power systems, LCOE Renewables + BESS can be considered a “base-case” with solar and battery storage added to the system at current battery cost and performance. LCOE 2035 presumes 2035 solar and battery cost and is split in two. “No technology change” assumes that today’s battery technology of choice is still applied in 2035. The hypothetical case presumes that cost and performance levels of utility-scale Li-ion battery technology are attained for the specific business case. This represents an estimated floor to LCOEs in the absence of disruptive technology change and with a highly successful mitigation of logistical, scale, regulatory, and knowledge barriers. Note that the latter is not applied to cases C and E as these already rely on utility-scale Li-ion technology. Section 4 describes each of the business cases analysed and the modelling results in more detail.



Case	Description
A-1	Mini-Grid (Off-grid), Greenfield, Located at a tea estate with high demand 4:00-6:00 and 17:00-21:00.
A-2	Mini-Grid (Off-grid), Greenfield, Island mini grid with high demand during day (businesses) and evening (domestic).
A-3	Mini-Grid (Off-grid), Brownfield, Village mini grid with peak demand at the evening (domestic).
B-1	Captive and Behind-the-Meter (Off-grid), Brownfield, Safari lodge in Tanzania.
B-2	Captive and Behind-the-Meter (Off-grid), Greenfield, Safari lodge in Tanzania.
B-3	Captive and Behind-the-Meter (On-grid), Brownfield, Manufacturing company in Kenya.
B-4	Captive and Behind-the-Meter (On-grid), Greenfield, Manufacturing company in Kenya.
C-1	Off-grid Industrial, Greenfield, Manufacturing company in Kenya, Diesel as reference.
C-2	Off-grid Industrial, Greenfield, Manufacturing company in Kenya, Natural gas as reference.
C-3	Off-grid Industrial, Brownfield, Processing factory in Sierra Leone, Diesel as reference.
C-4	Off-grid Industrial, Brownfield, Processing factory in Sierra Leone, Natural gas as reference.
E-1	Avoided Transmission & Distribution Expansion (On-grid), BESS connected at 33kV substation to avoid new overhead lines and substation expansion.
E-2	Avoided Transmission & Distribution Expansion (On-grid), Same as D-1 but also avoiding new generation capacity by reducing total peak demand.

Figure 1: Overview of LCOE results for business cases A to E

The results from the techno-economic modelling suggest that, for smaller and medium sized systems, a solar and BESS supported system does not yet provide a viable alternative to a diesel or gasoline only system in terms of cost. The green bars labelled ‘LCOE 2035 (no technology change)’ illustrate how forecasted cost reductions of the deployed battery technology do not result in cost parity with diesel or gasoline only systems. The dark blue bars labelled ‘LCOE 2035 hypothetical’ assume that forecasted utility-scale Li-ion prices and performance can be achieved for these small and medium sized systems. This hypothetical scenario shows that it is possible to achieve cost parity to thermal prices if the cost of small-scale BESS can approach that of the utility scale batteries per kWh. However, achieving this cost is subject to unlocking the technology for use in particular applications and locations.

Strategies to pursue this include:

- Enabling larger volume procurement to get access to lower factory pricing and more direct value chains with a lower overall mark-up
- Reducing transportation costs, which represent up to a third of BESS installed costs
- Standardising BESS offerings to lower plant costs
- Creating and disseminating tools which can correctly size BESS by applications, forecast the degradation, and optimise for augmentation of BESS rather than replacement during project lifetime.

- Standardising technical requirements (including grid codes) to reduce project specific engineering and design needs.

Off-grid industrial facilities that have considerable power and energy requirements do already benefit from utility-scale Li-ion technology. The LCOE of a hybrid system consisting of solar, BESS and diesel (or natural gas) generators is already lower than diesel only system at today's prices. As discussed in Section 4, this is already valid for the medium fuel price forecasts included in the techno-economic model. Forecasted reduction in cost of Li-ion technology will only improve the business case further.

The techno-economic modelling both mini-grids, and small- medium-scale behind-the-meter storage applications indicates that diesel-only configurations currently result in lower cost to end user than those incorporating battery technology for each of the case studies A and B (i.e. those pertaining to small and medium system). This is because the (specific) costs of smaller battery systems for these end-users are simply too high due to lack of scale in procurement, high transport cost, and less than optimal system design and operation. Forecasted cost reductions for small and medium sized systems of ~26% for small-scale Li-ion and ~23% for small-scale lead acid by 2035 to end-users will not make a significant change in the proposition of BESS for these small-scale projects.

Techno-economic modelling of the larger Li-ion BESS for off-grid industrial applications and utility-scale hybrid plants indicate that the technology is already competitive on displacing a large portion of diesel or natural gas consumption. Forecasted reductions in cost will only strengthen this conclusion. However, fully displacing diesel or natural gas generators by renewable energy with BESS is not yet feasible for traditional energy networks where flexibility in demand is limited or non-existing. If load demand for electricity remains constant, the cost of BESS (now and for the next five years) is too high to install batteries large enough to bridge multi-day periods of adverse solar and wind conditions.

1.4 Main Barriers for Further BESS Deployment

Recent improvements in the technical performance of Li-ion BESS have meant that most customer requirements have been met. The main remaining barrier to deployment is the (investment) costs, with purchasers (except utility-scale projects) finding it difficult to access the capital required to install the batteries. Figure 2 shows the large discrepancy in the installed cost of Li-ion systems of small to medium installations (<5MW) compared to large systems.

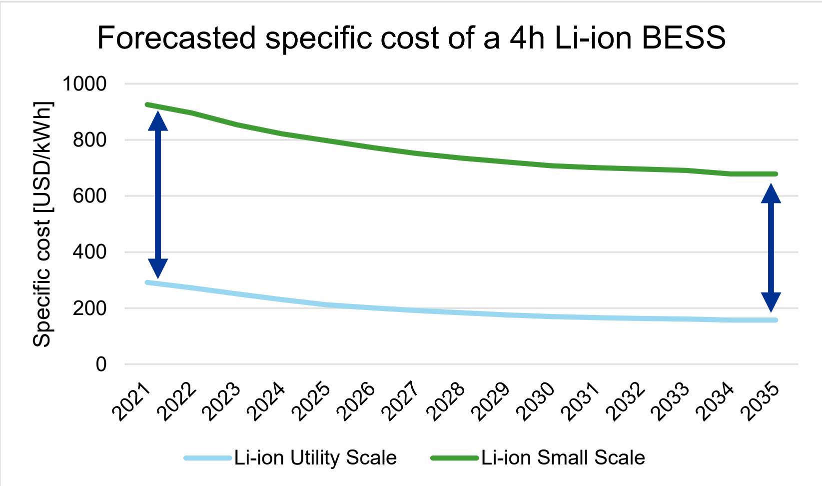


Figure 2: Specific cost for a small and utility-scale 4h Li-ion BESS

The installed cost of 1kWh up to 1MWh BESS is up to three times more expensive than the same (Li-ion) technology for utility scale systems. Addressing the cost of system integration, logistics, import duties, and relatively weak procurement positions should help bring the cost for smaller systems closer to that of the utility-scale systems. Although Li-ion technology is the same for small- and large-scale systems, operators deploying smaller systems generally do not have sufficient access to state-of-the-art expertise on designing battery energy storage systems, modelling the use cases, and resulting degradation. Nor do they install advanced monitoring to track the health of the battery. Improving these skills could help bring down the cost of Li-ion deployment for small and medium sized projects, and in doing so, enable the displacement of fossil fuel technology.

In summary, there is a need for capacity building in technical knowledge throughout the value chain to ultimately improve project returns through better planning, operation, and maintenance of systems.

There are also requirements for innovative business cases, payment structures and financing options, as well as the implementation of governmental policies that enable open market energy trading.

1.5 Role of Innovative Technology to Support BESS Deployment

A considerable amount of research and development (R&D) in energy storage technology is funded by a myriad of companies spanning various industries including automotive, aerospace and consumer electronics. This not only reflects the wide spectrum of applications of BESS, but also the interest and belief in its future potential. Within the stationary energy storage space, the past decade has seen a lot of innovation in the development of application specific solutions based on particularly Li-ion battery technology advancements by the automotive industry. There are increasingly novel energy storage solutions using all forms of energy (chemical, thermal, mechanical, electrical) coming to market, some exploiting a particular niche and others offering cross cutting benefits.

The Li-ion BESS industry has seen significant funding and R&D focussed on optimising performance, energy density and safety, from the growing electric vehicle market. As a result, BESS performance metrics have seen transformational improvements over the last five years. However, these gains on energy density, safety and cycle life are expected to be more incremental in the next few years rather than disruptive. Developments in next generation technologies such as solid-state batteries could deliver a further leap in performance in the next 5-10 years, however the time to commercialisation should not be a reason to wait for ‘the next generation’, as the current technologies already provide significant benefits in many applications.

Novel battery technologies with lower costs or better lifetimes than current Li-ion technology may represent a turning point for widespread implementation. As previously mentioned, the role of state-of-art battery degradation, usage and maintenance forecasting will enable advanced battery augmentation strategies as opposed to standardised replacement strategies. However, the modelling results indicate that even these augmentation strategies alone are insufficient to bring renewable electricity production down to the cost of small-scale petrol or diesel-only systems.

Li-ion BESS are now widely deployed in cars and can be considered safe if properly managed and monitored. However, safety concerns, particularly thermal and mechanical abuse tolerances, increase for Li-ion batteries that operate in rural locations, and without regular maintenance. The search for a safer battery is a driving force of innovation across multiple sectors such as automotive and defence applications, as well as the expected deployment of more Li-ion batteries in underground mining equipment, where safety is paramount. Due to these safety concerns and the generally harsh climates in Africa, a case for a generic “rural battery” can be made that makes use of a more robust battery that has the performance and cost reduction potential of Li-ion to act as a “drop-in” replacement to lead-acid batteries for small mini grids.

Globally, the automotive industry will deploy a large quantity of Li-ion batteries and manufacturers are targeting the recycling of Li-ion batteries to repurpose for BESS in SSA markets. Other manufacturers are experimenting with re-using (2^{nd} life) batteries in stationary storage, where used EV batteries can provide valuable services even if their use in a car is no longer attractive due to aging after years of use. The concept of 2^{nd} life batteries as a cost-effective source of stationary energy storage is interesting and it is being developed further. However, there are several challenges:

- A high degree of technical difficulty to assess the state-of-health and safety of 2^{nd} life batteries by third parties. However, EV manufacturers do extensive data logging, and can have a reasonable to good picture on a BESS state of health or overall quality.

- The logistics from sourcing to deployment is very complex. It is difficult to match batteries of different makes and state-of-health to produce functional refurbished battery modules/racks, containers, or entire systems. The maintenance of BESS at remote locations is already challenging and using 2nd life batteries will further increase the need for maintenance.
- National regulation would need to treat 2nd life batteries as a resource and not chemical waste, while also ensuring that the imported batteries are refurbished under acceptable conditions and not disposed of. This also represents a risk of reputational damage for EV manufacturers if their 2nd life batteries are not used as designed and cause accidents or negative environmental impacts.

Innovation in finance or payment structures has seen some success in Asia, where public charging pods allow electric scooter drivers to come and exchange their removable, depleted battery for a charged battery with payment via card or smartphone enabling a quick exchange. Different forms of leasing models can also play a role, moving towards energy storage as a service.

1.6 Emerging BESS Applications and Value Chains

Battery energy storage is increasingly being deployed across SSA. The following points characterise the market:

- Most batteries are imported from China as locally produced batteries cannot compete with imported batteries on quality, variety, and price.
- The availability of different types of BESS has been limited in most African markets:
    - Lead-acid BESS make up the largest share of all deployed energy storage
    - In many African countries, manufacturers of car batteries will also manufacture deep-cycle batteries
    - Mini grid operators experience shorter-than-expected lifetimes of lead-acid batteries
- Lithium-ion (Li-ion) batteries are starting to find application in more mature African markets (South Africa, Kenya, Nigeria) and for specific high-value cases:
    - Many of these are direct diesel replacement projects with estimated payback periods of 3-6 years
    - Affordability has been a challenge for smaller projects. In response, several start-ups are offering smaller lithium-ion systems combined with innovative financing arrangements
    - In solar home systems, Li-ion batteries are the technology of choice compared to lead-acid batteries
    - Innovative pay-as-you-use business models are emerging for small scale energy storage
    - Recent international tenders in countries like South Africa, Mozambique and DRC have called for the integration of Li-ion BESS along with renewables for utility-scale projects
    - Large mini-grid rollouts in west Africa are starting to prioritise Li-ion as the storage medium of choice
    - South Africa and Nigeria are in the process of implementing stand-alone storage projects to provide ancillary services, with added benefits being the avoidance of transmission and distribution extension costs and providing backup power for sudden failure of supply.

1.7 The Incumbent - Fossil Fuel Generators

Fossil fuel generators still play a crucial role in supplying electricity in SSA, predominantly due to unreliable grids. The value chains for fossil fuel generators (FFG) in SSA are at their most diverse and dynamic at the small-scale, where generators are centred around residential and commercial use. As the size of the generators increase, the value chains are more predictable, and have fewer providers and market interactions.

On every level of generation, from national power plants down to electricity generated by businesses and individuals, FFG play an important role. However, for small scale FFG, there is an added logistical and cost burden where businesses and individuals need to procure the generators, buy and supply expensive fuels, operate and maintain their generators.

Africa has only recently started investing in renewable energy plants at utility-scale. Coal fired power plants are prominent but fossil fuel generators like gas, diesel and duel-fuel turbines also play a big role in supplying power at the utility-scale. Ease of installation and established supply chains make them a favourite technology for developing countries, particularly as environmental policies of renewable energy generation have not yet limited their implementation.

This study assesses the feasibility of battery energy storage systems (BESS) replacing three types of fossil fuel generators:

- Small scale fossil fuel generators, (well) below 5 MW capacity
- Gas turbines, (well) above 5 MW capacity
- Diesel power plants, (well) above 5 MW capacity.

The benefits of BESS come from:

- Reducing fuel consumption by improving the operational efficiency of fossil fuel generators
- Reducing fuel consumption by allowing (further) integration of renewables
- Replacing back-up generators used for short durations each day (e.g. rolling black-outs)
- Reducing operations and maintenance (O&M) costs for generators by reducing load fluctuations and unit starts.

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1.8 Next Steps to Support BESS Deployment

Role of Technical Innovation

The performance of Li-ion batteries is already at a level that meets all the technical requirements for different applications. The techno-economic model shows that the impact of further improvements in performance, such as cycle efficiency, cycle life and charge/discharge power have on the economic feasibility (e.g. total LCOE or project IRR) is limited. This indicates that the impact of continued BESS technical improvements is useful but not sufficient to change the current situation in SSA. Innovative BESS technologies would be helpful mostly where they address the main issues seen for mass implementation in SSA which are reductions in CAPEX and OPEX costs.

Table 1 summarizes if current and anticipated technology performance and cost can offer a sufficiently feasible alternative on displacing diesel generators or natural gas fuelled plants. It denominates for each modelled business case and selected battery technology and cost combination whether it provides a feasible alternative to fossil fuel (green), is already feasible in selected markets or on the brink of feasibility (amber) or does not provide a feasible alternative under current assumptions (red). It shows the results for small-scale and utility-scale Li-ion costs, at current prices and projected costs for 2035.

Table 1: BESS feasibility on displacing diesel or gas

Business Case	Does BESS offer a sufficiently feasible solution on displacing diesel or gas?			
	Current BESS	2035 Small Li-ion	Utility Price Li-ion	2035 Utility Price Li-ion
A – Mini Grid	Lead-Acid	Small Li-ion	Utility Li-ion	Utility Li-ion
B – Captive Behind the Meter	Small Li-ion	Small Li-ion	Utility Li-ion	Utility Li-ion
C – Off Grid Industrial Facilities	Utility Li-ion	N/A	Utility Li-ion	Utility Li-ion
D – Avoided T&D Expansion	Utility Li-ion	N/A	Utility Li-ion	Utility Li-ion
E – Hybrid Solar and Wind Plant	Utility Li-ion	N/A	Utility Li-ion	Utility Li-ion
Legend:	Feasible	Approaching feasibility	Not feasible	

Cell manufacturers in the Li-on BESS industry design, optimise, and develop their battery cells to meet market demand and accommodate the favourable results from R&D. Innovation in the design and manufacturing of battery packs and system integration in mini grids (including solar) should help drive down cost for smaller scale projects. An example of this is the development of a standardised battery suitable for use in both mini grids and in small scale captive power solutions. Such a battery could be mass manufactured, imported at scale, distributed through large networks, and stored in warehouses, with prices expected to be much closer to that seen in utility-scale BESS projects.

Role of Pilot and Demonstration Projects

Funding and development of pilot projects or proof of concept demonstrations, either for new technologies or for new applications of existing technologies, is likely to be useful. Pilot projects often highlight unforeseen issues that were previously overlooked such as missing links in the supply chains, unexpected delays in shipping lead times, policy and regulation barriers, or skills shortages. Pilot or demonstration projects are not typically commercially viable and can face high risks of delays and complications and so will require financial and technical support. Well-selected BESS demonstration projects can not only address these blind spots, but also solve critical problems associated with the weak and unreliable grids throughout SSA.

Focus Areas

Several areas are identified where improvements would have the highest impact but currently lack sufficient attention or research and development funding. These include:

- The proportionately high costs of BESS (and renewable energy equipment) for small-scale projects in SSA:
    - Equipment (specific) costs are at least double that of utility-scale BESS, due to small capacity procurement resulting in higher factory prices and longer value chains with mark-ups along the chain
    - Transportation costs are currently up to a third of total installed BESS costs
    - The ongoing cost reductions and published prices for BESS focus on utility-scale systems and deployments in OECD countries. These do not represent the real prices seen in SSA for small-scale systems
- The development of Li-ion BESS technology is being driven by the EV sector and research in different (longer duration) storage technologies by OECD countries is also being pursued. However, developments for BESS specifically for the small-scale applications in remote areas in SSA will require support, including investigating:
    - Innovative BESS technology focused on cost reductions for small scale deployment
    - Standardisation and modularity to reduce balance of plant costs
    - Achieving economies of scale by setting up common procurement programs
    - Overcoming the challenges of utilising 2nd life batteries from EV applications
- The provision of information and tools to SSA project developers, such as:
    - Tools for correctly sizing BESS for the intended application
    - Assessing the economic feasibility of a project idea
    - An overview of BESS technology and installation guidelines that inform which types of BESS technologies are best suited for the applications and conditions in SSA

  This report and techno-economic model is a first step in this direction, but to achieve further impact will require a targeted effort focussed on providing information to SSA project developers, as well as the design and planning tools that can be used by users with different levels of technical expertise.
- There are several barriers that are neither technical nor economic in nature, but still limit the deployment of BESS and renewables in SSA. These would have to be addressed at a national level which requires external support, as commercial parties would not be well-placed to do this. These barriers include:
    - Lack of standardisation of technical requirements such as grid codes that make it possible for larger scale energy storage systems and renewables to connect to the grid
    - The Environmental Permitting process should reflect the zero emissions nature and limited environmental impact of BESS and renewables compared to fossil fuel generators. This could allow for a more streamlined permitting process

- Transparent grid planning and rules for connecting mini-grids to the main grid, to reduce the risk of mini-grid developers not being able to recover their investment costs after a mini-grid gets connected.

Table 2 shows, for each business case, the effect of possible scenarios surrounding BESS, such as cost reduction due to economies of scale, or from the use of 2nd life batteries. The table shows a high impact in overcoming the current barriers for BESS deployment in green, a medium impact is shown in yellow and a low impact in red.

Table 2: Impact on BESS feasibility by mitigating barriers

Business Case	**Expected impact of successfully mitigating or avoiding barriers:**				
	Standard battery(1)	**Economies of scale(2)**	**2nd life(3)**	**Tools to developers(4)**	**Enabling policies(5)**
A – Mini Grid	High	Medium	Low	Medium	Medium
B – Captive Behind the Meter	Medium	Medium	Medium	High	Low
C – Off Grid Industrial Facilities	Low	High	Low	High	Low
D – Avoided T&D Expansion	Low	Already in effect	Low	Low	Medium
E – Hybrid Solar and Wind Plant	Low	Already in effect	Low	Low	High

(1) The standard battery refers to the development, manufacturing and sale of a standardized Li-ion battery offering to the region and for the specific application. This avoids high mark-ups on the cost of equipment due to a long and complex value chain, and higher cost due to unfamiliarity with the technology by contractors and operators.
(2) Economies of scale refers to the shared or grouped procurement of batteries to create critical mass in driving down prices. This should not only apply to initial procurement but also to the installation, operation, and maintenance (incl. battery augmentation and replacement over its lifetime) (see pt B in the Focus areas)
(3) 2nd life refers to the use of spent Li-ion batteries from mainly electric vehicles.
(4) Tools for development refers to the development and/or provision of tools to enable correct sizing of BESS, assessing economic feasibility of projects, and monitoring and optimizing BESS over the lifetime.
(5) Enabling policies refer to incentivizing BESS or creating a level playing field via grid codes, environmental permitting process reflecting zero emission and other environmental benefits, and transparent rules for mini grid to connect to main grids (not including subsidies or tax incentives).

2 INTRODUCTION

2.1 Project Background

Transforming Energy Access (TEA) is funded by UK aid from the UK government. TEA is a research and innovation platform supporting the technologies, business models and skills needed to enable an inclusive clean energy transition. Through this program the Faraday Institution has received funding to research new battery technologies and conduct relevant techno-economic and related studies into battery-based solutions that have the potential to replace fossil-fuel powered generators and increase the uptake of cheaper, cleaner and more reliable energy in Overseas Development Assistance (ODA)-eligible countries.

This piece of work commissioned by the Faraday Institution explores how novel energy storage technologies can be viable and competitive in Africa, offering alternative solutions for resilience and grid independence, enabling the integration of more utility-scale renewables and bringing light and opportunity to the least developed corners of the continent.

2.2 Project General Approach

The assessment of how battery energy storage can reduce fossil fuel use in Sub-Saharan Africa is based on a dual approach:

1) Assess the current value chains, market structure and local conditions for fossil fuel generators. Assess the current and potential future value chain for battery energy storage solutions and review the main business cases or market sectors where energy storage would be competitive
2) Develop a techno-economic model that allows these and other business cases to be studied in detail and provides insights into when certain applications become viable and what the main drivers are.

The value chain assessments and business cases are split between small-scale (roughly up to five MW capacity) and utility-scale applications (usually from ten to hundred MW capacity), as these have very different dynamics and economics.

The following main business cases are assessed in this study:

- Mini Grid (small scale)
- Captive and Behind-the-Meter Applications (small scale)
- Off-Grid Industrial Facilities (utility-scale)
- Avoided T&D Expansion (utility-scale)
- Hybrid Solar and Wind Plants (utility-scale).

The model contains costs and future performance forecasts, allowing users to assess how a certain business case could develop over time and determine in which year it may become feasible.

2.3 Market Opportunity

aidReplacing generators and smoothing energy supply in areas where the national grid is unreliable or non-existent presents a significant market opportunity. 12-17 billion USD is spent on back-up generation every year in Nigeria alone and 9% of all the electricity consumed across SSA is supplied by generators. To further quantify this problem for firms in SSA [1]:

[1] *World Bank, https://www.enterprisesurveys.org*

- 78% routinely experience power outages
- 40% rank poor electricity service as the biggest constraint to their operation
- 53% of firms in Sub-Saharan Africa engage in self-generation – the highest in the world
- 29% of electricity used by firms in the region comes from self-generation.
- 8.4% of annual sales lost to power outages relative to the global average of 5.2%.

For businesses throughout SSA, there is a strong incentive to get some form of independency from the grid, as grid outages cause direct losses in revenues. This is illustrated in Table 3 for several countries. The differences are large, but what is true for all is that the lost revenues far exceed the grid electricity price, often by a factor of 100 or more.

Table 3: Value of lost load (USD per kWh)[2]

	Firms with self-generation			Firms without self-generation			
Country	Outage loss	Estimated loss without self-generation	Implied loss reduction due to self-generation	Outage loss	Estimated loss with self-generation	Potential benefit of self-generation	Grid electricity price
Ghana	2.9	3.3	15%	1.5	1.5	-6%	0.15
Kenya	20.9	22.3	7%	28.9	24.3	-16%	0.16
Mali	23.9	30.3	27%	25.2	23.5	-7%	0.31
Mozambique	23.6	46.6	98%	32.5	27.4	-16%	0.15
Nigeria	2.0	2.2	7%	1.8	1.7	-7%	0.07
Senegal	6.7	19.0	183%	25.1	13.5	-46%	0.24
Zambia	10.8	14.5	35%	15.4	10.1	-35%	0.04
South Africa	4.4	4.5	1%	9.3	6.0	-35%	0.04

2.4 Reading Guide

The content of this report consists of the following main parts:

- The executive summary, summarising the main findings and conclusions of the report (Section 1)
- The introduction, coving the project background and description of the general approach (this Section 2)
- The description of the developed techno-economic model (Section 3)
- Details on the different business cases or markets for BESS applications and techno-economic analysis results for selected case studies (Section 4)
- The value chain of battery energy storage systems (Section 5)
- The value chains of the various fossil fuel generators (Section 6)
- The main findings combining the case studies assessed in the techno-economic model with the value chain and market assessment (Section 7)

Further detailed information is provided in the following appendices:

- Appendix A: Techno-economic model
- Appendix B: Fossil fuel generator value chain
- Appendix C: Description of business cases

[2] Oseni, 2015, A firm-level analysis of outage loss differentials and self-generation

- Appendix D: Battery energy storage technologies.

3 TECHNO-ECONOMIC MODEL

3.1 Overview

DNV developed a spreadsheet-based techno-economic model for the Faraday Institution to simulate a variety of business cases where BESS are used to replace or reduce fossil fuel generation. The model optimises hybrid energy supply systems consisting of a combination of one or more of the following options:

- Battery Energy Storage System (BESS).
- Photovoltaic (PV) plant.
- Wind farm.
- Thermal plant (diesel generator or gas turbine, firing diesel or natural gas fuel).
- (Weak) Grid connection or off-grid

The model simulates energy-flows by the hybrid plant to meet a selected demand profile. The demand profile and hybrid plant configurations reflect a set of pre-defined business cases. Each business case can be adjusted by the user by changing the underlying assumption, resizing the components of the hybrid plant, or adjusting the cost assumptions. A *scenario analysis* enables the user to simulate up to five scenarios in parallel and compare results. A *sensitivity analysis* is included to quantify the impact of uncertainty in key technical, commercial, and cost assumptions.

The model is transparent and allows the user to adapt or expand its functionality and change assumptions or calculations where needed. DNV has taken the following steps to this end:

- The model is spreadsheet-based (MS Excel), all formulas & macros are visible when required.
- The model set-up is well-structured.
- All input values are clearly identified.
- All assumptions (explicit and implicit) in the model are clearly stated.
- Detailed (hourly) results are plotted to allow easy verification of detailed aspects of the interaction between different forms of generation, battery energy storage and dispatch requirements.

The model has an hourly resolution, which implies that for every hour of a year the electricity demand, electricity generation (e.g. by PV) and charging or discharging of the BESS is monitored and calculated. The results from this full year calculation are then extrapolated for the remaining years of the project life, taking degradation (of PV, wind and BESS) and augmentation (of the BESS) into account.

3.2 Model Structure

Table 4 shows a list of all the sheets included in the spreadsheet model.

Table 4: List of sheets in the model

Sheet	Type	Description
Instructions	Information	A short guide for the user on using, updating, and reading the model.
Dashboard	Operations	Main sheet for user to run, change and review business cases
Inputs (Annual)	Inputs	Technical and commercial inputs that are fixed for regular use, to be reviewed roughly every year.
Inputs (Hourly)	Inputs	For user to insert load profiles, solar generation profiles, wind profiles, grid profiles, etc.
Tariff	Inputs	For user to edit time of day tariff structures.
Business Cases	Inputs	Defines the default setting for each business case.
Energy Balance	Calculations	Calculates the energy-flows.
Annual Cash Flow	Calculations	Calculates the cash flows
Scenarios Runs	Operations	For user to run up to 5 scenarios and compare results.
Sensitivity Analysis	Operations	For user to conduct a sensitivity analysis to quantify specific influences.
Tornado_Sensitivity_Chart	Chart	Displays results from sensitivity analysis.
BESS	Chart	Displays (battery) energy storage system charge, discharge, and state of charge over the year
Energy	Chart	Displays output from all components of hybrid plant / mini grid over the year (incl. shortfall)
Shortfall	Chart	Displays the shortfall in meeting (mini)grid demand over the year
Day and Month Energy-flows	Chart	Displays the energy-flows for a user-selected day and month of the year
CAPEX OPEX Revenue	Chart	Displays breakdown on capex, opex and revenue streams over project lifetime
Admin	Administrative	Fixed inputs and underlying assumptions required for proper model operations.
Change Log	Administrative	For user and/or administrator to log (major) changes to the model.

Throughout the entire spreadsheet model, every input cell is coloured yellow to avoid interference by the user, accidentally or on purpose, with calculation steps. Calculation cells and comment cells are also formatted to avoid errors in using, updating, or expanding the model.

The spreadsheet contains the below VBA-coded macros:

- The ‘Run Scenarios’ macro calculates multiple scenarios, simulating each scenario sequentially and copying the results into a comparison table.
- The ‘Run Sensitivity’ macro calculates the same business cases by varying key assumptions (based on user input) and copies the key result(s) into a tornado diagram to quantify the impact of uncertainty of the key assumption on result(s).
- Multiple ‘Empty User Input’ macros that are used to empty any input provided by the user, effectively ‘resetting’ the model.

3.3 Operating the Model

Figure 3 illustrates a flow chart of the simulation or calculation from inputs to a dashboard for finetuning inputs (if desired) and to calculating the energy-flows and cash flows based on the energy balance.

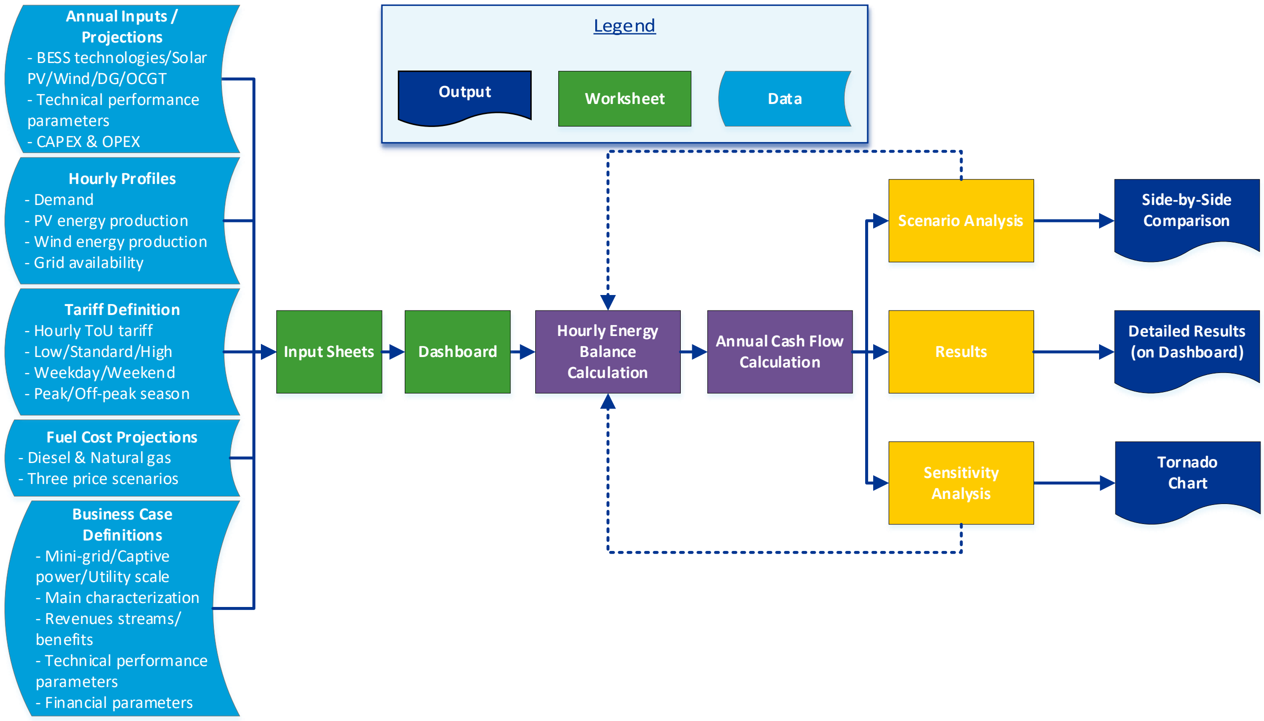

Figure 3: Schematic overview of the model's structure

3.3.1 Dashboard

The 'Dashboard' sheet lists all project or business case specific inputs, and the user can enter custom inputs to overrule the default values of a specific business case. The dashboard is divided into the following sections:

- Business case: to select one of the default business cases that serve as the baseline, for which the expected types of revenue streams can be switched on or off.
- Active revenue streams: Revenue streams can be turned on/off and impact financial results (incl. IRR) but not LCOE (reflects cost only). Care should be taken on from which perspective costs and revenues are observed, the model assumes all revenue streams are income to the mini-grid or hybrid plant. As an example: if "avoided fuel costs" is enabled as a revenue stream the financial calculations include the monetary value of not consumed fuel as a positive cashflow that counts towards e.g. the IRR. This can be considered unacceptable – and skew results – when observer from the perspective of a mini-grid owner and operator installing a new mini-grid, as fuel costs were not part of their balance sheet upon then. It can however be an important factor from the end-user or consumer perspective, who now needs to procure less fuel by connecting the new mini-grid.
- Project capacity definition: lists and allows overruling of the load profile and sizing of the hybrid system.
- Results: displays results.
- Major project techno-economic parameters list: allows overruling of key technical, financial, and commercial assumptions pertaining to the selected business case. This is split over:
    - Financial: defining how the project is to be financed.
    - Commercial: defining tariffs.

- Energy Storage System: defines cost and performance of the energy storage system.
- Solar PV Plant: defines cost and performance of the solar system.
- Wind Farm: defines cost and performance of the wind system.
- Thermal Plant: defines cost and performance of the diesel- or gas-powered system.
- Balance of Mini Grid System: defines cost of (mini)grid connections.

3.3.2 Inputs

The *Inputs (Annul)*, *Inputs (Hourly)* and *Tariff* sheets function as input sheets for the detailed or underlying assumptions to those on the Dashboard. The *Inputs (Annual)* sheet includes cost figures and cost projections of the hybrid plant's systems, but also technology assumptions on, for example, the degradation and augmentation of energy storage capacity, fuel consumption of diesel or natural gas systems and fuel price. The *Inputs (Hourly)* sheet comprises of the hourly profiles on load, electricity generation by solar and wind, and hourly profiles of electricity supplied by an electricity grid, if applicable. The *Tariff* sheet is only in effect when time-of-day or seasonal tariffs are under review, enabling the user to specify periods and rates for standard, off-peak and peak tariffs as well as a low and high demand season.

The *Business Cases* sheet can be considered a "fixed input" sheet, the assumptions herein are defined by and during the project works to best match with the goals of the project and model setup. Changing these assumptions is possible, but changes are ideally part of a model update or upgrade rather than day-to-day operations. Each column on this sheet defines a business case, which in turn is the basis to calculating project results.

3.3.3 Calculations

The *Energy Balance* and *Annual Cash Flow* sheets are where most calculations take place. The *Energy Balance* simulates energy-flows within the hybrid system. It calculates for each hour for the demand profile in the below order:

- Demand for energy not met by a selected grid electricity output profile.
- Available solar energy to meet demand, how much surplus can go towards battery charging, and the amount that must be curtailed.
- Available wind energy to meet any demand not met by solar, how much surplus can go towards battery charging, and the amount that must be curtailed.
- Energy flowing to storage (i.e. charging), the amount of energy discharged to meet demand that solar and wind cannot meet, the state of charge (i.e. how full is storage), and losses.
- Dispatching of any diesel or natural gas systems to meet demand that solar, wind and storage cannot meet, along with the amount of fuel required.
- Any shortfalls that exist, i.e. demand that cannot be met by the entire system.

The above list also denoted the order in which the model assumes subsystems are dispatched. It first calculates the net demand, correcting the demand curve for any grid electricity output profile that is selected. Note that this profile denotes the electricity supplied (capped at the amount demanded), and not the amount that is available. It then tries to meet demand with the available solar energy as per the selected supply profile and then the available wind energy as per the selected supply profile. Any available solar (or wind) energy above the net demand is presumed to be available for the energy storage system and losses associated with charging. Amount of energy charged is limited to the lowest of the available energy, state of charge and available capacity (or state of health). For discharging the maximum energy is limited to the lowest of net demand (after solar and wind), state of charge and available capacity (all incl. losses associated with discharging). Losses for charging and discharging are combined with self-discharge losses (if applicable) and used to calculate the state of charge of the energy storage system for the next hour. Any remaining demand is picked up by thermal generators (if applicable). The model dispatches any available generator based on the net demand and minimum load factor and calculates the fuel consumption based on load factor for each running generator and de corresponding heat rate provided by the input sheet.

The energy-flows are calculated for the first year only. The *Annual Cash Flow* sheet indexes result from the first year to subsequent years, based on the degradation of solar, wind, storage and thermal plants. The *Annual Cash Flow* sheet defines the amount of energy generated, discharged (storage) or consumed (diesel, gas) for each year along with capital and operational expenditures. It then calculates the expected revenue streams, but only includes the revenue streams activated by the default business case or user input (on the Dashboard) in financial calculations. The equity drawdown, debt schedule and working capital schedule are subsequently calculated, feeding into the financial statement and cashflow statements. Internal rates of returns and the levelized cost of electricity (for the full system) are calculated based on these statements. The sheet is limited to 31 years, allowing a project with an assumed one-year construction and up to 30 year financial or commercial lifetime.

3.3.4 Results

The *Scenario Runs* sheet resembles the *Dashboard* sheet but allows the user to define up to five scenarios based on a specific business case. This sheet includes macro's (i.e. automations) to empty user inputs, and to calculate each scenario. The latter sequentially loads each scenario into the model to generate results, pasting these results on the *Scenarios Runs* sheet. All inputs and results that can be changed or assessed on the *Dashboard* are reflected in the *Scenario Runs* sheet. The *Sensitivity Analysis* sheet facilitates the user to conduct a semi-automated sensitivity analysis. The user can change a subset of the assumption (e.g. varying cost of the storage system), then use the macro on this sheet to sequentially calculate the impact of uncertainty in the assumptions on the total cost of ownership. Results are displayed on the same sheet, and on a tornado diagram (separate sheet). Additional charts are available to aid in interpretation and analysis of results. These include a chart depicting battery system state of charge throughout a year, a chart with energy-flows from each component (solar, wind, battery, thermal) throughout a year, a chart depicting if- and when a shortfall in meeting demand occurs, and a chart for the user to select a specific day or month to view the energy-flows of the selected time-frame.

In addition, the above three administrative or supporting sheets are included in the model. The *Admin* sheets define selection lists, conversion factors, and correction tables to make sure the semi-automated macros can function. The *Change Log* can be used to log any major changes to the model, supporting version control and error checking. The *Instructions* sheet provides step-by-step instructions on using the model and includes a legend on colour coding used throughout the model.

3.4 Main Inputs and Assumptions

3.4.1 Inputs Hourly

Grouped into five sections, each spanning several columns. Each column represents a timeseries, with hourly values over an entire year. Leap years do not have to be entered.

- **Timestamp**: defining for each row the month, day, and hour.
- **Load Profile**: each column represents a specific load profile with hourly load data in kW. Each column includes a virtual check on the number of entries to ensure each hour of the year is accounted for, and a virtual check on the maximum, minimum and average load. Each load profile has a descriptive title, and a note to provide further details on what it represents.
- **Solar PV Generation**: each column represents a solar profile, the corresponding installed capacity, degradation, and spatial requirements. It also includes virtual checks on the number of entries, maximum, minimum, and average power. Each load profile has a descriptive title, and a note to provide further details on what it represents. The selected technologies span most of the solar installation that can be expected, for

which an energy production curve has been generated for three locations each reflecting a part of the large sub-Saharan region of Africa (Kenya, Nigeria, South Africa).

- **Wind Generation**: each column represents a wind profile, the corresponding installed capacity, degradation, and spatial requirements. It also includes virtual checks on the number of entries, maximum, minimum, and average power. The default wind generation profiles should not be relied upon, as any profile is extremely site specific. When wind is considered, a specific wind profile must be added.

- **Grid Electricity Supply**: each column represents a grid electricity supply profile, i.e. an amount of electricity (for each hour) that is supplied by the grid. It also includes virtual checks on the number of entries, maximum, minimum, and average power. These profiles are highly location specific, and thus only generic profiles have been added to enable analysis of partially grid powered solutions.

Users can add new profiles under one of the two “Custom” columns, or if needed add additional columns to include more profiles. Hourly production values for the solar or wind plants are scaled linearly to match the desired solar or wind plant size.

3.4.2 Inputs Annual

The annual inputs are grouped into four sections, each spanning several rows.

CAPEX and OPEX Projections:

- **Energy Storage system**: cost projections based on energy storage type and, where applicable, size (e.g. small vs large scale Li-ion systems). Split over eight capex categories and three opex categories, each with a 15-year forecast. Note that for certain storage system types, the breakdown is less granular to match either limited subsystems or limited data availability.

- **PV Plant**: cost projections based on plant type and plant size. 15-year projections based on full plant/system capex and opex figures.

- **Wind Farm**: cost projections based on plant size. 15-year projections based on full wind farm capex and opex figures.

- **Thermal Plant**: no cost projection, but specified per-plant type and plant size (Note: cost declines are expected to be marginal when compared to those of energy storage, solar and wind)

Adjustment Profiles for Technology:

- **BESS Degradation Profiles**: typical degradation profiles for the energy storage system included in the model.

- **BESS Capacity Augmentation Schemes**: typical capacity augmentation and battery replacement schemes, per battery type and/or business case. The cost of augmentation or replacement is based on the energy storage system forecast (i.e. components being added or replaced) with a mark-up that can be altered by the user. This mark-up ensures that all costs, not pertaining to the hardware itself but associated with replacement or augmentation, are reflected.

- **Fuel consumption profile:** defines fuel consumption of different diesel and natural gas systems from minimum load to full load.

Fuel Cost Scenarios:

- Defines three fuel cost scenarios for diesel and three for natural gas. Note that relevant fuel mark-ups due to taxes and logistics can be added to the business cases, or by the user if more detailed data is available.

BESS Operational Technology Parameters:

- Defines, for each energy storage system included in the model, the roundtrip efficiency, maximum and minimum state of charge (during operations), auxiliary load, self-discharge, and spatial requirements.

The model includes default input values provided by DNV, based on DNV data and experience and support by other data sources where applicable. Users can add new or specific data for energy storage systems in the ‘Custom 1’ and ‘Custom 2’ data entry fields to better match their specific project conditions.

3.4.3 Tariff

A detailed time-of-use tariff can be defined when applicable, where the user can specify:

- A low and high demand season.
- For each hour of each day in the week if an off-peak, standard, or peak tariff is in effect.

The tariffs corresponding to the categories within the rate structure are provided by the user in the Dashboard sheet and can thus be varied while keeping the time-of-day and seasonal rate structure intact.

3.4.4 Business cases

The *Business Cases* sheet lists for each business case all the inputs that are also visible on the Dashboard. Each business case represents a fixed baseline or base-case scenario, that can then be adjusted by user inputs on the *Dashboard* sheet, *scenario analysis* or *sensitivity analysis*.

Each business case is defined by the inputs and design choices as described in the previous subsections. There are however inputs to be provided by the user that are unique to the business cases sheet or deserve special attention:

- **BAU Thermal Plant**: Defines the business as usual’ thermal plant, i.e. the thermal plant that is already installed or would be installed if no solar/wind/storage is developed and operated. This creates a difference in utilization and efficiency of the diesel or gas power generators. The difference can be for several reasons. By example: the BAU may include an oversized generator that operates at low loads (and thus low efficiency) most of the time. It can also be the case that BAU includes a single generator and that the new business case includes multiple smaller generators to increase overall fuel efficiency.
- **Tariffs**: Provides the default tariffs to the mini-grid or hybrid plant, and to any electricity obtained from a regular grid (if available). The latter can only be provided as a fixed price. The former can be provided as either a fixed price, or on a time-of-day and seasonal basis. The model includes tariff functionality for two seasons – labelled low and high demand season – and for three price levels during the day, labelled off-peak standard and peak. The tariff sheet is a matrix in which the seasons and times of day can be configured. The actual tariffs are to be provided in the business cases sheet. If no seasons or time-of-day tariff is applied the same tariff should be entered for both seasons and all three times of day on the business cases sheet.
- **Avoided T&D Infrastructure and Downtime**: These pertain to the revenue stream labelled ‘avoided T&D CAPEX’, ‘avoided generation capex’ and ‘avoided downtime’. Transmission and Distribution CAPEX can be avoided or delayed by deploying energy storage to alleviate grid constraints or congestion. CAPEX for new-built generation can also be avoided with storage reducing peaks in demand. The rated power (transmission or generation) that is avoided and the cost of such infrastructure can be provided in a business case. The ‘avoided downtime’ can also be specified as an annual cost. This refers to – by example – commercial or industrial sites for which downtime in the electricity supply translates to cost or loss of revenue at their end. A hybrid plant or mini-grid resolving this downtime at commercial or industrial site may incorporate this in its business case.
- **Spatial Requirements**: Specific spatial requirements in terms of footprint can be included for the energy storage, solar, wind and thermal system. These values – e.g. m^2 per MW of solar plant – are multiplied with the

installed capacity used in the model to provide an initial indication of the footprint. These footprint figures do not impact the cost figures or plant configuration.

- **Balance of Mini Grid System**: This includes the size and cost of a connection to the grid for the hybrid plant or mini-grid (if applicable), and the annual cost associated with that connection (if applicable). The model uses a calculated grid connection capacity and multiplies it with a user-provided specific connection cost. The resulting CAPEX and OPEX figures are added to the financial calculations, impacting LCOE and other financial or commercial results.

3.5 Techno-Economic Analysis Results

The below are description of the results as generated by the techno-economic model. This is supplementary to the above described structure and operations of the model and helps explain the basis of (key) output and how the default charts in the model should be read. Description of available results

Main results

The main results are listed for a single selected business case on the *Dashboard*, and in the same format on the *Scenario Runs* sheet. The main results are an overview of the technical and commercial outcomes of a business case and can be used to compare different business cases or to assess the impact of changing input parameters. Table 5 shows the various results obtained from the model.

Table 5: Description of main results

Item	Unit	Description
Total LCOE	USDct/kWh	The levelized cost of electricity (see section 3.5.1 for details)
Total CAPEX	USD	Sum of all capital expenditures associated with the business case
Total OPEX	USD/a	Sum of all operational expenditures associated with the business case throughout its lifetime and divided by the lifetime in years.
Lifecycle cost	USD	Lifecycle cost (see section 3.5.1 for details)
Project IRR	%	Internal rate of return based on project valuation (see section 3.5.1 for details)
Equity IRR	%	Internal rate of return based on equity valuation (see section 3.5.1 for details)
Benefit ratio	-	Ratio at net present value of all revenues and benefits over all costs (see section 3.5.1 for details)
Total electricity demand	MWh/a	Demand for electricity of the chosen business case and its load profile.
Total net electricity demand	MWh/a	Net demand for electricity, which is the total electricity demand minus the demand met the grid connection defined by the chosen business case and its grid supply profile.
Total electricity exported to (mini)grid	MWh/a	Amount of electricity exported by the energy system (Solar, wind, BESS and/or thermal generators) to the mini-grid or grid that represent
Shortfall in meeting demand	%	Share of time in the first year of operation where the energy system cannot meet demand.
Time where demand is not met	hours/a	Actual hours in the first year of operation where the energy system cannot meet demand.
Total electricity via storage	MWh/a	Amount of electricity discharged from the BESS, i.e. that has passed through the BESS and is exported to use.
Total electricity curtailed	MWh/a	Amount of electricity not produced due to the curtailment of solar or wind.
Share of electricity from solar	%	The share of total exported electricity that is sourced from the solar plant.
Share of electricity from wind	%	The share of total exported electricity that is sourced from the wind plant.
Share of electricity from thermal	%	The share of total exported electricity that is sourced from the thermal plant.
Avoided fuel consumption	GJ	Amount of fuel that is not consumed due to the use of solar, wind and/or BESS.
Diesel: Conversion to Litres	Litre	Only in case of Diesel, amount of fuel that is not consumed due to the use of solar, wind and/or BESS.

Item	Unit	Description
CO2 emission reduction	tCO2/a	The avoided direct CO_2 emissions; calculated as direct emissions from combustion of the avoided fuel consumption.
Spatial requirements BESS	m2	The footprint of the BESS if the user has provided required special information (no default).
Spatial requirements PV	m2	The footprint of the PV if the user has provided required special information (no default).
Spatial requirements Wind	m2	The footprint of the Wind if the user has provided required special information (no default).
Spatial requirements Thermal	m2	The footprint of the Thermal if the user has provided required special information (no default).

BESS (Chart)

This chart includes, for each hour of the first year, the state of charge (SOC, usable capacity of the battery available), charging power, and discharging power. Figure 4 is an example of this chart: the blue dots represent the state of charge (values on left axis), and the "line" of many blue dots at the tops indicate that the BESS spends quite some time at maximum SOC. The yellow dots are charging power and the green dots discharging power. The "lines" of green dots point to a very constant discharge of energy, which is – in this case – a result of electricity demand in the evenings that the BESS meets in absence of solar and to avoid diesel consumption.

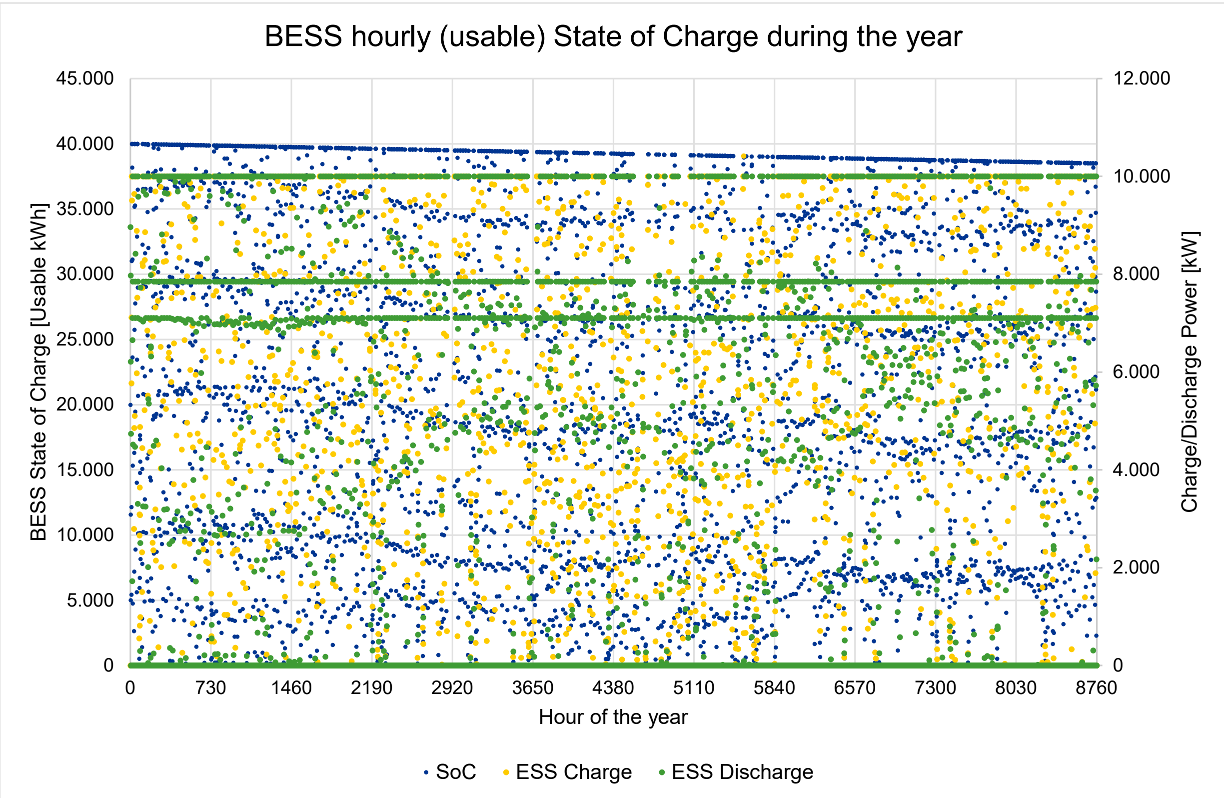

Figure 4: Example of the BESS Chart (output)

Energy (Chart)

This chart includes for each hour the first year the PV plant output, the PV plant power curtailment, the wind farm power output, the wind farm power curtailment, thermal plant output, and the power that is in shortfall.

Figure 5 is an example: the grey dots represent the output of the diesel generator, and the grey "lines" formed by the many dots imply that the diesel generator regularly operates at a few output levels. The thick line of red dots implies that there are none (or almost no) times at which there is a shortfall, i.e. the amount of power that is demanded but not supplied. The solar plant output represented by the yellow dots have a slightly "valley" around the mid of the year, indicating that less solar energy is available in the summer months. This is corroborated by the dark yellow dots that represent curtailed solar energy, which is hardly occurring in the summer months.

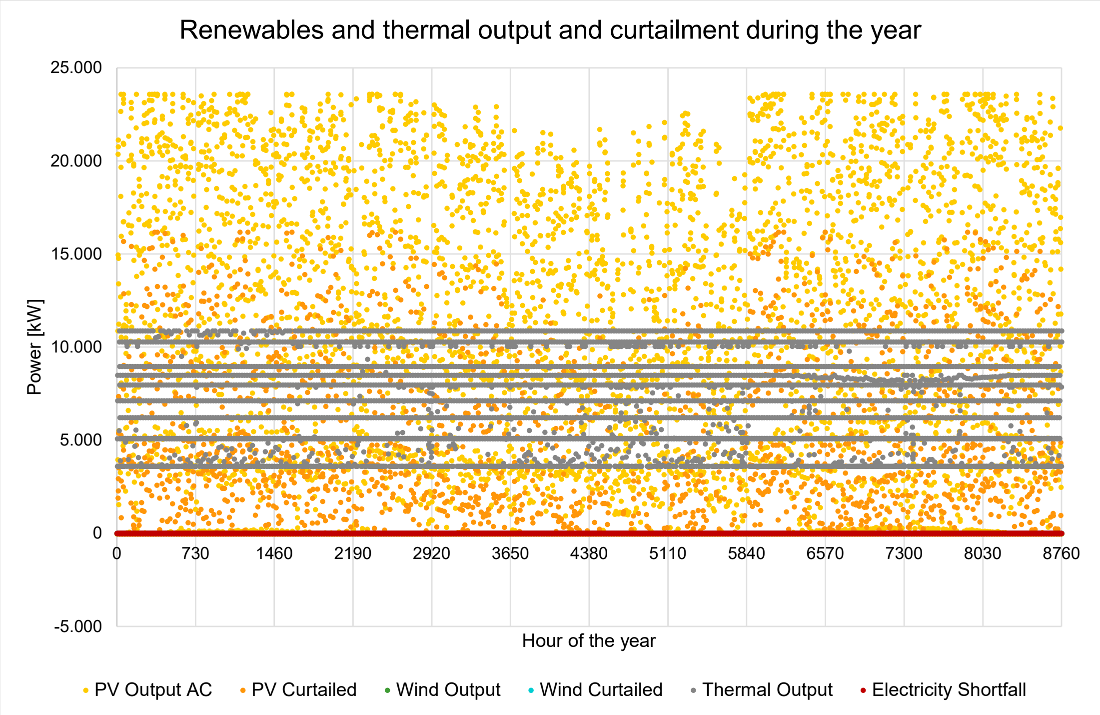

Figure 5: Example of the Energy Chart (output)

Shortfall (Chart)

This chart includes for each hour the first year the shortfall. Figure 6 is an example: the lines made up of red dots that form just above the 1800- and 1200-kW mark imply that there are significant times of the year where a shortfall of ~1900 kW or ~1300 kW occurs.

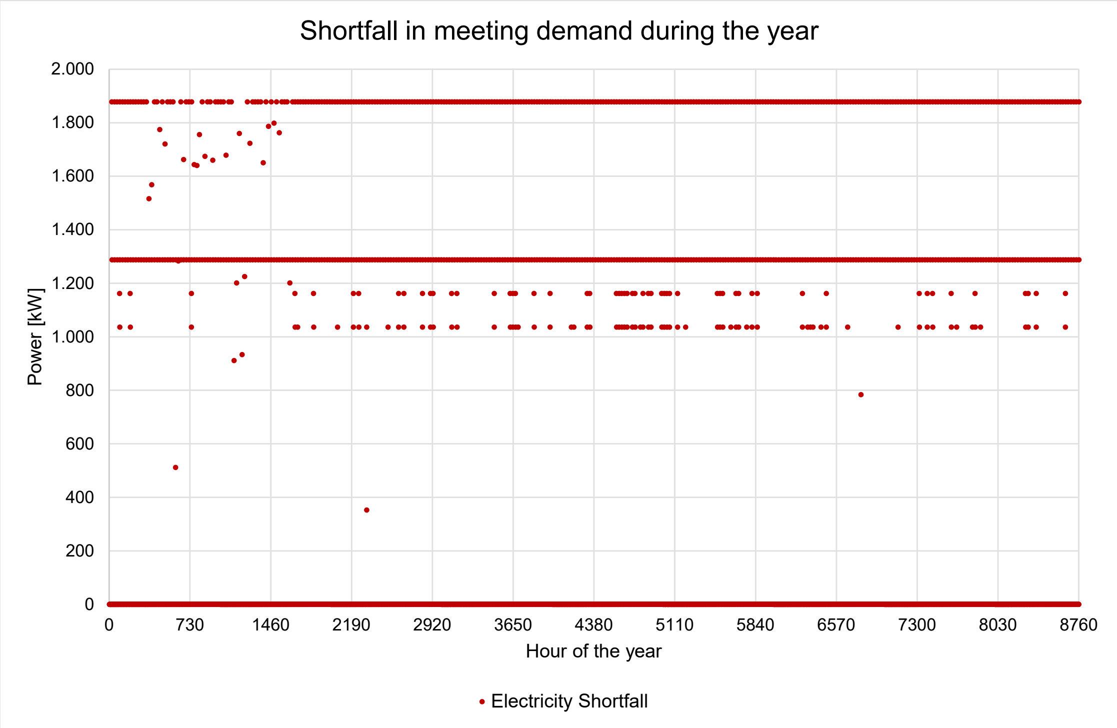

Figure 6: Example of the Shortfall Chart (output)

Day and Month Energy-flows (Charts)

These charts allow the user to view in detail any selection of a specific week and month. Figure 7 is an example of such a selection. For the selected week and month all the energy-flows (solar, wind, BESS, thermal) are visualised in the top left and bottom graph. The top left graph shows, for the same selected week, the PV and wind energy directed to charging the BESS, the state of charge of the BESS, and losses by BESS operation.

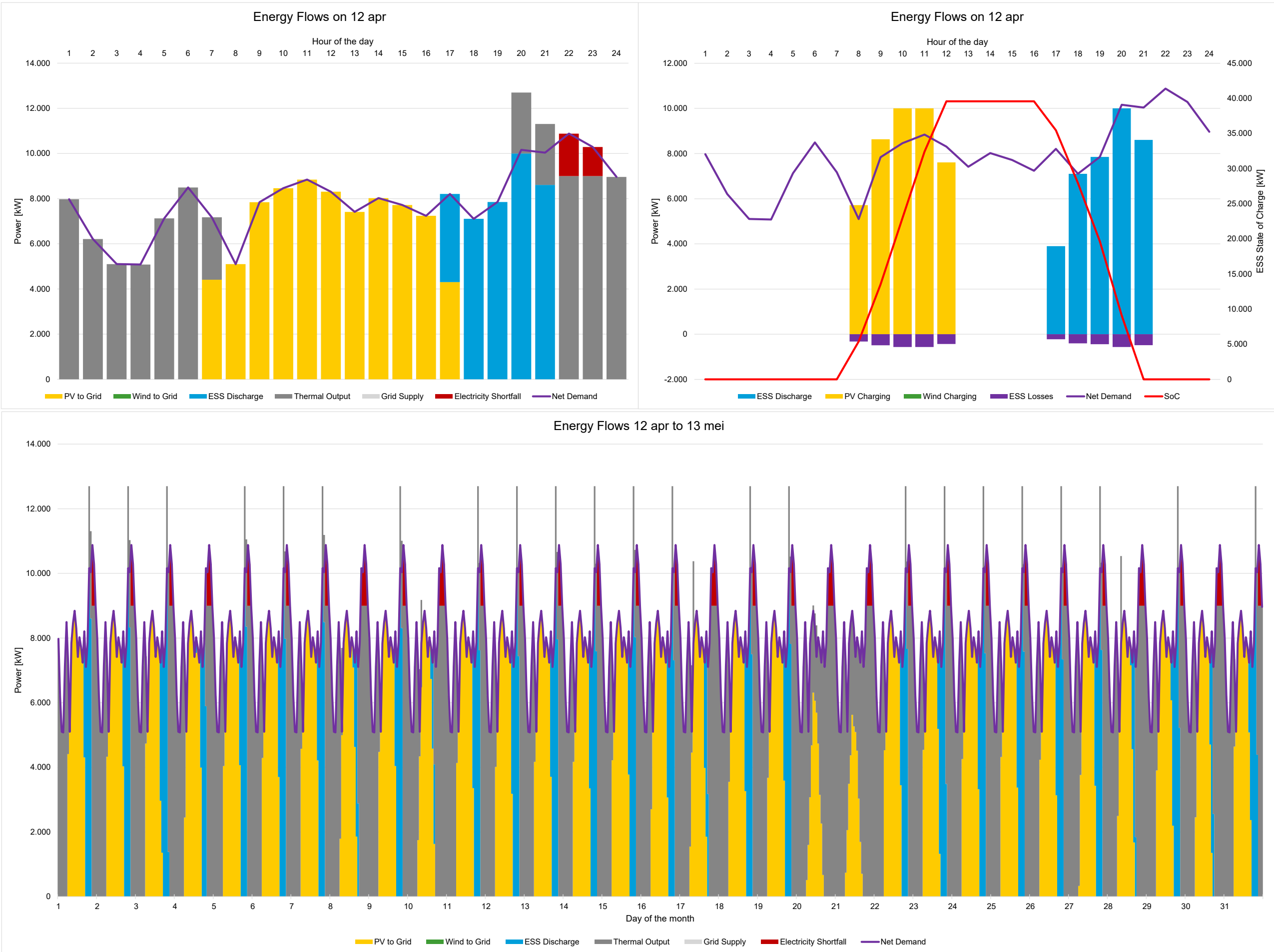

Figure 7: Example of the Day and Month Energy-flows Chart (output)

CAPEX OPEX Revenue (Charts)

These charts depict the annual CAPEX, OPEX and revenue (including breakdown) of the selected business case. Figure 8 is an example of this chart. The top left chart includes all CAPEX, OPEX and revenue figures. The top right excludes the CAPEX, and the bottom left only shows the revenue streams. The bottom right chart only shows OPEX. These charts can be used to assess the different cost and revenue streams. By example: the orange bars in the fifth and tenth column in the OPEX chart represent the battery augmentation cost, whereas the black bars represent fuel cost. The breakdown of all costs allows for an analysis on the impact of different costs and revenues. Note that as this is all part of a Microsoft Excel Spreadsheet, the graphs can also be filtered to hide specific costs, revenues, or years for detailed analysis.

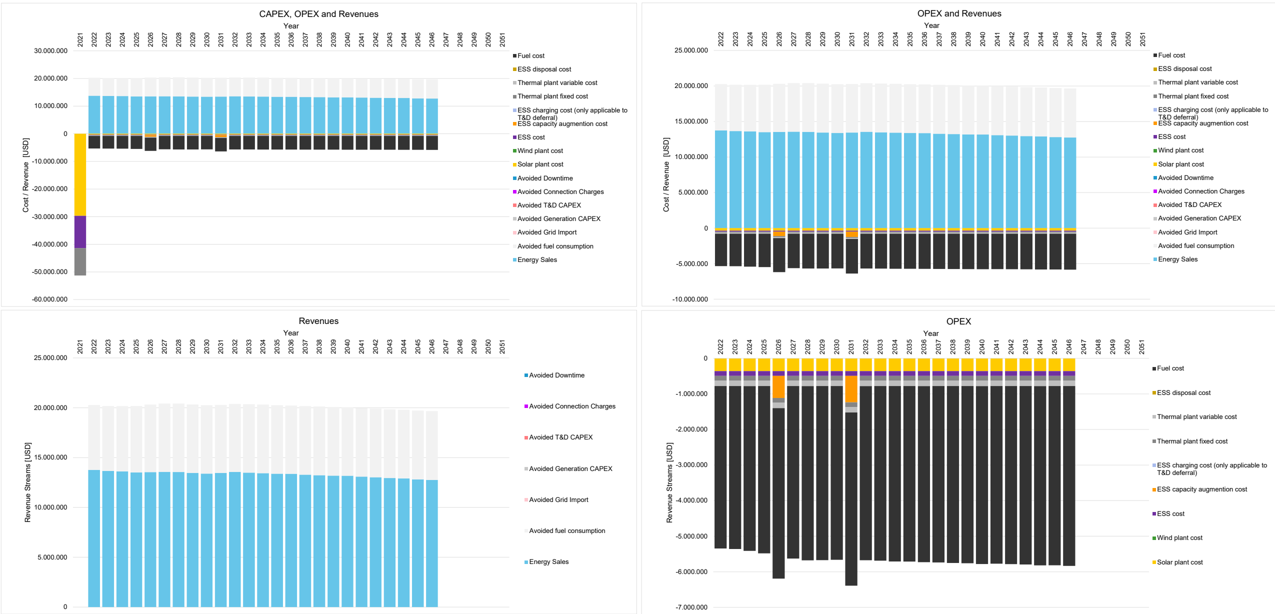

Figure 8: Example of the CAPEX OPEX Revenue Charts (output)

3.5.1 Economic Feasibility KPIs

Key Performance Indicators (KPIs) that are included in the model to judge the economic feasibility of a project or BESS business case. These are levelised cost of electricity, lifecycle cost, equity internal rate of return and benefit ratios.

Levelised cost of electricity (LCOE)

The Levelised Cost of Electricity is the average cost per kWh of energy produced, taking all costs and the time value of money into consideration for the entire project lifetime. The LCOE of the project is calculated as follows:

$$LCOE = \frac{NPV(\sum CAPEX + \ OPEX + Taxes + Net\ Working\ Capital\ Change)}{NPV(\sum electricity\ generation)}$$

The LCOE of the project is ideally lower than the required tariff to make the project financially viable. The required tariff includes the cost of financing, tax, and the expected rate of return by the investor.

Lifecycle cost

This is defined as the Net Present Value of a project’s CAPEX, grant funding and OPEX of the full lifetime. The present value means discounting future cash flows to account for the time value of money. The future value of a cash flow is reduced with a discount rate specific to the business case at hand.

The basis for the NPV-based lifecycle cost calculation is the sum of all CAPEX, grant funding and OPEX over the system or plant’s lifetime

Project internal rate of return (IRR)

The internal rate of return (IRR) of a project is the rate of return at which the project's NPV equals zero. At this point, the net present value of all the project's revenues is equal to the project's costs. The IRR is calculated based on the input of calculated EBIT (earnings before interest and taxes) on equal yearly intervals for the project's duration. This means solving the following equation iteratively:

$$0 = (equity\ investment) + \frac{(EBIT - \ Investment)_1}{(1 + IRR)^1} + \frac{(EBIT - \ Investment)_2}{(1 + IRR)^2} + \cdots + \frac{(EBIT - \ Investment)_t}{(1 + IRR)^t}$$

Where (EBIT – Investment)$_1$ = cash flow for project valuation in year 1, CF$_t$ = cash flow for project valuation in last year ($_t$) of the project.

Equity internal rate of return (IRR)

This follows the same logic as the Project IRR described above but determines the IRR from the equity holder's perspective. The annual cash flows used in this equity holder valuation are: $EBIT + change\ in\ working\ capital - debt\ principal\ repayment - debt\ interest - equity\ drawdown)$

Benefit Ratio

The benefit ratio is defined as the ratio of the net present value (NPV) of all benefits over the NPV of all costs. The benefits are the sum of all revenues, which can differ per business case and include electricity sales, avoided diesel fuel consumption costs, avoided grid import of electricity costs, avoided generation CAPEX, avoided transmission & distribution CAPEX, avoided grid connection charges and avoided downtime (penalties). The costs include all CAPEX and OPEX expenditures of the project.

Note that not all benefits are directly attributable to a financier or equity provider. For example: avoided diesel fuel consumption costs or avoided downtime penalties can be a benefit to a factory owner that is enabled or facilitated by a solar, battery and diesel-powered hybrid plant that has higher uptime and reliability and reduced fuel cost. A benefit ratio higher than 1 can therefore help identify business cases or configurations where despite a high cost of electricity production or unfavourable project finances there are still externalized benefits.

4 BUSINESS CASES

4.1 Introduction

The report contains extensive information about each business case including highlighting the following areas of interest:

1. Customer profile
2. Technical profile
3. Business model characteristics
4. Deployment and operation of the energy assets
5. End-of-Life considerations
6. Policy aspects

Detailed information on the business cases can be found in Appendix C140. The following subsections will focus on each business case individually. An overview of each business case provides context after which the results obtained from the techno-economic model analysis are discussed. Each subsection ends with conclusions drawn from the business case relating to the future applicability of BESS in replacing fossil fuels in those sectors. A summary of each modelled business case in given in Table 6.

Table 6: Summary of modelled business cases

Business Case Number	Business case category	Description
A-1	Mini Grid	Mini grid located at a tea estate. The demand is high at 4.00am- 6.00am and 17.00pm- 21.00pm due to domestic energy use.
A-2	Mini Grid	Island mini grid. The demand is high during the day and at 18.00pm- 22.00pm due to domestic energy use.
A-3	Mini Grid	Village mini grid. Peak demand is at the evening due to domestic energy uses e.g. Lighting
B-1	Captive and Behind-the-Meter Applications	Safari lodge in Tanzania (Greenfield)
B-2	Captive and Behind-the-Meter Applications	Safari lodge in Tanzania (Brownfield)
B-3	Captive and Behind-the-Meter Applications	Manufacturing company in Kenya (Greenfield)
B-4	Captive and Behind-the-Meter Applications	Manufacturing company in Kenya (Brownfield)
C-1	Off-Grid Industrial Facilities	Manufacturing company in Kenya (Diesel)
C-2	Off-Grid Industrial Facilities	Manufacturing company in Kenya (Gas)
C-3	Off-Grid Industrial Facilities	Processing factory in Sierra Leone (Diesel)
C-4	Off-Grid Industrial Facilities	Processing factory in Sierra Leone (Gas)

Business Case Number	Business case category	Description
D-1	Avoided Transmission & Distribution Expansion	BESS connected at 33kV substation to avoid new OHL and substation expansion
D-2	Avoided Transmission & Distribution Expansion	Same as D-1, but also avoiding investment in new generation capacity by reducing total peak demand
E-1	Hybrid Solar and Wind Plants	Hybrid PV + BESS + DG plant providing dispatchable power during high demand hours
E-2	Hybrid Solar and Wind Plants	Hybrid PV + Wind + BESS + GT plant providing baseload power

4.2 Mini Grid

4.2.1 Overview of mini grids in Sub-Saharan Africa

Historically, four generations of mini grid have emerged. The first generation is the small-sized mini grids with isolated generation and distribution networks that pre-date the centralisation of energy systems in countries such as the United States and the United Kingdom. Second generation mini grids are those typically found in developing countries today. The World Bank's Energy Sector Management Assistance Program (ESMAP) estimate that most of the 19,000 mini grids they have identified worldwide fall into this category. Second generation mini grids will typically have little or no battery capacity, instead relying on fossil fuel generators for power. Several development finance organisations like the UNDP have projects to hybridise these systems across Africa, adding PV and BESS capacity to diesel-based systems.

Third generation mini grids are typically built by the private sector and are characterised using better, usually renewable electricity generation, smart meters, and modern energy storage technologies. These systems have proliferated as the costs of the enabling technologies have fallen, the business models have evolved, and regulation has been put in place to allow grid operators to charge cost-reflective tariffs.

A tentative fourth generation of mini grids is now emerging. These are typically characterised as being intentionally embedded in a value chain, e.g. enabling increased or improved agricultural processing[3] or production but can also include weak-grid mini grids. Under-grid mini grids operate "under" an electricity grid, with a community served by a grid connection that only provides intermittent access to electricity. The mini grid operating "under" the grid ensures 24/7 electricity availability. The importance of productive energy users to the revenues of a mini grid operator is significant, and often underestimated. Increasingly, efforts to stimulate productive uses of energy on mini grids are becoming the focus of development finance. Another increasing trend is for mini grids to be integrated into the business models of private developers.

To stimulate local economies, the most productive uses of financial support are towards those applications for which there is already a significant market, like agriculture. In these cases, there is already local knowledge and technical experience and increased production can easily be absorbed into an existing supply chain. In some cases, there might be significant potential for the stimulation of a new value chain, but generally this requires more upfront technical assistance, education and investment.

Recent trends, like falling technology costs,[4] improved business models, improved regulation and innovations in finance and access to capital mean that mini grids are proliferating. Forecasts of this sector indicate exponential growth. A

[3] *Many non-agricultural value chains are also suitable for mini grid energy provision. The Jumume Keymaker model first trialled in Tanzania for example is built around the fish cold chain and linking rural fisherfolk directly to buyers in the capital.*
[4] *According to research from the Rocky Mountain Institute and AMMP, the LCOE of mini grids can be 60% lower in 2030 than in 2019. (link)*

recent report from the African Mini grid Developers Association describes mini grid connection growth rates of 161% in 2017 and 267% in 2018.[5] As of 2019, the top mini grid market in Sub-Saharan Africa in terms of number of mini grids being planned is Senegal, with 1,217 projects in the pipeline. Senegal is followed by Nigeria and Tanzania with 879 and 501 projects respectively.[6]

In many developing economies, mini grids are increasingly being included in energy or electrification strategies exclusively based on the least-cost. More recently, an increased understanding of the impact that energy access has on rural economic development is resulting in mini grids becoming an integral part of rural industrialisation strategies.

There are three primary delivery models for mini grids in emerging economies, they are defined by asset ownership:

1. **Utility ownership:** The utility builds and operates the mini grid. This is the case for the majority of the mini grids currently operating in Africa, most are diesel powered with little or no BESS. These systems will often run at a financial loss.
2. **Co-operative ownership:** Owned and managed by a locally based co-operative.
3. **Private sector based:** Mini grids currently being built are typically commercial, private sector based. Finance sources are often a blend of commercial, foreign capital and grant funding.

The prevalence of these models is linked primarily to the specific regulations in the country in question. There are many examples of hybrids of these models, where private companies operate assets that have been financed by and are owned by the utility. Favourable policies and regulations are crucial for the development of any mini grid industry.

The mini grid sub-sector ideally requires its own set of regulations because the operating conditions differ significantly from other forms of energy supply, especially other forms of decentralised energy supply. The risks of mini grid operations (and in turn investment risk) increase significantly when operating conditions are not fully understood in advance. Two important factors are the tariffs that operators can charge to their customers and also what happens when the national grid encroaches on a mini grid site. AMDA estimates that the average time for a mini grid to get all the required licenses and regulatory approvals in Africa is over a year. This significant time delay is a serious constraint on the mini grid sector.

It is estimated by Bloomberg NEF that 238 million households across SSA still need electricity access if universal access is to be achieved by 2030. Approximately half of this population, 111 million households, are estimated to be best served by mini grids.[7] While the current pace of electrification indicates that this target will not be reached, a number of promising trends are suggesting that the pace of deployment can increase significantly over the next five to ten years.

4.2.2 Techno-economic analysis results

Techno-economic modelling for this business case is based on three case studies. These case studies are rooted in research by DNV and TFE and supplemented with assumptions, anecdotal data points, and more generic superimposed data sets. These case studies therefore have merit for comparative analysis on key parameters and are a solid basis for the assessment of specific projects. The basics of the three case studies are presented in Table 7, all other inputs and assumptions are available in APPENDIX A.

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[5] *AMDA Benchmarking Report https://shellfoundation.org/app/uploads/2020/08/AMDA-Benchmarking-2020.pdf*
[6] *The World Bank, 2019, Mini grids for half a billion people, (link)*
[7] *Sustainable Energy for All,2020, State of the Global Mini grid Market Report, (link)*

Table 7: Business case – mini grid – basic parameters

Item	Unit	A-1	A-2	A-3
Description		Mini grid located at a tea estate. The demand is high at 4.00am- 6.00am and 17.00pm- 21.00pm due to domestic energy use.	Island mini grid. The demand is high during the day due to productive loads such fishing lamp charging businesses, likewise at 18.00pm- 22.00pm due to domestic energy use.	Village mini grid. Peak demand is at the evening due to domestic energy uses e.g. Lighting
Reference scenario (BAU)	-	No Electricity	Diesel	Diesel
Grid	-	Off-Grid	Off-Grid	Off-Grid
Type	-	Greenfield	Greenfield	Brownfield
Revenue streams	-	Energy sales	Energy sales, avoided fuel consumption	Energy sales, avoided fuel consumption
Load profile	-	Kenya – Mini Grid 1	Tanzania – Mini Grid 1	Sierra Leone – Mini Grid 1
Grid electricity supply profile	-	No Grid	No Grid	No Grid
BESS technology	-	Lead Acid	Lead Acid	Lead Acid
BESS energy capacity	kWh	6	72	160
BESS power capacity	kW	2,5	20	35
Solar plant	kWp	2,5	20	36
Wind farm	kW	-	-	-
Thermal plant	kW	-	15	50
BAU thermal plant	kW	1	15	50
Project lifetime	years	20	20	20
Grant funding	USD	7,500	10,000	10,000
Tariff electricity	USDct/kWh	60	60	60
Tariff grid electricity (import)	USDct/kWh	N/A	N/A	N/A
Diesel fuel price	USD/L	1,00	1,00	1,00
Natural gas price	USD/GJ	N/A	N/A	N/A
Cost of avoided T&D infrastructure	USD/kW	N/A	N/A	N/A
Cost of avoided downtime	USD/a	N/A	N/A	N/A

Battery vs Diesel

Only business case A-2 results in a levelized cost of electricity (LCOE) – at 0.48 USD/kWh – that is below the electricity tariff charged on the mini grid. Business case A-1 results in 0.73 USD/kWh and A-3 in 1.34 USD/kWh. If these mini grids were to be powered by small petrol (in the case of A-1) or small diesel gensets (A-2 and A-3) the LCOEs drop to below the charged tariff, even if the grant funding is subtracted: 0.34 USD/kWh (-53%) for A-1; 0.32 USD/kWh (-33%) for A-2; and 0.34 USD/kWh (-75%) for A-3. Batteries are therefore not deemed competitive for these business cases in the current setup.

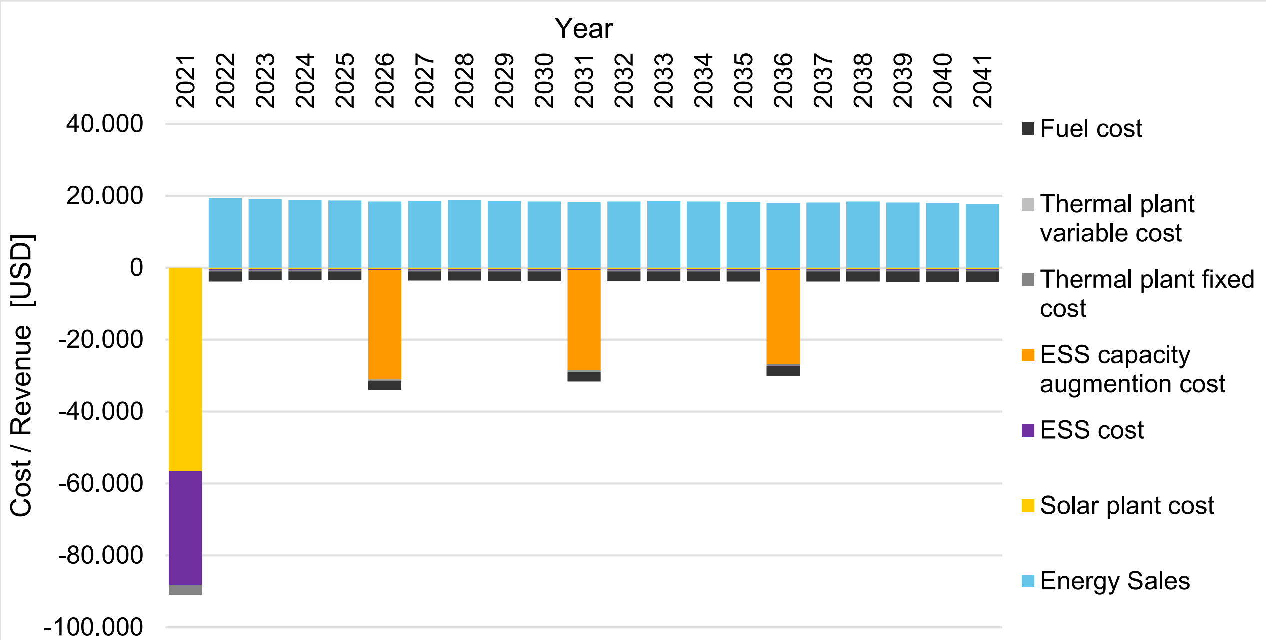


Figure 9: Business Case A-2 - CAPEX/OPEX/Revenues

The initial cost of the solar plant and battery systems, as well as the 5-year replacement cycle of the lead-acid batteries are the major cost impacts over the 20-year simulation. Figure 9 illustrates this for A-2. For this case, the revenues from energy sales (see graph) are sufficient to recover the costs, resulting in an LCOE below that of the applicable tariff. For cases A-1 and A-3 the cost of the solar plant and battery system (including replacement cost) are prohibitively high.

The use of solar and batteries do however translate in savings of fuels and CO_2 emissions. For A-1 the business-as-usual scenario would be an absence of electricity generation. If we assume a very small petrol engine to deliver the same power as the solar and battery mini grid, it translates to a fuel consumption of 800 litre/year, or roughly 2 tCO_2-/year emitted. For A-2 the same small diesel generator is likely to be used with or without solar and batteries, as it is sized for peak power (in the evening) and will simply be switched off when sufficient energy is available in the batteries. Fuel savings then amount to 6,600 litre/year, or 19 tCO_2/year. The potential fuel savings for A-3 is more significant as it is considered a brownfield site, meaning that the diesel generator already present is larger than required once solar and batteries are in use. The savings equal just short of 40,000 litre/year and 112 tCO_2/year.

Future Lead-Acid Prices

A further reduction in lead-acid battery prices for stationary applications is expected, despite the technology's maturity. Its widespread use supports further technology development of (more) advanced lead acid systems. However, the forecasted cost decline is significantly smaller than that of Li-ion batteries, where more gains are expected. Figure 10 depicts the impact of forecasted lead-acid battery prices on the LCOE of the mini-grid cases A-1 to 3. The impact on case A-1 is relatively large as it pertains a small system with a total investment of roughly 10,000 USD that is made commercially viable by grant funding of 7,500 USD. A drop in BESS cost therefore quickly turns the grant from a saving on investment cost to a contribution to revenues.

The impact of lower lead-acid battery prices on case A-2 is much smaller, with LCOE 12-13% lower if a project starts in 2035 vs in 2021. Case A-3 shows a slightly larger reduction of about 17%. This is due to the forecasted 22% lower cost of lead-acid batteries. These cases illustrate that the potential in cost reduction for lead-acid batteries is small and has a small potential to reduce LCOE in future small scale mini-grids.

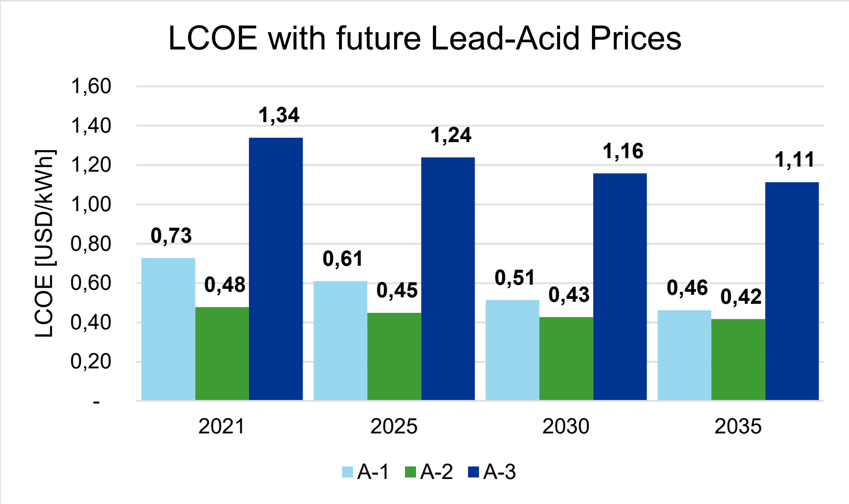


Figure 10: Impact of future lead-acid battery pricing on LCOE for cases A-1 to 3

Switch to Li-ion

The cost of Li-ion batteries is forecasted to drop significantly. However, the current and forecasted cost of small-scale Li-ion battery system are considerably higher than utility-scale Li-ion batteries. The Li-ion cells and modules deployed in these small systems are the same as those deployed in utility-scale system. A large share of the cost to the buyer of small-scale systems are associated with logistics, procurement at a (very) small scale, limited suppliers, etc. These factors drive up the cost considerably.

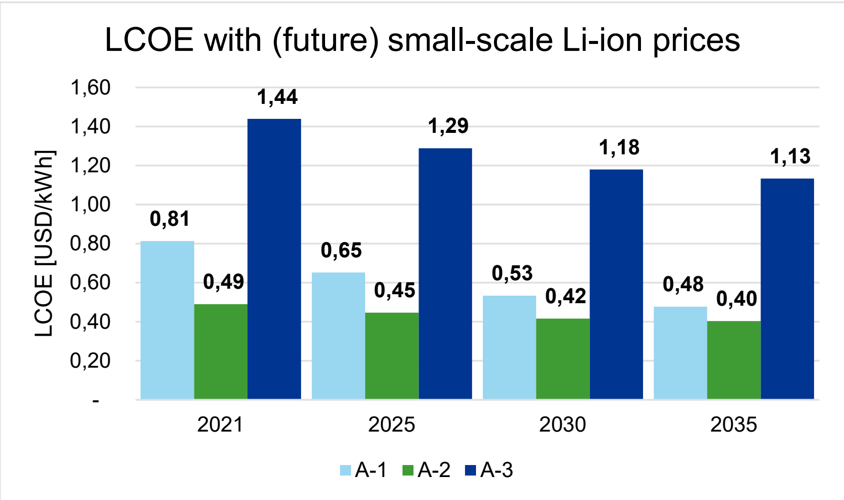


Figure 11: Impact of small-scale Li-ion pricing on LCOE for cases A-1 to 3

Figure 11 illustrates that the LCOE for the small mini-grids (represented by cases A-1 to 3) increased with the use of small-scale Li-ion batteries. Despite the better performance and lifetime of Li-ion batteries compared to lead-acid batteries, the simulations indicate higher LCOEs, and therefore higher costs. There is however a convergence towards 2035, when LCOEs with small-scale Li-ion systems are on par, or just below, those of lead-acid batteries. The forecasted cost reductions of small-scale Li-ion systems is therefore expected to displace lead-acid batteries over time. At present, and over the coming decade, the high cost of small-scale Li-ion system appears to be prohibitive in improving the cost and performance of small mini-grids.

If the higher cost of small-scale Li-ion over utility-scale Li-ion can be rectified, the above conclusions will change radically. Figure 12 depicts the same cases A-1 to 3 with Li-ion technology but assumes that utility-scale pricing for Li-ion can be attained even on the small-scale. The LCOEs are significantly lower, whether the project starts today or in

2035. The drop in LCOE ranges from 35% to 90% across these timeframes and cases. The most significant drop of 90% is for case A-1 with a project start in 2035, or 55% with a project start in 2021. This is partially due to the grant funding that is applied to this case, as lower cost batteries convert the grant from a reduction of investment to making cash available (i.e. the grant is larger than the investment). For cases A-2 and A-3 the drop in LCOE is 35-50%. If utility-scale Li-ion prices were available these business cases become significantly more attractive and tariffs to consumers on the mini-grid can be reduced considerably. Mitigating the cost "add-ons" for small scale Li-ion vs utility-scale Li-ion can turn these small mini-grid projects from costly endeavours to operations offering attractive tariffs to their users.

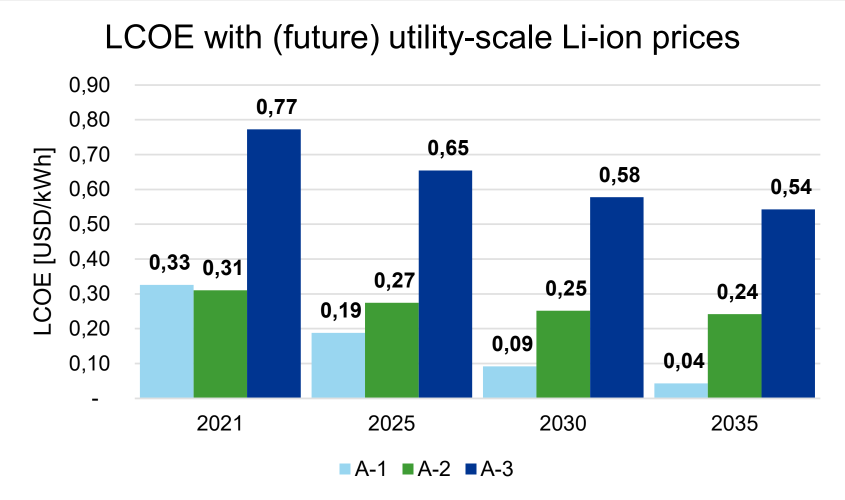


Figure 12: Impact of utility-scale Li-ion pricing on LCOE for cases A-1 to 3

Optimise sizing

Business case A-3 results in extraordinary high LCOEs, when compared to cases A-1 and A-2 that are based on similar technologies and cost levels. Capital expenditures are dominated by the BESS and solar plant, as the investment for a diesel generator is comparatively small. Figure 13 depicts the LCOE and annual CO_2 savings for business case A-3 for different energy storage capacities, and a scenario with no solar or battery storage at all.

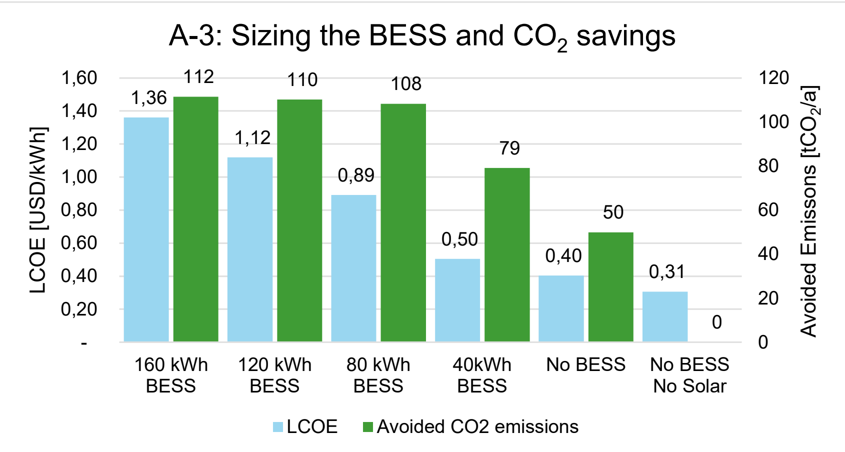


Figure 13: LCOE and CO2 savings for business case A-3

The scenario without any renewable energy or storage at all results in the lowest LCOE, implying that the lead-acid and solar technology deployed are more costly than the cost of diesel fuel. However, the scenarios with a 40 kWh BESS results in an LCOE (0.50 USD/kWh) below the tariff that is applicable for such a mini grid (0.60 USD/kWh). The scenarios also indicate that a drop in CO_2 savings (by avoided fuel consumption) only occurs between the scenarios with an 80 and 40 kWh BESS. A 120 kWh or larger battery can store more energy than the 80 kWh battery, but there will only be a few occasions in a year where it is actually used. These tend to be periods with sustained adverse solar irradiance (i.e. very limited solar power generation) where the extra capacity extends the period in which a diesel generator is not switched on. On average the daily operations simply do not utilize the extra storage capacity as its capacity is larger than the daily demand for electricity. In other words: the BESS for this mini grid is oversized, it does not meaningfully avoid diesel generator runtime and fuel consumption. For business case A-3, the potential benefits are not only in reducing the cost of lead-acid batteries or making available (near) utility-scale Li-on prices, but also in optimising the mini grid configuration itself.

4.2.3 Conclusions

Cases A-1 to A-3 represent small mini-grids. Table 8 summarises the LCOEs for each case with the different BESS approaches discussed above. Case A-3 has a larger than required battery and stands to gain from optimising the mini grid itself, regardless of which battery technology is deployed. Cases A-1 and A-2 are therefore better examples. The results of these two cases indicate that displacement of petrol or diesel only solutions, without increasing the cost to the electricity consumers, is only possible if significantly lower battery prices can be achieved. Waiting for cost reduction on lead-acid batteries or small-scale Li-ion system does not yield favourable results.

Table 8: LCOE for cases A-1 to 3 over different BESS approaches

Item	Unit	A-1	A-2	A-3
Petrol/Diesel only	USD/kWh	0.34	0.32	0.34
With lead-acid BESS	USD/kWh	0.73	0.48	1.34
With 2035 lead-acid BESS	USD/kWh	0.46	0.42	1,11
With 2021 small-scale Li-ion	USD/kWh	0,81	0,49	1,44
With 2035 small-scale Li-ion	USD/kWh	0,48	0,40	1,13
With 2021 utility-scale Li-ion	USD/kWh	0,33	0,31	0,77
With 2035 utility-scale Li-ion	USD/kWh	0,04	0,24	0,54

Significantly lower battery prices are available in the form of utility-scale Li-ion systems, but not yet attainable when deployed at a small scale. The Li-ion cell chemistry, materials, manufacturing process and vendors are the same for a utility-scale system as for a small-scale system. The performance of the cells used is also the same. The factors that increase the cost are the systems integration of such cells, modules to manufacture a battery energy storage system, the cost to implement or develop the project, and the logistics of stock transportation. If these costs are reduced considerably then small mini grids – represented by cases A-1 to A-3 – can displace petrol and diesel generators and offer electricity to the consumer or end-user at a same or lower rates than if it were powered by diesel or petrol only. The green marked cells in Table 8 indicate which LCOEs are attainable if 2021 and 2035 utility scale Li-ion cost levels are applied to these small systems. This is a hypothetical exercise, marking the lowest achievable LCOE with current battery technology. It is unlikely that small-scale Li-ion system can attain these figures without sweeping changes in the way small systems are designed, procured, and operated. Data and estimates made during this study put small-scale li-ion cost in 2035 about a factor three to four more times expensive than utility scale Li-ion.

4.3 Captive and Behind-the-Meter Applications

4.3.1 Overview of the Captive and Behind-the-Meter sector

The captive power market is experiencing unprecedented growth across SSA. This is driven by unreliable grid electricity supply (fewer than half (43%) of Africans have a reliable electricity connection[8]), high grid tariffs and falling renewable energy and energy storage costs. A large proportion of electricity generation, transmission, and distribution infrastructure in many African countries such as South Africa and Zimbabwe is failing. These infrastructure assets are

[8] *Afrobarometer, 5 Dec. 2019, "Accessible, reliable power still in short supply ... - Afrobarometer."*, https://afrobarometer.org/sites/default/files/publications/Dispatches/ab_r7_dipstachno334_pap11_reliable_electricity_still_out_of_reach_for_most_africans.pdf.

largely legacy, pre-independence, infrastructure and was designed for a small ruling class population. Since independence, this infrastructure has been weakening under the pressure of growing populations, rapid urbanization, cable theft, poor maintenance, mismanagement, corruption and ordinary wear and tear. Alarmingly, line losses in SSA are on average 16%, compared to 9% in other developing regions.[9] In Nigeria, a typical business owner will experience power outages on average for 239 hours out of 720 hours in a month.[10] In Southern Africa, the South African utility, ESKOM, has been struggling to meet demand for more than a decade and the supply shortfall is expected to worsen in the coming years.

Captive power systems can play an important role in weak grid areas of economically vibrant countries - these trends have been observed in Nigeria, South Africa, Ghana, and Kenya. In these settings, the systems play an important role in ensuring continuous power supply to counter unreliable central supply. Industries with critical loads such as telecoms, data centres and healthcare have a high prevalence of energy storage and generator back-up. These industries place uninterrupted service and power quality as a high priority.

Ever increasing grid tariffs are also forcing many businesses across SSA to resort to captive power generation. This is especially the case in countries such as Ghana and Senegal, where low voltage commercial customers pay as much as \$0.18/kWh and \$0.25/kWh respectively. In response, many industries are resorting to on-site generation. Diesel generation has been the standard option for industries with high power demand and petrol generation has been the standard for small-scale industries. Solar PV and BESS are increasingly becoming a viable option in the face of volatile fuel costs and declining renewable energy and battery costs. More details on cost reductions are presented in the appendix.

The high upfront costs of BESS, and especially that of small-scale Li-ion batteries, influences the uptake of BESS in different industries. Industries with low access to affordable capital often opt for generators and lead acid batteries. It follows that industries with high access to capital opt for advanced battery technologies, such as lithium-ion batteries. This present trend is expected to change in the future with upfront costs of battery systems falling and captive power developers' efforts to work around high upfront costs with energy-as-a-service or lease-to-own business models.

There are three main business models in use: out-right ownership, lease to own and Energy-as-Service/Product-as-Service. Large systems are typically designed, installed, and maintained by EPCs and smaller (solar home) systems are often sold outright, and then maintained through a network of distributors. In an outright ownership model, the developer sells and often installs the energy system. The customer can opt for a separate operation and maintenance agreement or to maintain the technology themselves. Lease-to-own systems follow a similar path as that of out-right ownership. EPCs themselves, often in partnership with financial institutions, offer technology on credit to customers. The technology is owned by the EPC and is transferred to customers after credit is paid off through fixed instalments (usually 12-36 months). Energy-as-Service and Product-as-Service (such as Cooling-as-Service, Towercos etc) is an emerging business model. These companies shift the cost of technology ownership from end-consumers to the company. These companies often can access long term credit at more competitive rates than typical African consumers or businesses. As a result, they typically opt for lithium-ion technology over lead acid batteries.

Table 9 illustrates the prominent captive power markets and highlights the possible use of BESS in these markets. In some market segments limited information was available. These are shown in grey.

[9] *IEA, 2019, Africa Energy Outlook, (link)*
[10] *Access to Energy Institute, #StopGuessing, 2020 (link)*

Table 9: Summary of the prominent captive power markets

Applications	Grid connection	Use of battery storage	Critical load	Access to Capital	Motivation	Detail
Telecom Towers (MNO operated)	Good	Limited	Yes	High	-Uninterrupted service -Carbon emission targets	-Limited emergency battery backup -High security vulnerability
	Weak	Intermediate	Yes	High	-Reduced TCO -Carbon emission targets	-Battery backup -High security vulnerability
	No	High	Yes	High	-Reduced diesel OPEX -Reduced maintenance costs -Carbon Emission Targets	-Solar-Battery-Diesel hybrid solutions -High security vulnerability
Telecom Towers (TowerCo operated)	Good					There is limited usage of TowerCos on good grid
	Weak	Limited	Yes	High	-Reduced diesel OPEX	-Battery backup -Capital constraints (short payback period requirements) -Threat of grid improvement inhibiting factors -High security vulnerability
	No	Intermediate	Yes	High	-Reduced diesel OPEX	-Solar-Battery-Diesel hybrid solutions -Capital constraints (short payback period requirements) -Threat of grid expansion inhibiting factor - High security vulnerability
Telecom Towers (ESCO operated)	Good and Weak					There is limited usage of ESCOs on good grid
	No	High	Yes	High	-Price p/kW relative to PPA	-Solar-Battery-Diesel hybrid solutions -ABC mini grids -High security vulnerability
Lodges/ Hotels	Good	Limited	No	Medium	-No strong motivation for battery storage	
	Weak	Limited	No	Medium	-Limited battery storage for uninterrupted power supply of critical operational infrastructure	
	No	High	No	High	-Reduced OPEX, -Carbon emissions targets, -Preservation of the environment, -Reduced noise pollution, -Remoteness of locations (safaris and island resorts) -Green Image	-Solar-Battery-Diesel hybrid solutions -High margin business

Applications	Grid connection	Use of battery storage	Critical load	Access to Capital	Motivation	Detail
High Value Agriculture	Good and Weak	Limited	No	High	-Reduced OPEX -Carbon emissions targets (of big buyers and industry (certification) associations) -Green image	-High value agriculture has prioritised grid access and often subsidised (commercial) electricity prices -Solar irrigation systems often use gravitational energy storage -Use of renewable energy peak load shaving
	No					Limited large scale off-grid high value agriculture
Mining	Good and Weak	High	No	High	-Reduced OPEX -Uninterrupted service	-Large scale mining has prioritised grid access and often subsidised (commercial) electricity prices, -Use of renewable energy peak load shaving, -predominant use of industrial scale generators
	No	Intermediate	No	High	-Remote and Off-grid operation	-Large scale off-grid mining actively lobby for grid connection prioritization as part of mining contracts
Data Centres	Good and Weak	High	Yes	High	-Uninterrupted service -Power quality -Reduced OPEX	-High levels of battery usage as uninterrupted Power Supply top priority, category includes Data as a Service Centres and private business data centres (i.e. Banks)
	No					Limited number of off-grid data centres
Education	Good					Limited usage of batteries on good grid facilities
	Weak	Intermediate	Yes	Low	-Reduced OPEX -Uninterrupted service	-Capital limiting factor, -Growing usage in "flagship" and private facilities
	No	Limited	Yes	Low	-Reduced OPEX, -Uninterrupted service	-Capital limiting factor -Predominantly government and donor funded,
Traffic Lights	Good	Limited	Yes	Medium	-Uninterrupted Service	-Uninterrupted service top priority -Capital limiting factor -High security vulnerability - Government Funded
	Weak	Intermediate	Yes	Medium	-Uninterrupted Service	-Uninterrupted service top priority -Emerging application, capital limiting factor, -High security vulnerability -Government Funded
	No					Limited number of off-grid traffic lights
Solar Street Lights	Good					Limited usage of solar streetlights on Good grid
	Weak and No	Limited	Yes	Medium	-Reduced OPEX, -Uninterrupted Service	-Uninterrupted service top priority -Emerging application, capital limiting factor,

Applications	Grid connection	Use of battery storage	Critical load	Access to Capital	Motivation	Detail
						-High security vulnerability -Government Funded
Health	Good	Limited	Yes	Low	-Reduced OPEX, -Uninterrupted Service	-Capital limiting factor -predominantly government and donor funded - growing usage in "flagship" and private facilities -high energy demand-predominant use of generators
	Weak	Intermediate	Yes	Low	-Reduced OPEX, -Uninterrupted Service	-Capital limiting factor -predominantly government and donor funded -growing usage in "flagship" and private facilities -high energy demand-predominant use of generators-battery usage for critical loads
	No	Intermediate	Yes	Low	-Reduced OPEX, -Uninterrupted Service	-Limited number of off-grid health facilities. -Capital limiting factor -predominantly government and donor funded

4.3.2 Techno-economic analysis results

Techno-economic modelling for this business case is based on four case studies. These case studies are rooted in research by DNV and TFE and supplemented with assumptions, anecdotal data points, and more generic superimposed data. These case studies therefore have merit for comparative analysis on key parameters and are a solid basis for the assessment of specific projects. The basics of the three case studies are presented in Table 10 below, all other inputs and assumptions are available in in APPENDIX A.

Table 10: Business case – captive and BTM – basic parameters

Item	Unit	B-1	B-2	B-3	B-4
Description		Safari lodge in Tanzania		Manufacturing company in Kenya	
Reference scenario (BAU)	-	Diesel		Diesel	
Grid	-	Off-Grid		On-Grid	
Type	-	Brownfield	Greenfield	Brownfield	Greenfield
Revenue streams	-	Energy sales, avoided fuel consumption, avoided downtime		Energy sales, avoided fuel consumption, avoided downtime, avoided grid connection charges	
Load profile	-	Tanzania - C&I - Safari Lodge		Kenya - C&I - Manufacturing Company	
Grid electricity supply profile	-	No Grid		24/7 at max 20% of Peak Load	
BESS technology	-	Li-ion small scale		Li-ion small scale	
BESS energy capacity	kWh	60		2,000	
BESS power capacity	kW	15		500	
Solar plant	kWp	30		500	
Wind farm	kW	-		-	
Thermal plant	kW	15	10	450	200
BAU thermal plant	kW	15	15	450	450
Project lifetime	Years	20		20	
Grant funding	USD	-		-	
Tariff electricity	USDct/kWh	40		40	
Tariff grid electricity (import)	USDct/kWh	N/A		22	
Diesel fuel price	USD/L	1,00		1,00	
Natural gas price	USD/GJ	N/A		N/A	
Cost of avoided T&D infrastructure	USD/kW	N/A		N/A	
Cost of avoided downtime	USD/a	Undefined		Undefined	

Battery vs Diesel

The difference between cases B-1 and B-2, and between B-3 and B-4, is that 1 and 3 are brownfield projects and 2 and 4 are greenfield projects. The brownfield projects are already powered by a diesel generator, which is in many cases larger than necessary when solar, wind and batteries are added to a mini-grid or hybrid plant. The savings versus a diesel-only scenario will therefore be slightly higher for greenfield projects, as the size of the diesel generator can be optimised.

The LCOE of cases B-3 and B-4 (the manufacturing company) are calculated at 0.38 and 0.37 USD/kWh respectively. This is below the tariff of 0.40 USD/kWh and the configuration is therefore expected to be feasible. For cases B-1 and B-2 the LCOE comes in just above the tariff at 0.43 and 0.42 USD/kWh respectively. The diesel generator provides about

25% of power for cases B-1 and B-2, and 40% of power for cases B-3 and B-4. This translates to avoided CO_2 emissions of approximately 50 tCO_2/year for B-1 and B-2 and 700 tCO_2/year for B-3 and B-4. However, the LCOE USD/kWh) for a diesel-only system is significantly lower at 0.27 for B-1; 0.26 for B-2; 0.27 for B-3; and 0.26 for B-4.

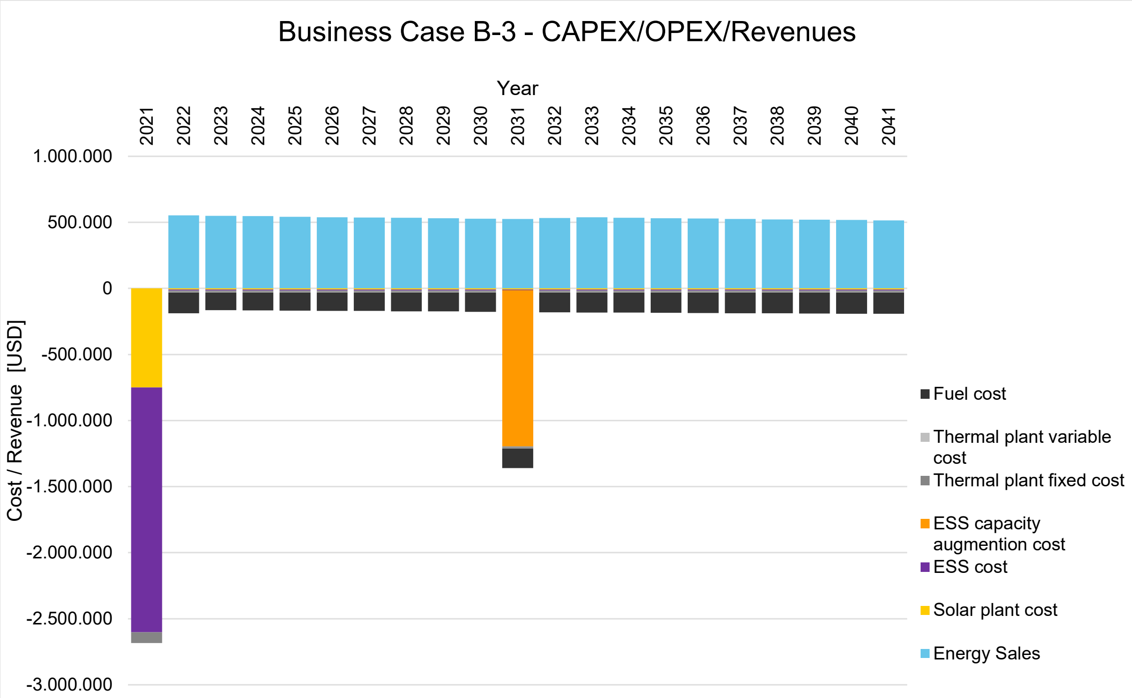


Figure 14: Business Case B-3 - CAPEX/OPEX/Revenues

Over the course of the system lifetime, the two dominant cost impacts are the capex of the solar plant and BESS, as well as the 10-year replacement cost of the Li-ion battery. Figure 9 illustrates this for B-3 with a significant battery augmentation cost in year 10. Replacement strategies are common for small-scale BESS systems, in contrast to augmentation strategies used in utility scale projects. The reason for this is one of access to data. Visibility on the actual usage and associated degradation is limited. Forecasting expected usage of the battery is also challenging as demand patterns tend to change or grow once solar and battery systems are in place. Regular servicing or on-site monitoring may be too costly, or developers are faced with logistical challenges.

The avoided fuel consumption of the greenfield projects, as opposed to a diesel-only solution, is higher than for brownfield projects. However, the difference is limited at ~1% and ~3% for B-1 vs 2 and B-3 vs 4 respectively. Multiple smaller generators are typically deployed for such cases, to achieve sufficient redundancy. If a generator fails, there is a back-up generator so that the load, e.g. a safari lodge or manufacturing company, is not disrupted. The use of multiple smaller generators allows them to be operated close to the optimal fuel efficiency points and avoid operation under inefficient partial load conditions.

Change augmentation strategy

Imposing a Li-ion battery augmentation strategy that reflects a utility-scale system can significantly reduce cost. Such a augmentation strategy is typically defined up-front and based on the expected usage of the battery system over its lifetime. If significant changes are expected during the project's lifetime then multiple augmentation strategies are developed. The goal of an augmentation strategy is to counteract degradation of battery capacity and ensure sufficient storage capacity is available. It seeks to add a small amount of battery capacity at multiple instances over the project lifetime, thereby offsetting the drop of energy storage capacity caused by degradation. Such strategies can also be optimised based on price forecasts of Li-ion batteries and the cost of these augmentation efforts.

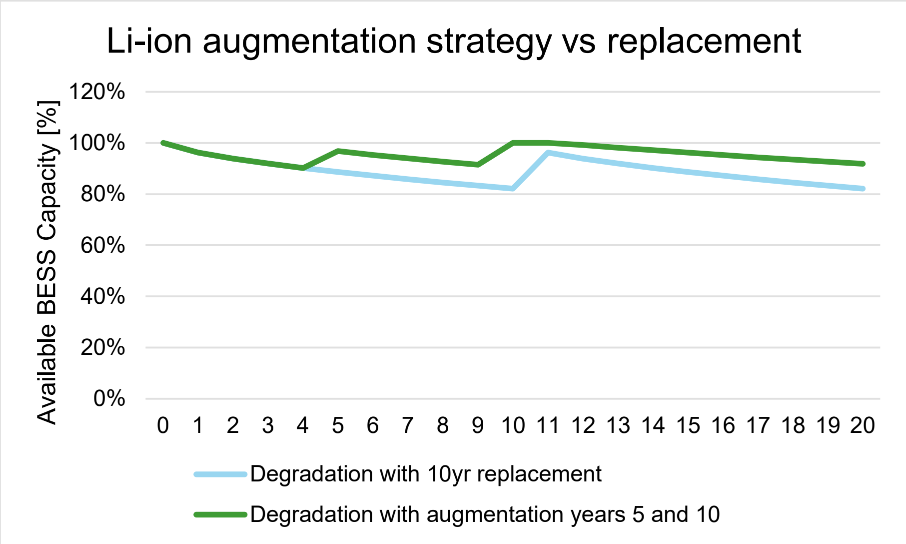


Figure 15: Li-ion augmentation vs replacement

A well-designed Li-ion augmentation strategy has multiple benefits. Figure 15 shows the expected battery degradation with a 10-year replacement strategy and with an augmentation strategy where ~8% storage capacity is added in year 5 and 11% in year 10. The lower available energy storage capacity associated with the 10-year replacement strategy also affects the revenues (or offset of diesel consumption) as less energy can be stored. However, if the actual usage of the Li-ion battery is more intense than planned or anticipated, it will degrade, and the augmentation strategy may have to be revised. A 10-year replacement strategy will simply bring capacity back up to spec regardless of use.

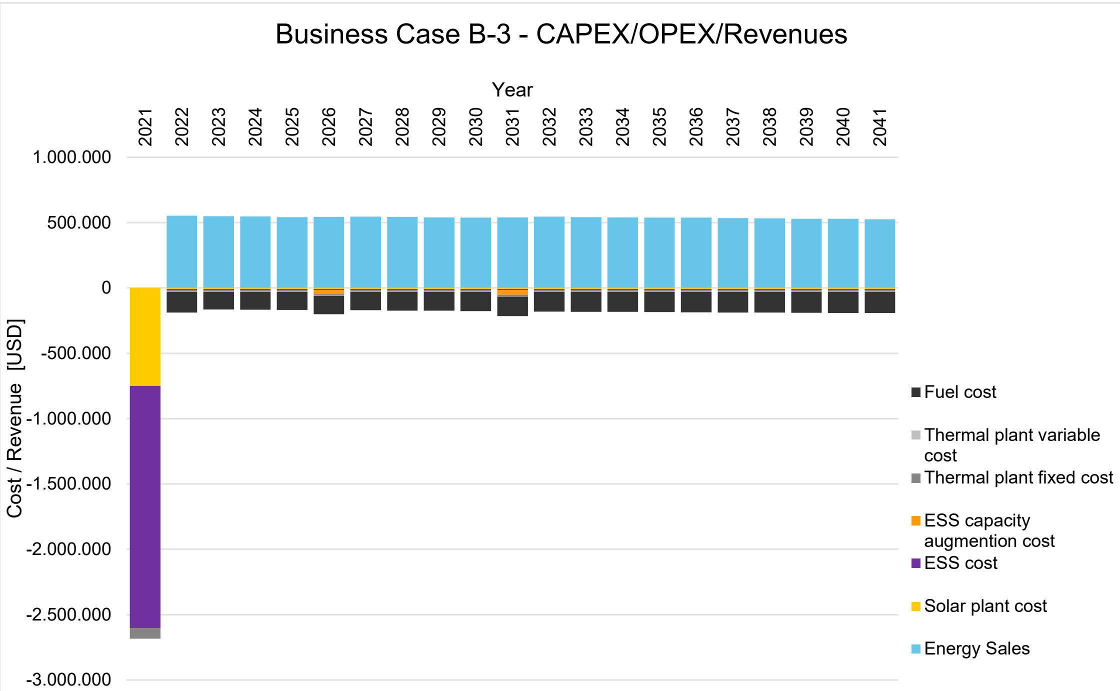


Figure 16: CAPEX, OPEX and revenue with Li-ion augmentation strategy

The augmentation strategy implies a significantly lower expenditure on the battery cost during the project's lifetime. Figure 16 above illustrates this, with a relatively minor expenditure on batteries in years 2026 and 2031 vs the single major expenditure in 2031 (see Figure 14). The resulting LCOE is about 11% lower, at 0.34 USD/kWh vs the 0.38 USD/kWh with a battery replacement in year 10. As noted above, the lower cost of augmentation may not be attainable if actual usage of the battery is unpredictable over the project lifetime, or indeed if the cost of procuring, transporting and installing the batteries prohibits the addition of small amounts of capacity at a time.

Future Li-ion prices

The cost reduction of Li-ion systems is largely driven by advancements in performance, manufacturing, and scale. All of which is most prevalent in the electric vehicle market. The major cost reductions are in the battery cells, and the modules and racks in which these are grouped for larger storage systems. Balance of plant, EPC, and developer cost are also expected to drop, albeit at a lesser rate. However, the impact on small-scale Li-ion systems is expected to be less significant, as a large share of the cost to the buyer is associated with mark-ups in logistics and procurement as well as the limitation of suppliers at local level, making pricing less competitive.

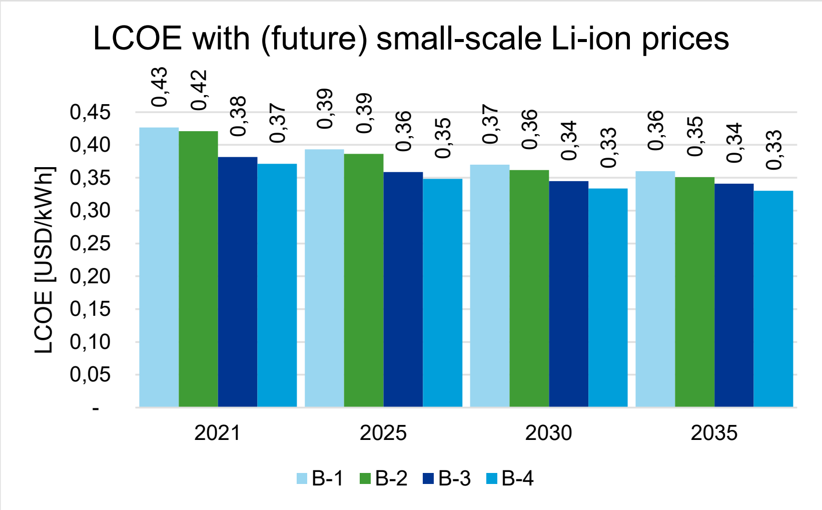


Figure 17: Impact of Li-ion pricing on LCOE for cases B-1 to 4

Figure 17 above illustrates the relatively small impact of future small-scale Li-ion prices, depicting a project start in 2021, 2024, 2030 and 2035 with each capitalizing on the forecasted Li-ion prices at that time. For cases B-1 and B-2 the LCOE is about 15-16% lower for 2035 than it is for 2021. For cases B-3 and B-4 the LCOE reduction is less, at about 10-11%, due to a higher share of diesel in the electricity mix. The reductions in battery cost therefore have a less pronounced effect on LCOE.

Achieving utility-scale Li-ion prices

A more significant reduction in LCOE can be achieved by obtaining utility-scale Li-ion prices for the small to medium sized batteries of cases B-1 to 4. Figure 18 illustrates the forecasted specific cost of a 4-hour Li-ion BESS with utility-scale and small-scale prices. The absolute difference in cost, indicated by the blue arrows, drops over time. However, the cost for a small scale 4h system in 2035 is forecasted to be roughly 27% lower than in 2021 whereas the cost of a 4h utility-scale system is forecasted to be about 46% lower. The gap between the cost experienced by small Li-ion systems vs utility-scale system is forecasted to grow wider.

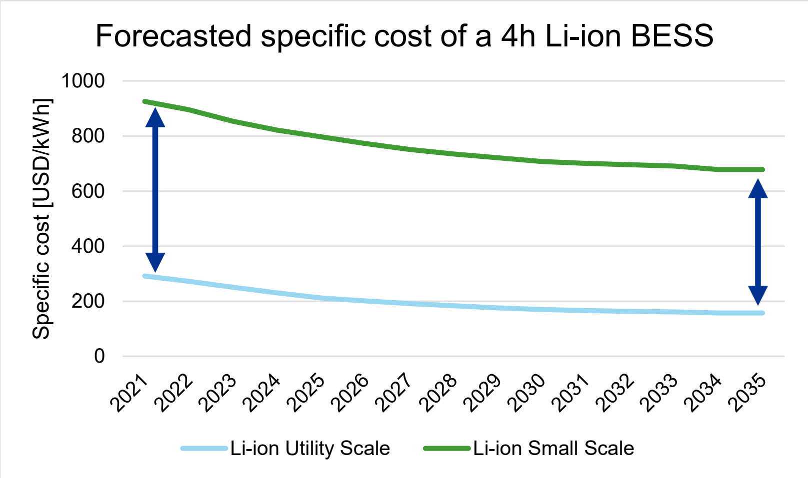
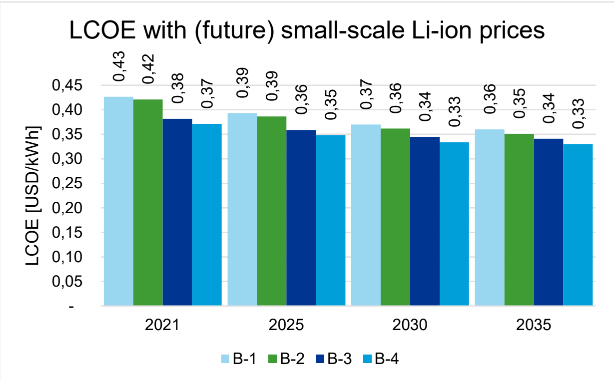


Figure 18: Specific cost for a small and utility-scale 4h Li-ion BESS

Reducing this gap has a significant effect on the reduction the LCOE, and thereby on the electricity tariff that needs to be charged to customers to create a viable business case. For cases B-1 and B-2 the LCOE at the project start in 2021 drops by 25%, and 27% if the project starts in 2035. For cases B-1 and B-2 – for which the BESS represents a larger share of CAPEX – the LCOE drops by about 35%.



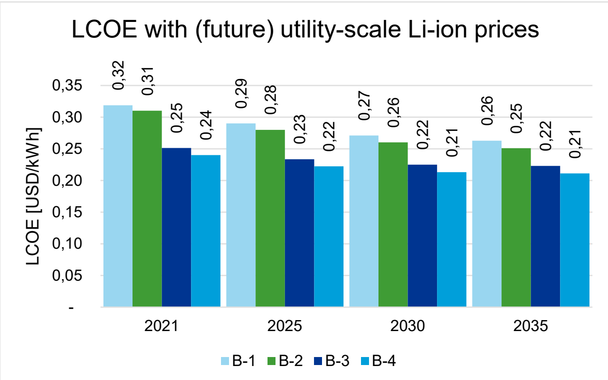


Figure 19: LCOE for (future) small and utility-scale Li-ion prices for cases B-1 to 4

4.3.3 Conclusions

The LCOE of cases B-1 to B-4 is significantly lower for a diesel generator only scenario compared to those that deploy Li-ion technology at small-scale system prices. For cases B-1 and B-2 the configurations with BESS are about 37% more expensive in terms of LCOE, and for cases B-3 and B-4 this is roughly 30%. As the LCOE represents the cost on a per kWh basis it is a good indicator for the tariff that is to be charged to end-users for the mini-grid or hybrid energy supply system to be commercially feasible. The higher LCOEs for configurations with a BESS therefore require alternative incentives or a reduction in cost of the BESS itself for these business cases to be commercially feasible.

Changing to the augmentation strategy is a potentially worthwhile approach to reduce the LCOE of a system with a small-scale Li-ion battery. The practice of replacing Li-ion batteries after approximately 10 years to ensure sufficient battery capacity is robust, but costly. Advanced software tools and the correct know-how can help forecast the usage profile of the BESS, forecast the degradation of BESS capacity, and infer augmentation rather than replacement strategies. Monitoring of the Li-ion system during operation provides information about actual usage and can help inform decision making on adjusting the usage of a BESS or to adjust the augmentation strategy if needed. However, this only works if additional Li-ion modules can be procured, transported, and added to the battery system at reasonable costs.

Augmentation- instead of replacement strategies will not alone be sufficient to reduce LCOE to the figures resulting from a diesel only operation. Future small-scale Li-ion prices, based on price forecasts, reduces the achievable LCOE for cases B-1 to 4 but does not enable sufficiently low LCOEs. The cost difference between small-scale and utility-scale Li-ion system is too large and is forecasted to remain large. However, if the cost “add-ons” that make a small-scale Li-ion system so much costlier can be reduced to near utility-scale Li-ion BESS prices, for the clientele of. cases B-1 to 4, the cost of electricity can drop to equal or lower figures as that of diesel-only configurations. This will also yield significant savings on fuel consumption and the associated CO_2 emissions.

4.4 Off-Grid Industrial Facilities

4.4.1 Overview of the Off-Grid industrial facilities market

Since 2011, Africa has seen linear growth in off-grid electrification. In 2018, IRENA reported that the population served from off-grid generated power increased from 2 million people in 2011 to 52 million people in 2016[11] . Most of these facilities are small, only providing energy for the most basic of human needs, such as lighting. However, the market for off-grid renewables holds a lot more promise beyond lighting unlit households or reducing costs and fuel variability for remote, diesel-dependent industries. Off-grid renewables represents a fundamental and dramatic evolution in the utility business model towards customer-centricity. Accordingly, there are various opportunities to provide reliable power to commercial and industrial users to foster economic growth.

Many large-scale industrial plants and complexes produce their own electricity for two reasons: 1) local electricity production is cheaper than electricity from the grid; and 2) reliability and the need for uninterrupted power supply is a priority or a necessity. Industrial facilities, typically those for mining, manufacturing, and processing, are prevalent in all economically active countries in SSA. These facilities are typically designed for operational schedules requiring constant electricity demand 24 hours a day. Furthermore, the processes of industrial facilities are often adversely affected by power outages as it can lead to product or material getting stuck in parts of the plant which requires labour- and time intensive reset before the processing can be continued.

Off-grid facilities depend on the cost and quality of both the generation assets, predominantly Solar PV, and the energy storage systems. Falling PV prices and a lack of reliability in the grid is stimulating sales of on-site PV to commercial customers in SSA. A report entitled “Solar for Businesses in Sub-Saharan Africa” finds that the commercial and industrial (C&I) solar sector in SSA is growing, not because of regulatory support – as has been the case in many developed economies – but purely because of economics. On-site solar power is cheaper than the electricity tariffs paid by commercial or industrial clients in 7 out of 15 markets in SSA studied by BNEF. This BNEF study excludes South Africa, but solar PPA rates are well below that of grid rates in South Africa. Data shows a total pipeline of more than 500 MW of commercial and industrial solar under development in SSA [12].

Industrial loads typically range from 0.5MW for small factories or processing plants up to 20MW or more for large mining operations or heat intensive furnaces. Most industrial facilities will fall under 5MW load. Historically, large off-grid loads were exclusively served by diesel generators, typically run in parallel to allow for units to switch on and off, as the load requires, to save on fuel costs. With reducing costs of renewables and BESS, and with growing pressure on companies to offset their carbon footprint, large industrial clients are increasingly turning towards renewables for their off-grid energy needs.

Per unit of electricity delivered, off-grid solutions are currently more expensive than a well-managed and efficient national grid. However, it is often the case that off-grid renewable electricity is the only option available. Even where off-grid electricity is the only option, the up-front costs are still often a major barrier for such projects. Businesses face a credit challenge in many African countries due to high and fluctuating interest rates and a customer base, particularly those in more remote locations, who have uncertain and very low incomes. All of this makes lending a challenge and

[11] *IRENA, 2018, Off-grid Renewable Energy Solutions*
[12] *WoodMac: Nearly $470M Invested Into Off-Grid Energy Access Companies Last Year | Greentech Media*

project returns uncertain. To get around these challenges, businesses in SSA must be innovative in trying to ensure they have the best possible business models for uptake and growth of the sector.

The success of pay-as-you-go energy models is also going beyond household ownership and being adapted for use in mini grids with businesses now adapting the model to serve other rural and off-grid sectors. A range of other commercial and industrial uses for off-grid electricity from supermarkets to mining also have potential. For off-grid systems which are developed for one customer directly and only serve a single building or site, standard PPA models are utilised to bill the client monthly. O&M contracts can also be included in the PPAs to guarantee a level of energy production and to uphold technical specifications and warrantees.

4.4.2 Techno-economic analysis results

Techno-economic modelling for this business case is based on four case studies. These case studies are rooted in research by DNV and TFE and supplemented with assumptions, anecdotal data points, and more generic superimposed data. These case studies therefore have merit for comparative analysis on key parameters and are a solid basis for the assessment of specific projects. The basics of the three case studies are presented in Table 11 below, all other inputs and assumptions are available in APPENDIX A.

Table 11: Business case – off-grid industrial facilities – basic parameters

Item	Unit	C-1	C-2	C-3	C-4
Description		Manufacturing company in Kenya		Processing factory in Sierra Leone	
Reference scenario (BAU)	-	Diesel	Gas	Diesel	Gas
Grid	-	Off-Grid			
Type	-	Greenfield		Brownfield	
Revenue streams	-	Energy sales, avoided fuel consumption, avoided downtime		Energy sales, avoided fuel consumption, avoided downtime, avoided generation capex	
Load profile	-	Kenya - C&I - Manufacturing Company 10 MW		Sierra Leone - C&I - Processing Factory 13 MW	
Grid electricity supply profile	-	No Grid			
BESS technology	-	Li-ion utility-scale			
BESS energy capacity	MWh	40		40	
BESS power capacity	MW	10		15	
Solar plant	MWp	30		20	
Wind farm	MW	-		-	
Thermal plant	MW	12	12	16	16
BAU thermal plant	MW	12	12	16	16
Project lifetime	years	25			
Grant funding	USD	-			
Tariff electricity	USDct/kWh	20		20	
Tariff grid electricity (import)	USDct/kWh	N/A		N/A	
Diesel fuel price	USD/L	1,00		1,00	
Natural gas price	USD/GJ		12,36		12,36
Cost of avoided T&D infrastructure	USD/kW	N/A		N/A	
Cost of avoided downtime	USD/a	Undefined		Undefined	

Battery vs Diesel/Gas

Cases C-2 and C-4 are assumed to be natural gas powered, whereas cases C-1 and C-3 are diesel powered. C-1 and C-2 are greenfield, and C-3 and C-4 are brownfield projects. The brownfield projects are already powered by a diesel generator or natural gas engine, which is in many cases larger than required once solar, wind and batteries are added to a mini-grid or hybrid plant. The savings are slightly higher for greenfield projects, compared to that of diesel-only scenarios, as the size of the diesel generator can be optimised.

For cases C-1 and C-2 the LCOE is calculated at 0.17 and 0.16 USD/kWh, and for cases C-3 and C-4 at 0.17 and 0.18 USD/kWh. In both instances the hybrid plant supported by natural gas is deemed more expensive than the same plant supported by a diesel generator. This is based on medium fuel price projections, with a 20% mark-up applied to diesel to reflect taxes and other charges and a 2 USD/GJ mark-up for transport and logistics. For natural gas a 6 USD/GJ mark-up is applied to reflect the cost of liquefaction, regasification, and logistics. A diesel or gas only configuration results in a higher LCOE for all cases C-1 to C4, with 0.23 USD/kWh for C-1; 0.19 USD/kWh for C-2; 0.25 USD/kWh for C-3; and 0.26 USD/kWh for C-4. A battery (and solar) supported configuration is therefore already deemed commercially viable for these cases.

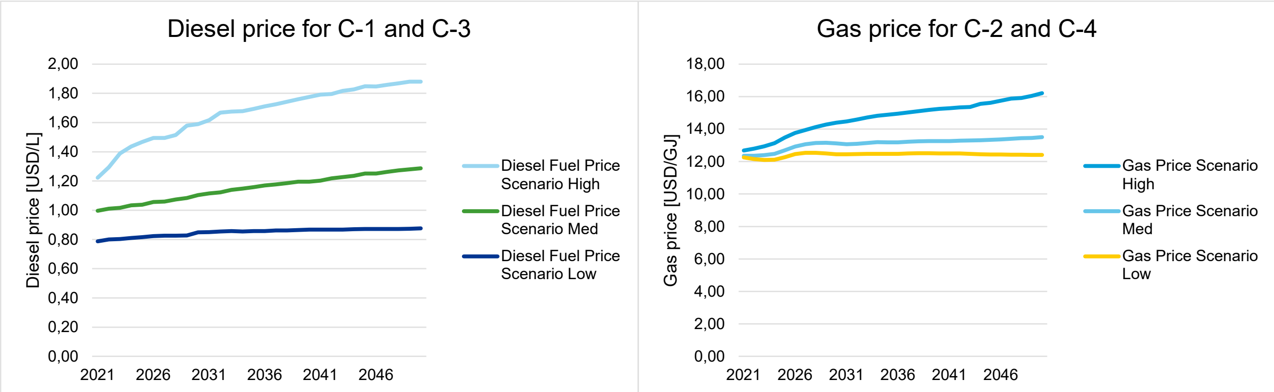


Figure 20: Diesel and gas prices for cases C-1 to C-4[13]

Taking case C-1 as an example, the BESS can be increased in size to further reduce fuel consumption. Switching to a PV plant with bi-facial PV modules on trackers (vs standard PV modules on a fixed mounting structure) increases the solar energy output with only a minor impact on cost, but also results in improved solar power production during the morning and evenings. Figure 21 below depicts the LCOE and share of electricity provided by the diesel generator for case C-1 over the standard PV solution vs bi-facial modules on a tracker, and the impact of increasing the battery capacity.

[13] Diesel and gas prices are sourced from the US Energy Information Administration's annual energy outlook of 2020. Diesel: retail prices at low, high and reference oil price scenarios. Gas: spot price at Henry Hub at low, high and reference oil and gas resource and technology scenarios.

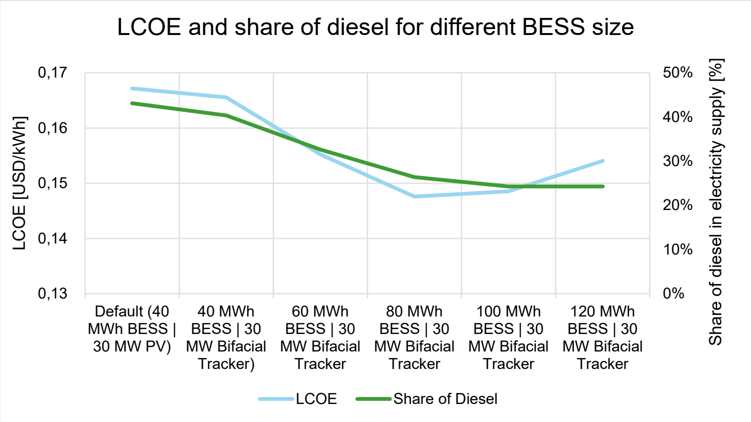


Figure 21: LCOE and share of diesel for different BESS size for C-1

Note that:

- Both the LCOE and the share of diesel drops when switching to bi-facial modules on a tracker.
- The share of diesel drops as the battery capacity is increased, as the battery can absorb more solar power and meet demand for longer periods.
- The share of diesel in the electricity mix levels out for larger battery capacities. It becomes increasingly difficult for battery capacity to replace diesel as it not only bridges daily periods with limited to no solar energy but also has to bridge days or weeks of sustained low solar irradiance.
- The LCOE initially drops as the battery grows but rises again as the effect of displacing diesel (i.e. fuel cost savings) by battery capacity (i.e. higher energy storage cost) diminishes.

For this specific scenario a battery roughly twice the energy capacity results in a lower LCOE and further reduction in diesel consumption and the associated CO_2 emissions.

Future Li-ion prices

The impact of reduced Li-ion prices on case C-1 is limited. Figure 22 depicts the LCOE and share of diesel in the electricity mix for case C-1, if the project starts in 2025 or 2030. As opposed to a project start in 2021 (see Figure 21) the energy storage capacity of the BESS can be increased by another 25%. With 2025 forecasted Li-ion prices, a further reduction in LCOE is achieved by offsetting diesel consumption and capitalising on cheaper batteries. However, 2030 forecasted Li-ion prices do not enable a further decrease in LCOE by increasing battery capacity. A lower LCOE is only achieved by capitalising on cheaper batteries. This is a result of the very limited further reduction in diesel consumption with increasing battery capacity. The energy storage system not only has to bridge daily periods with limited to no solar energy, but also has to bridge days or weeks of sustained low solar irradiance.

Lower electricity tariffs are therefore possible in the medium to long term, based on the forecasted Li-ion prices. However, the cost declines do not contribute to significant further reductions in diesel consumption, nor the total displacement of diesel generators.

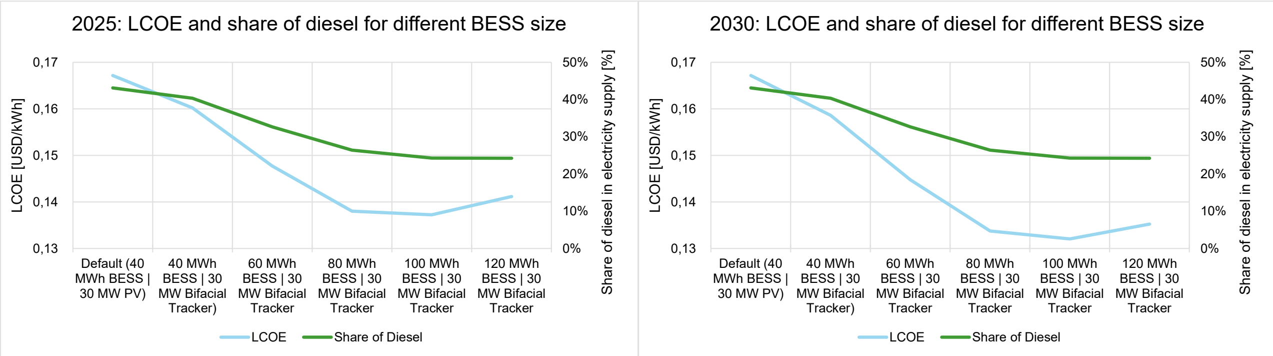


Figure 22: Effect of 2025 and 2030 project start on LCOE and share of diesel for different BESS size for C-1

Higher fuel cost

Three fuel cost scenarios (see Figure 20) can be used to gauge the impact of (diesel) fuel price on the LCOE and optimisation of battery size. Figure 23 depicts the relationship of BESS size, fuel price scenario and LCOE. The smaller the BESS, the more fuel is consumed and consequently the effect of fuel price is on the LCOE increases. Conversely, at the high fuel price scenario, a larger BESS makes sense (100 vs 80 MWh). Even though it only avoids a relatively small amount of extra diesel, it does represent a more significant cost.

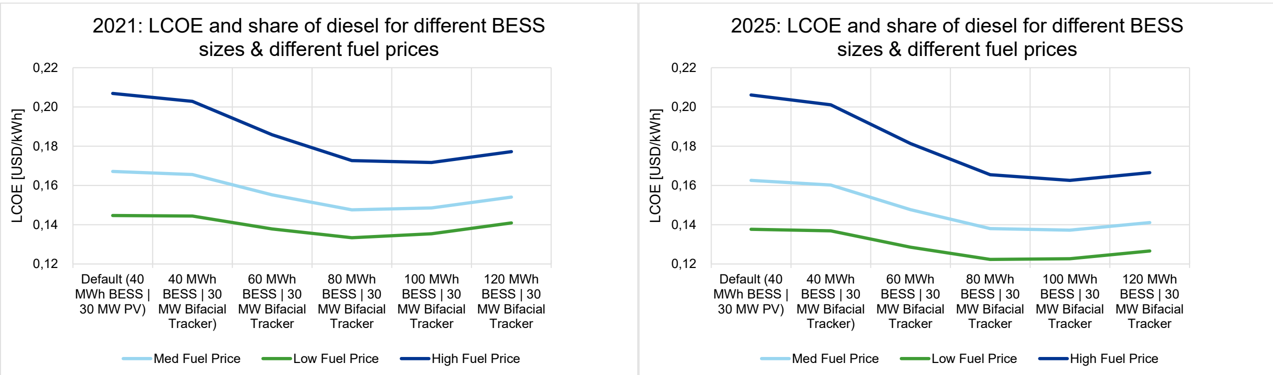


Figure 23: Effect of fuel cost and future BESS price on LCOE for different BESS size for C-1

Figure 23 also illustrates the impact on LCOE of the different fuel prices over different BESS sizes for projects starting in 2025, with the latter exhibiting lower Li-ion prices. Higher fuel prices and lower Li-ion BESS cost complement each other but warrants a gradual rather than significant change of the optimization of BESS size over LCOE and avoiding fuel consumption. Future Li-ion pricing alone already enables a larger BESS (see Figure 22), an effect that simply becomes more pronounced with higher fuel prices and is not counteracted by the low fuel price scenario. Note that the fuel prices underlying the results include mark-ups to reflect taxes, transport, logistics and other potential charges. These charges are subject to location and context of a specific battery project and can be higher or lower and thus influence the sizing of BESS in relation to avoiding diesel fuel consumption and LCOE.

4.4.3 Conclusions

A diesel or gas only configuration results in a higher LCOE for all cases C-1 to C4 compared with a battery (and solar) supported configuration. Battery systems are therefore likely making their mark on off-grid industrial facilities. This is evidenced by some projects already gaining momentum in Africa. Forecasted reductions in the cost of utility-scale Li-ion will help to drive down cost, and improve competitiveness, of BESS supported electricity supply systems for off-grid industrial facilities.

Cost reductions of BESS are not sufficient to fully displace diesel generators. However, cost reductions for Li-ion systems do enable larger batteries to displace more diesel or gas consumption, an effect which is amplified when higher fuel prices are in effect. The further reductions in diesel or gas consumption are not very large, and fully displacing diesel generators is not yet commercially attractive. The BESS technology, at current and forecasted costs are commercially viable for bridging the, more-or-less daily, variability and adverse weather events for solar energy to power off-grid sites at this scale. However, they are not yet cost effective at bridging the load supply for sustained periods (> 1 day) of limited solar resource availability.

4.5 Avoided Transmission & Distribution Expansion

4.5.1 Overview of the Avoided T&D expansion business case

Storage systems located in the MV distribution network can provide several services to the grid, some of which can be provided in parallel, a term called stacking, to add more value with the same energy storage asset. The following are the main services that can be provided, more information is included in Appendix C.4:

1. (Fast) Frequency Response / Spinning Reserve capacity / Frequency Containment Reserve
2. Frequency Regulation / Regulating Reserves
3. Investment avoidance or deferral for (local) infrastructure upgrades (by solving grid congestion issues)
4. Investment avoidance or deferral for generation capacity (by reducing grid peak load and need for new generation capacity)
5. Emergency local power supply during power outages
6. Power Quality improvement (including voltage control)

Storage systems connected to the transmission system (HV) can mostly provide the same services. However, emergency power supply and improving power quality would often not be possible due to the limited BESS power capacity compared to the transmission system capacity. Grid connection costs are normally much higher when connecting to the transmission system, as the transformers, switchgear and cabling rated for HV have much higher costs.

The first two services, providing two different grid frequency-based (power) services, are well-established applications for BESS around the world, and are currently the main application where BESS outperforms existing thermal power plants. The main issue is that the market rules or competitive tender specifications should consider the characteristics of BESS projects:

- Contracts should be long-term (ideally 10 years or more) to allow for the projects to be bankable based on providing just this service (compared to thermal plants that provide this service in addition to energy production
- There should be clear limits on how much the BESS can be used daily and annually, to ensure that degradation is manageable and avoid excessive capacity maintenance agreement costs

This project focusses on the more energy-based type of grid services, especially deferred or avoided investment in new transmission & distribution assets or new generation capacity.

The electricity grid's transmission and distribution infrastructure must be sized to meet peak demand, and thus can vary widely from one location to the next. Typically, these systems are connecting to 11kV or 33kV connections and are sized upwards from 1MW up to 100MW. An example layout of the system is illustrated in Figure 24.

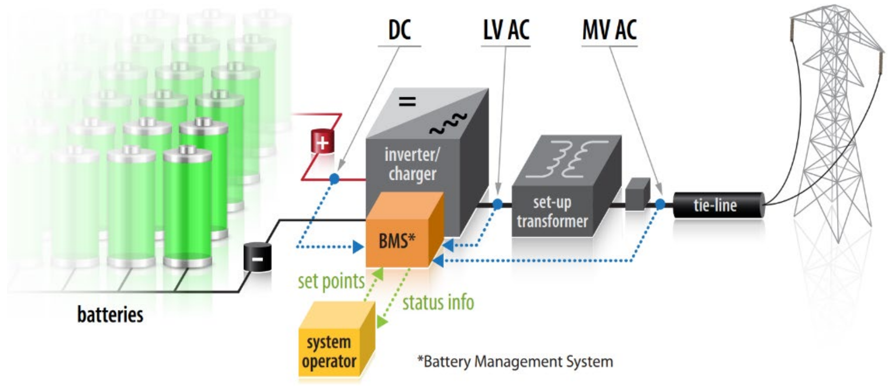


Figure 24: Key components of BESS interconnected at the transmission substation level[14]

In cases where the utility company is deregulated, the primary customer would be the entity operating and overseeing the infrastructure development of the transmission of electricity. In cases where the utility fulfils all the roles of generation, transmission, and distribution, such as the South African utility, ESKOM, then they alone stand to benefit.

The assets implemented to avoid T&D expansion are typically stand-alone BESS systems connected at a critical substation. By combining BESS with solar and/or wind (based on resource and land availability) charging from the grid can be minimised.

Payment or reimbursement of these assets are seldom only from one function. Globally the trend is to make use of the various functions that BESS can deliver; a term called value stacking. The contract will have to be set up to reflect how the different functions will be reimbursed, but in principle electricity meters are installed at the output of the inverter and read in conjunction with the BESS software to establish discharge times, MWh throughput and other important characteristics that determines the asset's performance. In the modelled business cases two options are reviewed:

a) BESS that is used in the morning and evening peak hours to reduce demand, allowing the demand to be met while avoiding investment in a new transformer and overhead line investment in the distribution grid (Case D-1)

b) Same as in a), but the reduction in peak demand also allows avoiding investing in new generation capacity to meet the annual peak demand (Case D-2)

Other potential revenue streams that are not included in the current business cases, but could be considered, are:

- **Arbitrage**: energy discharged during peak hours would be of a higher value/tariff than energy charged during off-peak hours. This would require a time-of-use tariff or market with varying prices during the day, this is not available in most SSA countries
- **Frequency response/regulating reserve**: during the off-peak hours the BESS could provide power-based grid services. This would require a dynamic grid services market or very flexible grid services contracts, this is not available in most SSA countries (or anywhere outside of the US)
- **Emergency local power supply**: depending on the local grid layout, the BESS could supply emergency power during power outages. However, the value of this service would be difficult to determine and translating the added value for the end-users to revenues for the BESS project/distribution company would be difficult
- **Power Quality improvement**: the BESS could be a source of both active and reactive power, allowing better control of the power quality in the distribution grid. This would bring benefits to the end-users. However, the value of this service would again be difficult to determine and translating this added value to revenues for the BESS project/distribution company would be difficult

[14] *NREL, 2019, Grid-Scale Battery Storage, (link)*

Barriers for BESS

The following areas are where the main (non-economic) barriers are for the implementation of BESS projects power grids:

Lack of specific regulation and standards: Although storage may be technically able to provide essential grid services, if no regulations or guidelines explicitly state that storage can provide these services, utilities and market operators may be unwilling to procure services from BESS. Often the grid code (the standard that describes which assets can connect to the power grid) is still based on thermal power plant characteristics, that do not fit the specific technical characteristics of a BESS: a) output is available for a limited duration only, and b) the BESS needs to charge (consume energy) from the grid.

Lack of understanding: BESS are a new kind of power sector asset, not fitting neatly with the traditional generation, transmission, distribution, and end-use categories. Also, the specific characteristics of BESS make them very well-suited for some applications/service, but much less so, for others. The constraints on how BESS can be operated cause many utilities to be doubtful of the benefits the BESS would bring in the end, compared to the greater certainty of the fixed capacity of a thermal power plant, substation or overhead line (OHL).

Lack of clear market structure: in most SSA countries, grid services are provided as a by-product by thermal power plants, and their costs are included in the overall energy costs from the thermal power plants. For BESS, the value of these services needs to be determined more explicitly as this would be the main source of revenue. When the BESS is owned and operated by an integrate utility, the benefits do not have to be translated into specific revenue streams, as any avoided costs due to the BESS would flow to the integrated utility in the end. Many utilities in SSA are undercapitalised and lacking sufficient revenues for large scale investments, leading to a need to mobilise private capital through IPP or PPP type projects. Those would require very clear market rules and tariff structures to be bankable.

4.5.2 Techno-economic analysis results

The main input parameters for the “Avoided T&D Expansion” business cases used in the techno-economic model are listed in Table 12.

Table 12: Business case – Avoided T&D Expansion – basic parameters

Item	Unit	D-1	D-2
Description		BESS connected at 33kV substation to avoid new OHL and substation expansion	Same as D-1, but also avoiding investment in new generation capacity by reducing total peak demand
Reference scenario (BAU)	-	T&D Investment	T&D + Generation Investment
Grid	-	On-Grid	
Type	-	Green-field	
Revenue streams	-	Avoided T&D CAPEX and OPEX	Avoided T&D CAPEX and OPEX, and avoided Generation CAPEX
Load profile	-	Avoided T&D expansion (reduce peak)	
Grid electricity supply profile	-	Avoided T&D expansion (reduce peak)	
BESS technology	-	Li-ion Utility Scale	
BESS energy capacity	MWh	80	
BESS power capacity	MW	20	
Solar plant	MWp	-	
Wind farm	MW	-	
Thermal plant	MW	-	
BAU thermal plant	MW	-	12
Project lifetime	years	25	

Item	Unit	D-1	D-2
Grant funding	USD	-	
Tariff electricity	USDct/kWh	20	
Tariff grid electricity (import)	USDct/kWh	6.0	
Diesel fuel price	USD/L	-	
Natural gas price	USD/GJ	-	
Avoided T&D infrastructure (CAPEX)	USD/kW	150	
Avoided T&D infrastructure (OPEX)	%CAPEX/a	2%	
Avoided Generation capacity (CAPEX)	USD/kW	-	800
Cost of avoided downtime	USD/a	-	

Battery vs Business-As-Usual (grid and generation capacity expansion)

This business case does not directly relate to replacing fossil fuel generators, as the BESS still would need to be charged from the grid (likely consuming fossil fuel generated electricity). By meeting peak demand, it is still likely that the BESS would allow the most expensive diesel-fired thermal plant to be operated less, and the BESS could be charged from the grid at times of high renewable energy output. Using a BESS to avoid further grid and generation capacity investments does have likely additional benefits in supporting the further integration of renewables.

Several drivers determine the business case:

a) **Duration of peak demand**: this determines the required energy capacity of the BESS (in MWh/MW power output), the longer the duration the higher the BESS CAPEX.

b) **Number of peak demand periods**: twice daily, daily, or only during a specific season. This determines how often the BESS is (dis)charged, more peak periods mean more BESS cycle energy losses and associated OPEX.

c) **BESS specific CAPEX**: the specific CAPEX (USD/MWh) determines the total investment costs for a given BESS capacity, sized to solve the identified grid constraint. The higher the (specific) costs, the higher the BESS (total) CAPEX.

d) **Value of avoided T&D assets**: depending on the grid constraint that is addressed, the avoided costs of the BAU approach would vary. This would include costs of the substation expansion and cables/OHLs (depending on the distance and power capacity rating). The higher this value, the greater the benefits of the BESS.

e) **Value of avoided generation assets**: in case the current power generation capacity is close to the (regulatory) required capacity to be able to reliably meet peak demand, the BESS can avoid or defer the investment in new thermal power generation capacity as the effective peak demand is reduced. The value of this benefit would vary depending on the projected (specific) costs of this new power plant and would only be applicable if the BESS can be shown to reliably reduce demand for each peak demand period in the year. The higher this value, the greater the benefits of the BESS.

f) **Costs of energy for charging the BESS**: depending on the regulation, the value of energy discharged from the BESS could offset the costs of energy for charging the BESS. This is only if the costs of energy during peak hours are higher than the costs during off-peak hours, as the BESS cycle losses (around 15-20% in practice) would need to be covered as well.

As most of these drivers are highly location- and project-specific, it is difficult to extrapolate the results from a few business cases to a general conclusion that is valid across SSA. The main consideration for this business case is that when the avoided T&D (and generation) CAPEX exceeds the BESS CAPEX, the project quickly becomes economically feasible.

These business cases also differ by nature, as the savings of avoided investments would be realised at the same time as the investments in the BESS, meaning that the project IRR is not defined as your return on investment would be instantaneous. Instead the Benefits/Costs (B/C) Ratio is the only relevant KPI for these business cases, and the project would be economically feasible when the B/C ratio exceeds 1.

Results

As can be seen in Figure 25, achieving a feasible business case when only considering avoided T&D CAPEX (light blue lines) is not possible. When also considering avoided Generation CAPEX (green lines) the business case can become feasible for certain niche cases, where the avoided T&D CAPEX exceeds 750 USD/kW. BESS CAPEX would need to reduce significantly (to around 120 USD/kWh) for Case D-2 to become feasible, which is not realistic in the short and medium-term future.

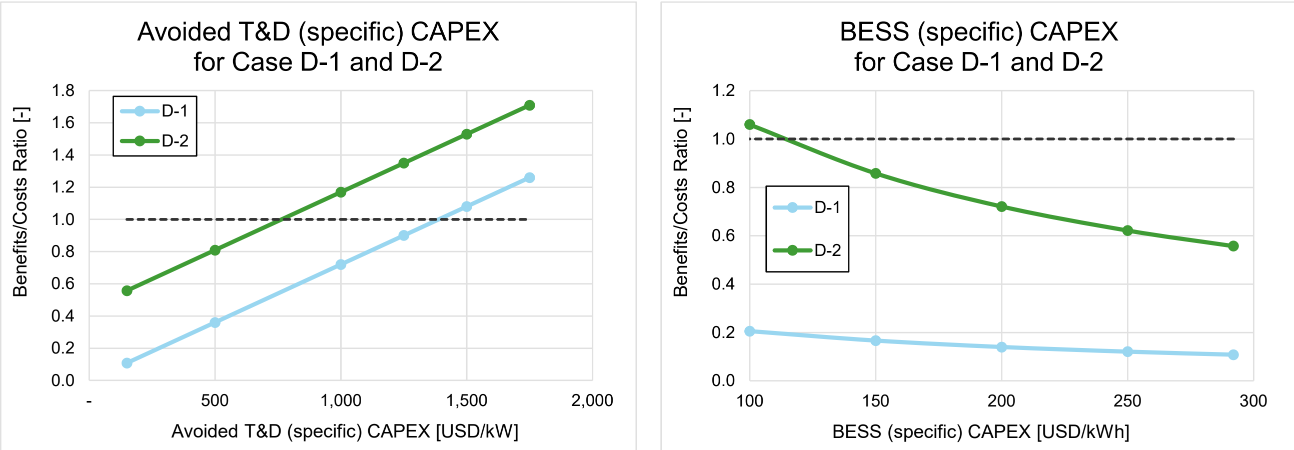


Figure 25: B/C Ratio results vs avoided T&D specific CAPEX (left) and BESS specific CAPEX (right)

It should be noted that this is for a scenario where there are two daily peaks (morning and evening) of three hours, every day of the year. As mentioned in subsection, no additional revenue streams are considered. When the BESS is utilised for spinning reserve or other grid services during the non-peak hours when the BESS is not discharging, the project becomes feasible for a capacity tariff of about 6 USD/MWh for Case D-2 (including avoided generation capacity) and at 12 USD/MWh for Case D-1 as shown in Figure 26.

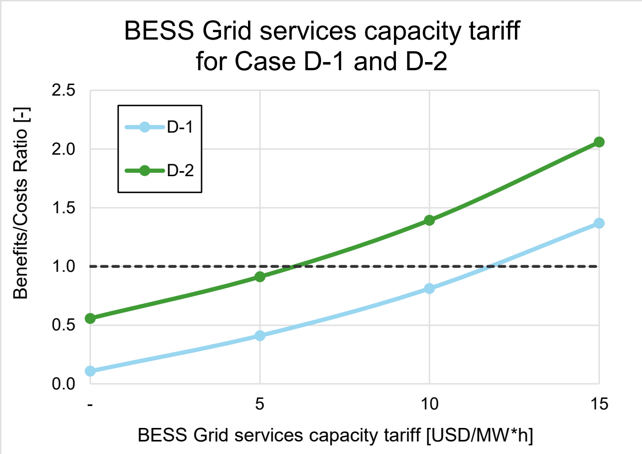


Figure 26: B/C Ratio results vs BESS Grid services capacity tariff

4.5.3 Conclusions

The business case for avoiding T&D (and Generation) capacity expansion investments is complicated, as it is very location and project specific. Due to the large cost difference between T&D capacity and BESS specific CAPEX, it is only in very specific circumstances (where the T&D expansion has high costs) that a BESS is a cost-effective option. When the BESS is designed to reliably reduce peak demand and the generation capacity expansion can be avoided, then the business case improves significantly, but is still only feasible in certain niche situations. Examples would be in cases where either grid expansion is not possible, due to right-of-way issues, and where the BESS would be the only available option to solve the grid constraint.

The additional added value of the BESS for the grid would have to be considered. For instance, in the form of capacity payments that provides spinning reserve capacity for the project to be more economically feasible. However, due to the lack of capacity markets in SSA for grid services, this would only apply to BESS (services) procured by integrated utilities, where these benefits to the system are for the same party that caries the costs for the BESS (services).

4.6 Hybrid Solar and Wind Plants

4.6.1 Overview of Hybrid Solar and Wind Plants business case

In most cases battery energy storage systems (BESS) are used to provide short-duration power in the range of several hours. However, in the case of hybrid solar PV and wind plants, the aim is to replace dispatchable thermal power with the addition of BESS (potentially augmented with back-up generators). The first large scale application has been seen in the emergency power tender in South Africa: The Risk Mitigation Independent Power Producers Procurement Programme (RMIPPPP). The aim of this program (project completion scheduled for 2022) is to obtain dispatchable power while avoiding excessive fuel costs and (CO_2) emissions. The initial results of the tender show that different combinations of solar, wind and BESS can be competitive with conventional power plants at utility-scale. The added benefit of renewables and storage-based power plants is the predictability of future costs, as there is no need to procure and import unpredictably priced fossil fuels.

This concept is likely to be applied in some form in other countries in SSA, where there is an aim to increase renewable energy generation, but where security of supply also needs to improve to support economic growth. Naturally, demand changes over the time of day and thus there will likely not be a need for full baseload output. However, there is a need for predictable or reliable power capacity that can be dispatched (scheduled) by the central grid operator.

This business model works best as a competitive IPP tender, to which developers offer competitive solutions based on minimum functional specifications. The detailed requirements determine the amount of energy storage required to achieve a certain flexibility and availability of power output.

Procuring, installing, and commissioning BESS at utility-scale power plants is in general much more straight forward than thermal generators. This is due to the interfaces and foundation requirements being much simpler for BESS. The main complexity is the hybrid plant control system (advanced energy management system, EMS) which optimises the dispatch of the different generation units and BESS charging/discharging. There are several suppliers of these control systems that have sufficient operational experience to reduce the risk of communication and control issues between the different assets. These suppliers are often the larger suppliers including Siemens, Emerson, GE, and ABB. This risk should be managed more closely when the supplier has less operational experience.

4.6.2 Techno-economic analysis results

Two separate cases are modelled to illustrate the business case of energy storage connected to hybrid solar and wind plants:

- **Case E-1**: Hybrid PV + BESS + DG plant (diesel-fired) providing dispatchable power during high demand hours (similar to RMIPPPP)
- **Case E-2**: Hybrid PV + Wind + BESS + GT plant (gas-fired) providing flexible baseload power, effectively replacing an open cycle gas turbine-based power plant

In both cases, the economic feasibility is determined based on avoided CAPEX, diesel/gas fuel, Fixed O&M and Variable O&M costs of the alternative (diesel power plant for Case E-1 and OCGT power plant for Case E-2). If the NPV of the avoided costs exceed the hybrid plant CAPEX and OPEX, then the project would be economically more attractive than the fossil fuel alternative. This approach assumes implicitly that the grid export tariff will be sufficient to cover the (avoided) costs of the thermal power plant alternative, instead of defining an explicit tariff that the hybrid power plant would receive.

The main input parameters for the "Hybrid Solar and Wind Plants" business cases used in the techno-economic model are listed in Table 13.

Table 13: Business case – Hybrid Solar and Wind Plants with storage – basic parameters

Item	Unit	E-1	E-2
Description		Hybrid PV + BESS + DG plant providing dispatchable power during high demand hours	Hybrid PV + Wind + BESS + GT plant providing baseload power
Reference scenario (BAU)	-	Diesel generator plant	OCGT plant
Grid	-	On-Grid	
Type	-	Green-field	
Revenue streams	-	Avoided Generation CAPEX, OPEX and diesel fuel	Avoided Generation CAPEX, OPEX and gas fuel
Load profile	-	Hybrid RE + Storage Peaker Plant (South Africa)	Hybrid RE + Storage Baseload Plant (South Africa)
Grid electricity supply profile	-	-	
BESS technology	-	Li-ion Utility Scale	
BESS energy capacity	MWh	700	600
BESS power capacity	MW	100	100
Solar plant	MWp	250	200
Wind farm	MW	-	125

Item	Unit	E-1	E-2
Thermal plant	MW	101.5	100
BAU thermal plant	MW	112	150
Project lifetime	years	25	
Grant funding	USD	-	
Tariff electricity	USDct/kWh	-	
Tariff grid electricity (import)	USDct/kWh	-	
Diesel fuel price	USD/L	0.77	-
Natural gas price	USD/GJ	-	6.36
Avoided T&D infrastructure (CAPEX)	USD/kW	-	
Avoided T&D infrastructure (OPEX)	%CAPEX/a	-	
Avoided Generation capacity (CAPEX)	USD/kW	900	800
Avoided Generation capacity	MW	10.5	50
Avoided Generation Fixed and Variable OPEX	USD/a	2,564,250	3,841,200

Hybrid & storage plants vs fossil fuel power plants)

The continuous cost reductions in renewables and energy storage technologies have reached the point where utility scale hybrid renewables, storage and back-up thermal generation plants can outperform OCGT and DG-based thermal power plants. Several drivers determine the business case:

a) **Required dispatch profile and flexibility**: this determines the required power and energy capacities of the hybrid for each of the parts (BESS/PV/Wind/back-up thermal). In cased where requirements are very strict and long duration output is required, the likely outcome is a hybrid plant that has a (close to) 100% thermal power back-up. This thermal power block would not operate often during the year but would add costs and emissions. These additional costs might be avoided in several ways and would depend on the exact needs of the power system. The flexibility that can be allowed to the hybrid plant without reducing the value/dispatchability too much:

- Have an allowance that the hybrid plant does not require to meet the full contracted power capacity every hour of the day. Rather define peak periods where capacity should be available under all circumstances
- Have a more flexible contracted power capacity that can vary by month or season, thus allowing the hybrid plant to guarantee higher capacity during summer months but lower during winter months
- Allow the hybrid plant to declare partial unavailability on a day-ahead notice with relatively low penalties. The hybrid plant can use solar and wind forecasting services to provide a more accurate guaranteed available capacity

b) **Value of avoided fossil fuel**: depending on the BAU thermal power plant efficiency, the type of fuel (natural gas or diesel fuel) and the projected fuel prices, the value of avoided fossil fuel would vary. Lower alternative plant efficiency, use of diesel fuel and higher future prices all increase the value of this benefit.

c) **BESS/PV/Wind specific CAPEX**: the specific CAPEX (USD/MWh and USD/MW) determine the total investment costs for a given BESS/PV/Wind capacity, sized to meet the required dispatch/demand profile. The higher the (specific) costs, the higher the hybrid plant (total) CAPEX.

d) **Value of avoided generation assets**: depending on the type of thermal power plant that would be the available alternative, the value of this benefit would vary depending on the projected (specific) CAPEX, Fixed OPEX and Variable OPEX of this alternative power plant. The higher this value, the greater the benefits of the BESS.

The currently modelled business cases make a conservative assumption that the hybrid plant should be able to meet the dispatch demand every hour of the year and include a 100% thermal plant backup capacity.

Results

The main results for the two modelled business cases are shown in Table 14. These results are including a 100% back-up by thermal power generation as part of the hybrid plant, though these thermal units are only providing 3.4% and 8.1% of the total annual energy. This means the costs of the hybrid plant can be greatly reduced by slightly decreasing the compliance/reliability requirements resulting in an affordable 100% renewable and storage hybrid plant becoming feasible.

Table 14: Business case – Hybrid Solar and Wind Plants with storage – Main results

Description	Unit	E-1 Hybrid PV +BESS+DG plant providing dispatchable power during high demand hours	E-2 Hybrid PV+Wind+BESS+GT plant providing baseload power
Total LCOE	USDct/kWh	14.5	11.2
Total CAPEX	USD	616,340,157	758,066,382
Total OPEX	USD/a	12,292,960	21,423,334
Lifecycle cost	USD	761,539,324	1,009,067,392
Project IRR	%	13.2%	9.8%
Equity IRR	%	17.2%	11.0%
Benefit ratio	%	1.53	1.20
Total electricity demand	MWh/a	470,850	810,300
Shortfall in meeting demand	%	0.0%	0.0%
Time where demand is not met	hours	-	-
Total electricity via storage	MWh	197,223	118,428
Total electricity curtailed	MWh	140,373	207,247
Share of electricity from solar	%	96.6%	52.7%
Share of electricity from wind	%	0.0%	39.2%
Share of electricity from thermal	%	3.4%	8.1%
Avoided fuel consumption	GJ	3,646,941	7,438,809
CO2 emission reduction	tCO2/a	270,968	417,317

The techno-economic model can perform a sensitivity analysis of the different KPIs: assessing the impact of uncertainty (or changes) in different input parameters on the selected KPI. An example for the Benefits/Costs ratio for Case E-1 is shown in Figure 27 and for Case E-2 in Figure 28. These tornado charts are generated by varying each parameter in turn to their three specified values:

- **Base**: most likely (expected) value, used in the base case calculation of the required tariff (centre line)
- **Low**: the lowest reasonable value foreseen, to show the best-case or worst-case outcome (blue bars)
- **High**: the highest reasonable value foreseen, to show the best-case or worst-case outcome (green bars)

The tornado diagram provides a clear view of the impact of different parameters. The parameters are sorted by decreasing impact: the parameter with the highest impact on the tariff due to its uncertainty is shown at the top. The parameters with the least impact are shown at the bottom: uncertainty in these parameters has less impact on the outcome. The parameters with a high impact (listed at the top of the tornado diagram) should be focussed on during project development to further reduce the uncertainty.

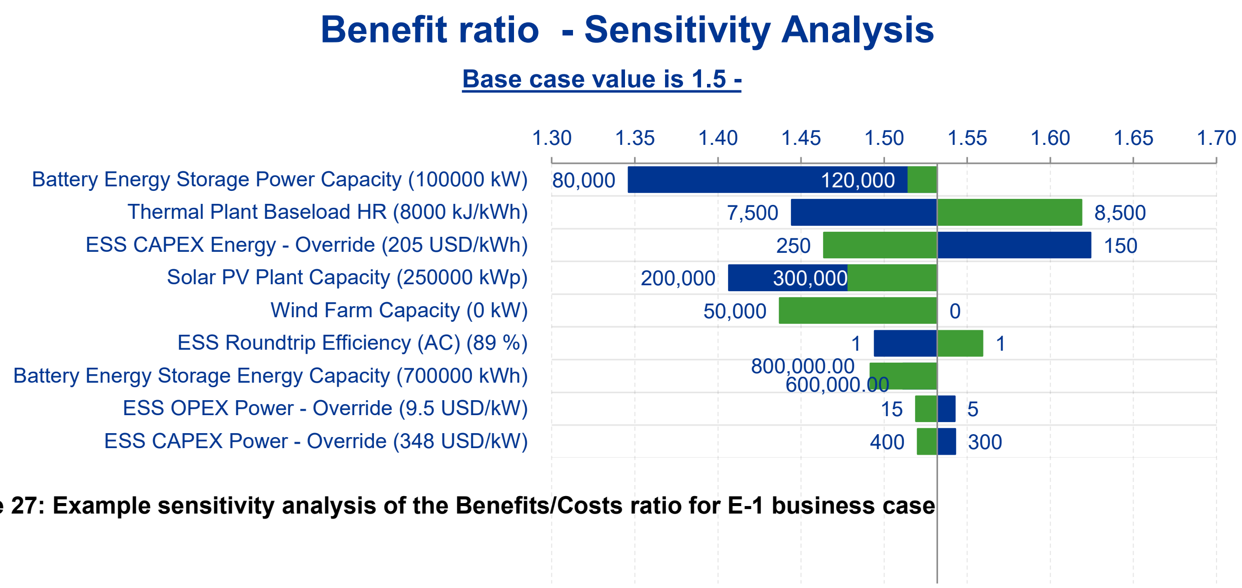


Figure 27: Example sensitivity analysis of the Benefits/Costs ratio for E-1 business case

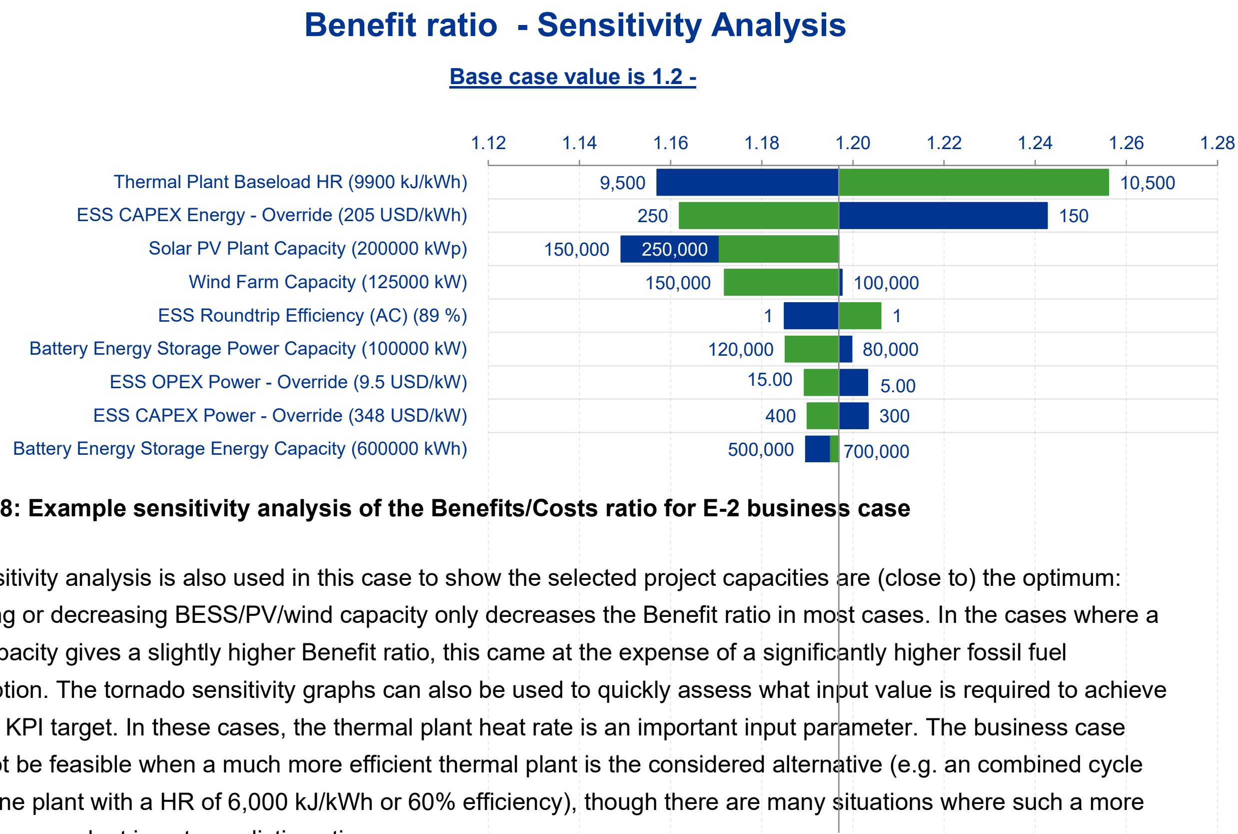


Figure 28: Example sensitivity analysis of the Benefits/Costs ratio for E-2 business case

The sensitivity analysis is also used in this case to show the selected project capacities are (close to) the optimum: increasing or decreasing BESS/PV/wind capacity only decreases the Benefit ratio in most cases. In the cases where a lower capacity gives a slightly higher Benefit ratio, this came at the expense of a significantly higher fossil fuel consumption. The tornado sensitivity graphs can also be used to quickly assess what input value is required to achieve a certain KPI target. In these cases, the thermal plant heat rate is an important input parameter. The business case would not be feasible when a much more efficient thermal plant is the considered alternative (e.g. an combined cycle gas turbine plant with a HR of 6,000 kJ/kWh or 60% efficiency), though there are many situations where such a more complex power plant is not a realistic option.

The model provides more in-depth graphs to help understand how the modelled system behaves and identifies bottlenecks/areas of improvement. The hourly energy production to meet demand or the requested dispatch for the E-2 business case is shown in Figure 29. The minimum loading of the thermal generator means that there are hours where total production exceeds demand. The model makes the conservative assumption that this energy is curtailed (similar to PV and wind energy exceeding demand/required dispatch), though in practice part of this energy can be charged to the BESS, or the BESS discharge for that hour can be reduced to use the excess thermal output.

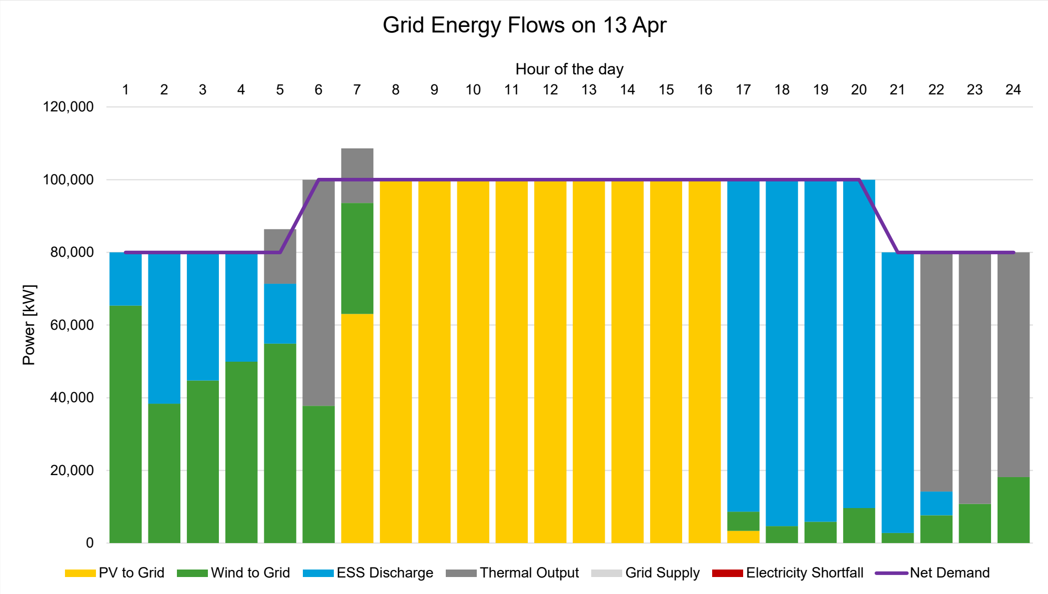


Figure 29: Breakdown of hourly energy production to meet demand

The BESS operation is shown in more detail in Figure 30, illustrating the hourly energy flows and BESS state of charge (on the right vertical axis).

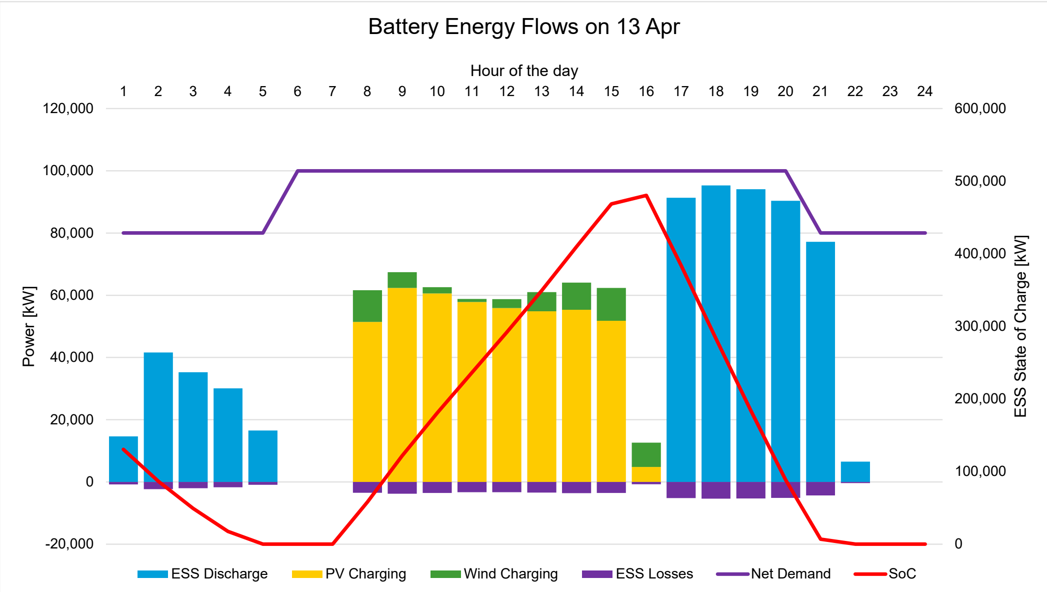


Figure 30: Hourly energy flows to and from the BESS

4.6.3 Conclusions

The example business cases shown in this subsection illustrate that hybrid renewables and storage plants can compete with fossil power plants in certain situations, especially when the fossil fuel alternatives have relatively low efficiency or high fuel prices. This is also shown in practice in South Africa, where most of the qualified projects for the emergency power tender were hybrid renewable and storage plants (some with back-up thermal generators). This represents a large economic opportunity as most countries in SSA import fossil fuels.

By carefully weighting the grid requirements for flexibility and reliability the costs for hybrid renewable and storage plants can be further optimised and able to provide power when it is needed at competitive costs and with no (or very low) emissions.

4.7 Overview of results for all business cases

Figure 31 shows the LCOE results for all the business cases, and how these LCOEs change as cost of battery technology drops and other actions are implemented. The horizontal bars represent the tariffs applicable to the business cases, and the vertical bars the calculated LCOE for the power supply systems. Result from business case D (avoided transmission and distribution expansion) are omitted from this graph as the LCOE is an unsuitable metric for this application. For case E the tariff is not shown as this can be assumed to be equal to LCOE of the thermal option. These figures are an overview of the main results discussed in the above sections.

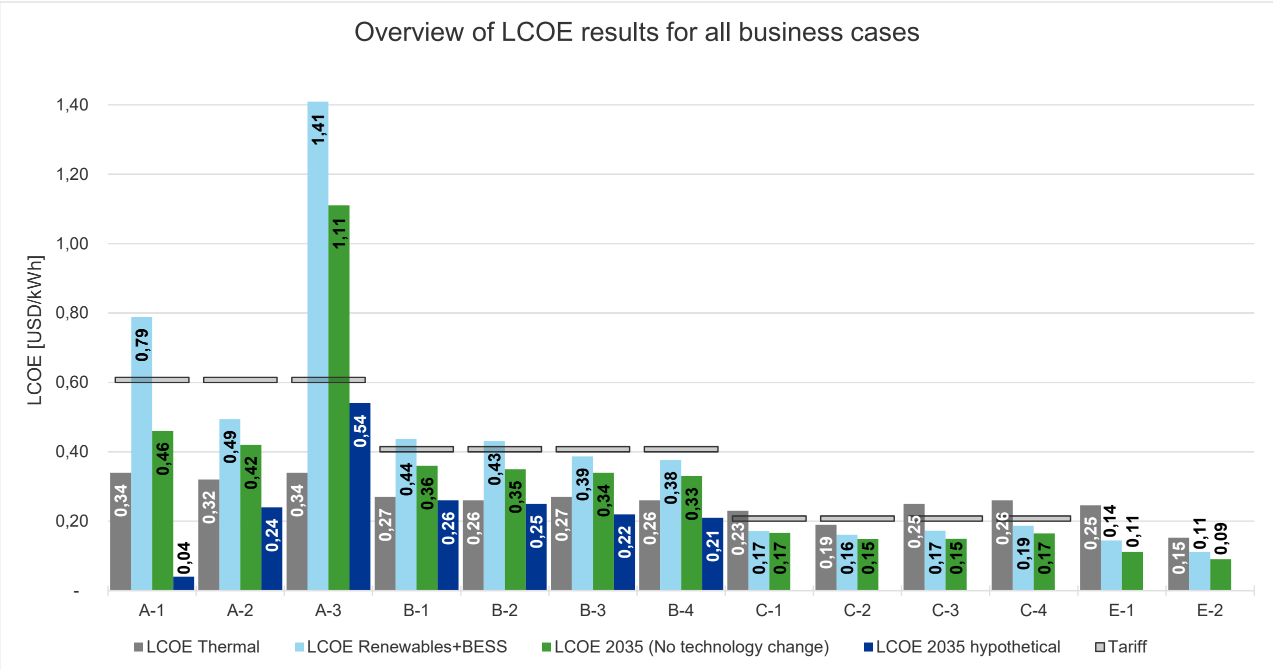


Figure 31: Overview of LCOE results for business cases A to C

For the smaller and medium sized systems, a solar and BESS supported system does not yet provide a viable alternative to a diesel or gasoline only system in terms of cost. The green bars labelled ‘LCOE 2035 (no technology change)’ illustrate how forecasted cost reductions of the deployed battery technology do not result in cost parity with diesel or gasoline only systems. The dark blue bars labelled ‘LCOE 2035 hypothetical’ assume that forecasted utility-scale Li-ion prices and performance can be achieved for these small and medium sized systems. This is purely hypothetical, illustrating that the technology is, or will soon be, available to achieve cost parity. However, achieving this cost is subject to unlocking the technology for use in these particular applications and locations.

Strategies to pursue this include:

- Enable larger volume procurement to get access to lower factory pricing and more direct value chains with a lower overall mark-up.
- Reduction of transportation cost, which represent up to a third of BESS installed cost.
- Standardisation of BESS offerings to lower the balance of plant cost.
- Create and disseminate tools to correctly size BESS for the intended applications, forecast the degradation, and optimise for augmentation of BESS rather than replacement during project lifetime.
- Strive for standardisation of technical requirements (including grid codes) to reduce project specific engineering and design needs.

The off-grid industrial facilities that have considerable power and energy requirements are estimated to already benefit from current utility-scale Li-ion technology. The LCOE of a hybrid system consisting of solar, BESS and diesel (or natural gas) generators is already lower than diesel only system at today's prices. As discussed in the previous sections this is already valid for the medium fuel price forecasts included in the techno-economic model. Forecasted reduction in cost of Li-ion technology only improves the business case further.

5 BATTERY STORAGE VALUE CHAIN

5.1 Introduction

This section focuses on the value chain of BESS which is illustrated in Figure 32. Overall, this section is focused on the production, use and disposal of a BESS product, but there are also other value chains that run in parallel to this, but are not covered in this report. Examples include:

- Research and Development (R&D), education, and training.
- Information and Communications Technology (ICT) and digitalisation.
- Development, production, and servicing of manufacturing equipment.
- Standards, norms, certification, and homologation.
- Regulation and law.

The first subsection covers the prominent technologies of the current markets. More detailed information on different storage technologies can be found in Appendix D.

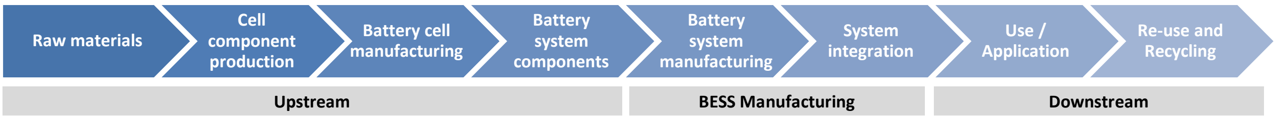


Figure 32: Schematic representation of Li-ion BESS Value Chain

Subsection 5.3 details the upstream value chain, that of the component manufacturing. Subsection 5.4 details the BESS manufacturing and downstream segments of the value chain of BESS used in small scale projects, such as mini grids, captive & behind the meter and some off grid applications. Similarly, subsection 5.5 details the value chain of utility scale BESS, used in hybrid power plants and for transmission and distribution interventions.

5.2 BESS Technology Comparison

Detailed information on storage chemistries as well as emerging BESS technology and innovations can be found in Appendix D on page 178. The chemistries covered are:

- Lead Acid
- Lithium Ion
- Sodium Sulphur
- Redox Flow
- Nickel Metal Hydride (NiMH or Ni–MH)
- Zinc Electrolyte.

The main BESS technologies in use today are compared in Table 15 according to their most influential characteristics. The flexibility in application, combined with good energy density and relatively low cost have made NMC and $LiFePO_4$ the dominant chemistries in the BESS markets today. Historically lead-acid- and advanced lead-acid batteries took the largest market share due their good safety and low CAPEX. NaS batteries hold promise, but currently high CAPEX remains the main barrier into the global market.

Table 15: Comparison between Battery technologies

Technology	High Energy Application	High Power Application	Energy density (footprint)	Cycle Life	Calendar Life	Cost (CAPEX)*	Safety	Flexible C-rates	Coulombic Efficiency
LTO	++	++	o	++	++	--	++	++	++
NMC	++	++	++	+	+	o	+	++	++
LiFePO$_4$	++	+	o	+	o	+	+	++	++
NaS	++	++	++	+	++	--	o	+	+
NiNaCl	+	++	++	+	+	--	o	+	+
VRB	++	-	--	++	++	-	++	-	+
ZnBr	++	-	--	++	o	-	o	-	+
Lead-acid	o	--	--	--	-	++	++	--	+
Advanced Lead-acid	o	++	-	-	o	-	++	o	++
NiCd	+	o	--	o	--	-	++	o	+

++ Highly Favourable
+ Favourable
o Neutral
- Unfavourable
-- Extremely Unfavourable

*CAPEX refers to only the one-time cost of installation and not the total cost of ownership over the lifetime of the project, which is very application specific.
**Cycle life is strongly dependent on factors such as duty cycle DoD, C-rate, ambient conditions etc.

Table 16: Selected performance values of various storage chemistries

Technology	Energy density *	Energy density (footprint)*	Cycle Life*	Calendar Life*	Round Trip Efficiency*
	Wh/kg	kWh/m^2	Cycles	Years	%
LTO	60-90	75-100	~10000	15-20	82-85
NMC	150-220	130-160	~8000	10-15	82-89
LiFePO$_4$	90-120	80-110	~5000	10-15	79-85
NaS	120-240	190-200	~8000	10-15	86-90
NiNaCl	120-240	180-200	~8000	5-15	86-90
VRB	40-180	40-60	~15000	15-20	62-68
ZnBr	30-160	40-75	~15000	15-20	60-68
Lead-acid	20-45	40-85	~900	3-7	40-60
Advanced Lead-acid	25-45	40-100	~1500	8-10	60-75
NiCd	40-65	55-85	~2500	10-15	60-75

***Note:**

- Energy density figures may vary based on the actual proportion of individual elements that comprise of the respective chemistries. For example, the energy density of LCO based Li-ion batteries may vary based on the proportion of lithium and cobalt oxide used and this ratio is OEM specific.
- Footprints are based on datasheets of OEMs and have been calculated by dividing the energy capacity of storage material (Wh) by the plan view area of the standardised containers required to encapsulate them. This does not take into count the area covered by energy transformation equipment such as inverters and transformers and their associated auxiliaries.

- Cycle life figures quoted here are for 80% DoD at 1C charge/discharge rate and can vary based on other parameters as mentioned in the previous section of the report.
- Calendar life estimates are to reflect the typical lifespan of individual chemistries
- Round trip efficiency figures have been sourced from datasheets of various OEMs and are subject to variation based on the efficiencies of inverters and other AC side equipment (transformers, cables etc.) as well as the accuracy of the Battery Management System (BMS).

5.3 BESS component manufacturing

5.3.1 Raw Materials

A wide range of commodities are required for battery production. Lithium, cobalt, manganese, aluminium, copper, and graphite are the raw materials most used in Li-ion battery manufacturing. Other commodities are required for the manufacturing of battery casings, cables, battery packs, battery racks, system enclosures, control boards, inverters, transformers, climate control systems, etc.

This part of the value chain is characterised by capital intensive activities with long lead times required for mining and minerals refining activities. There are some social and environmental concerns with cobalt and lithium mining, which has led to large businesses like Apple and VW Group to take steps on monitoring and managing this supply chain more closely and potentially move towards direct purchase- or long-term contracts. R&D efforts on recycling and alternative materials for batteries may influence which materials are sourced from environmentally compromised regions in the future.

5.3.2 Cell Component Production

This stage of the value chain concerns the manufacturing of specialised materials for the battery cells like the anode, cathode, separator and electrolyte. Active materials for the anode and cathode tend to be manufactured via the slurry mixing process, where all active materials are mixed with solvents, binders, and other additives into a slurry. The slurry is then coated on very thin copper and/or aluminium foil under careful control of the thickness and consistency. Electrodes are subsequently dried in an oven, followed by vacuum drying to remove residual moisture and solvents.

This section of the value chain is characterised by vertical integration or strong partnerships by OEMs. It is R&D intensive, with advancements on material chemistry crucial to improve battery performance. These advancements come, to some extent, with the need to change or advance manufacturing processes. However, this tends to be limited to replacing certain parts of a manufacturing line to meet the needs of improved or novel active materials.

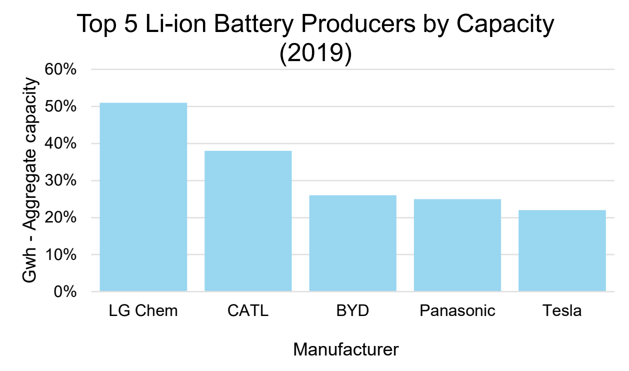
5.3.3 Battery Cell Manufacturing

The fabrication of battery cells involves the process of coating, lamination, filling, packaging, and testing the cells. For prismatic cells, sheets of cathode and anode are punched or fed directly from rolls. The cathode and anode are then stacked, with the separator material placed in between the cathode and anode. For cylindrical cells the rolls of anode, cathode and separator are spun or wound, creating a spiral of the anode-separator-cathode film. This last step is sometimes referred to as a swiss roll or jelly roll.

Contact terminals are then connected to the stacker or wound cells and encased in a cell housing along with a separator or insulator film to avoid shorting between electrodes and casing material. The case is then sealed (e.g. by laser welding) before it is filled with electrolyte. Electrolyte filling, via a valve or needle, can be repeated several times to ensure that entire cell is saturated with electrolyte.

Completed cells are then subjected to a formation process with the first charging and discharging cycles. These are carefully defined and controlled to form the solid electrolyte interface (SEI), a passivating layer between the electrolyte and anode. The SEI conducts lithium ions, but also prevents further reaction between electrolyte and anode. A quality assurance step, referred to as aging, follows. Aging involves monitoring the performance and characteristics of the cell under high and normal temperatures over a period of weeks.

A majority of the world's cell production facilities are based out of China and these cells are procured and assembled into battery racks by mostly Chinese, South Korean, or Japanese companies, who are the leaders in the energy storage space. These battery manufacturers are ahead of their global competition and that is evident from their production capacity, investments and market share as is shown in the below two figures:



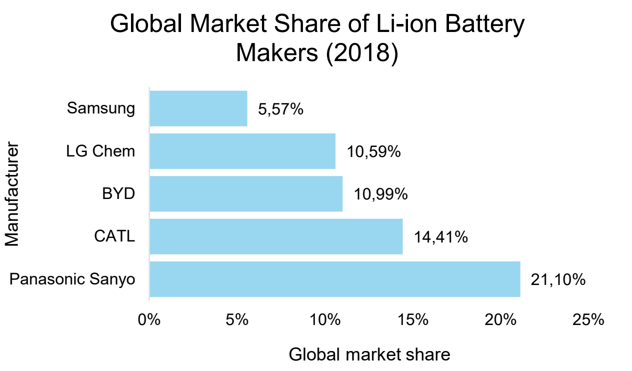


Figure 33: Largest Li-ion Battery Producers[15]

Battery cell manufacturing is R&D intensive and resembles an oligopoly. The expected significant growth in demand for batteries in the coming years and decades may further increase competition. Novel technologies could potentially disrupt the industry which is already making incremental but significant improvements in cost and performance. Security of supply concerns from governments and large corporates may lead to a shift in battery cell production locations, as illustrated by the recent announcement and investments on Li-ion battery factories in Europe.

5.3.4 Battery System Components

This is a diverse part of the value chain that mostly runs parallel to the value chain as depicted in section **Error! Reference source not found.** and refers to the fabrication or assembly of system components other than the battery cells. This includes, but is not limited to, power electronics, climate control, sensors, control systems, communication systems, etc. These components or subassemblies are largely sourced from specialised companies.

5.4 Small Scale BESS Value Chain

5.4.1 Battery System Manufacturing

Globally, most of the R&D and manufacturing of batteries takes place in Asia, North America, and Europe. China is the leading manufacturer of both lead-acid and lithium-ion batteries used in SSA. There are a few examples of lithium-ion battery assembly in South Africa, with Freedom Won, Blue Nova and Solar MD currently assembling batteries for use in local markets. These companies have similar business models whereby they import lithium iron phosphate prismatic cells from Chinese manufacturers like CALB and CATL. These cells are then assembled into battery packs in South Africa. The companies have since developed their own proprietary Battery Management Systems (BMS) as well as their own Energy Management Systems (EMS). This approach gives the company the flexibility to build battery packs more suitable to local conditions as well as sizing the packs to suit local customer usage profiles. The benefits of local assembly and continued increase of local components in the battery pack assembly has a positive impact on job creation in a country battling unemployment. Other industries that benefit include sheet metal benders for casings, manufacturers of electrical cables and manufactures of associated accessories that are part of local supply chains.[16]

[15] *Benchmark Mineral Intelligence, Jan 2019, and Statista.com - Global market share of lithium-ion battery makers, 2018*
[16] *"Solar MD's South Africa Ramp-Up Shows Demand For Battery ...." 24 Sep. 2020, Accessed 4 Feb. 2021,* *https://cleantechnica.com/2020/09/24/south-africas-solar-mds-ramp-up-shows-demand-for-battery-storage-is-growing/*

In terms of large-scale BESS manufacturing operations, Megamillion group and Metair have plants in early development phases in South Africa. The Megamillion group is looking to vertically integrate its production given that the bulk of raw materials for production are available locally. The Megamillion group of companies will include the Megamillion Minerals Company (producing battery-grade powders and cathodes), the Megamillion Energy Company (producing lithium-ion cells), LionESS Energy Solutions (producing lithium-ion battery packs and end-products) and The Megamillion Recycling Company (recycling lithium-ion end-products and waste minerals).[17] Metair will partner with the South African Institute for Advanced Materials Chemistry (SAIAMC), located at the University of the Western Cape (UWC), which houses the only pilot scale li-ion battery cell assembly facility in Africa.[18] Production will focus on mining cap lamp cells, 12 V Li-ion automotive batteries, 48V Li-ion batteries for energy storage applications and solar panel recharge technology.

There is large potential for local lithium-ion battery production at various stages of the value chain given the abundant availability of component raw materials across the continent (illustrated in Table 17), however this remains largely unexplored.

South Africa is especially well-placed to take advantage of this opportunity given the following:

- Relatively strong industrial base
- Pre-existing automotive assembly base (plants and skills)
- Availability of engineering skills and tertiary institutions
- Relatively stable economic and political environment
- National incentives for production of renewable energy technologies in its Special Economic Zones (SEZ)
- Geographical proximity to component raw materials, major ports, and major trading routes (which will be boosted by the recently ratified African Continental Free Trade Area (AfCFTA), and
- Local market for automotive and stationary battery applications.

[17] *"Local lithium-ion battery plant to open its doors ... - Engineering News, 2 Feb. 2021,." https://www.engineeringnews.co.za/print-version/coega-based-lithium-ion-battery-plant-to-open-its-doors-this-year-2020-01-20*

[18] *"Metair launches SA lithium-ion battery production programme - Metair.", 2 Feb. 2021, https://www.metair.co.za/metair-launches-sa-lithium-ion-battery-production-programme/*

Table 17: Lithium-ion component mineral resources available in Southern Africa

Country	Minerals	Country	Minerals
South Africa	Manganese (80% of the world's reserves) Lithium Aluminium Copper Nickel	**Namibia**	Lithium Graphite Copper
DRC	Cobalt Copper Manganese	**Zambia**	Manganese Cobalt Copper
Mozambique	Aluminium Graphite	**Zimbabwe**	Lithium Copper Nickel Graphite

5.4.2 Shipping and procurement

Due to the market for BESS still being in its infancy, the procurement of BESS in SSA does not yet benefit from economies of scale.

Mini grid and captive power developers often do not meet the minimum order volumes required for direct battery purchases from manufacturers. Lead-acid batteries, which are still the most used energy storage technology in Africa, are expensive to store due to the maintenance required whether they are in use or stored in a warehouse. These costs, added to the relatively high capex, result in risk aversion and consequently to not hold large stocks of batteries. This is exacerbated by the fact that minimum quantities are required per order, usually based on container volume. On average, 400 lead-acid batteries typically fit into a standard 40 ft container.

A key difference between generator and battery supply chains is the considerably longer lead time for batteries. In most cases, these products are made to order, and the lead times vary between 3-4 months for manufacturing and up to 2 months for shipping. This makes it challenging for mini grid developers to purchase directly from manufacturers due to specific project timelines. In such cases, developers are forced to buy locally and must factor in the expense of distributor mark-ups which can be exorbitant. For example, lithium-ion battery costs typically amount to $500/kWh when purchased from manufacturers in Germany, and this can increase to $700/kWh when purchased from local distributors in Kenya, Tanzania, and Uganda (costs inclusive of battery racking and other ancillary equipment). Lead-acid battery costs are about $300/kWh when purchased from manufacturers in Germany, and $600/kWh when purchased from local distributors.

	Lead-acid	**Lithium Ion**
Primary manufacturing countries	China, Germany	China, Germany
CAPEX International price (USD)	$300 per kWh	$500 per kWh
CAPEX Local price (USD)	$600 per kWh	$700 per kWh
Manufacturing lead times (weeks)	12-16	12-17

Figure 34: Lead-acid and lithium-ion cost and manufacturing indication

Both lead-acid and lithium-ion batteries are taxed in most SSA countries, with VAT rates ranging from 7.5% in Nigeria to 18% in Uganda and Senegal. The same applies to import duties. While some countries have exempted batteries from duties, duties in other countries range between 7.5% and 35%. Some challenges do arise when distinguishing between car batteries (which are typically not tax exempt) and renewable energy lead-acid batteries. As batteries can only use sea freight, the lower weight and volume of lithium-ion batteries relative to lead-acid batteries do not have a significant impact on the overall cost of shipping. The same is true for trucking batteries to warehouses and project sites.

5.4.3 Assembly and Integration

Leading developers have been assembling “complete systems” which include batteries, inverters, charge controllers, for example PowerGen’s Powerbox. Standardisation reduces procurement and maintenance costs and the complete systems are quicker and easier to deploy at site level. However, extensive investment is required to set up manufacturing facilities and this process can be complex in some countries because of varying skill levels. In addition, countries need a minimum level of demand to warrant the development of a manufacturing facility. And finally, there is a risk of double taxation if complete systems are assembled in one country and deployed in another country.

5.4.4 Operations and maintenance

Contrary to fossil fuel generators, there is limited scope to outsource battery maintenance among mini grid and captive power developers. Battery maintenance skills are unique and difficult to find given the relatively young age of the technology in many applications across SSA. As a result, developers train technicians and maintain these skills in-house. In some countries these technicians need to be licensed - this is especially true for lithium-ion technology. For example, to be able to install Tesla batteries, specific technician training is conducted by Tesla itself (in addition to general training). Failure to use a certified trainer will nullify a Tesla product warranty. It is particularly important to have competent battery technicians as battery failure can result in systematic failure across a battery bank and the system at large.

Batteries require simpler and cheaper maintenance in comparison to generators. Lead-acid batteries require bi-annual sample checks on voltage, temperature, visible leakage, and cable fastenings. Lithium-ion batteries require even less maintenance. Li-ion batteries are hermetically sealed, and thus maintenance is limited to annual cleaning and ongoing remote monitoring of cell voltage. Remote monitoring of lithium-ion batteries has an advantage over remote monitoring of lead-acid batteries as the former can monitor voltage down to the individual cell. This assists greatly in early fault detection. Ensuring sufficient cooling is important as research has shown that air conditioners substantially increased the expected lifetime for lead-acid batteries, particularly in warmer climates, such as Kenya.[19]

5.4.5 Re-use and Recycling

Battery waste is a serious concern,[20] however lithium-ion batteries in use in Africa are yet to reach their end of life, and as a result there is limited evidence on how batteries will be re-used or recycled. It is likely that there will be a good second-hand local market for recycled batteries and start-ups are beginning to develop business models to address this opportunity. South African start up REVOV currently retails and installs second life batteries for example. The batteries are lithium-ion batteries which have spent their first five to eight-year lifespan powering EVs. They are then converted to serve the greater part of its lifespan as part of a stationary energy storage (back-up/off-grid) solution.[21]

Disposal of the more common lead-acid batteries is regulated to varying degrees across Africa. In Kenya for example, the national environmental authority is the regulator on battery disposal. Developers can apply and get a licence to dispose of batteries itself, but the developer would require a recycling plant. As a result, developers use local battery

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[19] *"Comparative Study of Techno-Economics of Lithium-Ion and Lead ...." , 5 Feb 2021,* [*https://www.nrel.gov/docs/fy19osti/73238.pdf*](https://www.nrel.gov/docs/fy19osti/73238.pdf)
[20] *"Circular – Creating a sustainable battery value chain - ERG Africa." 1 Sep. 2020, Accessed 3 Feb. 2021* [*https://www.ergafrica.com/battery-passport-to-prevent-waste/*](https://www.ergafrica.com/battery-passport-to-prevent-waste/)
[21] *"What batteries do when they grow up - 2nd life energy storage ....", 3 Feb. 2021,* [*https://revov.co.za/*](https://revov.co.za/)

suppliers or recycling facilities such as Chloride Exide who buy back batteries from developers and give developers a certificate for regulatory and compliance use.

5.4.6 Value Chain Dynamics

Batteries make up close to 60% of typical mini grid costs. Price is therefore the largest driving factor in battery purchasing decisions in this sub-sector. There is a significant price difference of 20-40% dependent on whether purchasing is done from the manufacturer, international wholesale distributor or local distributor. Mini grid developers are beginning to explore ways in which they can aggregate projects to enable them to exercise bulk procurement to unlock manufacturing discounts. For example, PowerGen built 23 mini grids in Sierra Leone and were able to exercise bulk procurement, purchase directly from the manufacturer and drastically reduce battery costs. Given their steady and growing project pipeline, PowerGen is looking to procure on a quarterly or bi-annual basis. The increasing ability of mini grid developers to “sell” their project pipeline is shifting bargaining power and beginning to provide developers with economies of scale and increasing the overall economic viability of mini grids. CrossBoundary is currently researching the viability of conducting a similar exercise across multiple mini grid developers. This study tests whether aggregating multiple mini grid developers’ orders for certain components of a mini grid into a single bulk order reduces the overall procurement costs for developers. Mini-grid developers currently procure all components on their own, yet some are consistently used by a wide range of developers. As such, aggregating developer demand into a single bulk order could increase developers’ negotiating power and lead to lower prices and improved payment terms. This would allow developers to save significantly on capital expenditure costs and reduce project lead times.[22] Early results point to a 35% cost reduction for lead-acid batteries bought in bulk.

Mini grid and captive power developers are increasingly focusing less efforts on manufacturing energy systems and more on developing projects. This is partly due to the emergence of commercial containerised systems. The admin and cost advantages of complete systems are attractive relative to importing multiple components. In the past three years, the number of reputable companies in Africa offering these systems have significantly increased. Companies like Tesla and AlphaESS are for example growing in popularity amongst developers. These systems work well in captive power projects with a relatively standardised load profile and stable demand. In contrast, they are not well suited to mini grids where greater modularity is required in response to changing energy demands. Developers might also experience increased system-wide failure risk (vulnerability) which can be caused by the failure of a single component.

5.4.7 Sub-Saharan Africa Perspective

Batteries produced locally in Africa are not competitive with imported batteries in terms of quality, variety, and price. Consequently, most batteries will be imported, predominantly from China.

The variety and availability of various BESS chemistries is very limited in SSA, with lead-acid batteries (see Figure 35 and Figure 36) making up the majority of deployed energy storage. Lead-acid batteries, which are suitable for consumer- and commercial level static energy storage, has largely been driven by the automotive industry. The exact configuration of the lead-acid BESS does not vary widely with a gel-type electrolyte or absorbent glass matt (AGM) configuration typically used. Non-sealed battery configurations require more maintenance including the periodic topping up of electrolyte.

[22] *"Study Design: Bulk Procurement 2020 - CrossBoundary." 20 Jan. 2020, Accessed 3 Feb. 2021, https://www.crossboundary.com/wp-content/uploads/2020/01/CrossBoundary-Innovation-Lab-Study-Design-Bulk-Procurement-Anonymized-20-Jan-2020.pdf*

Figure 35: A basic household system in rural Kenya

Figure 36: Lead-acid batteries power a mini-grid in Entesopia, Kenya

Li-ion batteries, which are discussed in detail in section Appendix D, are starting to find some application in the more mature markets and for specific high value cases. Tesla set up offices in South Africa in 2016 and have since delivered more than 60 contracts across 14 African countries between 100kWh and 6MWh. Many of these are direct diesel replacement projects, typically for luxury resorts or small island mini grids. Depending on the market and local cost of diesel, Tesla estimates that their payback period is between 3 to 6 years. DNV has seen Li-ion batteries used as the storage technology of choice in all utility and large commercial and industrial applications in recent years.

The problem of affordability of BESS has been the principal challenge for smaller systems. In response, several start-ups offer smaller lithium-ion systems combined with innovative financing arrangements. In South Africa and Nigeria, lithium-ion batteries are replacing lead-acid batteries in solar home systems and there are examples of battery-only business models gaining traction. For example, a company called Mobile Power[23] who offer 50Wh batteries at low cost through a pay-as-you-go platform, has recently raised $2.7 million[24] for regional expansion. The model allows users to pay for access to the batteries in 24-hour increments. The batteries are then recharged in centralised 'Mopo Hubs'.

[23] https://www.mobile-power.co.uk/
[24] https://www.afrik21.africa/en/africa-repp-finances-access-to-electricity-through-battery-storage/

TFE Database insights

TFE has created a database of 374 mini-grid and 322 captive power active sites across SSA to better understand DRE market dynamics. The database is recorded along 10 indicators namely:

- Developer name
- Site name
- Generation technology (Biomass, Diesel, Geothermal, Hydro, Solar, Wind and respective hybrids)
- Generation installed capacity (kW)
- Generator capacity (if applicable)
- Battery storage capacity (if applicable)
- Battery type (if applicable)
- Loads powered (agricultural, commercial, industrial, public or residential)

In the mini grid database of 374 sites, 31.28% of the mini grids use batteries and the most prominent battery type is lead-acid as shown in Figure 37.

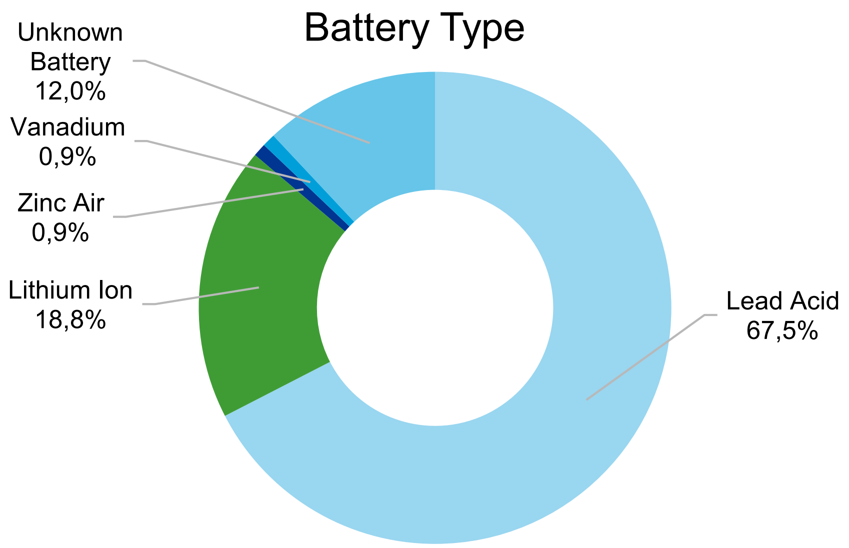


Figure 37: Battery type distribution in mini grids

When comparing the different generation technologies that are paired with batteries (Figure 38), it is clear that solar PV is the dominant generation technology and is paired with diesel about a third of the time.

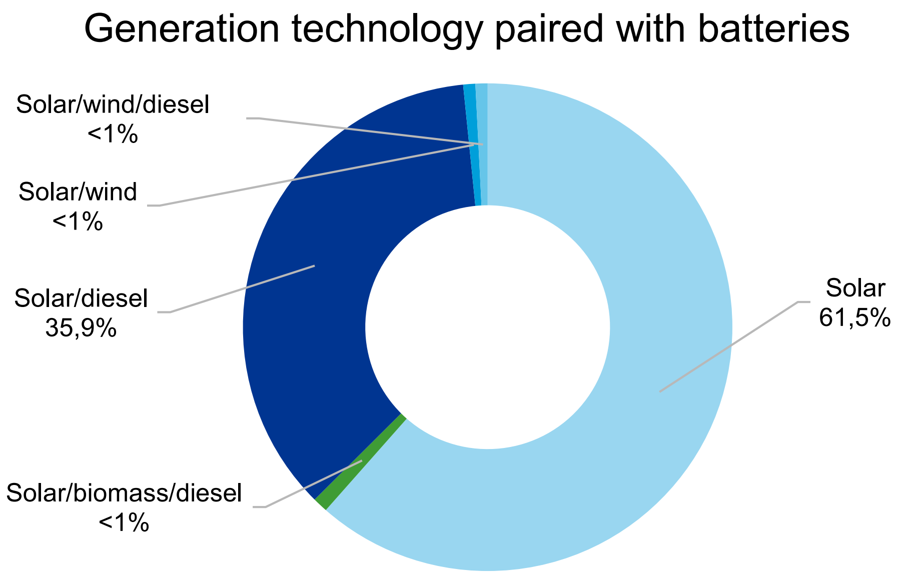


Figure 38: Breakdown of the generation technologies paired with BESS

Figure 39 shows the geographical percentage split of all mini grids (374 sites) and of all mini grids with batteries (117 sites) in the TFE database.

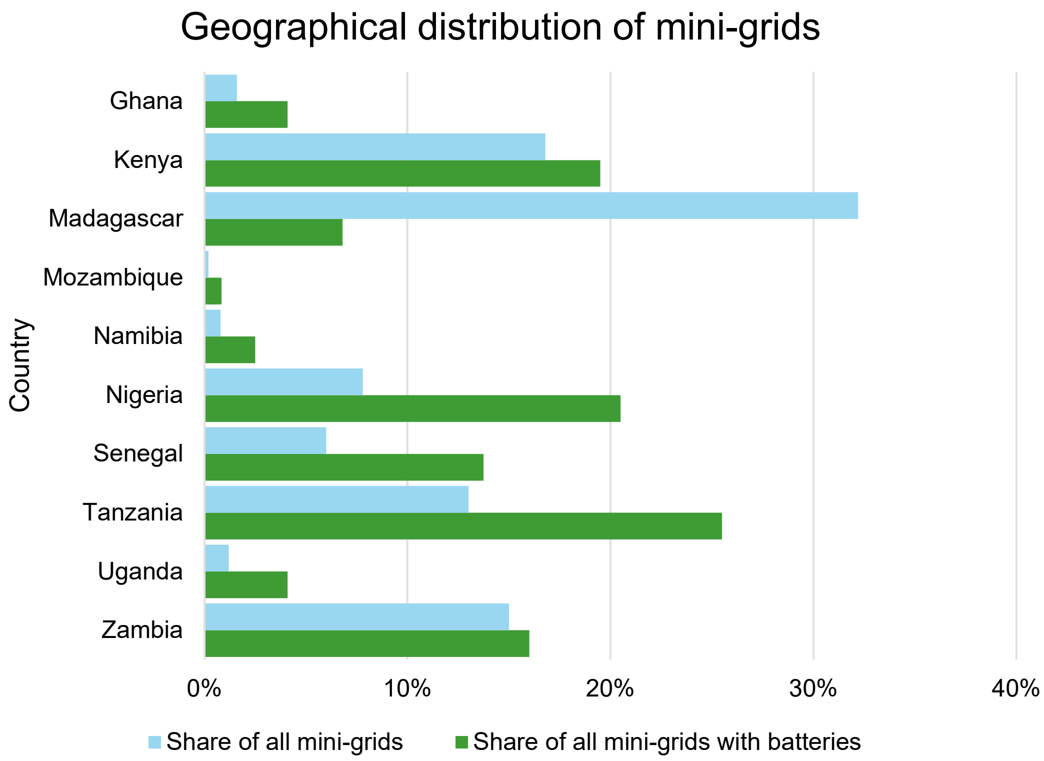


Figure 39: Geographical distribution of mini grids

In the captive power database of 322 sites 97 sites (30.12%) use batteries.

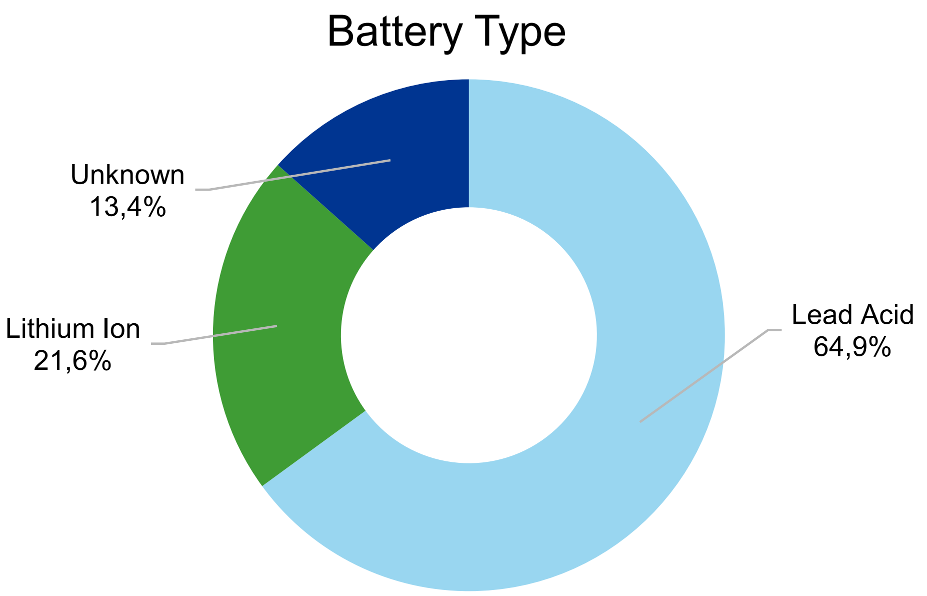


Figure 40: Battery type distribution in captive power markets

Another insight from this dataset is that batteries are used predominantly in residential and commercial applications. Furthermore, 47.62% of lithium applications are in the tourism sector. This is likely due to:

- Remote (often off-grid) location of (island/safari) lodges.
- High profit margins and access to credit.
- Moderate energy demand
- Sustainability requirements within industry
- National parks and demanded by customers.

Major & Key Players

The key BESS suppliers are listed in Table 18 together with their focus countries, main applications, and partners.

Table 18: Key BESS suppliers for small scale applications in SSA

Indicator	SimpliPhi	Pylontech	BAE Gel Secura	Tesla Power Wall	Freedom Won	BYD BBOX	Hoppecke	Tesvolt
Battery type	Lithium	Lithium	Gel Lead-acid	Lithium	Lithium	Lithium	Lead-acid	Lithium
Countries		Nigeria	Kenya	Namibia, Zimbabwe, Seychelles	Zambia, Botswana		Tanzania, Zambia, Ethiopia, Madagascar	Namibia, Mali
Applications			Commercial, Public	Tourism, Telecoms	Tourism		Education, Mini grids, Tourism	Commercial, mini grids
Developers		Sygnite, PowerGen	Knights Energy	New Southern Energy, Distributed Power Africa, Sustainable Power Solutions, PowerGen, Grid X Africa	The Solar Guys, Solar BW	PowerGen	PowerGen, Green Link, SunTransfer Tech, Mada Green Power, Harmonic	HopSol

5.5 Utility-scale BESS Value Chain

5.5.1 Battery System Manufacturing

The assembly of cells into a module (or battery pack) is often carried out by the Li-ion cells manufacturer. This refers to the packaging and connecting of cells into an appropriate format. This also includes adding the battery management system hardware and its accompanying software, and the provisions for air- or liquid cooling system of the battery module. These manufacturing activities are labour intensive but there is a current drive towards automation. Fire safety, thermal management and application are options for differentiation for tailored battery modules or packs used in utility-scale BESS.

5.5.2 System Integration

The system integration entails the integration of battery modules with electronics, other (sub) systems, and software to create an energy storage system. For this report an energy storage system refers to stationary systems, but it's important to note that system integration for battery energy storage systems for ships, electric vehicles and other heavy-duty vehicles follows a similar process with similar components.

An overview of the main stakeholders that are actively involved in the American and European energy storage sectors are shown in Figure 41 where they are classified under residential/commercial/utility-scale and by the role they typically play in the energy storage value chain.

Figure 41: International players in the energy storage value chain[25]

The system integration segment of the value chain stands to profit from the vast R&D spending on improved Li-ion chemistries, novel solid-state Li-ion batteries, and specialised materials for Li-ion cells. It requires knowledge of local conditions for the development and deployment of energy storage systems. More recently, this sector has seen system integrators that pioneered the space being bought or absorbed by much larger companies, typically with a background in the design, engineering, and delivery of energy systems.

[25] *Wood Mackenzie, 2021, U.S. Energy Storage Monitor, (link)*

5.5.3 Financing and Ownership

This is a particularly diverse and wide-ranging aspect of the energy storage value chain. It concerns the products and services for the various use cases of energy storage, including development, construction, operation and maintenance. Utility-scale projects tend to be project financed, which implies that the energy storage system (or the larger project of which it is a part) is owned by a project company (or special purpose vehicle). Financing of these projects is typically a mix between equity from developers and/or utilities and loans. It is common that the financing is provided on a non-recourse basis with repayments only from project returns and not from other assets of the borrower.

These project companies appoint one or more engineering, procurement, and construction (EPC) companies to deliver, install and commission the energy storage system. Internationally operating EPC companies include Wärtsilä, Fluence, GE, Tesla, Stirling & Wilson, Nidec, GRS and Nippon Koei etc. An operator is also appointed by the project company, which can be the EPC or specific operation and maintenance companies. Several large developers or utilities have their own operating teams, which can be contracted by a project company. The project company itself can also outsource the asset management tasks, for example to one or more of the original developers and utilities.

The use and application of storage has also seen a rise of ‘smart energy storage system operating’ solutions. Virtual power plants dispatch or operate storage assets together with energy generators located elsewhere or many small storage assets as a single large, virtual power plant that operates on the electricity market. Asset management and monitoring software solutions that are more commonplace for wind and solar plant assets are also emerging for energy storage systems.

5.5.4 Re-use and Recycling

The recycling of lead-acid batteries is relatively successful, with very high shares of all batteries collected and sent for refurbishment or recycling. This is in part due to the profitable nature of lead recovery and recycling for batteries. There are however health and environmental concerns on poorly or not regulated lead recycling activities by “backyard battery recyclers”. The collection and recycling of other batteries (incl. Li-ion) is a challenge due to logistical issues, technology barriers, economic incentives, and gaps in regulation. There is no industry-wide roadmap or strategy yet to collect and recycle Li-ion batteries on a large scale. Li-ion batteries that are sent for recycling in Europe typically undergo material recovery processes akin to the refining processes in the mining sector, including high-temperature melting and extraction of the most valuable materials in large facilities. This is a costly process that is not yet capable of recovering all the valuable materials of a battery cell.

The rapidly increasing adoption of electric vehicles is a forebode to large quantities of used or depleted Li-ion batteries. This is a driver for start-ups, large recycling companies and few battery manufacturers to research and develop new methods to recycle batteries or recover valuable materials. Re-use of batteries – especially Li-ion – has received attention from various stakeholders, on the basis that especially electric vehicle batteries can start a second life in stationary storage systems. Challenges on assessing battery performance and safety have become a hurdle to this approach, with the rapid decline in cost of virgin Li-ion cells complicating the business case. Governments are investing in R&D and working on regulation to improve battery recycling. This part of the value chain is however likely to face high costs and technology challenges in the foreseeable future, effectively positioning any recycling mandates at odds with the need for energy storage as a vital link in the global energy transition.

5.5.5 Value Chain Dynamics

Li-ion: The Li-ion BESS value chain is extensively protected by intellectual property and is capital intensive. However, due to the significant growth in demand, it is no longer concentrated to a few players. Demand growth is mostly driven by electric mobility, but demand includes consumer electronics and the different applications of stationary storage. The market is also defined by high volumes, with especially Li-ion cell manufacturing moving towards large scale manufacturing and geared towards highly modularised systems. Rapid developments, high growth and significant price drops make strong innovation a must. Innovation occurs along the entire value chain with significant funding and interest by Li-ion battery off-takers, particularly from automotive, in different industries. For stationary storage the market for system integrators is set to grow rapidly and is currently serviced by large and global operating companies as well as small and medium sized companies that service a particular region or niche of the market. As the industry grows and lessons learned become more widespread the boundary between system integrators and EPCs is likely to become more blurred.

Flow Batteries: The demand or production of flow batteries has not seen significant growth in the past years. The industry is currently a mix of start-up companies developing and commercialisation systems, and larger corporates with intentions and access to the necessary intellectual property to manufacture flow batteries. Growth is however anticipated in the near future. This is expected to be mostly driven by demand for stationary storage with longer duration. This is an important distinction with Li-ion battery systems, where the Li-ion batteries are applied in a wide range of different applications and demand growth is largely driven by electric mobility. Market forecasts on flow batteries are uncertain. DNV's 2020 Energy Transition Outlook (Figure 42) forecasts a strong uptake of longer duration storage systems in 5-10 years.

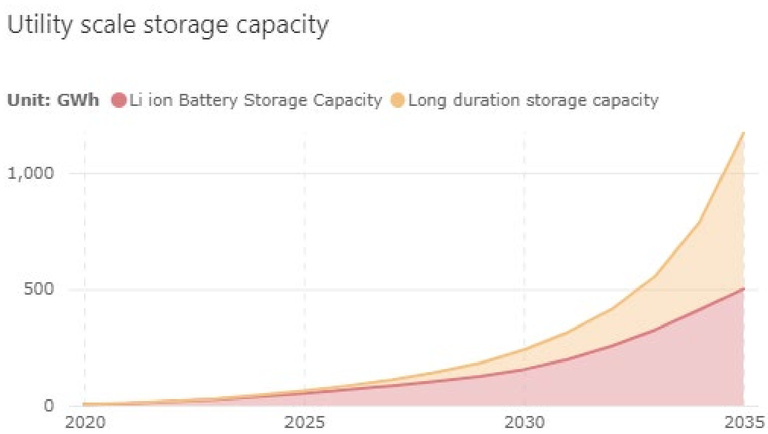


Figure 42: DNV ETO 2020 Forecasted Li-ion and Long Duration Storage Capacity

Other Batteries: Lead-acid and NiMH batteries are not expected to play a significant role in utility-scale storage due to the fierce competition from Li-ion batteries and development of novel storage solutions. The adoption of Sodium Sulphur (NaS) batteries have been relatively slow due to competition from Li-ion systems and a market looking for energy storage systems that deliver a few hours of storage at the most. Ongoing R&D, pilot and demonstration activities at large corporates, universities and start-ups is expected to lead to the commercial introduction of multiple novel energy storage systems. These are expected to be wide ranging in terms of technology (from advanced electrochemistry to relatively low-tech heat storage) and applications (from EVs to multi-day utility-scale energy storage).

Regional Perspective: The market for utility-scale energy storage in Sub-Saharan Africa is currently small to very small. There are several projects announced or under tendering that will represent the first utility-scale battery energy storage projects (BESS) in the respective countries. These include an 80 MW / 320 MWh BESS by Eskom in South Africa that is under tender, and the inclusion of BESS in some of the bids to Eskom's Risk Mitigation IPP Procurement Programme. The World Bank is also targeting the deployment of further BESS in South Africa, as well as in the West African Power Pool. These systems are likely to utilise Li-ion technology with deployment in the coming 5 to 10 years. Local content, local manufacturing or local service providers are encouraged or mandated in some projects. However, this is largely unfeasible at present for energy storage projects. The utility-scale projects are expected to rely on the manufacturing capabilities and system integration knowledge of global players for the foreseeable future. Local or regional contractors may be able to position themselves for EPC works and O&M activities. The absence of a well-defined path outlining the specific needs for energy storage (e.g. energy storage applications) and uncertainty or absence on the valuation of energy storage services are likely to remain a barrier for the development of a local or regional energy storage industry in the near future.

6 FOSSIL FUEL GENERATOR VALUE CHAIN

6.1 Introduction

This chapter summarises FFG, particular with respect to power capacity, implementation, and value chain. Appendix B provides more detailed information.

The value chains of FFGs in SSA is at its most diverse and dynamic at the small-scale, where they are centred around residential and commercial use. As the size of the generators increase, the value chains are more predictable, and have fewer providers and market interactions.

Fossil fuel generators currently play a crucial role in supplying electricity to Sub-Saharan Africa, predominantly due to weak and unreliable grids. Electricity grids often have a shortfall in the necessary generation capacity causing rolling blackouts that have severe consequences for the economy and the lives of millions of people. Additionally, the transmission and distribution networks are weak and unreliable. These weak networks further contribute to self-reliance for individuals and businesses alike.

On every level of generation, from national power plants to electricity generated by businesses and individuals, FFGs play an important role. However, this reliance on generation at the small scale also adds the burden of logistics to businesses and individuals who need to procure the generators, buy and supply expensive fuels, as well as operate and maintain their generators. This intricate and broken-up supply of electricity creates value for companies who act as intermediaries in the value chain, distributing machines, parts, fuel, and services to keep the industry and livelihoods of millions of people going.

Africa has only recently started investing in renewable energy plants at utility-scale. Apart from the prominent coal fired power plants, fossil fuel generators like gas, diesel and duel-fuel turbines therefore play a big role in supplying power at the utility-scale. Ease of installation and established supply chains make them the favourite technology for developing countries, particularly as the environmental policies of renewable energy generation have not yet limited their implementation.

6.2 Small Scale Fossil Fuel Generators

The high penetration of fuel generators across Africa has historically been a response to the lack of transmission infrastructure in rural areas and a low quality of service from the national grid. A 2019 report by A2EI[26] estimates that in Nigeria there are between 22 million and 60 million generators in use in the domestic and the micro, small and medium-sized enterprises (MSME) sector. A large proportion of these generators will be powered by fuel delivered via informal supply chains for the ‘last mile’. The affordability of these smaller petrol-powered generators means they are widely found in urban on-grid and rural off-grid areas.

Generators are made up of at least nine parts including the engine, alternator, fuel system, voltage regulator, battery charger, cooling system, lubrication system, assembly frame and control panel. Petrol generators, which have the largest share of market volumes in SSA, typically have small power capacities of less than 10 kVA. Generators larger than 10 kVA are generally diesel powered, although this is a crude threshold given that overlap does exist. Smaller petrol generators provide single phase AC output and larger diesel gensets generate three phase AC output, with the size threshold at approximately 10 – 20 kVA. Efficiency depends on generator size and engine loading. Typical efficiencies for diesel generators ranging between 20 kW and 200 kW are presented in Figure 43. Note that diesel generators are more efficient than their petrol counterparts.

[26] *Access to Energy Institute, Putting an End to Nigeria’s Generator Crisis: The Path Forward June 2019*

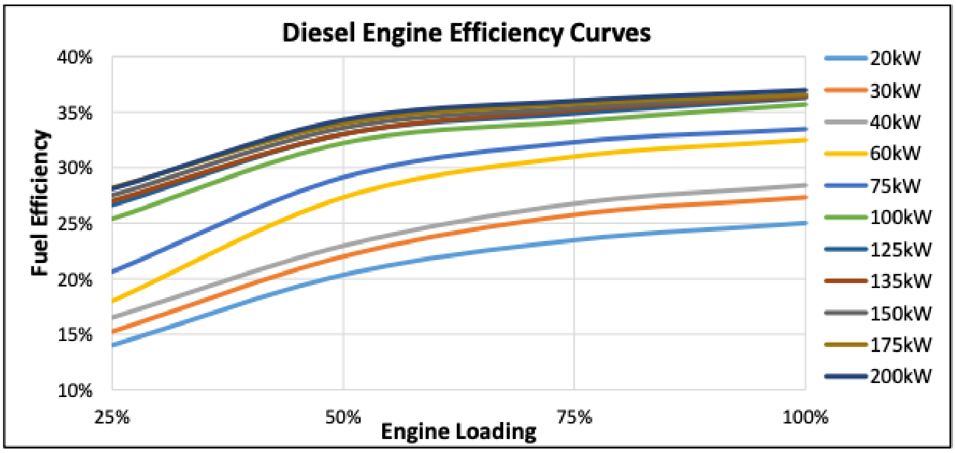


Figure 43: Typical diesel generator efficiencies[27]

The backup generator fleet across the developing world is estimated to be 450 GW.[28] While this generator fleet has been instrumental in plugging the gaps left by unreliable and non-existent grids, it has also caused negative impacts on health and the environment. In particular, carbon dioxide emissions contribute to climate change and nitrogen dioxide, sulphur dioxide and carbon monoxide emissions cause a variety of negative health impacts.

Electricity from fossil fuel generators can be as much as four times the price of grid power,[29] and is heavily influenced by fuel cost and in turn fuel subsidies. On average, governments in SSA subsidise diesel with an amount equal to 0.61% of gross domestic product (GDP) and petrol with an amount equal to 0.81% of GDP.[30,31] Levelized cost of energy (LOCE) of diesel-only mini grids range between \$0.89/kWh - \$1.28/kWh, while hybridisation with solar can bring this range down to \$0.49/kWh - \$0.68/kWh.[32]

Key characteristics of the value chain include the following:

- The weak grid market is significantly larger than the off-grid market, given that 75% of FFGs are operated at sites that are already grid connected.
- Most of the FFGs being used across SSA are small imported petrol generators
- Larger diesel generators are used for critical loads (hospitals), high-end clients (safari) or high density residential (apartment blocks, hotels)
- Containerised diesel generators are used in minigrids
- The knowledge to operate and repair FFGs is widespread and the fuel supply chains are shared, active, and established.
- China is the leading manufacturer of diesel generators used in SSA.[33]
- Nigeria is one of the largest petrol generator markets in the world. In 2019, the country was the second largest export market for Chinese petrol generators – a total of 1.45 million units was imported into the country from China.[34]

[27] *Ireland, 2017, G. Techno-economic modelling of hybrid renewable mini grids for rural electrification planning in Sub-Saharan Africa, (link)*
[28] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*
[29] *McKinsey & Company, 2015, Brighter Africa - The growth potential of the sub-Saharan electricity sector, (link)*
[30] *TFE Africa analysis based on IMF data*
[31] *Sudan has been excluded from the analysis due to its unusually high fossil fuel subsidies. The country subsidises diesel to the extent of 29.07% of GDP and petrol with 12.79% of GDP.*
[32] *Sustainable Energy for All, 2020, State of the Global Mini grid Market Report, (link)*
[33] *African Review, 2018, Is the genset market going to turn in 2018? (link)*
[34] *Kent Power, 2020, Overview of China's Generator Set Exports in 2019, (link)*

- Captive power and mini grid developers tend to enjoy better pricing when buying from international suppliers compared to local suppliers.
- Wholesale supply is limited to capital cities and some larger towns with limited supply elsewhere.
- Manufacturing lead times tend to be 4-6 weeks and shipping approximately 8 weeks.[35]
- The average dwell time in ports across SSA is 16 days
- Most generators can be purchased pre-configured to different local country voltages. Alterations are limited to adding remote monitoring capabilities, custom exhaust systems and increasing fuel tank size.
- Maintenance is cumbersome and costly in comparison to batteries. O&M tasks can add expenses of approximately 10-20% on top of fuel costs.[36]

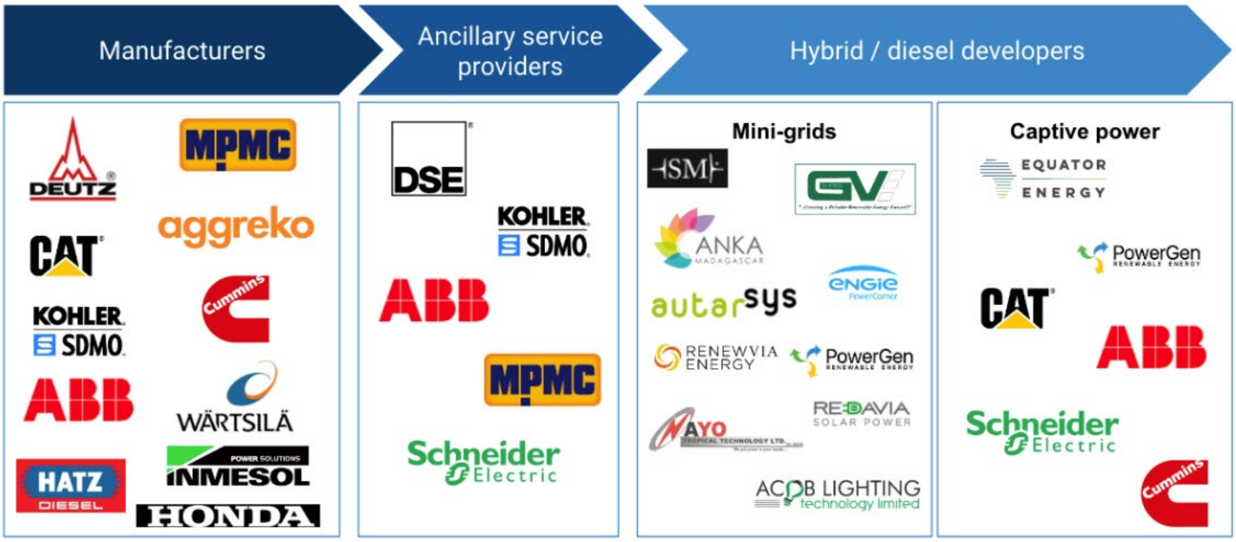


Figure 44: Key stake holders in the small-scale FFG value chain – Source: TFE Database

6.3 Gas Turbines

For utility-scale power generation, gas turbines are the main power generation technology used in much of the world due to the availability of relatively low-cost natural gas fuel and the low emissions compared to coal. A main benefit of gas turbines is that the hot exhaust gases can be used to provide steam for industrial processes as well, producing energy not only as electricity but also as usable heat. Gas turbines depend on the availability of natural gas fuel (delivered through pipelines), as the alternatives of LNG (liquified natural gas) or diesel fuel oil are much more expensive. Availability of natural gas is very limited in most of SSA, but there are developments in Southern Africa towards producing and supplying more natural gas.

Gas turbine power plants come in two main configurations: open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT).

The main benefit of OCGT is flexibility and fast response time of the power plant. The power output can quickly be ramped up or down to meet demand or grid requirements, although not as quick as diesel generators can. The downside is a relatively low thermal efficiency of about 30-36% (depending on the size and design). OCGT are often used for peaking operation (short duration power output to meet peaks in demand) and have a lower efficiency that allows for more savings compared to the alternative BESS (+ renewables) power supply.

[35] *Indicative based on interviews*
[36] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*

The main benefit of a CCGT power plant is the high thermal efficiency of up to 61%. This comes at a cost of lower flexibility as the steam cycle cannot respond quickly as that causes thermal stress on the equipment. CCGTs are therefore most suitable for relatively constant (base) load operation at a large scale. CCGT's are complex generators requiring longer construction periods (i.e. several years instead of weeks or months for OCGT) and a more skilled O&M workforce.

The footprint of the turbine is small. For a 20 MW industrial gas turbine an area of about 10x20 m could be sufficient. An example of a large industrial gas turbine is shown in Figure 45.

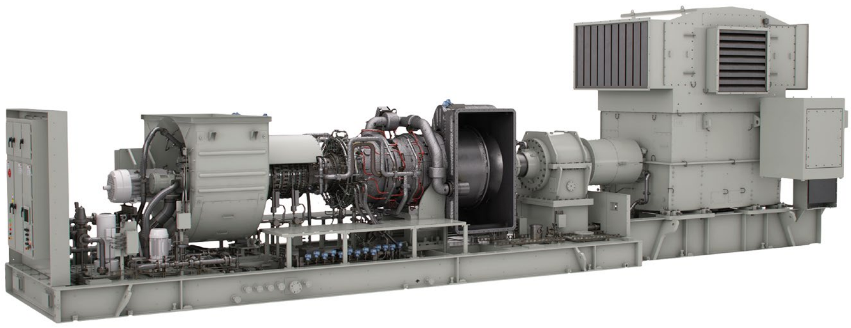


Figure 45: Example 23 MW Industrial gas turbine and generator package[37]

OCGT maintenance is based on periodic inspections and replacement of parts that can be categorised as follows (from minor to major maintenance, with example intervals in hours of operation and starts[38]):

- Combustion Inspection (CI, interval: 12,000 hours or 800 starts)
- Hot Gas Path (HGPI, interval: 24,000 hours or 1200 starts)
- Major Inspection (MI, interval: 48,000 hours or 2400 starts.

These maintenance intervals are influenced (and can be reduced) by factors such as the type of fuel used (gas, diesel, HFO), (fast) starts, trips and high ramp rates. BESS can play a role in the following ways to reduce maintenance costs:

a) Allow gas turbines to operate closer to full load and at their lowest heat rate (maximum thermal efficiency)

b) Gas turbine specific fuel consumption is higher in regions with higher ambient temperatures, making energy storage and renewables more competitive

c) Avoid start/stop behaviour and reduce ramp rates to reduce maintenance costs.

The main gas turbine manufacturers acknowledge the benefits BESS can bring and started offering different energy storage products to augment their gas turbine offerings (e.g. GE, Siemens, Solar Turbines).

6.4 Diesel Power Plants

Throughout Africa, utilities make use of thermal power plants. Some plants are designed only for burning liquid diesel fuel, whereas others operate only on gas. However, the growing trend is for engines that can utilise both gas and diesel, as illustrated in Figure 46.

[37] *Solar Turbines, Titan 250 Gas Turbine Generator set datasheet*
[38] *GE GER 3620P, Jan 2021, Heavy-Duty Gas Turbine Operating and Maintenance Considerations*

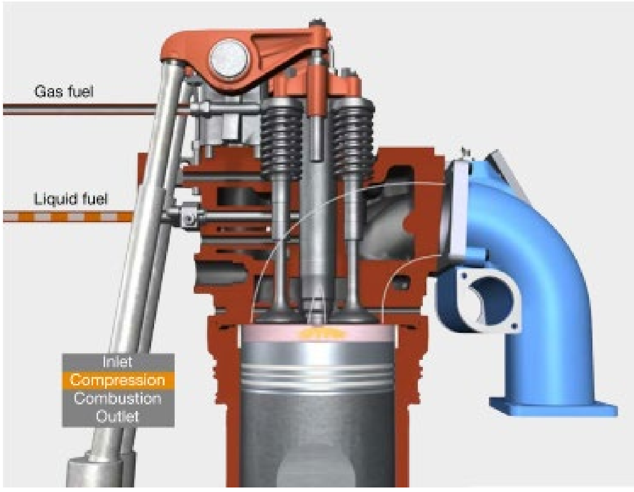


Figure 46: Gas-Diesel combustion engine[39]

Off-grid containerised energy systems are used by utilities as a (relatively) rapidly deployable supply to make up for regional shortfall in centralised grid supply. At the utility-scale, it is not unusual to find multiple containerised generation units connected, however for most applications single generators will be used. Grid support generators are typically provided as a service by a private company. An example of this is the UK company Aggreko employed by the Kenyan government to provide grid support services in the western part of the country. The 30MW diesel plant sold energy into the grid at the relatively high price of $0.49/kWh.

Because liquid fuels are more expensive than natural gas, these engines are often designed for duel fuel capabilities. The gas-diesel engine can be switched instantly from gas to liquid fuel mode operation. The liquid fuel can be either light fuel oil, heavy fuel oil or crude oil. The advantages of liquid fuel engines are reliability and quick ramp up time which makes power available anywhere and at any time. These same characteristics make these plants suitable for stationary and floating baseload operations as well as for stand-by applications. In South Africa, where the utility ESKOM provides 95% of the power in the country (42% of the power in Africa), diesel power plants are increasingly used for peaking plants. In 2019 when the utility could not provide enough power to meet demand, due to failing plants, the utility spent $524 million on diesel to avoid "load shedding", but still ended up rationing power for 46 days[40].

Other characteristics of the value chain include the following:

- The market for liquid fuel power plants are dominated by 5 manufacturers. These companies manufacture in-house and have vast global networks and supply chains, enabling them to serve customers all over the world
- The large suppliers of these plants, like MAN Diesel & Turbo and Wärtsilä have their own O&M service packages to ensure reliability and performance of the units
- Compared to smaller scale diesel generators, outsourcing major maintenance to 3rd party maintenance companies is difficult, as the large-scale diesel generators often require specific spare parts and tools from the OEM.

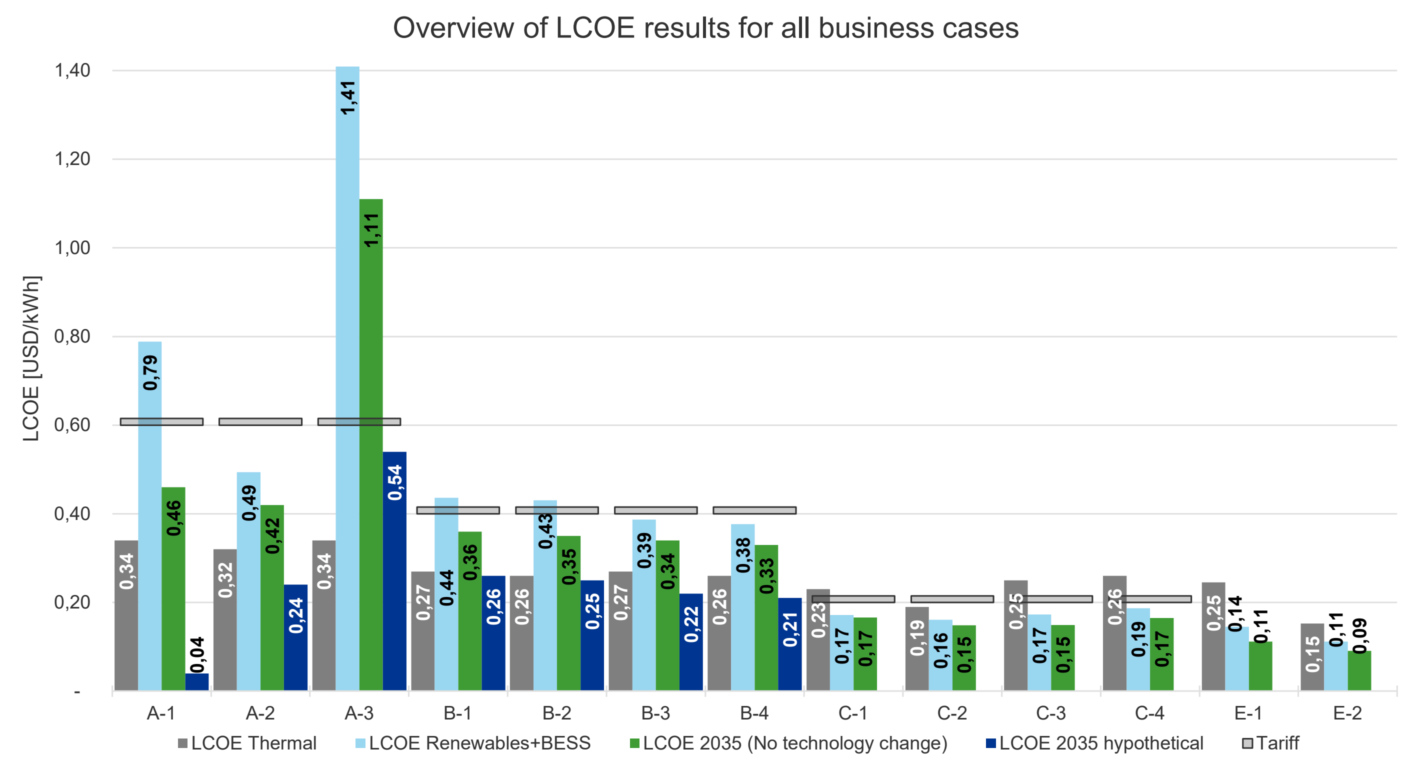
[39] Wartsila Brochure
[40] Eskom needs R1 billion a week from government to keep the lights on in 2021 (businessinsider.co.za)

7 MAIN FINDINGS

7.1 Techno-economic Modelling Findings

The results from the techno-economic modelling suggest that, for smaller and medium sized systems, a solar and BESS supported system does not yet provide a viable alternative to a diesel or gasoline only system in terms of cost. Figure 47 shows the LCOE results for all the business cases developed in the techno-economic model, and how these LCOEs change as the cost of battery technology decreases and other actions are implemented.

As the LCOE represents the cost on a per kWh basis it is a good indicator for the tariff that is to be charged to end-users for the mini-grid or hybrid energy supply system to be commercially feasible. The higher LCOEs for configurations with a BESS therefore require alternative incentives or a reduction in cost of the BESS itself for these business cases to be commercially feasible. The horizontal bars represent the tariffs applicable to the business cases (A-1, A-2, A-3, B-1 etc.) and the vertical columns the calculated LCOE for the power supply systems.



Case	Description
A-1	Mini-Grid (Off-grid), Greenfield, Located at a tea estate with high demand 4:00-6:00 and 17:00-21:00.
A-2	Mini-Grid (Off-grid), Greenfield, Island mini grid with high demand during day (businesses) and evening (domestic).
A-3	Mini-Grid (Off-grid), Brownfield, Village mini grid with peak demand at the evening (domestic).
B-1	Captive and Behind-the-Meter (Off-grid), Brownfield, Safari lodge in Tanzania.
B-2	Captive and Behind-the-Meter (Off-grid), Greenfield, Safari lodge in Tanzania.
B-3	Captive and Behind-the-Meter (On-grid), Brownfield, Manufacturing company in Kenya.
B-4	Captive and Behind-the-Meter (On-grid), Greenfield, Manufacturing company in Kenya.
C-1	Off-grid Industrial, Greenfield, Manufacturing company in Kenya, Diesel as reference.
C-2	Off-grid Industrial, Greenfield, Manufacturing company in Kenya, Natural gas as reference.
C-3	Off-grid Industrial, Brownfield, Processing factory in Sierra Leone, Diesel as reference.
C-4	Off-grid Industrial, Brownfield, Processing factory in Sierra Leone, Natural gas as reference.
E-1	Avoided Transmission & Distribution Expansion (On-grid), BESS connected at 33kV substation to avoid new overhead lines and substation expansion.
E-2	Avoided Transmission & Distribution Expansion (On-grid), Same as D-1 but also avoiding new generation capacity by reducing total peak demand.

Figure 47: Overview of LCOE results for business cases A to E

The LCOE Thermal column presumes diesel or gas only power systems, LCOE Renewables + BESS can be considered a “base-case” with solar and battery storage added to the system at current battery cost and performance. LCOE 2035 presumes 2035 solar and battery cost and is split in two. “No technology change” assumes that today’s battery technology of choice is still applied in 2035. The hypothetical case presumes that cost and performance levels of utility-scale Li-ion battery technology are attained for the specific business case. This represents an estimated floor to LCOEs in the absence of disruptive technology change and with a highly successful mitigation of logistical, scale, regulatory, and knowledge barriers. Note that the latter is not applied to cases C and E as these already rely on utility-scale Li-ion technology. Section 4 describes each of the business cases analysed and the modelling results in more detail.

The green bars labelled ‘LCOE 2035 (no technology change)’ illustrate how forecasted cost reductions of the deployed battery technology do not result in cost parity with diesel or gasoline only systems. The dark blue bars labelled ‘LCOE 2035 hypothetical’ assume that forecasted utility-scale Li-ion prices and performance can be achieved for these small and medium sized systems. This hypothetical scenario shows that it is possible to achieve cost parity to thermal prices if the cost of small-scale BESS can approach that of the utility scale batteries per kWh. However, achieving this cost is subject to unlocking the technology for use in particular applications and locations.

Strategies to pursue this include:

- Enabling larger volume procurement to get access to lower factory pricing and more direct value chains with a lower overall mark-up
- Reducing transportation costs, which represent up to a third of BESS installed cost
- Standardising BESS offerings to lower plant costs
- Creating and disseminating tools which can correctly size BESS by applications, forecast the degradation, and optimise for augmentation of BESS rather than replacement during project lifetime.

Standardising technical requirements (incl. grid codes) to reduce project specific engineering and design needs. 2. Off-grid industrial facilities that have considerable power and energy requirements do already benefit from utility-scale Li-ion technology. The LCOE of a hybrid system consisting of solar, BESS and diesel (or natural gas) generators is already lower than diesel only system at today’s prices. As discussed in Section 4, this is already valid for the medium fuel price forecasts included in the techno-economic model. Forecasted reduction in cost of Li-ion technology will only improve the business case further.

The techno-economic modelling of mini-grids and small- to medium-scale behind-the-meter storage applications indicates that diesel-only configurations currently result in lower cost to end user than those incorporating battery technology for each of the case studies A and B (i.e. those pertaining to small and medium system). This is because the cost of smaller battery systems to this end-user is simply too high due to lack of scale in procurement, high transport cost, and less than optimal system design and operation. Forecasted cost reductions for small and medium sized systems of ~26% for small-scale Li-ion and ~23% for small-scale lead acid by 2035 to end-users will not make a significant change in the proposition of BESS for these small-scale projects.

Techno-economic modelling of the larger Li-ion BESS for off-grid industrial applications and utility-scale hybrid plants indicate that the technology is already competitive on displacing a large portion of diesel or natural gas consumption. Forecasted reductions in cost will only strengthen this conclusion. However, fully displacing diesel or natural gas generators by renewable energy with BESS is not yet feasible for traditional energy networks where flexibility in demand is limited or non-existing. If load demand for electricity remains constant, the cost of BESS (now and for the next five years) is too high to install batteries large enough to bridge multi-day periods of adverse solar and wind conditions.

7.1.1 Mini Grid Conclusions

Cases A-1 to A-3 represent small mini-grids. Table 19 summarises the LCOEs for each case with the different BESS approaches discussed above. Case A-3 has a larger than required battery and stands to gain from optimising the mini grid itself, regardless of which battery technology is deployed. Cases A-1 and A-2 are therefore better examples. The results of these two cases indicate that displacement of petrol or diesel only solutions, without increasing the cost to the electricity consumers, is only possible if significantly lower battery prices can be achieved. Waiting for cost reduction on lead-acid batteries or small-scale Li-ion system does not yield favourable results.

If these costs can be reduced then small mini grids – represented by cases A-1 to A-3 – can displace petrol and diesel generators and offer electricity to the consumer or end-user at a same or lower rates than if it were powered by diesel or petrol only. The green marked cells in Table 19 indicate which LCOEs are attainable if 2021 and 2035 utility scale Li-ion cost levels are applied to these small systems. Data and estimates made during this study put small-scale li-ion cost in 2035 about a factor three to four more times expensive than utility scale Li-ion.

Table 19: LCOE for cases A-1 to 3 over different BESS approaches

Item	Unit	A-1	A-2	A-3
Petrol/Diesel only	USD/kWh	0.34	0.32	0.34
With lead-acid BESS	USD/kWh	0.73	0.48	1.34
With 2035 lead-acid BESS	USD/kWh	0.46	0.42	1,11
With 2021 small-scale Li-ion	USD/kWh	0,81	0,49	1,44
With 2035 small-scale Li-ion	USD/kWh	0,48	0,40	1,13
With 2021 utility-scale Li-ion	USD/kWh	0,33	0,31	0,77
With 2035 utility-scale Li-ion	USD/kWh	0,04	0,24	0,54

7.1.2 Captive and Behind-the-Meter Applications Conclusions

The LCOE of cases B-1 to B-4 is significantly lower for a diesel generator only scenario compared to those that deploy Li-ion technology at small-scale system prices. For cases B-1 and B-2 the configurations with BESS are about 37% more expensive in terms of LCOE, and for cases B-3 and B-4 this is roughly 30%.

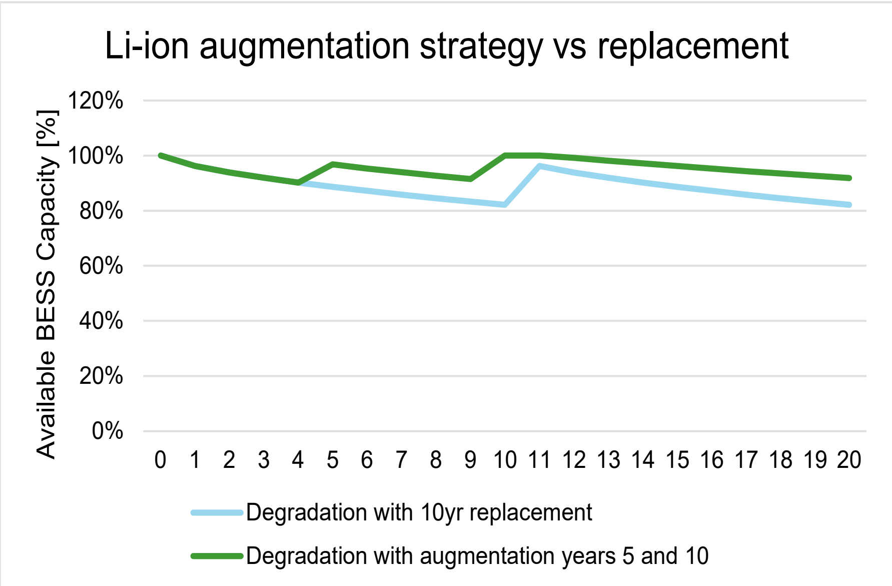


Figure 48: Li-ion augmentation vs replacement

Changing to the augmentation strategy is a potentially worthwhile approach to reduce the LCOE of a system with a small-scale Li-ion battery, resulting in a 11% decrease in LCOE. The practice of replacing Li-ion batteries after approximately 10 years to ensure sufficient battery capacity is robust, but costly. Advanced software tools and the correct know-how can help forecast the usage profile of the BESS, forecast the degradation of BESS capacity, and infer augmentation rather than replacement strategies. Monitoring of the Li-ion system during operation provides information about actual usage and can help inform decision making on adjusting the usage of a BESS or to adjust the augmentation strategy if needed. However, this only works if additional Li-ion modules can be procured, transported, and added to the battery system at reasonable costs.

Augmentation- instead of replacement strategies will not alone be sufficient to reduce LCOE to the figures resulting from a diesel only operation. Future small-scale Li-ion prices, based on price forecasts, reduces the achievable LCOE for cases B-1 to 4 but does not enable sufficiently low LCOEs. The cost difference between small-scale and utility-scale Li-ion system is again too large and is forecasted to remain large. However, if the cost “add-ons” that make a small-scale Li-ion system so much costlier can be reduced to near utility-scale Li-ion BESS prices, for the clientele of cases B-1 to 4, the cost of electricity can drop to equal or lower figures as that of diesel-only configurations. This will also yield significant savings on fuel consumption and the associated CO_2 emissions.

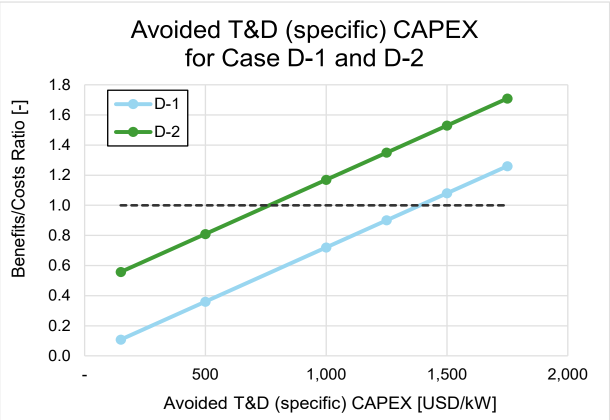
7.1.3 Off-Grid Industrial Facilities Conclusions

A diesel or gas only configuration results in a higher LCOE for all cases C-1 to C4 compared with a battery (and solar) supported configuration. Battery systems are therefore likely making their mark on off-grid industrial facilities. This is evidenced by some projects already gaining momentum in Africa. Forecasted reductions in the cost of utility-scale Li-ion will help to improve competitiveness, of BESS supported electricity supply systems for off-grid industrial facilities.

Cost reductions of BESS are not sufficient to fully displace diesel generators. However, cost reductions for Li-ion systems do enable larger batteries to displace more diesel or gas consumption, an effect which is amplified when higher fuel prices are in effect. The further reductions in diesel or gas consumption are not very large, and fully displacing diesel generators is not yet commercially attractive. The BESS technology, at current and forecasted costs are commercially viable for bridging the, more-or-less daily, variability and adverse weather events for solar energy to power off-grid sites at this scale. However, they are not yet cost effective at bridging the load supply for sustained periods (> 1 day) of limited solar resource availability.

7.1.4 Avoided Transmission & Distribution Expansion Conclusions

The business case for avoiding T&D (and Generation) capacity expansion investments is complicated, as it is very location and project specific. Due to the large cost difference between T&D capacity and BESS specific CAPEX, it is only in very specific circumstances (where the T&D expansion has high costs) that a BESS is a cost-effective option.



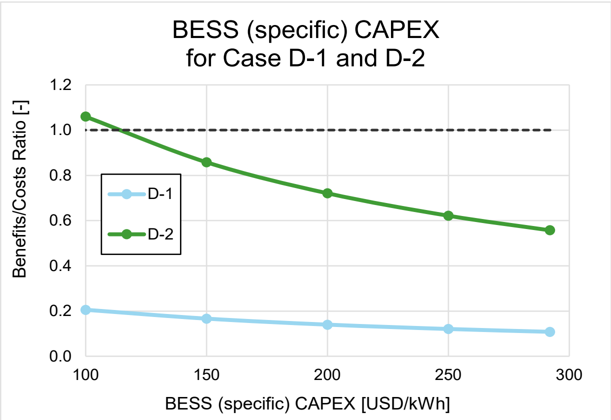


Figure 49: B/C Ratio results vs avoided T&D specific CAPEX (left) and BESS specific CAPEX (right)

As can be seen in Figure 52, achieving a feasible business case when only considering avoided T&D CAPEX (light blue lines) is not possible. When also considering avoided Generation CAPEX (green lines) the business case can become feasible for certain niche cases, where the avoided T&D CAPEX exceeds 750 USD/kW. BESS CAPEX would need to reduce significantly (to around 120 USD/kWh) for Case D-2 to become feasible, which is not realistic in the short and medium-term future.

When the BESS is designed to reliably reduce peak demand and the generation capacity expansion can be avoided, then the business case improves significantly, but is still only feasible in certain niche situations. Examples would be in cases where either grid expansion is not possible, due to right-of-way issues, and where the BESS would be the only available option to solve the grid constraint.

The additional added value of the BESS for the grid would have to be considered. For instance, in the form of capacity payments that provides spinning reserve capacity for the project to be more economically feasible. However, due to the lack of capacity markets in SSA for grid services, this would only apply to BESS (services) procured by integrated utilities, where these benefits to the system are for the same party that caries the costs for the BESS (services).

7.1.5 Hybrid Solar and Wind Plants Conclusions

The example business cases shown in this subsection illustrate that hybrid renewables and storage plants can compete with fossil power plants in certain situations, especially when the fossil fuel alternatives have relatively low efficiency or high fuel prices. This is also shown in practice in South Africa, where most of the qualified projects for the emergency power tender were hybrid renewable and storage plants (some with back-up thermal generators). This represents a large economic opportunity as most countries in SSA import fossil fuels.

By carefully weighting the grid requirements for flexibility and reliability the costs for hybrid renewable and storage plants can be further optimised and able to provide power when it is needed at competitive costs and with no (or very low) emissions.

7.2 Conclusions and Recommendations

7.2.1 Current Opportunities for BESS to Displace Fossil Fuel Generators

The current opportunities for BESS replacing FFGs is driven by the following economic drivers or sector characteristics:

- High cost of fuel
- High opportunity cost due to unreliable electricity supply
- Weak, unreliable, or non-existent main power grids
- Availability of BESS in the local market at competitive costs
- Government or IDB support for implementing BESS and renewables projects

The first three points are especially true for many regions in SSA, while BESS availability and support schemes are improving but still lacking in many countries. Several business cases that should already be economically feasible are identified in this study:

7.2.2 Main Barriers for Further BESS Deployment

As the technical improvements of Li-ion BESS have reached a level where all technical requirements are met, the obvious barrier to deployment is for purchasers to access the capital required to install these batteries for all sectors apart from utility-scale.

There is a vast difference between the price for deployed Li-ion BESS between that of utility-scale and small scale. This is primarily due to the cost of logistics almost doubling the cost of the BESS by the time it is installed. There is also still a lack of skills required for maintenance and augmentation of Li-ion BESS, and thus the OPEX costs are also a barrier to entry. It can be assumed that, in time, skills transfer will pass down to grassroots level, as it has done for lead-acid batteries.

Another barrier is that of access to software or the correct knowledge regarding system design, optimisation of augmentation schedules which rely on the prediction and managing of BESS degradation. There is a need for capacity building throughout the value chain to ultimately improve project returns through better planning and maintenance of systems.

Further to the lack of technical knowledge related to measurements and software, is that of business cases, payment structures and other financial innovations. This links closely to the implementation of governmental policies that enable open market energy trading.

7.2.3 Role of Innovative Technology to Support BESS Deployment

Over the past decade, the energy storage industry has seen a lot of innovation in the development of solutions for different energy storage applications. A considerable amount of research and development (R&D) across the globe is funded by a myriad of companies spanning various industries. This not only reflects the wide spectrum of applications of BESS, but also the interest and belief in its future potential. There are increasingly novel energy storage solutions using all forms of energy (chemical, thermal, mechanical, electrical) coming to market, each exploiting a niche.

The Li-ion BESS industry has seen the most funding and R&D put towards optimising performance, energy density and safety, fuelled by the ever-growing electric vehicle market. The pace of development has seen rapid gains in BESS performance metrics, but these gains are expected to be incremental in the next few years, rather than disruptive. Developments like solid-state batteries can represent a leap in performance, however the timeline to commercialisation should not be a reason to wait for ‘the next generation’, as the current technologies already provide significant benefits in many applications, and the development of new technologies will keep progressing.

Techno-economic modelling results indicate that forecasted cost declines for small-scale Li-ion systems or the lead-acid alternative are insufficient to make BESS deployment a widespread commercially attractive option to displace diesel or petrol fuel consumption. Whereas novel battery technologies with even lower costs or better lifetimes may tip the scale on the long-run, unlocking state-of-art forecasting of battery usage and monitoring battery usage and degradation as well as enabling advanced battery augmentation, rather than standardized replacement strategies for small systems, are likely to make a bigger impact in the near future. The modelling work does however indicate that this alone is likely insufficient to enable electricity production at the cost of petrol or diesel only systems.

Regarding safety, or specifically thermal and mechanical abuse tolerance: Li-ion BESS are now widely deployed in cars and can be considered safe if properly managed and monitored. This can be more of a challenge for Li-ion batteries that operate far away from regular maintenance. A case for an (even) more robust battery with the performance of Li-ion and cost reduction potential of Li-ion can be made to create more of a “drop-in” replacement to lead-acid than current Li-ion is for small mini grids. The drive for a safer battery is a driving force of innovation across multiple sectors such as automotive, defence applications as well as the expected deployment of more Li-ion batteries in underground mining equipment, where safety is paramount.

The automotive industry will deploy – globally – a massive quantity of Li-ion technology (with EVs expected to represent up to 90% of the total BESS market). Some manufacturers are targeting recycling of Li-ion batteries, harvesting its most valuable components to secure supply to manufacture new batteries. Other manufacturers are experimenting with re-using (2^{nd} life) batteries in stationary storage, where used EV batteries can provide valuable services even if their use in a car is no longer attractive due to aging after years of use. This idea of 2^{nd} life batteries as a cost-effective source of stationary energy storage is interesting and it is being developed further. It however faces several challenges, including:

- It is difficult to assess the state-of-health and safety of 2nd life batteries by third parties, though EV manufacturers do extensive data logging, and can have a reasonable to good picture on a BESS state of health or overall quality.
- Logistics are very complex, to match batteries of different makes and state-of-health to produce refurbished battery modules/racks, containers, or entire systems. Maintenance of BESS at remote locations is already challenging and using 2nd life batteries will further increase the need for maintenance or augmentation.
- National regulation would need to treat 2nd life batteries as a resource and not chemical waste, while also ensuring the imported batteries are indeed refurbished under acceptable conditions and not disposed of. This also represents a risk of reputational damage for the EV manufacturers when their 2nd life batteries are not used correctly and cause accidents or negative environmental impact.

Innovation in finance or payment structures has seen some success in Asia, where public charging pods allow electric scooter riders to come and exchange their removable, depleted battery for a charged battery with payment via card or smartphone enabling a quick exchange. Different forms of leasing models can also play a role, moving towards energy storage as a service.

7.2.4 Next Steps to Support BESS Deployment

There is a huge potential for battery energy storage to support replacing fossil fuel generators in SSA, but realising this potential is hindered by one main factor: actual BESS (capital) costs for the user. This is especially the case for small-scale BESS, where the total specific costs (per kWh capacity) in SSA are about three times the costs of a utility-scale BESS system.

Role of Technical Innovation

The performance of Li-ion batteries is already at a level that meets all the technical requirements for different applications. The techno-economic model shows that the impact of further improvements in performance, such as cycle efficiency, cycle life and charge/discharge power have on the economic feasibility (e.g. total LCOE or project IRR) is limited. This indicates that the impact of continued BESS technical improvements is useful but not sufficient to change the current situation in SSA. Innovative BESS technologies would be helpful only where they address the main issues seen for mass implementation in SSA which are reduction in CAPEX and OPEX costs.

Table 20 summarizes if current and anticipated technology performance and cost can offer a sufficiently feasible alternative on displacing diesel generators or natural gas fuelled plants. It denominates for each modelled business case and selected battery technology and cost combination whether it provides a feasible alternative to fossil fuel (green), is already feasible in selected markets or on the brink of feasibility (amber), or does not provide a feasible alternative under current assumptions (red).

Table 20: BESS feasibility on displacing diesel or gas

Business Case	Does BESS offer a sufficiently feasible solution on displacing diesel or gas?			
	Current BESS	2035 Small Li-ion	Utility Price Li-ion	2035 Utility Price Li-ion
A – Mini Grid	Lead-Acid	Small Li-ion	Utility Li-ion	Utility Li-ion
B – Captive Behind the Meter	Small Li-ion	Small Li-ion	Utility Li-ion	Utility Li-ion
C – Off Grid Industrial Facilities	Utility Li-ion	N/A	Utility Li-ion	Utility Li-ion

Business Case	Does BESS offer a sufficiently feasible solution on displacing diesel or gas?			
	Current BESS	2035 Small Li-ion	Utility Price Li-ion	2035 Utility Price Li-ion
D – Avoided T&D Expansion	Utility Li-ion	N/A	Utility Li-ion	Utility Li-ion
E – Hybrid Solar and Wind Plant	Utility Li-ion	N/A	Utility Li-ion	Utility Li-ion
Legend:	Feasible	Approaching feasibility	Not feasible	

Within the Li-ion BESS industry, cell manufacturers design, optimise, and develop their battery cells to meet market demand and accommodate the favourable results from R&D. Innovation in the design and manufacturing of battery packs and system integration in mini grids (including solar) should help drive down cost for smaller scale projects. An example of this is the development of a standardised battery suitable for use in both mini grids and in small scale captive power solutions. Such a battery could be mass manufactured, imported at scale, distributed through large networks, and stored in warehouses, with prices expected to be much closer to that seen in utility-scale BESS projects.

Role of Pilot and Demonstration Projects

Funding and development of pilot projects or proof of concept demonstrations, either for new technologies or for new applications of existing technologies, are highly effective in breaking through previously existing market barriers. Often these projects highlight unforeseen difficulties, from missing links in the supply chains, unexpected delays shipping lead times, policy and regulation, or skill shortages that were previously overlooked. As pilot and demonstration projects are not commercially viable by nature and often face high risks of delays and complications, financial and other support is crucial to enable these projects and the associated learning. Well-selected BESS demonstration projects can not only address these blind spots, but also solve critical problems associated with the weak and unreliable grids throughout SSA.

Improvement Focus Areas

Several areas are identified where improvements would have the highest impact but currently lack sufficient attention or research and development funding, these include:

- The proportionately very high costs of BESS (and renewable energy equipment) for small-scale projects in SSA:
  - Equipment (specific) costs are at least double that of utility-scale BESS, due to small capacity procurement resulting in higher factory prices and longer value chains with mark-ups along the chain
  - Transportation costs are currently up to a third of total installed BESS costs
  - The ongoing cost reductions and published prices for BESS focus on utility-scale systems and deployments in OECD countries. These do not represent the real prices seen in SSA for small-scale systems
- The development of Li-ion BESS technology is being driven by the EV sector and research in different (longer duration) storage technologies by OECD countries is also being pursued. However, developments for BESS specifically for the small-scale applications in remote areas in SSA will require support, including investigating:
  - Innovative BESS technology focused on cost reductions for small scale deployment
  - Standardisation and modularity to reduce balance of plant costs

  - Achieving economies of scale by setting up common procurement programs
  - Overcoming the challenges of utilising 2nd life batteries from EV applications
- The provision of information and tools to SSA project developers, such as:
  - Tools for correctly sizing BESS for the intended application
  - Assessing the economic feasibility of a project idea
  - An overview of BESS technology- and installation guidelines that inform which types of BESS technologies are best suited for the applications and conditions in SSA

  This report and techno-economic model is a first step in this direction, but to achieve further impact will require a targeted effort focussed on providing information to SSA project developers, as well as the design and planning tools that can be used by users with different levels of technical expertise.

- There are several barriers that are neither technical nor economic in nature, but still limit the deployment of BESS and renewables in SSA. These would have to be addressed at a national level which requires external support, as commercial parties would not be well-placed to do this. These barriers include:
  - Lack of standardisation of technical requirements such as grid codes that make it possible for larger scale energy storage systems and renewables to connect to the grid
  - The Environmental Permitting process should reflect the zero emissions nature and limited environmental impact of BESS and renewables compared to fossil fuel generators. This could allow for a more streamlined permitting process
  - Transparent grid planning and rules for connecting mini-grids to the main grid, to reduce the risk of mini-grid developers not being able to recover their investment costs after a mini-grid gets connected.

Table 21 shows, for each business case, the effect of possible scenarios surrounding BESS, such as cost reduction due to economies of scale, or from the use of 2nd life batteries. The table shows a high impact in overcoming the current barriers for BESS deployment in green, a medium impact is shown in yellow and a low impact in red.

Table 21: Impact on BESS feasibility by mitigating barriers

Business Case	Expected impact of successfully mitigating or avoiding barriers:				
	Standard battery(1)	Economies of scale(2)	2nd life(3)	Tools to developers(4)	Enabling policies(5)
A – Mini Grid	High	Medium	Low	Medium	Medium
B – Captive Behind the Meter	Medium	Medium	Medium	High	Low
C – Off Grid Industrial Facilities	Low	High	Low	High	Low
D – Avoided T&D Expansion	Low	Already in effect	Low	Low	Medium
E – Hybrid Solar and Wind Plant	Low	Already in effect	Low	Low	High

Business Case	Expected impact of successfully mitigating or avoiding barriers:				
	Standard battery(1)	Economies of scale(2)	2nd life(3)	Tools to developers(4)	Enabling policies(5)

(6) The standard battery refers to the development, manufacturing and sale of a standardized Li-ion battery offering to the region and for the specific application. This avoids high mark-ups on the cost of equipment due to a long and complex value chain, and higher cost due to unfamiliarity with the technology by contractors and operators.

(7) Economies of scale refers to the shared or grouped procurement of batteries to create critical mass in driving down prices. This should not only apply to initial procurement but also to the installation, operation, and maintenance (incl. battery augmentation and replacement over its lifetime) (see pt B in the Focus areas)

(8) 2nd life refers to the use of spent Li-ion batteries from mainly electric vehicles.

(9) Tools for development refers to the development and/or provision of tools to enable correct sizing of BESS, assessing economic feasibility of projects, and monitoring and optimizing BESS over the lifetime.

(10) Enabling policies refer to incentivizing BESS or creating a level playing field via grid codes, environmental permitting process reflecting zero emission and other environmental benefits, and transparent rules for mini grid to connect to main grids (not including subsidies or tax incentives).

APPENDIX A. TECHNO-ECONOMIC MODEL

A.1. CAPEX and OPEX Projections - BESS

CAPEX and OPEX Projections

BESS

Li-ion Utility Scale — Year — Source: DNV 2021 data and analysis, and Bloomberg New Energy Finance 2018 data.

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	158	89,9%	80,4%	70,3%	60,8%	57,0%	53,2%	50,0%	46,8%	44,3%	43,0%	42,4%	41,8%	41,1%	41,1%
CAPEX: PCS (Inverters)	USD/kW	64	93,8%	87,5%	81,3%	81,3%	75,0%	68,8%	68,8%	62,5%	62,5%	62,5%	62,5%	62,5%	56,3%	56,3%
CAPEX: EMS (control system)	USD/kW	56	92,9%	85,7%	78,6%	78,6%	71,4%	71,4%	64,3%	64,3%	57,1%	57,1%	57,1%	57,1%	50,0%	50,0%
CAPEX: Balance of System	USD/kW	160	100,0%	95,0%	92,5%	85,0%	85,0%	82,5%	80,0%	75,0%	75,0%	71,4%	66,7%	66,7%	64,4%	64,4%
CAPEX: Civil works	USD/kWh	37	97,3%	91,9%	89,2%	86,5%	81,1%	78,4%	75,7%	75,7%	73,0%	73,0%	73,0%	70,3%	70,3%	70,3%
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	68	100,0%	94,1%	94,1%	94,1%	94,1%	88,2%	88,2%	88,2%	88,2%	85,3%	85,3%	85,3%	85,3%	85,3%
CAPEX: Transport and Insurance	USD/kWh	5	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
CAPEX: Taxes & Fees	USD/kWh	5	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
OPEX: O&M	USD/kW/a	20	96,9%	91,3%	86,9%	83,1%	80,0%	75,6%	74,4%	68,8%	68,8%	67,0%	64,6%	64,6%	60,3%	60,3%
OPEX: Capacity Maintenance	USD/kWh/a	4	93,4%	85,8%	78,6%	71,9%	68,5%	64,4%	62,2%	57,8%	56,5%	55,0%	53,5%	53,2%	50,7%	50,7%
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	1	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	158,0	142,0	127,0	111,0	96,0	90,0	84,0	79,0	74,0	70,0	68,0	67,0	66,0	65,0	65,0
USD/kW	64,0	60,0	56,0	52,0	52,0	48,0	44,0	44,0	40,0	40,0	40,0	40,0	40,0	36,0	36,0
USD/kW	56,0	52,0	48,0	44,0	44,0	40,0	40,0	36,0	36,0	32,0	32,0	32,0	32,0	28,0	28,0
USD/kW	160,0	160,0	152,0	148,0	136,0	136,0	132,0	128,0	120,0	120,0	114,3	106,7	106,7	103,1	103,1
USD/kWh	37,0	36,0	34,0	33,0	32,0	30,0	29,0	28,0	28,0	27,0	27,0	27,0	26,0	26,0	26,0
USD/kW	68,0	68,0	64,0	64,0	64,0	64,0	60,0	60,0	60,0	60,0	58,0	58,0	58,0	58,0	58,0
USD/kWh	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0
USD/kWh	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0
USD/kW/a	20,0	19,4	18,3	17,4	16,6	16,0	15,1	14,9	13,8	13,8	13,4	12,9	12,9	12,1	12,1
USD/kWh/a	4,0	3,7	3,4	3,1	2,9	2,7	2,6	2,5	2,3	2,3	2,2	2,1	2,1	2,0	2,0
USD/kWh/a	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0

NaS — Year — Source: US DOE, 2019 data (sourced from multiple studies), and DNV 2021 analysis.

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	569	95,1%	90,4%	86,0%	81,8%	77,8%	74,0%	70,3%	66,9%	63,6%	60,5%	57,5%	54,7%	52,0%	49,5%
CAPEX: PCS (Inverters)	USD/kW	282	93,0%	86,5%	80,5%	74,9%	69,7%	64,8%	60,3%	56,1%	52,2%	48,5%	45,1%	42,0%	39,1%	36,3%
CAPEX: EMS (control system)	USD/kW	39	99,3%	98,5%	97,8%	97,1%	96,4%	95,7%	95,0%	94,3%	93,6%	92,9%	92,3%	91,6%	90,9%	90,3%
CAPEX: Balance of System	USD/kW	59	99,3%	98,5%	97,8%	97,1%	96,4%	95,7%	95,0%	94,3%	93,6%	92,9%	92,3%	91,6%	90,9%	90,3%
CAPEX: Civil works	USD/kWh	65	99,3%	98,7%	98,0%	97,4%	96,8%	96,1%	95,5%	94,9%	94,2%	93,6%	93,0%	92,4%	91,8%	91,2%
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	65	99,3%	98,7%	98,0%	97,4%	96,8%	96,1%	95,5%	94,9%	94,2%	93,6%	93,0%	92,4%	91,8%	91,2%
CAPEX: Transport and Insurance	USD/kWh	5	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
CAPEX: Taxes & Fees	USD/kWh	5	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
OPEX: O&M	USD/kW/a	10	97,0%	94,1%	91,3%	88,6%	85,9%	83,4%	80,9%	78,5%	76,2%	73,9%	71,7%	69,6%	67,6%	65,6%
OPEX: Capacity Maintenance	USD/kWh/a	0	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	1	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	568,5	540,7	514,2	489,0	465,0	442,2	420,5	399,9	380,3	361,7	344,0	327,1	311,1	295,8	281,3
USD/kW	281,8	262,1	243,8	226,8	211,0	196,3	182,6	169,9	158,0	147,0	136,7	127,2	118,3	110,1	102,4
USD/kW	39,1	38,8	38,6	38,3	38,0	37,7	37,4	37,2	36,9	36,6	36,4	36,1	35,8	35,6	35,3
USD/kW	58,7	58,3	57,8	57,4	57,0	56,6	56,2	55,8	55,4	54,9	54,5	54,2	53,8	53,4	53,0
USD/kWh	65,2	64,8	64,3	63,9	63,5	63,1	62,7	62,3	61,8	61,4	61,0	60,6	60,2	59,8	59,4
USD/kW	65,2	64,8	64,3	63,9	63,5	63,1	62,7	62,3	61,8	61,4	61,0	60,6	60,2	59,8	59,4
USD/kWh	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0
USD/kWh	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0
USD/kW/a	9,5	9,2	8,9	8,7	8,4	8,2	7,9	7,7	7,5	7,2	7,0	6,8	6,6	6,4	6,2
USD/kWh/a	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh/a	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0

Lead Acid Small Scale — Year — Source: CAPEX from PowerGen and TFE. OPEX and Forecast from US DOE, 2019 data (sourced from multiple studies) and DNV 2021 analysis.

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	367	97,4%	94,9%	92,6%	90,3%	88,1%	86,0%	84,0%	82,1%	80,2%	78,4%	76,7%	75,0%	73,4%	71,8%
CAPEX: PCS (Inverters)	USD/kW															
CAPEX: EMS (control system)	USD/kW															
CAPEX: Balance of System	USD/kW															
CAPEX: Civil works	USD/kWh															
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW															
CAPEX: Transport and Insurance	USD/kWh	73	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
CAPEX: Taxes & Fees	USD/kWh															
OPEX: O&M	USD/kW/a	10	97,0%	94,1%	91,3%	88,6%	85,9%	83,4%	80,9%	78,5%	76,2%	73,9%	71,7%	69,6%	67,6%	65,6%
OPEX: Capacity Maintenance	USD/kWh/a															
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	1	72,5%	61,0%	56,1%	56,1%	0,0%	69,1%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	366,9	357,4	348,4	339,7	331,3	323,3	315,6	308,2	301,1	294,2	287,6	281,3	275,1	269,2	263,5
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4	73,4
USD/kWh	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW/a	9,5	9,2	8,9	8,7	8,4	8,2	7,9	7,7	7,5	7,2	7,0	6,8	6,6	6,4	6,2
USD/kWh/a	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh/a	1,0	0,7	0,6	0,6	0,6	0,0	0,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Flow Vanadium — Year — Source: US DOE, 2019 data (sourced from multiple studies), and DNV 2021 analysis.

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	407	95,2%	90,6%	86,2%	82,1%	78,1%	74,4%	70,8%	67,4%	64,2%	61,1%	58,1%	55,3%	52,7%	50,1%
CAPEX: PCS (Inverters)	USD/kW	282	93,0%	86,5%	80,5%	74,9%	69,7%	64,8%	60,3%	56,1%	52,2%	48,5%	45,1%	42,0%	39,1%	36,3%
CAPEX: EMS (control system)	USD/kW	39	99,3%	98,5%	97,8%	97,1%	96,4%	95,7%	95,0%	94,3%	93,6%	92,9%	92,3%	91,6%	90,9%	90,3%
CAPEX: Balance of System	USD/kW	59	99,3%	98,5%	97,8%	97,1%	96,4%	95,7%	95,0%	94,3%	93,6%	92,9%	92,3%	91,6%	90,9%	90,3%
CAPEX: Civil works	USD/kWh	70	99,2%	98,5%	97,7%	97,0%	96,2%	95,5%	94,7%	94,0%	93,3%	92,6%	91,9%	91,1%	90,4%	89,8%
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	93	99,2%	98,5%	97,7%	97,0%	96,2%	95,5%	94,7%	94,0%	93,3%	92,6%	91,9%	91,1%	90,4%	89,8%
CAPEX: Transport and Insurance	USD/kWh	5	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
CAPEX: Taxes & Fees	USD/kWh	5	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
OPEX: O&M	USD/kW/a	10	97,0%	94,1%	91,3%	88,6%	85,9%	83,4%	80,9%	78,5%	76,2%	73,9%	71,7%	69,6%	67,6%	65,6%
OPEX: Capacity Maintenance	USD/kWh/a	0	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	1	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	406,9	387,3	368,7	350,9	334,1	318,0	302,7	288,1	274,3	261,1	248,5	236,5	225,2	214,3	204,0
USD/kW	281,8	262,1	243,8	226,8	211,0	196,3	182,6	169,9	158,0	147,0	136,7	127,2	118,3	110,1	102,4
USD/kW	39,1	38,8	38,6	38,3	38,0	37,7	37,4	37,2	36,9	36,6	36,4	36,1	35,8	35,6	35,3
USD/kW	58,7	58,3	57,8	57,4	57,0	56,6	56,2	55,8	55,4	54,9	54,5	54,2	53,8	53,4	53,0
USD/kWh	69,6	69,1	68,6	68,0	67,5	67,0	66,5	66,0	65,4	64,9	64,4	63,9	63,5	63,0	62,5
USD/kW	92,8	92,1	91,4	90,7	90,0	89,3	88,6	87,9	87,3	86,6	85,9	85,3	84,6	84,0	83,3
USD/kWh	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0
USD/kWh	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0
USD/kW/a	9,5	9,2	8,9	8,7	8,4	8,2	7,9	7,7	7,5	7,2	7,0	6,8	6,6	6,4	6,2
USD/kWh/a	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh/a	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0

Li-ion Small Scale — Year — Source: PowerGen & TFE (avg. Price per kWh (Kenya, Nigeria, Tanzania) incl. intial purchase cost, spare parts, required assecories, remote montoring equipment. And Customs & Duties cost.) and DNV Analysis (estimate cost forecast and assumed OPEX cost at similar price as large-scale system) (2021)

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	620	96,8%	93,1%	89,9%	86,8%	84,5%	82,9%	81,4%	80,6%	79,3%	79,0%	78,8%	78,0%	77,9%	77,9%
CAPEX: PCS (Inverters)	USD/kW															
CAPEX: EMS (control system)	USD/kW															
CAPEX: Balance of System	USD/kW															
CAPEX: Civil works	USD/kWh															
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW															
CAPEX: Transport and Insurance	USD/kWh	305	96,7%	90,6%	86,6%	84,7%	81,4%	77,7%	75,3%	72,5%	70,7%	69,1%	67,9%	67,9%	64,0%	64,0%
CAPEX: Taxes & Fees	USD/kWh															
OPEX: O&M	USD/kW/a	20	96,9%	91,3%	86,9%	83,1%	80,0%	75,6%	74,4%	68,8%	68,8%	67,0%	64,6%	64,6%	60,3%	60,3%
OPEX: Capacity Maintenance	USD/kWh/a															
OPEX: Other (royalties, fees, land lease)	USD/kWh/a															

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	620,5	600,6	577,5	557,6	538,7	524,4	514,3	505,2	500,3	492,2	490,2	489,2	484,0	483,1	483,1
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh	305,4	295,2	276,7	264,5	258,8	248,6	237,4	230,0	221,4	216,0	211,0	207,4	207,4	195,5	195,5
USD/kWh	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kW/a	20,0	19,4	18,3	17,4	16,6	16,0	15,1	14,9	13,8	13,8	13,4	12,9	12,9	12,1	12,1
USD/kWh/a	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
USD/kWh/a	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Custom 1 — Year

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: PCS (Inverters)	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: EMS (control system)	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Balance of System	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Civil works	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Transport and Insurance	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Taxes & Fees	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
OPEX: O&M	USD/kW/a	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
OPEX: Capacity Maintenance	USD/kWh/a	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW/a	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh/a	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh/a	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0

Custom 2 — Year

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CAPEX: Battery System	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: PCS (Inverters)	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: EMS (control system)	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Balance of System	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Civil works	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Transport and Insurance	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
CAPEX: Taxes & Fees	USD/kWh	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
OPEX: O&M	USD/kW/a	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
OPEX: Capacity Maintenance	USD/kWh/a	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	100	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kW/a	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh/a	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0
USD/kWh/a	100,0	100,0	95,0	90,0	85,0	80,0	75,0	70,0	65,0	60,0	55,0	50,0	45,0	40,0	35,0

A.2. CAPEX and OPEX Projections – PV

CAPEX and OPEX Projections

PV Plant

Rooftop

Year — Source: | >1MW systems: WoodMac Sub Saharan Africa 2020-2025 PV CAPEX, long term forecast by DNV ETO 2020 | <1MW systems: based on Lazard LCOE v14, with long term forecast assumed to be same as for larger systems.

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	2825	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
<50 kW OPEX	USD/kWp/a	0	50	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	1500	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	813	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	15	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	813	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	12	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	813	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	10	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	2825,0	2726,3	2640,0	2567,8	2503,5	2442,3	2387,4	2336,0	2289,6	2248,1	2211,0	2179,1	2150,9	2126,0	2103,9
USD/kWp/a	18,0	17,9	17,8	17,7	17,6	17,6	17,5	17,4	17,3	17,2	17,1	17,0	16,9	16,8	16,7
USD/kWp	1500,0	1447,6	1401,8	1363,4	1329,3	1296,8	1267,7	1240,4	1215,7	1193,7	1174,0	1157,0	1142,1	1128,9	1117,1
USD/kWp/a	18,0	17,9	17,8	17,7	17,6	17,6	17,5	17,4	17,3	17,2	17,1	17,0	16,9	16,8	16,7
USD/kWp	813,5	785,0	760,2	739,4	720,9	703,3	687,5	672,7	659,3	647,3	636,7	627,5	619,4	612,2	605,8
USD/kWp/a	15,0	14,9	14,9	14,8	14,7	14,6	14,6	14,5	14,4	14,3	14,3	14,2	14,1	14,0	14,0
USD/kWp	813,5	785,0	760,2	739,4	720,9	703,3	687,5	672,7	659,3	647,3	636,7	627,5	619,4	612,2	605,8
USD/kWp/a	12,0	11,9	11,9	11,8	11,8	11,7	11,6	11,6	11,5	11,5	11,4	11,3	11,3	11,2	11,2
USD/kWp	813,5	785,0	760,2	739,4	720,9	703,3	687,5	672,7	659,3	647,3	636,7	627,5	619,4	612,2	605,8
USD/kWp/a	10,0	10,0	9,9	9,9	9,8	9,8	9,7	9,7	9,6	9,6	9,5	9,5	9,4	9,4	9,3

Fixed Tilt MonoPerc

Year — Source: | >1MW systems: WoodMac Sub Saharan Africa 2020-2025 PV CAPEX, long term forecast by DNV ETO 2020 | <1MW systems: based on Lazard LCOE v14, with long term forecast assumed to be same as for larger systems.

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	2825	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
<50 kW OPEX	USD/kWp/a	0	50	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	1500	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	991	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	15	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	991	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	12	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	991	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	10	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	2825,0	2726,3	2640,0	2567,8	2503,5	2442,3	2387,4	2336,0	2289,6	2248,1	2211,0	2179,1	2150,9	2126,0	2103,9
USD/kWp/a	18,0	17,9	17,8	17,7	17,6	17,6	17,5	17,4	17,3	17,2	17,1	17,0	16,9	16,8	16,7
USD/kWp	1500,0	1447,6	1401,8	1363,4	1329,3	1296,8	1267,7	1240,4	1215,7	1193,7	1174,0	1157,0	1142,1	1128,9	1117,1
USD/kWp/a	18,0	17,9	17,8	17,7	17,6	17,6	17,5	17,4	17,3	17,2	17,1	17,0	16,9	16,8	16,7
USD/kWp	990,5	948,3	921,2	891,6	869,6	856,3	837,1	819,1	802,8	788,2	775,2	764,0	754,2	745,4	737,7
USD/kWp/a	15,0	14,9	14,9	14,8	14,7	14,6	14,6	14,5	14,4	14,3	14,3	14,2	14,1	14,0	14,0
USD/kWp	990,5	948,3	921,2	891,6	869,6	856,3	837,1	819,1	802,8	788,2	775,2	764,0	754,2	745,4	737,7
USD/kWp/a	12,0	11,9	11,9	11,8	11,8	11,7	11,6	11,6	11,5	11,5	11,4	11,3	11,3	11,2	11,2
USD/kWp	990,5	948,3	921,2	891,6	869,6	856,3	837,1	819,1	802,8	788,2	775,2	764,0	754,2	745,4	737,7
USD/kWp/a	10,0	10,0	9,9	9,9	9,8	9,8	9,7	9,7	9,6	9,6	9,5	9,5	9,4	9,4	9,3

Fixed Tilt Bifacial

Year — Source: Assumption cost of bifacial solar systems are 1% higher than monoperc systems.

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	2853	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
<50 kW OPEX	USD/kWp/a	0	50	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	1515	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	1000	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	15	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	1000	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	12	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	1000	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	10	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	2853,3	2753,6	2666,4	2593,4	2528,6	2466,7	2411,3	2359,4	2312,5	2270,6	2233,1	2200,9	2172,5	2147,3	2125,0
USD/kWp/a	18,2	18,1	18,0	17,9	17,8	17,7	17,6	17,5	17,5	17,4	17,3	17,2	17,1	17,0	16,9
USD/kWp	1515,0	1462,1	1415,8	1377,0	1342,6	1309,7	1280,3	1252,8	1227,9	1205,6	1185,7	1168,6	1153,5	1140,1	1128,3
USD/kWp/a	18,2	18,1	18,0	17,9	17,8	17,7	17,6	17,5	17,5	17,4	17,3	17,2	17,1	17,0	16,9
USD/kWp	1000,4	957,8	930,4	900,5	878,3	864,9	845,5	827,3	810,8	796,1	783,0	771,7	761,7	752,9	745,1
USD/kWp/a	15,2	15,1	15,0	14,9	14,8	14,8	14,7	14,6	14,5	14,5	14,4	14,3	14,2	14,2	14,1
USD/kWp	1000,4	957,8	930,4	900,5	878,3	864,9	845,5	827,3	810,8	796,1	783,0	771,7	761,7	752,9	745,1
USD/kWp/a	12,1	12,1	12,0	11,9	11,9	11,8	11,8	11,7	11,6	11,6	11,5	11,5	11,4	11,3	11,3
USD/kWp	1000,4	957,8	930,4	900,5	878,3	864,9	845,5	827,3	810,8	796,1	783,0	771,7	761,7	752,9	745,1
USD/kWp/a	10,1	10,0	10,0	9,9	9,9	9,8	9,8	9,7	9,7	9,6	9,6	9,5	9,5	9,4	9,4

1-axis Tracking MonoPerc

Year — Source: | >1MW systems: WoodMac Sub Saharan Africa 2020-2025 PV CAPEX, long term forecast by DNV ETO 2020 | <1MW systems: based on Lazard LCOE v14, with long term forecast assumed to be same as for larger systems.

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	2825	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
<50 kW OPEX	USD/kWp/a	0	50	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	1500	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	1102	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	15	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	1102	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	12	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	1102	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	10	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	2825,0	2726,3	2640,0	2567,8	2503,5	2442,3	2387,4	2336,0	2289,6	2248,1	2211,0	2179,1	2150,9	2126,0	2103,9
USD/kWp/a	18,0	17,9	17,8	17,7	17,6	17,6	17,5	17,4	17,3	17,2	17,1	17,0	16,9	16,8	16,7
USD/kWp	1500,0	1447,6	1401,8	1363,4	1329,3	1296,8	1267,7	1240,4	1215,7	1193,7	1174,0	1157,0	1142,1	1128,9	1117,1
USD/kWp/a	18,0	17,9	17,8	17,7	17,6	17,6	17,5	17,4	17,3	17,2	17,1	17,0	16,9	16,8	16,7
USD/kWp	1101,8	1054,9	1024,7	991,7	967,3	952,5	931,2	911,1	893,0	876,8	862,3	849,9	838,9	829,2	820,6
USD/kWp/a	15,0	14,9	14,9	14,8	14,7	14,6	14,6	14,5	14,4	14,3	14,3	14,2	14,1	14,0	14,0
USD/kWp	1101,8	1054,9	1024,7	991,7	967,3	952,5	931,2	911,1	893,0	876,8	862,3	849,9	838,9	829,2	820,6
USD/kWp/a	12,0	11,9	11,9	11,8	11,8	11,7	11,6	11,6	11,5	11,5	11,4	11,3	11,3	11,2	11,2
USD/kWp	1101,8	1054,9	1024,7	991,7	967,3	952,5	931,2	911,1	893,0	876,8	862,3	849,9	838,9	829,2	820,6
USD/kWp/a	10,0	10,0	9,9	9,9	9,8	9,8	9,7	9,7	9,6	9,6	9,5	9,5	9,4	9,4	9,3

1-axis Tracking Bifacial

Year — Source: Assumption cost of bifacial solar systems are 1% higher than monoperc systems.

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	2853	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
<50 kW OPEX	USD/kWp/a	0	50	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	1515	96,5%	93,5%	90,9%	88,6%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	18	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	1113	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	15	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	1113	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	12	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	1113	95,7%	93,0%	90,0%	87,8%	86,5%	84,5%	82,7%	81,0%	79,6%	78,3%	77,1%	76,1%	75,3%	74,5%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	10	99,5%	99,0%	98,5%	98,0%	97,5%	97,0%	96,5%	96,0%	95,5%	95,0%	94,5%	94,0%	93,5%	93,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	2853,3	2753,6	2666,4	2593,4	2528,6	2466,7	2411,3	2359,4	2312,5	2270,6	2233,1	2200,9	2172,5	2147,3	2125,0
USD/kWp/a	18,2	18,1	18,0	17,9	17,8	17,7	17,6	17,5	17,5	17,4	17,3	17,2	17,1	17,0	16,9
USD/kWp	1515,0	1462,1	1415,8	1377,0	1342,6	1309,7	1280,3	1252,8	1227,9	1205,6	1185,7	1168,6	1153,5	1140,1	1128,3
USD/kWp/a	18,2	18,1	18,0	17,9	17,8	17,7	17,6	17,5	17,5	17,4	17,3	17,2	17,1	17,0	16,9
USD/kWp	1112,8	1065,4	1035,0	1001,7	977,0	962,1	940,5	920,2	901,9	885,6	871,0	858,4	847,3	837,5	828,8
USD/kWp/a	15,2	15,1	15,0	14,9	14,8	14,8	14,7	14,6	14,5	14,5	14,4	14,3	14,2	14,2	14,1
USD/kWp	1112,8	1065,4	1035,0	1001,7	977,0	962,1	940,5	920,2	901,9	885,6	871,0	858,4	847,3	837,5	828,8
USD/kWp/a	12,1	12,1	12,0	11,9	11,9	11,8	11,8	11,7	11,6	11,6	11,5	11,5	11,4	11,3	11,3
USD/kWp	1112,8	1065,4	1035,0	1001,7	977,0	962,1	940,5	920,2	901,9	885,6	871,0	858,4	847,3	837,5	828,8
USD/kWp/a	10,1	10,0	10,0	9,9	9,9	9,8	9,8	9,7	9,7	9,6	9,6	9,5	9,5	9,4	9,4

Custom 1

Year

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	600	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
<50 kW OPEX	USD/kWp/a	0	50	15	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	600	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	15	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	600	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	15	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	600	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	15	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	480	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	15	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	600,0	600,0	570,0	540,0	510,0	480,0	450,0	420,0	390,0	360,0	330,0	300,0	270,0	240,0	210,0
USD/kWp/a	15,0	15,0	14,3	13,5	12,8	12,0	11,3	10,5	9,8	9,0	8,3	7,5	6,8	6,0	5,3
USD/kWp	600,0	600,0	570,0	540,0	510,0	480,0	450,0	420,0	390,0	360,0	330,0	300,0	270,0	240,0	210,0
USD/kWp/a	15,0	15,0	14,3	13,5	12,8	12,0	11,3	10,5	9,8	9,0	8,3	7,5	6,8	6,0	5,3
USD/kWp	600,0	600,0	570,0	540,0	510,0	480,0	450,0	420,0	390,0	360,0	330,0	300,0	270,0	240,0	210,0
USD/kWp/a	15,0	15,0	14,3	13,5	12,8	12,0	11,3	10,5	9,8	9,0	8,3	7,5	6,8	6,0	5,3
USD/kWp	600,0	600,0	570,0	540,0	510,0	480,0	450,0	420,0	390,0	360,0	330,0	300,0	270,0	240,0	210,0
USD/kWp/a	15,0	15,0	14,3	13,5	12,8	12,0	11,3	10,5	9,8	9,0	8,3	7,5	6,8	6,0	5,3
USD/kWp	480,0	480,0	456,0	432,0	408,0	384,0	360,0	336,0	312,0	288,0	264,0	240,0	216,0	192,0	168,0
USD/kWp/a	15,0	15,0	14,3	13,5	12,8	12,0	11,3	10,5	9,8	9,0	8,3	7,5	6,8	6,0	5,3

Custom 2

Year

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kWp	0	50	125	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
<50 kW OPEX	USD/kWp/a	0	50	5	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
50kW <> 1 MW CAPEX	USD/kWp	50	1.000	124	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
50kW <> 1 MW OPEX	USD/kWp/a	50	1.000	4	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
1 MW <> 20 MW CAPEX	USD/kWp	1.000	20.000	123	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
1 MW <> 20 MW OPEX	USD/kWp/a	1.000	20.000	3	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
20 MW <> 100 MW CAPEX	USD/kWp	20.000	100.000	122	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
20 MW <> 100 MW OPEX	USD/kWp/a	20.000	100.000	2	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
> 100 MW CAPEX	USD/kWp	100.000	999.999	121	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
> 100 MW CAPEX	USD/kWp/a	100.000	999.999	1	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kWp	125,0	125,0	118,8	112,5	106,3	100,0	93,8	87,5	81,3	75,0	68,8	62,5	56,3	50,0	43,8
USD/kWp/a	5,0	5,0	4,8	4,5	4,3	4,0	3,8	3,5	3,3	3,0	2,8	2,5	2,3	2,0	1,8
USD/kWp	124,0	124,0	117,8	111,6	105,4	99,2	93,0	86,8	80,6	74,4	68,2	62,0	55,8	49,6	43,4
USD/kWp/a	4,0	4,0	3,8	3,6	3,4	3,2	3,0	2,8	2,6	2,4	2,2	2,0	1,8	1,6	1,4
USD/kWp	123,0	123,0	116,9	110,7	104,6	98,4	92,3	86,1	80,0	73,8	67,7	61,5	55,4	49,2	43,1
USD/kWp/a	3,0	3,0	2,9	2,7	2,6	2,4	2,3	2,1	2,0	1,8	1,7	1,5	1,4	1,2	1,1
USD/kWp	122,0	122,0	115,9	109,8	103,7	97,6	91,5	85,4	79,3	73,2	67,1	61,0	54,9	48,8	42,7
USD/kWp/a	2,0	2,0	1,9	1,8	1,7	1,6	1,5	1,4	1,3	1,2	1,1	1,0	0,9	0,8	0,7
USD/kWp	121,0	121,0	115,0	108,9	102,9	96,8	90,8	84,7	78,7	72,6	66,6	60,5	54,5	48,4	42,4
USD/kWp/a	1,0	1,0	1,0	0,9	0,9	0,8	0,8	0,7	0,7	0,6	0,6	0,5	0,5	0,4	0,4

A.3. CAPEX and OPEX Projections - Wind and Thermal

CAPEX and OPEX Projections

Wind Farm

Year

NOTE: CAPEX and OPEX of wind farms <20MW are very rough assumptions and should be validated before use. Source: | Utility scale wind: DNV ETO 2020 (Sub Saharan Africa forecast), O&M cost sources from IRENA 2019 Power Generation Cost report |

Description	Unit	Size Min	Size Max	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<50 kW CAPEX	USD/kW	0	50	7500	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
<50 kW OPEX	USD/kW/a	0	50	180	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
50kW <> 1 MW CAPEX	USD/kW	50	1.000	5000	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
50kW <> 1 MW OPEX	USD/kW/a	50	1.000	120	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
1 MW <> 20 MW CAPEX	USD/kW	1.000	20.000	3400	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
1 MW <> 20 MW OPEX	USD/kW/a	1.000	20.000	80	100,0%	95,0%	90,0%	85,0%	80,0%	75,0%	70,0%	65,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%
20 MW <> 100 MW CAPEX	USD/kW	20.000	100.000	1708	98,6%	97,3%	96,1%	94,9%	93,7%	92,5%	91,2%	89,9%	88,6%	87,4%	86,2%	85,2%	84,2%	83,2%
20 MW <> 100 MW OPEX	USD/kW/a	20.000	100.000	40	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
> 100 MW CAPEX	USD/kW	100.000	999.999	1708	98,6%	97,3%	96,1%	94,9%	93,7%	92,5%	91,2%	89,9%	88,6%	87,4%	86,2%	85,2%	84,2%	83,2%
> 100 MW CAPEX	USD/kW/a	100.000	999.999	40	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%

Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
USD/kW	7500,0	7500,0	7125,0	6750,0	6375,0	6000,0	5625,0	5250,0	4875,0	4500,0	4125,0	3750,0	3375,0	3000,0	2625,0
USD/kW/a	180,0	180,0	171,0	162,0	153,0	144,0	135,0	126,0	117,0	108,0	99,0	90,0	81,0	72,0	63,0
USD/kW	5000,0	5000,0	4750,0	4500,0	4250,0	4000,0	3750,0	3500,0	3250,0	3000,0	2750,0	2500,0	2250,0	2000,0	1750,0
USD/kW/a	120,0	120,0	114,0	108,0	102,0	96,0	90,0	84,0	78,0	72,0	66,0	60,0	54,0	48,0	42,0
USD/kW	3400,0	3400,0	3230,0	3060,0	2890,0	2720,0	2550,0	2380,0	2210,0	2040,0	1870,0	1700,0	1530,0	1360,0	1190,0
USD/kW/a	80,0	80,0	76,0	72,0	68,0	64,0	60,0	56,0	52,0	48,0	44,0	40,0	36,0	32,0	28,0
USD/kW	1707,8	1684,3	1661,6	1641,4	1621,5	1599,8	1579,2	1558,2	1535,8	1513,5	1491,9	1472,3	1454,2	1437,3	1421,5
USD/kW/a	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0
USD/kW	1707,8	1684,3	1661,6	1641,4	1621,5	1599,8	1579,2	1558,2	1535,8	1513,5	1491,9	1472,3	1454,2	1437,3	1421,5
USD/kW/a	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0

Thermal Plant (by generator unit type)

Description	Unit	Unit Size Min (kW)	Unit Size Max (kW)	Diesel fuel	Natural gas	
Small Petrol Engine CAPEX	USD/kW	1	50	1.170	-	Source: | Diesel: PowerGen, TFE. Average over Nigeria, Tanzania and Kenya cost
Small Petrol Engine OPEX Fixed	USD/kW/a	1	50	25	-	Source: | Diesel: DNV data
Small Petrol Engine OPEX Variable	USD/kWh	1	50	0,005	-	Source: | Diesel: DNV data
Small Diesel Generator CAPEX	USD/kW	50	500	183	-	Source: | Diesel: PowerGen, TFE. Average over Nigeria, Tanzania and Kenya cost
Small Diesel Generator OPEX Fixed	USD/kW/a	50	500	25	-	Source: | Diesel: DNV data
Small Diesel Generator OPEX Variable	USD/kWh	50	500	0,005	-	Source: | Diesel: DNV data
High Speed Diesel Generator CAPEX	USD/kW	500	4.000	650	-	Source: | DNV data, imported equipment
High Speed Diesel Generator OPEX Fixed	USD/kW/a	500	4.000	25	-	Source: | Diesel: DNV data
High Speed Diesel Generator OPEX Variable	USD/kWh	500	4.000	0,005	-	Source: | Diesel: DNV data
Medium Speed Diesel Generator CAPEX	USD/kW	3.000	20.000	900	-	Source: | DNV data, imported equipment
Medium Speed Diesel Generator OPEX Fixed	USD/kW/a	3.000	20.000	20	-	Source: | Diesel: DNV data
Medium Speed Diesel Generator OPEX Variable	USD/kWh	3.000	20.000	0,005	-	Source: | Diesel: DNV data
Aeroderivative Gas Turbine CAPEX	USD/kW	10.000	30.000	1.100	1.100	Source: | DNV data, imported equipment
Aeroderivative Gas Turbine OPEX Fixed	USD/kW/a	10.000	30.000	15	15	Source: | DNV data, international costs
Aeroderivative Gas Turbine OPEX Variable	USD/kWh	10.000	30.000	0,010	0,005	Source: | DNV data, international costs
Heavy-duty Gas Turbine CAPEX	USD/kW	30.000	100.000	800	800	Source: | DNV data, imported equipment
Heavy-duty Gas Turbine OPEX Fixed	USD/kW/a	30.000	100.000	12	12	Source: | DNV data, international costs
Heavy-duty Gas Turbine OPEX Variable	USD/kWh	30.000	100.000	0,008	0,004	Source: | DNV data, international costs

A.4. Adjustment Profiles – Technology

Adjustment Profiles - Technology

BESS Degradation Profiles

Note: the below reflects a generalized degradation profile per BESS technology or type. Degradation profiles are subject to BESS usage conditions, the below should therefore only be used for comparative purposes. For all degradation profiles applies that uncertainty increase significantly from roughly year 15, and that data >20 years is highly uncertair

Year:

Description	Unit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Linear Degradation	%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	
Li-ion Utility Scale	%	100,0%	96,2%	93,9%	91,9%	90,2%	88,7%	87,2%	85,8%	84,6%	83,4%	82,2%	81,1%	80,0%	79,0%	78,0%	77,0%	76,1%	75,2%	74,3%	73,5%	72,6%	70,2%	68,4%	66,7%	65,0%	63,4%	61,8%	60,3%	58,5%	56,8%	55,2%	Source: DNV (2021), in
NaS	%	100,0%	97,4%	94,9%	92,5%	90,1%	87,8%	85,5%	83,3%	81,2%	79,1%	77,0%	75,0%	73,1%	71,2%	69,4%	67,6%	65,9%	64,2%	62,5%	60,9%	59,3%	57,8%	56,3%	54,9%	53,4%	52,1%	50,7%	49,4%	48,1%	46,9%	45,7%	Source: TEPCO & NGK
Lead Acid Small Scale	%	100,0%	96,0%	92,0%	88,0%	84,0%	80,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	35,0%	Note: lead acid batterie
Flow Vanadium	%	100,0%	99,9%	99,8%	99,7%	99,6%	99,5%	99,4%	99,3%	99,2%	99,1%	99,0%	98,9%	98,8%	98,7%	98,6%	98,5%	98,4%	98,3%	98,2%	98,1%	98,0%	97,9%	97,8%	97,7%	97,6%	97,5%	97,4%	97,3%	97,2%	97,1%	97,0%	Source: DNV (2021), in
Li-ion Small Scale	%	100,0%	96,2%	93,9%	91,9%	90,2%	88,7%	87,2%	85,8%	84,6%	83,4%	82,2%	81,1%	80,0%	79,0%	78,0%	77,0%	76,1%	75,2%	74,3%	73,5%	72,6%	70,2%	68,4%	66,7%	65,0%	63,4%	61,8%	60,3%	58,5%	56,8%	55,2%	Source: DNV (2021), in
Custom 1	%	100,0%	94,4%	91,8%	89,8%	88,0%	86,5%	85,1%	83,9%	82,7%	81,6%	80,5%	79,5%	78,5%	77,6%	76,7%	75,9%	75,0%	73,0%	69,0%	66,0%	63,0%	60,0%	57,0%	54,0%	51,0%	48,0%	45,0%	42,0%	39,0%	36,0%	33,0%	
Custom 2	%	100,0%	96,0%	93,6%	91,3%	89,0%	86,8%	84,6%	82,5%	80,4%	78,4%	76,4%	73,8%	71,2%	68,7%	66,3%	64,0%	60,0%	55,0%	50,0%	45,0%	40,0%	35,0%	30,0%	25,0%	25,0%	25,0%	25,0%	25,0%	25,0%	25,0%	25,0%	

BESS Capacity Augmentation Schemes

Percentage of original capacity to be added

Year: Note: the below refers to replacement of batteries (or electrolyte for flow). Repairs and replacement of PCS, pumps, HVAC, etc. are part of OPEX.

Description	Unit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Manual	%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Li-ion Utility Scale Scheme A	%	-	-	-	-	-	+8,2%	-	-	-	-	+11,0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Source: DNV. Based o
Li-ion Utility Scale Scheme B	%	-	-	-	-	+9,0%	-	-	-	-	-	+7,0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Source: DNV. Based o
Li-ion Utility Scale - MiniGrid Replacement at 10yrs	%	-	-	-	-	-	-	-	-	-	-	+100,0%	-	-	-	-	-	-	-	-	-	-	+100,0%	-	-	-	-	-	-	-	-	-	Source: hypothetical sc
NaS	%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+100,0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Source: DNV. Based o
Lead Acid Small Scale - MiniGrid Replacement at 5	%	-	-	-	-	-	+100,0%	-	-	-	-	+100,0%	-	-	-	-	+100,0%	-	-	-	-	+100,0%	-	-	-	-	+100,0%	-	-	-	-	-	Source: Powergen, TFI
Flow Vanadium	%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+20,0%	-	-	-	-	-	-	-	-	-	-	Source: DNV. Assumpt
Li-ion Small Scale - MiniGrid Replacement at 10yrs	%	-	-	-	-	-	-	-	-	-	-	+100,0%	-	-	-	-	-	-	-	-	-	-	+100,0%	-	-	-	-	-	-	-	-	-	Source: Powergen, TFI
Custom 1	%	-	-	-	-	-	+50,0%	-	-	-	-	+50,0%	-	-	-	-	+50,0%	-	-	-	-	+50,0%	-	-	-	-	+50,0%	-	-	-	-	-	
Custom 2	%	-	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	+2,0%	-	-	
Active Augmentation Scheme	%	-	-	-	-	-	+8,2%	-	-	-	-	+11,0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

Cost of the capacity to be added

Year:

Description	Unit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Markup	
Manual	kUSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	N/A	Calculation
Li-ion Utility Scale Scheme A	USD/kWh	258	242	227	211	196	190	184	179	174	170	168	167	166	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	100	Cost of the
Li-ion Utility Scale Scheme B	USD/kWh	258	242	227	211	196	190	184	179	174	170	168	167	166	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	100	Cost of the
Li-ion Utility Scale - MiniGrid Replacement at 10yrs	USD/kWh	258	242	227	211	196	190	184	179	174	170	168	167	166	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	165	100	Cost of the
NaS	USD/kWh	669	641	614	589	565	542	521	500	480	462	444	427	411	396	381	381	381	381	381	381	381	381	381	381	381	381	381	381	381	381	381	100	Cost of the
Lead Acid Small Scale - MiniGrid Replacement at 5	USD/kWh	467	457	448	440	431	423	416	408	401	394	388	381	375	369	363	363	363	363	363	363	363	363	363	363	363	363	363	363	363	363	363	100	Cost of the
Flow Vanadium	USD/kWh	507	487	469	451	434	418	403	388	374	361	348	337	325	314	304	304	304	304	304	304	304	304	304	304	304	304	304	304	304	304	304	100	Cost of the
Li-ion Small Scale - MiniGrid Replacement at 10yrs	USD/kWh	720	701	677	658	639	624	614	605	600	592	590	589	584	583	583	583	583	583	583	583	583	583	583	583	583	583	583	583	583	583	583	100	Cost of the
Custom 1	USD/kWh	200	200	195	190	185	180	175	170	165	160	155	150	145	140	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	100	Cost of the
Custom 2	USD/kWh	200	200	195	190	185	180	175	170	165	160	155	150	145	140	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	100	Cost of the
Active Augmentation Cost	kUSD	-	-	-	-	-	620	-	-	-	-	741	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		

Thermal Plant Fuel Consumption Profile

User can enter relative specific fuel consumption data (or Heat Rate Correction Factor) for 4 standard load points. This will update the graph on the right. The (updated) polynomial constants from the fit then have to be entered in the next table

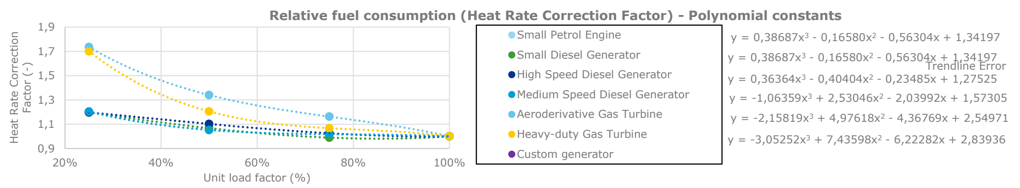
Description	Unit	Baseload HR	Ideal Load Factor (%)	Minimum load (%)
Small Petrol Engine	kJ/kWh	11.000	80%	30%
Small Diesel Generator	kJ/kWh	10.000	80%	40%
High Speed Diesel Generator	kJ/kWh	8.900	100%	40%
Medium Speed Diesel Generator	kJ/kWh	8.000	100%	40%
Aeroderivative Gas Turbine	kJ/kWh	10.700	100%	40%
Heavy-duty Gas Turbine	kJ/kWh	9.900	100%	40%
Custom generator	kJ/kWh			

Relative fuel consumption (Heat Rate Correction Factor)

25%	50%	75%	100%
1,1969	1,0674	0,9896	1,0000
1,1969	1,0674	0,9896	1,0000
1,1970	1,1023	1,0253	1,0000
1,2046	1,0528	1,0178	1,0000
1,7351	1,3401	1,1626	1,0000
1,7007	1,2054	1,0672	1,0000

HRCF Polynomial Constants: y = a*x^3 + b*x^2 + c*x + d

a	b	c	d
0,38687	-0,16580	-0,56304	1,34197
0,38687	-0,16580	-0,56304	1,34197
0,36364	-0,40404	-0,23485	1,27525
-1,06359	2,53046	-2,03992	1,57305
-2,15819	4,97618	-4,36769	2,54971
-3,05252	7,43598	-6,22282	2,83936



A.5. Fuel Cost Scenarios

Fuel Cost Scenarios

Fuel Price

Base fuel price only. Any markups (taxes, subsidies, transport cost, etc.) are added in Dashboard sheet

Year

Description	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Diesel Fuel Price Scenario High	USD/GJ	25,15	26,71	28,80	29,82	30,52	31,12	31,12	31,55	32,96	33,18	33,77	34,92	35,07	35,12	35,46
Diesel Fuel Price Scenario Med	USD/GJ	20,18	20,50	20,61	20,99	21,11	21,50	21,55	21,88	22,08	22,54	22,80	22,96	23,33	23,52	23,73
Diesel Fuel Price Scenario Low	USD/GJ	15,59	15,90	15,93	16,09	16,24	16,38	16,46	16,45	16,49	16,95	16,97	17,06	17,14	17,07	17,12
Gas Price Scenario High	USD/GJ	6,68	6,80	6,94	7,13	7,48	7,76	7,94	8,12	8,28	8,39	8,47	8,58	8,71	8,82	8,88
Gas Price Scenario Med	USD/GJ	6,36	6,36	6,39	6,48	6,69	6,92	7,06	7,14	7,16	7,11	7,07	7,09	7,14	7,19	7,18
Gas Price Scenario Low	USD/GJ	6,25	6,15	6,10	6,11	6,26	6,46	6,54	6,54	6,50	6,45	6,44	6,46	6,47	6,48	6,47

Description	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	
Diesel Fuel Price Scenario High	35,86	36,18	36,54	36,93	37,27	37,62	37,72	38,18	38,40	38,87	38,83	39,08	39,32	39,57	39,56	Source: US E
Diesel Fuel Price Scenario Med	23,97	24,14	24,34	24,55	24,55	24,70	25,07	25,23	25,42	25,76	25,78	26,03	26,25	26,41	26,56	Source: US E
Diesel Fuel Price Scenario Low	17,13	17,24	17,22	17,30	17,36	17,37	17,37	17,36	17,40	17,45	17,46	17,44	17,45	17,47	17,56	Source: US E
Gas Price Scenario High	8,94	9,03	9,10	9,18	9,24	9,28	9,34	9,37	9,55	9,62	9,74	9,87	9,92	10,05	10,21	Source: US E
Gas Price Scenario Med	7,18	7,22	7,25	7,26	7,26	7,26	7,28	7,30	7,31	7,33	7,36	7,41	7,44	7,45	7,50	Source: US E
Gas Price Scenario Low	6,48	6,50	6,51	6,51	6,51	6,50	6,50	6,47	6,45	6,44	6,43	6,43	6,42	6,41	6,40	Source: US E

Quick Calculator Diesel	Unit	Value
Fuel Energy Content	MJ/L	38,6
Fuel Price	USD/L	1,00
Fuel Price	USD/GJ	25,91

Quick Calculator Gas	Unit	Value
Fuel Price	USD/MMBtu	6,00
Fuel Price	USD/GJ	5,68

A.6. BESS Operational Technology Parameters

BESS Operational Technology Parameters

Assumptions by DNV (2021). Note: to be observed in relation to system boundaries and cost assumptions (e.g. Li-ion concerns full BESS, not only the battery cells or batter packs).

Description	Unit	Li-ion Utility Scale	NaS	Lead Acid Small Scale	Flow Vanadium	Li-ion Small Scale	Custom 1	Custom 2
Roundtrip Efficiency (AC)	%	89,0%	78,0%	70,0%	65,0%	88,0%		
Maximum SoC	% SoC	100,0%	100,0%	100,0%	100,0%	100,0%		
Minimum SoC	% SoC	0,0%	0,0%	40,0%	0,0%	0,0%		
Auxiliary load	kW/kWh	0,0	0,0	0,0	0,0	0,0		
Self Discharge	%/day	0,05%	0,00%	0,20%	0,02%	0,05%		
ESS spatial requirements	m2/MWh							

Note: auxiliary loads of the BESS are reflected in the round trip efficiency and/or self discharge. Project specifics may be cause to add auxiliary loads (e.g. long periods of stand-by).

A.7. Load Profiles

Load and Generation Profiles

Timestamp

Load Profile

	Kenya - Mini Grid 1	Kenya - Mini Grid 2	Sierra Leone - Mini Grid 1	Tanzania - Mini Grid 1	Tanzania - Mini Grid 2	Nigeria - Mini Grid 1	Sierra Leone - Telco Tower	Sierra Leone - C&I - Processing Factory	Tanzania - C&I - Safari Lodge	Kenya - C&I - Manufacturing Company
Check, No of entries:	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760
Check, Max Load	0,4	1,1	30,7	14,4	7,2	11,5	2,5	66	10	272
Check, Min Load	-	-	-	-	-	2,2	2,5	25	3	127
Check, Average Load	0,1	0,2	2,4	3,7	1,4	5,2	2,5	39	6	198
Annual energy demand	1	2	21	32	12	45	22	342	51	1.730

Timestamp dd mmm hh:mm	Month	Day	Hour	Kenya - Mini Grid 1 Load kW	Kenya - Mini Grid 2 Load kW	Sierra Leone - Mini Grid 1 Load kW	Tanzania - Mini Grid 1 Load kW	Tanzania - Mini Grid 2 Load kW	Nigeria - Mini Grid 1 Load kW	Sierra Leone - Telco Tower Load kW	Sierra Leone - C&I - Processing Factory Load kW	Tanzania - C&I - Safari Lodge Load kW	Kenya - C&I - Manufacturing Company Load kW
01 jan 00:00	1	1	0	0,1	-	3,2	8,1	1,7	5,3	2,5	25,6	3,0	224,1
01 jan 01:00	1	1	1	0,1	-	1,5	6,7	0,8	4,7	2,5	25,5	3,0	199,4
01 jan 02:00	1	1	2	0,1	-	0,1	6,9	0,6	4,3	2,5	25,8	3,0	155,3
01 jan 03:00	1	1	3	0,1	-	0,1	4,9	0,4	4,6	2,5	25,1	3,0	127,5
01 jan 04:00	1	1	4	0,1	-	0,1	3,9	0,2	4,8	2,5	25,5	9,8	127,0
01 jan 05:00	1	1	5	0,1	-	0,1	3,1	0,2	5,3	2,5	27,0	8,3	178,2
01 jan 06:00	1	1	6	0,1	-	0,1	3,9	0,4	5,0	2,5	30,1	6,8	212,4
01 jan 07:00	1	1	7	0,1	0,0	0,1	4,4	0,2	5,6	2,5	35,5	7,0	179,3
01 jan 08:00	1	1	8	0,1	0,3	0,1	4,9	0,1	3,9	2,5	54,2	7,0	127,5
01 jan 09:00	1	1	9	0,1	0,3	0,1	7,2	0,3	3,5	2,5	55,3	6,3	196,0
01 jan 10:00	1	1	10	0,1	0,2	0,1	6,1	1,1	3,1	2,5	57,9	6,2	211,5
01 jan 11:00	1	1	11	0,1	0,2	0,9	7,1	0,9	3,3	2,5	65,2	5,8	221,1
01 jan 12:00	1	1	12	0,0	0,2	2,7	6,4	0,9	3,1	2,5	56,8	5,6	207,7
01 jan 13:00	1	1	13	0,1	0,2	3,5	7,6	1,0	4,2	2,5	50,3	4,8	185,3
01 jan 14:00	1	1	14	0,1	0,2	3,4	9,2	0,9	4,4	2,5	57,3	4,8	200,6
01 jan 15:00	1	1	15	0,1	0,2	3,2	8,2	1,4	3,6	2,5	66,0	5,0	193,0
01 jan 16:00	1	1	16	0,0	0,2	2,9	6,9	1,2	6,5	2,5	42,1	5,0	181,0
01 jan 17:00	1	1	17	0,0	0,2	3,1	6,9	1,2	10,7	2,5	36,8	9,7	205,2
01 jan 18:00	1	1	18	0,1	0,4	4,7	6,1	1,4	6,3	2,5	34,0	9,1	177,6
01 jan 19:00	1	1	19	0,2	0,8	6,1	7,8	2,3	6,4	2,5	30,7	6,7	196,3
01 jan 20:00	1	1	20	0,2	0,4	6,7	9,4	3,2	5,7	2,5	29,4	5,9	254,1
01 jan 21:00	1	1	21	0,2	0,0	6,1	8,9	3,1	5,8	2,5	27,7	5,1	250,9
01 jan 22:00	1	1	22	0,1	-	5,1	8,9	2,5	7,0	2,5	26,5	5,1	272,0
01 jan 23:00	1	1	23	0,1	-	-	6,6	1,3	5,6	2,5	25,4	4,6	257,2
02 jan 00:00	1	2	0	0,1	-	2,0	5,5	0,6	6,8	2,5	25,6	3,0	224,1
02 jan 01:00	1	2	1	0,1	-	0,2	5,3	0,1	4,9	2,5	25,5	3,0	199,4
02 jan 02:00	1	2	2	0,1	-	0,2	4,0	0,1	5,5	2,5	25,8	3,0	155,3
02 jan 03:00	1	2	3	0,1	-	0,2	2,7	0,1	4,4	2,5	25,1	3,0	127,5
02 jan 04:00	1	2	4	0,1	-	0,2	2,4	0,1	4,2	2,5	25,5	9,8	127,0
02 jan 05:00	1	2	5	0,2	-	0,2	2,3	0,1	5,3	2,5	27,0	8,3	178,2
02 jan 06:00	1	2	6	0,1	-	0,2	2,1	0,2	4,7	2,5	30,1	6,8	212,4
02 jan 07:00	1	2	7	0,1	0,0	0,2	1,9	0,2	4,7	2,5	35,5	7,0	179,3
02 jan 08:00	1	2	8	0,1	0,3	0,2	4,3	0,0	4,7	2,5	54,2	7,0	127,5
02 jan 09:00	1	2	9	0,1	0,3	0,2	5,7	0,1	2,4	2,5	55,3	6,3	196,0
02 jan 10:00	1	2	10	0,1	0,2	0,2	4,0	0,4	2,8	2,5	57,9	6,2	211,5
02 jan 11:00	1	2	11	0,1	0,2	0,2	5,5	1,1	3,8	2,5	65,2	5,8	221,1
02 jan 12:00	1	2	12	0,1	0,2	1,6	6,9	0,7	2,9	2,5	56,8	5,6	207,7
02 jan 13:00	1	2	13	0,0	0,2	3,4	6,4	1,2	4,0	2,5	50,3	4,8	185,3
02 jan 14:00	1	2	14	0,1	0,2	3,6	7,8	0,7	7,9	2,5	57,3	4,8	200,6
02 jan 15:00	1	2	15	0,1	0,2	3,9	6,0	0,7	5,7	2,5	66,0	5,0	193,0
02 jan 16:00	1	2	16	0,1	0,2	3,8	6,0	1,9	9,9	2,5	42,1	5,0	181,0
02 jan 17:00	1	2	17	0,1	0,2	4,1	5,7	1,4	10,7	2,5	36,8	9,7	205,2
02 jan 18:00	1	2	18	0,1	0,4	5,9	5,2	1,5	8,5	2,5	34,0	9,1	177,6
02 jan 19:00	1	2	19	0,2	0,8	7,4	5,8	2,3	6,4	2,5	30,7	6,7	196,3
02 jan 20:00	1	2	20	0,2	0,4	7,4	8,2	3,7	6,0	2,5	29,4	5,9	254,1
02 jan 21:00	1	2	21	0,2	0,0	6,6	9,2	3,8	5,8	2,5	27,7	5,1	250,9
02 jan 22:00	1	2	22	0,1	-	2,8	8,3	2,9	5,6	2,5	26,5	5,1	272,0
02 jan 23:00	1	2	23	0,1	-	-	7,9	1,5	5,0	2,5	25,4	4,6	257,2
03 jan 00:00	1	3	0	0,1	-	3,2	5,7	1,1	5,3	2,5	25,6	3,0	224,1
03 jan 01:00	1	3	1	0,1	-	1,5	4,2	0,9	4,9	2,5	25,5	3,0	199,4
03 jan 02:00	1	3	2	0,1	-	0,1	4,8	0,5	4,8	2,5	25,8	3,0	155,3
03 jan 03:00	1	3	3	0,1	-	0,1	3,1	0,0	5,6	2,5	25,1	3,0	127,5
03 jan 04:00	1	3	4	0,1	-	0,1	2,2	0,0	5,4	2,5	25,5	9,8	127,0
03 jan 05:00	1	3	5	0,1	-	0,1	2,1	0,1	4,1	2,5	27,0	8,3	178,2
03 jan 06:00	1	3	6	0,1	-	0,1	2,9	0,2	5,4	2,5	30,1	6,8	212,4
03 jan 07:00	1	3	7	0,1	0,0	0,1	4,8	0,2	5,3	2,5	35,5	7,0	179,3
03 jan 08:00	1	3	8	0,1	0,3	0,1	4,4	0,0	3,9	2,5	54,2	7,0	127,5
03 jan 09:00	1	3	9	0,0	0,3	0,1	6,3	0,1	3,0	2,5	55,3	6,3	196,0
03 jan 10:00	1	3	10	0,1	0,2	0,1	6,2	0,1	3,2	2,5	57,9	6,2	211,5
03 jan 11:00	1	3	11	0,0	0,2	0,9	10,0	0,3	3,4	2,5	65,2	5,8	221,1
03 jan 12:00	1	3	12	0,0	0,2	2,7	11,4	0,8	3,1	2,5	56,8	5,6	207,7
03 jan 13:00	1	3	13	0,0	0,2	3,5	9,3	0,7	4,8	2,5	50,3	4,8	185,3
03 jan 14:00	1	3	14	0,0	0,2	3,4	9,4	0,7	3,3	2,5	57,3	4,8	200,6
03 jan 15:00	1	3	15	0,1	0,2	3,2	6,7	0,5	2,9	2,5	66,0	5,0	193,0
03 jan 16:00	1	3	16	0,1	0,2	2,9	5,0	0,6	5,3	2,5	42,1	5,0	181,0
03 jan 17:00	1	3	17	0,0	0,2	3,1	4,9	0,7	8,8	2,5	36,8	9,7	205,2
03 jan 18:00	1	3	18	0,1	0,4	4,7	4,5	0,7	8,1	2,5	34,0	9,1	177,6
03 jan 19:00	1	3	19	0,2	0,8	6,1	7,3	1,7	6,0	2,5	30,7	6,7	196,3
03 jan 20:00	1	3	20	0,2	0,4	6,7	10,0	3,2	6,7	2,5	29,4	5,9	254,1
03 jan 21:00	1	3	21	0,2	0,0	6,1	8,7	2,7	7,5	2,5	27,7	5,1	250,9
03 jan 22:00	1	3	22	0,2	-	5,1	8,7	1,8	6,5	2,5	26,5	5,1	272,0
03 jan 23:00	1	3	23	0,2	-	-	6,8	1,0	5,1	2,5	25,4	4,6	257,2

Note: only the first three days are shown. The full dataset is available in the MS Excel Spreadsheet.

Load and Generation Profiles

Timestamp

Load Profile

Check, No of entries:	8.760	8.760	8.760	8.760	8.760	8.760	8.760	-	-
Check, Max Load	34	10.878	13.198	5.000	100.000	100.000	100	-	-
Check, Min Load	22	5.081	2.508	-	-	80.000	0	-	-
Check, Average Load	28	7.900	3.907	1.250	53.750	92.500	50	#DIV/0!	#DIV/0!
Annual energy demand	247	69.206	34.223	10.950	470.850	810.300	439	-	-

				Kenya - C&I - Refugee Camp	Kenya - C&I - Manufacturing Company 10 MW	Sierra Leone - C&I - Processing Factory 13 MW	Avoided T&D expansion (reduce peak)	Hybrid RE+Storage Peaker Plant (South Africa)	Hybrid RE+Storage Baseload Plant (South Africa)	Random Load	Custom Load 1	Custom Load 2
Timestamp dd mmm hh:mm	Month	Day	Hour	Load kW	Load kW	Load kW	Load kW	Load kW	Load kW	Load kW	Load kW	Load kW
01 jan 00:00	1	1	0	25,0	8.963,3	5.120,5	-	-	80.000,0	3,5		
01 jan 01:00	1	1	1	23,9	7.974,4	5.109,8	-	-	80.000,0	25,2		
01 jan 02:00	1	1	2	24,3	6.211,7	5.167,8	-	-	80.000,0	73,3		
01 jan 03:00	1	1	3	23,0	5.101,9	5.016,2	-	-	80.000,0	74,3		
01 jan 04:00	1	1	4	22,8	5.081,4	5.099,2	-	-	80.000,0	3,8		
01 jan 05:00	1	1	5	22,1	7.127,8	5.402,5	-	100.000,0	80.000,0	40,8		
01 jan 06:00	1	1	6	23,7	8.495,3	6.017,6	5.000,0	100.000,0	100.000,0	70,5		
01 jan 07:00	1	1	7	25,9	7.172,1	7.091,7	5.000,0	100.000,0	100.000,0	18,4		
01 jan 08:00	1	1	8	28,5	5.099,9	10.845,7	5.000,0	100.000,0	100.000,0	89,2		
01 jan 09:00	1	1	9	32,9	7.841,4	11.067,4	-	60.000,0	100.000,0	8,4		
01 jan 10:00	1	1	10	33,5	8.461,6	11.582,1	-	60.000,0	100.000,0	57,7		
01 jan 11:00	1	1	11	33,1	8.843,1	13.041,2	-	60.000,0	100.000,0	10,4		
01 jan 12:00	1	1	12	32,2	8.308,3	11.353,6	-	60.000,0	100.000,0	96,4		
01 jan 13:00	1	1	13	28,4	7.413,8	10.050,1	-	60.000,0	100.000,0	62,3		
01 jan 14:00	1	1	14	30,0	8.023,3	11.460,8	-	60.000,0	100.000,0	6,6		
01 jan 15:00	1	1	15	33,3	7.718,5	13.197,7	-	60.000,0	100.000,0	42,4		
01 jan 16:00	1	1	16	30,8	7.238,3	8.413,3	-	60.000,0	100.000,0	17,1		
01 jan 17:00	1	1	17	28,0	8.206,5	3.676,2	-	60.000,0	100.000,0	78,9		
01 jan 18:00	1	1	18	32,0	7.105,6	3.397,5	5.000,0	100.000,0	100.000,0	56,2		
01 jan 19:00	1	1	19	32,1	7.850,9	3.070,0	5.000,0	100.000,0	100.000,0	86,8		
01 jan 20:00	1	1	20	31,5	10.162,6	2.941,7	5.000,0	100.000,0	100.000,0	53,4		
01 jan 21:00	1	1	21	28,8	10.036,3	2.769,0	-	50.000,0	80.000,0	65,1		
01 jan 22:00	1	1	22	26,8	10.878,2	2.650,3	-	-	80.000,0	69,7		
01 jan 23:00	1	1	23	25,0	10.288,2	2.539,1	-	-	80.000,0	8,2		
02 jan 00:00	1	2	0	25,0	8.963,3	2.560,3	-	-	80.000,0	25,4		
02 jan 01:00	1	2	1	23,9	7.974,4	2.554,9	-	-	80.000,0	28,6		
02 jan 02:00	1	2	2	24,3	6.211,7	2.583,9	-	-	80.000,0	55,2		
02 jan 03:00	1	2	3	23,0	5.101,9	2.508,1	-	-	80.000,0	10,3		
02 jan 04:00	1	2	4	22,8	5.081,4	2.549,6	-	-	80.000,0	50,8		
02 jan 05:00	1	2	5	22,1	7.127,8	2.701,2	-	100.000,0	80.000,0	18,2		
02 jan 06:00	1	2	6	23,7	8.495,3	3.008,8	5.000,0	100.000,0	100.000,0	53,9		
02 jan 07:00	1	2	7	25,9	7.172,1	3.545,9	5.000,0	100.000,0	100.000,0	48,9		
02 jan 08:00	1	2	8	28,5	5.099,9	5.422,8	5.000,0	100.000,0	100.000,0	96,4		
02 jan 09:00	1	2	9	32,9	7.841,4	5.533,7	-	60.000,0	100.000,0	63,0		
02 jan 10:00	1	2	10	33,5	8.461,6	5.791,0	-	60.000,0	100.000,0	1,7		
02 jan 11:00	1	2	11	33,1	8.843,1	6.520,6	-	60.000,0	100.000,0	64,4		
02 jan 12:00	1	2	12	32,2	8.308,3	5.676,8	-	60.000,0	100.000,0	19,5		
02 jan 13:00	1	2	13	28,4	7.413,8	5.025,1	-	60.000,0	100.000,0	32,5		
02 jan 14:00	1	2	14	30,0	8.023,3	5.730,4	-	60.000,0	100.000,0	98,5		
02 jan 15:00	1	2	15	33,3	7.718,5	6.598,8	-	60.000,0	100.000,0	36,4		
02 jan 16:00	1	2	16	30,8	7.238,3	4.206,6	-	60.000,0	100.000,0	80,1		
02 jan 17:00	1	2	17	28,0	8.206,5	3.676,2	-	60.000,0	100.000,0	73,4		
02 jan 18:00	1	2	18	32,0	7.105,6	3.397,5	5.000,0	100.000,0	100.000,0	50,3		
02 jan 19:00	1	2	19	32,1	7.850,9	3.070,0	5.000,0	100.000,0	100.000,0	73,5		
02 jan 20:00	1	2	20	31,5	10.162,6	2.941,7	5.000,0	100.000,0	100.000,0	28,7		
02 jan 21:00	1	2	21	28,8	10.036,3	2.769,0	-	50.000,0	80.000,0	97,3		
02 jan 22:00	1	2	22	26,8	10.878,2	2.650,3	-	-	80.000,0	0,2		
02 jan 23:00	1	2	23	25,0	10.288,2	2.539,1	-	-	80.000,0	98,4		
03 jan 00:00	1	3	0	25,0	8.963,3	2.560,3	-	-	80.000,0	12,6		
03 jan 01:00	1	3	1	23,9	7.974,4	2.554,9	-	-	80.000,0	26,1		
03 jan 02:00	1	3	2	24,3	6.211,7	2.583,9	-	-	80.000,0	45,8		
03 jan 03:00	1	3	3	23,0	5.101,9	2.508,1	-	-	80.000,0	95,3		
03 jan 04:00	1	3	4	22,8	5.081,4	2.549,6	-	-	80.000,0	60,4		
03 jan 05:00	1	3	5	22,1	7.127,8	2.701,2	-	100.000,0	80.000,0	80,7		
03 jan 06:00	1	3	6	23,7	8.495,3	3.008,8	5.000,0	100.000,0	100.000,0	53,7		
03 jan 07:00	1	3	7	25,9	7.172,1	3.545,9	5.000,0	100.000,0	100.000,0	2,2		
03 jan 08:00	1	3	8	28,5	5.099,9	5.422,8	5.000,0	100.000,0	100.000,0	97,7		
03 jan 09:00	1	3	9	32,9	7.841,4	5.533,7	-	60.000,0	100.000,0	52,4		
03 jan 10:00	1	3	10	33,5	8.461,6	5.791,0	-	60.000,0	100.000,0	96,2		
03 jan 11:00	1	3	11	33,1	8.843,1	6.520,6	-	60.000,0	100.000,0	57,2		
03 jan 12:00	1	3	12	32,2	8.308,3	5.676,8	-	60.000,0	100.000,0	55,0		
03 jan 13:00	1	3	13	28,4	7.413,8	5.025,1	-	60.000,0	100.000,0	53,4		
03 jan 14:00	1	3	14	30,0	8.023,3	5.730,4	-	60.000,0	100.000,0	34,7		
03 jan 15:00	1	3	15	33,3	7.718,5	6.598,8	-	60.000,0	100.000,0	7,6		
03 jan 16:00	1	3	16	30,8	7.238,3	4.206,6	-	60.000,0	100.000,0	80,2		
03 jan 17:00	1	3	17	28,0	8.206,5	3.676,2	-	60.000,0	100.000,0	94,4		
03 jan 18:00	1	3	18	32,0	7.105,6	3.397,5	5.000,0	100.000,0	100.000,0	70,2		
03 jan 19:00	1	3	19	32,1	7.850,9	3.070,0	5.000,0	100.000,0	100.000,0	63,4		
03 jan 20:00	1	3	20	31,5	10.162,6	2.941,7	5.000,0	100.000,0	100.000,0	16,9		
03 jan 21:00	1	3	21	28,8	10.036,3	2.769,0	-	50.000,0	80.000,0	46,0		
03 jan 22:00	1	3	22	26,8	10.878,2	2.650,3	-	-	80.000,0	30,6		
03 jan 23:00	1	3	23	25,0	10.288,2	2.539,1	-	-	80.000,0	69,2		

Note: only the first three days are shown. The full dataset is available in the MS Excel Spreadsheet.

A.8. Solar PV Generation Profiles

Load and Generation Profiles

Timestamp

Solar PV Generation

Check, No of entries:	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760	8.760
Check, Max Power:	54	48	49	48	54	47	49	47	54	50	52	50
Check, Min Power:	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
Check, Average Power:	12	12	13	12	12	11	11	11	14	14	15	13
kW AC capacity installed:	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0	50,0
kW DC capacity installed:	63,6	53,0	52,5	64,0	63,6	53,0	52,5	64,0	63,6	53,0	52,5	64,0
Loading Ratio:	1,3	1,1	1,1	1,3	1,3	1,1	1,1	1,3	1,3	1,1	1,1	1,3
Degradation [%/yr]:	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%
Spatial Requirement [m2/MW]:												

Timestamp dd mmm hh:mm	Month	Day	Hour	Kenya - Monoperc Fixed Tilt PV Export kW	Kenya - Monoperc Tracker PV Export kW	Kenya - Bifacial Tracker PV Export kW	Kenya - Monoperc Rooftop East-West PV Export kW	Nigeria - Monoperc Fixed Tilt PV Export kW	Nigeria - Monoperc Tracker PV Export kW	Nigeria - Bifacial Tracker PV Export kW	Nigeria - Monoperc Rooftop East-West PV Export kW	South Africa - Monoperc Fixed Tilt PV Export kW	South Africa - Monoperc Tracker PV Export kW	South Africa - Bifacial Tracker PV Export kW	South Africa - Monoperc Rooftop East-West PV Export kW
01 jan 00:00	1	1	0	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 01:00	1	1	1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 02:00	1	1	2	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 03:00	1	1	3	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 04:00	1	1	4	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 05:00	1	1	5	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 06:00	1	1	6	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	5,3	14,4	14,6	8,7
01 jan 07:00	1	1	7	8,4	12,5	12,7	7,6	6,5	7,5	7,7	5,5	3,9	2,4	3,0	4,3
01 jan 08:00	1	1	8	23,0	31,7	32,6	21,3	17,9	22,2	23,2	15,7	3,2	1,9	2,4	3,5
01 jan 09:00	1	1	9	31,7	33,1	34,5	29,7	29,5	29,9	31,3	26,1	13,2	10,4	11,7	14,3
01 jan 10:00	1	1	10	43,2	39,5	40,9	39,7	38,6	33,8	35,2	34,3	3,5	2,9	3,1	3,8
01 jan 11:00	1	1	11	44,8	37,5	39,1	41,2	43,7	35,0	36,4	39,0	21,5	19,1	20,1	22,5
01 jan 12:00	1	1	12	44,0	35,7	37,2	40,9	45,1	34,8	36,3	40,2	46,2	39,5	41,2	43,7
01 jan 13:00	1	1	13	31,3	25,9	27,3	30,0	43,0	34,5	35,9	38,3	26,7	23,7	25,0	27,4
01 jan 14:00	1	1	14	28,4	24,0	25,5	27,2	37,2	32,6	33,9	33,1	39,4	37,9	39,5	39,6
01 jan 15:00	1	1	15	23,8	21,3	22,9	22,8	28,2	28,8	30,1	24,9	32,9	36,5	38,1	34,1
01 jan 16:00	1	1	16	11,7	9,6	10,9	11,4	16,8	21,2	22,1	14,8	17,2	19,1	20,8	18,9
01 jan 17:00	1	1	17	3,3	2,6	2,8	3,3	5,8	6,6	6,8	4,9	8,6	11,0	11,8	10,1
01 jan 18:00	1	1	18	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	2,2	5,6	5,7	3,9
01 jan 19:00	1	1	19	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 20:00	1	1	20	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 21:00	1	1	21	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 22:00	1	1	22	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
01 jan 23:00	1	1	23	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 00:00	1	2	0	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 01:00	1	2	1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 02:00	1	2	2	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 03:00	1	2	3	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 04:00	1	2	4	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 05:00	1	2	5	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 06:00	1	2	6	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	4,3	13,6	13,7	7,8
02 jan 07:00	1	2	7	6,9	8,4	8,6	6,5	6,8	8,5	8,6	5,5	15,1	28,8	29,7	18,2
02 jan 08:00	1	2	8	16,7	17,4	18,9	16,0	19,3	26,2	27,0	16,6	25,9	33,7	35,3	28,0
02 jan 09:00	1	2	9	26,9	25,7	27,6	25,6	31,4	32,7	34,0	27,5	34,5	36,6	38,2	35,4
02 jan 10:00	1	2	10	38,4	34,5	36,0	36,1	40,2	35,3	36,7	35,7	41,5	38,9	40,5	40,7
02 jan 11:00	1	2	11	48,1	40,3	41,9	43,1	45,4	36,4	37,8	40,2	45,5	39,7	41,4	43,1
02 jan 12:00	1	2	12	50,1	40,6	42,1	44,5	47,1	36,4	37,9	41,5	46,2	39,4	41,1	43,7
02 jan 13:00	1	2	13	41,7	34,8	36,3	39,2	45,1	36,3	37,6	40,2	43,1	38,3	39,8	42,1
02 jan 14:00	1	2	14	33,8	29,4	31,0	32,1	39,3	34,7	36,0	34,9	38,4	36,9	38,5	38,6
02 jan 15:00	1	2	15	22,3	19,5	21,2	21,5	29,7	30,8	32,0	26,1	30,1	32,0	33,7	31,5
02 jan 16:00	1	2	16	17,1	17,8	19,2	16,4	18,0	24,5	25,2	15,4	21,1	28,0	29,4	23,3
02 jan 17:00	1	2	17	7,9	10,0	10,3	7,4	6,1	7,6	7,7	4,9	11,0	23,0	23,6	14,0
02 jan 18:00	1	2	18	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	2,2	7,3	7,4	4,5
02 jan 19:00	1	2	19	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 20:00	1	2	20	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 21:00	1	2	21	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 22:00	1	2	22	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
02 jan 23:00	1	2	23	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 00:00	1	3	0	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 01:00	1	3	1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 02:00	1	3	2	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 03:00	1	3	3	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 04:00	1	3	4	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 05:00	1	3	5	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 06:00	1	3	6	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	3,9	19,4	19,4	9,4
03 jan 07:00	1	3	7	10,0	16,8	16,9	8,7	7,4	9,7	9,8	5,7	18,1	41,5	41,8	22,7
03 jan 08:00	1	3	8	23,5	34,6	35,3	21,6	20,8	29,1	29,8	17,6	32,2	46,3	47,1	34,9
03 jan 09:00	1	3	9	35,5	38,7	39,8	33,0	33,1	35,1	36,3	28,9	43,5	47,9	49,0	42,0
03 jan 10:00	1	3	10	44,4	40,9	42,2	40,4	42,5	37,5	38,8	37,5	51,4	48,4	49,8	46,5
03 jan 11:00	1	3	11	49,4	41,5	43,0	43,8	47,6	38,1	39,5	41,3	53,7	48,3	50,0	49,0
03 jan 12:00	1	3	12	51,3	41,6	43,1	45,2	49,0	37,8	39,3	42,5	53,7	48,0	49,8	49,3
03 jan 13:00	1	3	13	49,0	40,9	42,4	44,1	46,2	37,1	38,4	41,0	53,7	47,5	49,1	48,5
03 jan 14:00	1	3	14	44,3	40,4	41,7	41,1	40,6	36,0	37,2	35,9	48,3	47,0	48,3	45,9
03 jan 15:00	1	3	15	35,5	38,1	39,1	32,9	31,6	33,6	34,6	27,6	39,3	45,8	46,8	40,3
03 jan 16:00	1	3	16	23,7	33,9	34,5	21,8	19,3	27,3	28,0	16,3	27,4	43,5	44,0	30,4
03 jan 17:00	1	3	17	10,4	17,7	17,7	9,2	6,7	8,8	9,0	5,1	13,3	35,9	35,9	18,1
03 jan 18:00	1	3	18	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	1,2	12,0	12,0	5,8
03 jan 19:00	1	3	19	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 20:00	1	3	20	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 21:00	1	3	21	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 22:00	1	3	22	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
03 jan 23:00	1	3	23	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1

Note: only the first three days are shown. The full dataset is available in the MS Excel Spreadsheet.

A.9. Wind Generation Profiles

Load and Generation Profiles

Timestamp

Wind Generation

Check, No of entries:	8.760	-	-
Check, Max Power	40.000	-	-
Check, Min Power	-	-	-
Check, Average Power	17.340	#DIV/0!	#DIV/0!
kW AC capacity installed:	40.000,0	90,0	120,0
Degradation [%/yr]:	1,60%	1,60%	1,60%
Spatial requirement [m2/MW]:			

Timestamp dd mmm hh:mm	Month	Day	Hour	Wind Profile A (South Africa) Wind Export to Grid kW (AC)	Wind Profile B Wind Export to Grid kW (AC)	Wind Profile C Wind Export to Grid kW (AC)
01 jan 00:00	1	1	0	32.870		
01 jan 01:00	1	1	1	38.060		
01 jan 02:00	1	1	2	37.940		
01 jan 03:00	1	1	3	33.560		
01 jan 04:00	1	1	4	20.180		
01 jan 05:00	1	1	5	23.210		
01 jan 06:00	1	1	6	33.100		
01 jan 07:00	1	1	7	37.140		
01 jan 08:00	1	1	8	33.780		
01 jan 09:00	1	1	9	33.800		
01 jan 10:00	1	1	10	35.070		
01 jan 11:00	1	1	11	33.680		
01 jan 12:00	1	1	12	29.720		
01 jan 13:00	1	1	13	30.180		
01 jan 14:00	1	1	14	29.880		
01 jan 15:00	1	1	15	22.050		
01 jan 16:00	1	1	16	22.070		
01 jan 17:00	1	1	17	18.900		
01 jan 18:00	1	1	18	18.730		
01 jan 19:00	1	1	19	24.760		
01 jan 20:00	1	1	20	24.960		
01 jan 21:00	1	1	21	20.020		
01 jan 22:00	1	1	22	13.700		
01 jan 23:00	1	1	23	7.710		
02 jan 00:00	1	2	0	5.620		
02 jan 01:00	1	2	1	950		
02 jan 02:00	1	2	2	2.650		
02 jan 03:00	1	2	3	1.160		
02 jan 04:00	1	2	4	1.680		
02 jan 05:00	1	2	5	-		
02 jan 06:00	1	2	6	-		
02 jan 07:00	1	2	7	-		
02 jan 08:00	1	2	8	-		
02 jan 09:00	1	2	9	140		
02 jan 10:00	1	2	10	1.230		
02 jan 11:00	1	2	11	1.380		
02 jan 12:00	1	2	12	950		
02 jan 13:00	1	2	13	770		
02 jan 14:00	1	2	14	1.920		
02 jan 15:00	1	2	15	2.680		
02 jan 16:00	1	2	16	2.990		
02 jan 17:00	1	2	17	4.980		
02 jan 18:00	1	2	18	5.370		
02 jan 19:00	1	2	19	19.810		
02 jan 20:00	1	2	20	31.540		
02 jan 21:00	1	2	21	22.390		
02 jan 22:00	1	2	22	19.210		
02 jan 23:00	1	2	23	21.510		
03 jan 00:00	1	3	0	22.420		
03 jan 01:00	1	3	1	14.130		
03 jan 02:00	1	3	2	8.960		
03 jan 03:00	1	3	3	5.100		
03 jan 04:00	1	3	4	4.960		
03 jan 05:00	1	3	5	21.770		
03 jan 06:00	1	3	6	33.180		
03 jan 07:00	1	3	7	24.220		
03 jan 08:00	1	3	8	16.250		
03 jan 09:00	1	3	9	10.620		
03 jan 10:00	1	3	10	4.030		
03 jan 11:00	1	3	11	1.750		
03 jan 12:00	1	3	12	1.070		
03 jan 13:00	1	3	13	640		
03 jan 14:00	1	3	14	2.280		
03 jan 15:00	1	3	15	1.860		
03 jan 16:00	1	3	16	2.090		
03 jan 17:00	1	3	17	1.970		
03 jan 18:00	1	3	18	3.510		
03 jan 19:00	1	3	19	26.230		
03 jan 20:00	1	3	20	30.120		
03 jan 21:00	1	3	21	37.590		
03 jan 22:00	1	3	22	39.530		
03 jan 23:00	1	3	23	39.400		

Note: only the first three days are shown. The full dataset is available in the MS Excel Spreadsheet.

A.10. Grid Electricity Supply Profiles

Load and Generation Profiles (Should be a non-leap year of 8760 hours)

All input data as non-leap years of 8760 hours.

Timestamp

Grid Electricity Output (power provided by grid and used by the mini-grid or hybrid plant)

	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - 24/7 at max 20% of Peak Load	Grid Electricity Output Profile - 24/7 at max 35% of Peak Load	Avoided T&D expansion (reduce peak)	Custom 1 Grid Electricity Output Profile	Custom 2 Grid Electricity Output Profile
Check, No of entries:	8.760	8.760	8.760	8.760	-	-
Check, Max Load	-	54	95	-	-	-
Check, Min Load	-	25	44	-	-	-
Check, Average Load	-	40	69	-	#DIV/0!	#DIV/0!

Timestamp dd mmm hh:mm	Month	Day	Hour	Grid Electricity Output Profile - No Grid Load kW	Grid Electricity Output Profile - 24/7 at max 20% of Peak Load Load kW	Grid Electricity Output Profile - 24/7 at max 35% of Peak Load Load kW	Avoided T&D expansion (reduce peak) Load kW	Custom 1 Grid Electricity Output Profile Load kW	Custom 2 Grid Electricity Output Profile Load kW
01 jan 00:00	1	1	0	-	44,8	78,4	-		
01 jan 01:00	1	1	1	-	39,9	69,8	-		
01 jan 02:00	1	1	2	-	31,1	54,4	-		
01 jan 03:00	1	1	3	-	25,5	44,6	-		
01 jan 04:00	1	1	4	-	25,4	44,5	-		
01 jan 05:00	1	1	5	-	35,6	62,4	-		
01 jan 06:00	1	1	6	-	42,5	74,3	-		
01 jan 07:00	1	1	7	-	35,9	62,8	-		
01 jan 08:00	1	1	8	-	25,5	44,6	-		
01 jan 09:00	1	1	9	-	39,2	68,6	-		
01 jan 10:00	1	1	10	-	42,3	74,0	-		
01 jan 11:00	1	1	11	-	44,2	77,4	-		
01 jan 12:00	1	1	12	-	41,5	72,7	-		
01 jan 13:00	1	1	13	-	37,1	64,9	-		
01 jan 14:00	1	1	14	-	40,1	70,2	-		
01 jan 15:00	1	1	15	-	38,6	67,5	-		
01 jan 16:00	1	1	16	-	36,2	63,3	-		
01 jan 17:00	1	1	17	-	41,0	71,8	-		
01 jan 18:00	1	1	18	-	35,5	62,2	-		
01 jan 19:00	1	1	19	-	39,3	68,7	-		
01 jan 20:00	1	1	20	-	50,8	88,9	-		
01 jan 21:00	1	1	21	-	50,2	87,8	-		
01 jan 22:00	1	1	22	-	54,4	95,2	-		
01 jan 23:00	1	1	23	-	51,4	90,0	-		
02 jan 00:00	1	2	0	-	44,8	78,4	-		
02 jan 01:00	1	2	1	-	39,9	69,8	-		
02 jan 02:00	1	2	2	-	31,1	54,4	-		
02 jan 03:00	1	2	3	-	25,5	44,6	-		
02 jan 04:00	1	2	4	-	25,4	44,5	-		
02 jan 05:00	1	2	5	-	35,6	62,4	-		
02 jan 06:00	1	2	6	-	42,5	74,3	-		
02 jan 07:00	1	2	7	-	35,9	62,8	-		
02 jan 08:00	1	2	8	-	25,5	44,6	-		
02 jan 09:00	1	2	9	-	39,2	68,6	-		
02 jan 10:00	1	2	10	-	42,3	74,0	-		
02 jan 11:00	1	2	11	-	44,2	77,4	-		
02 jan 12:00	1	2	12	-	41,5	72,7	-		
02 jan 13:00	1	2	13	-	37,1	64,9	-		
02 jan 14:00	1	2	14	-	40,1	70,2	-		
02 jan 15:00	1	2	15	-	38,6	67,5	-		
02 jan 16:00	1	2	16	-	36,2	63,3	-		
02 jan 17:00	1	2	17	-	41,0	71,8	-		
02 jan 18:00	1	2	18	-	35,5	62,2	-		
02 jan 19:00	1	2	19	-	39,3	68,7	-		
02 jan 20:00	1	2	20	-	50,8	88,9	-		
02 jan 21:00	1	2	21	-	50,2	87,8	-		
02 jan 22:00	1	2	22	-	54,4	95,2	-		
02 jan 23:00	1	2	23	-	51,4	90,0	-		
03 jan 00:00	1	3	0	-	44,8	78,4	-		
03 jan 01:00	1	3	1	-	39,9	69,8	-		
03 jan 02:00	1	3	2	-	31,1	54,4	-		
03 jan 03:00	1	3	3	-	25,5	44,6	-		
03 jan 04:00	1	3	4	-	25,4	44,5	-		
03 jan 05:00	1	3	5	-	35,6	62,4	-		
03 jan 06:00	1	3	6	-	42,5	74,3	-		
03 jan 07:00	1	3	7	-	35,9	62,8	-		
03 jan 08:00	1	3	8	-	25,5	44,6	-		
03 jan 09:00	1	3	9	-	39,2	68,6	-		
03 jan 10:00	1	3	10	-	42,3	74,0	-		
03 jan 11:00	1	3	11	-	44,2	77,4	-		
03 jan 12:00	1	3	12	-	41,5	72,7	-		
03 jan 13:00	1	3	13	-	37,1	64,9	-		
03 jan 14:00	1	3	14	-	40,1	70,2	-		
03 jan 15:00	1	3	15	-	38,6	67,5	-		
03 jan 16:00	1	3	16	-	36,2	63,3	-		
03 jan 17:00	1	3	17	-	41,0	71,8	-		
03 jan 18:00	1	3	18	-	35,5	62,2	-		
03 jan 19:00	1	3	19	-	39,3	68,7	-		
03 jan 20:00	1	3	20	-	50,8	88,9	-		
03 jan 21:00	1	3	21	-	50,2	87,8	-		
03 jan 22:00	1	3	22	-	54,4	95,2	-		
03 jan 23:00	1	3	23	-	51,4	90,0	-		

Note: only the first three days are shown. The full dataset is available in the MS Excel Spreadsheet.

A.11. Tariff definition input sheet

Tariff definition

No Time of Day Tariff						
		1-1-2021	Start date	End date	Start day	End day
		Low demand season	1-sep	31-mei	243	150
		High demand season	1-jun	31-aug	151	242

Tariffs	USD/kWh		Off-peak	Standard	Peak
		Low demand season	0,20	0,20	0,20
		High demand season	0,20	0,20	0,20
			01-jan 00:00		

#	Day #	Hour #	Timestamp	Day	Season	Period	Tariff
1	1	1	01-jan 00:00	do	Low	Off-peak	0,20
2	1	2	01-jan 01:00	do	Low	Off-peak	0,20
3	1	3	01-jan 02:00	do	Low	Off-peak	0,20
4	1	4	01-jan 03:00	do	Low	Off-peak	0,20
5	1	5	01-jan 04:00	do	Low	Off-peak	0,20
6	1	6	01-jan 05:00	do	Low	Off-peak	0,20
7	1	7	01-jan 06:00	do	Low	Standard	0,20
8	1	8	01-jan 07:00	do	Low	Peak	0,20
9	1	9	01-jan 08:00	do	Low	Peak	0,20
10	1	10	01-jan 09:00	do	Low	Peak	0,20
11	1	11	01-jan 10:00	do	Low	Standard	0,20
12	1	12	01-jan 11:00	do	Low	Standard	0,20
13	1	13	01-jan 12:00	do	Low	Standard	0,20
14	1	14	01-jan 13:00	do	Low	Standard	0,20
15	1	15	01-jan 14:00	do	Low	Standard	0,20
16	1	16	01-jan 15:00	do	Low	Standard	0,20
17	1	17	01-jan 16:00	do	Low	Standard	0,20
18	1	18	01-jan 17:00	do	Low	Standard	0,20
19	1	19	01-jan 18:00	do	Low	Peak	0,20
20	1	20	01-jan 19:00	do	Low	Peak	0,20
21	1	21	01-jan 20:00	do	Low	Standard	0,20
22	1	22	01-jan 21:00	do	Low	Standard	0,20
23	1	23	01-jan 22:00	do	Low	Off-peak	0,20
24	1	24	01-jan 23:00	do	Low	Off-peak	0,20
25	2	1	02-jan 00:00	vr	Low	Off-peak	0,20
26	2	2	02-jan 01:00	vr	Low	Off-peak	0,20
27	2	3	02-jan 02:00	vr	Low	Off-peak	0,20
28	2	4	02-jan 03:00	vr	Low	Off-peak	0,20
29	2	5	02-jan 04:00	vr	Low	Off-peak	0,20
30	2	6	02-jan 05:00	vr	Low	Off-peak	0,20
31	2	7	02-jan 06:00	vr	Low	Off-peak	0,20
32	2	8	02-jan 07:00	vr	Low	Standard	0,20
33	2	9	02-jan 08:00	vr	Low	Standard	0,20
34	2	10	02-jan 09:00	vr	Low	Standard	0,20
35	2	11	02-jan 10:00	vr	Low	Standard	0,20
36	2	12	02-jan 11:00	vr	Low	Standard	0,20
37	2	13	02-jan 12:00	vr	Low	Off-peak	0,20
38	2	14	02-jan 13:00	vr	Low	Off-peak	0,20
39	2	15	02-jan 14:00	vr	Low	Off-peak	0,20
40	2	16	02-jan 15:00	vr	Low	Off-peak	0,20
41	2	17	02-jan 16:00	vr	Low	Off-peak	0,20
42	2	18	02-jan 17:00	vr	Low	Off-peak	0,20
43	2	19	02-jan 18:00	vr	Low	Standard	0,20
44	2	20	02-jan 19:00	vr	Low	Standard	0,20
45	2	21	02-jan 20:00	vr	Low	Off-peak	0,20
46	2	22	02-jan 21:00	vr	Low	Off-peak	0,20
47	2	23	02-jan 22:00	vr	Low	Off-peak	0,20
48	2	24	02-jan 23:00	vr	Low	Off-peak	0,20
49	3	1	03-jan 00:00	za	Low	Off-peak	0,20
50	3	2	03-jan 01:00	za	Low	Off-peak	0,20
51	3	3	03-jan 02:00	za	Low	Off-peak	0,20
52	3	4	03-jan 03:00	za	Low	Off-peak	0,20
53	3	5	03-jan 04:00	za	Low	Off-peak	0,20
54	3	6	03-jan 05:00	za	Low	Off-peak	0,20
55	3	7	03-jan 06:00	za	Low	Off-peak	0,20
56	3	8	03-jan 07:00	za	Low	Off-peak	0,20
57	3	9	03-jan 08:00	za	Low	Off-peak	0,20
58	3	10	03-jan 09:00	za	Low	Off-peak	0,20
59	3	11	03-jan 10:00	za	Low	Off-peak	0,20
60	3	12	03-jan 11:00	za	Low	Off-peak	0,20
61	3	13	03-jan 12:00	za	Low	Off-peak	0,20
62	3	14	03-jan 13:00	za	Low	Off-peak	0,20
63	3	15	03-jan 14:00	za	Low	Off-peak	0,20
64	3	16	03-jan 15:00	za	Low	Off-peak	0,20
65	3	17	03-jan 16:00	za	Low	Off-peak	0,20
66	3	18	03-jan 17:00	za	Low	Off-peak	0,20
67	3	19	03-jan 18:00	za	Low	Off-peak	0,20
68	3	20	03-jan 19:00	za	Low	Off-peak	0,20
69	3	21	03-jan 20:00	za	Low	Off-peak	0,20
70	3	22	03-jan 21:00	za	Low	Off-peak	0,20
71	3	23	03-jan 22:00	za	Low	Off-peak	0,20
72	3	24	03-jan 23:00	za	Low	Off-peak	0,20

Note: only the first three days are shown. The full dataset is available in the MS Excel Spreadsheet.

Low demand season tariff schedule

Hour #	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
2	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
3	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
4	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
5	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
6	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
7	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
8	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
9	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
10	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
11	Standard	Standard	Standard	Standard	Standard	Standard	Off-peak
12	Standard	Standard	Standard	Standard	Standard	Standard	Off-peak
13	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
14	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
15	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
16	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
17	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
18	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
19	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
20	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
21	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
22	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
23	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
24	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak

High demand season tariff schedule

Hour #	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
2	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
3	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
4	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
5	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
6	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
7	Peak	Peak	Peak	Peak	Peak	Off-peak	Off-peak
8	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
9	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
10	Standard	Standard	Standard	Standard	Standard	Standard	Off-peak
11	Standard	Standard	Standard	Standard	Standard	Standard	Off-peak
12	Standard	Standard	Standard	Standard	Standard	Standard	Off-peak
13	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
14	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
15	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
16	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
17	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
18	Peak	Peak	Peak	Peak	Peak	Off-peak	Off-peak
19	Peak	Peak	Peak	Peak	Peak	Standard	Off-peak
20	Standard	Standard	Standard	Standard	Standard	Standard	Off-peak
21	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
22	Standard	Standard	Standard	Standard	Standard	Off-peak	Off-peak
23	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak
24	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak	Off-peak

A.12. Business Cases - A to C

Example business cases (full input definition)

Business Case

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Business Case	-	Reliable (critical load) mini-grids	Reliable (critical load) mini-grids	Reliable (critical load) mini-grids	Reliable (critical load) behind-the-meter applications	Reliable (critical load) behind-the-meter applications	Reliable (critical load) behind-the-meter applications	Reliable (critical load) behind-the-meter applications	Off-grid industrial facilities	Off-grid industrial facilities	Off-grid industrial facilities	Off-grid industrial facilities
Category		Mini-Grid	Mini-Grid	Mini-Grid	Captive / BTM	Captive / BTM	Captive / BTM	Captive / BTM	Captive	Captive	Captive	Captive
Examples		health centers and schools, or complying with Tier 4 or 5 of ESMAP Multi-Tier Framework (MTF)	health centers and schools, or complying with Tier 4 or 5 of ESMAP Multi-Tier Framework (MTF)	health centers and schools, or complying with Tier 4 or 5 of ESMAP Multi-Tier Framework (MTF)	telecom towers, data centers, off-grid lodges, traffic lights, streetlights, health centers, affluent households and educational facilities	telecom towers, data centers, off-grid lodges, traffic lights, streetlights, health centers, affluent households and educational facilities	telecom towers, data centers, off-grid lodges, traffic lights, streetlights, health centers, affluent households and educational facilities	telecom towers, data centers, off-grid lodges, traffic lights, streetlights, health centers, affluent households and educational facilities	mining operations (maybe breweries, bottling facilities)	mining operations (maybe breweries, bottling facilities)	mining operations (maybe breweries, bottling facilities)	mining operations (maybe breweries, bottling facilities)
Reference scenario (BAU)		No Electricity	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Gas	Diesel	Gas
Grid		Off-Grid	Off-Grid	Off-Grid	Off-Grid	Off-Grid	On-Grid	On-Grid	Off-Grid	Off-Grid	Off-Grid	Off-Grid
Type		Green-field	Green-field	Brown-field	Brown-field	Green-field	Brown-field	Green-field	Green-field	Green-field	Brown-field	Brown-field

Active revenue streams:	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Energy Sales	on/off	1	1	1	1	1	1	1	1	1	1	1
Avoided Fuel Consumption	on/off	-	1	1	1	1	1	1	1	1	1	1
Avoided Grid Import	on/off	-	-	-	-	-	1	1	-	-	-	-
Avoided Generation CAPEX	on/off	-	-	-	-	-	-	-	-	-	1	1
Avoided T&D CAPEX	on/off	-	-	-	-	-	-	-	-	-	-	-
Avoided Grid Connection Charges	on/off	-	-	-	-	-	1	1	-	-	-	-
Avoided downtime	on/off	-	-	-	1	1	1	1	1	1	1	1

Project capacity definition

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Load Profile	-	Kenya - Mini Grid 1	Tanzania - Mini Grid 1	Sierra Leone - Mini Grid 1	Tanzania - C&I - Safari Lodge	Tanzania - C&I - Safari Lodge	Kenya - C&I - Manufacturing Company	Kenya - C&I - Manufacturing Company	Kenya - C&I - Manufacturing Company 10 MW	Kenya - C&I - Manufacturing Company 10 MW	Sierra Leone - C&I - Processing Factory 13 MW	Sierra Leone - C&I - Processing Factory 13 MW
Annual energy demand	MWh	1,0	32,2	20,6	51,4	51,4	1.730,1	1.730,1	69.205,7	69.205,7	34.222,8	34.222,8
Maximum load	kW	0,4	14,4	30,7	9,8	9,8	272,0	272,0	10.878,2	10.878,2	13.197,7	13.197,7
Minimum load	kW	-	-	-	3,0	3,0	127,0	127,0	5.081,4	5.081,4	2.508,1	2.508,1
Average load	kW	0,1	3,7	2,4	5,9	5,9	197,5	197,5	7.900,2	7.900,2	3.906,7	3.906,7
Grid Electricity Output Profile	-	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - 24/7 at max 20% of Peak Load	Grid Electricity Output Profile - 24/7 at max 20% of Peak Load	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid
Maximum supply	kW	-	-	-	-	-	54	54	-	-	-	-
Minimum supply	kW	-	-	-	-	-	25	25	-	-	-	-
Average supply	kW	-	-	-	-	-	40	40	-	-	-	-
Battery Energy Storage Energy Capacity	kWh	6	72	160	60	60	2.000	2.000	40.000	40.000	40.000	40.000
Battery Energy Storage Power Capacity	kW	3	20	35	15	15	500	500	10.000	10.000	15.000	15.000
Solar PV Plant Capacity	kWp	3	20	36	30	30	500	500	30.000	30.000	20.000	20.000
Wind Farm Capacity	kW	-	-	-	-	-	-	-	-	-	-	-
Thermal Plant Unit Capacity	kW	-	5	50	8	5	150	50	3.000	12.000	4.000	16.000
Thermal Plant Number of Units	#	-	3	1	2	2	3	4	4	1	4	1
Thermal Plant Total Capacity	kW	-	15	50	15	10	450	200	12.000	12.000	16.000	16.000
BAU Thermal Plant Unit Capacity	kW		5	50	8	8	150	150	3.000	12.000	4.000	16.000
BAU Thermal Plant Number of Units	#		3	1	2	2	3	3	4	1	4	1
BAU Thermal Plant Total Capacity	kW	-	15	50	15	15	450	450	12.000	12.000	16.000	16.000

Major project techno-economic parameters

Financial

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Reference year	year	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021
Discount rate	%/year	5,0%	5,0%	5,0%	7,0%	7,0%	7,0%	7,0%	5,0%	5,0%	5,0%	5,0%
Starting year (year 0 / construction)	-	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021
Project lifetime	years	20	20	20	20	20	20	20	25	25	25	25
Development cost	% of total CAPEX	5,0%	5,0%	5,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%
Grant funding	USD	7.500	10.000	10.000	-	-	-	-	-	-	-	-
Debt share	%	0%	0%	0%	0%	0%	0%	0%	70%	70%	70%	70%
Debt tenor	years	5	5	5	7	7	7	7	10	10	10	10
Debt interest rate	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	7,0%	7,0%
Minimum Debt Service Coverage Ratio	Factor	1,20	1,20	1,20	1,20	1,20	1,20	1,20	1,20	1,20	1,20	1,20
Equity share	%	100%	100%	100%	100%	100%	100%	100%	30%	30%	30%	30%
Tax credits (on CAPEX)	%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Tax rate	%	0,0%	0,0%	0,0%	20,0%	20,0%	20,0%	20,0%	20,0%	20,0%	20,0%	20,0%

Commercial

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Tariff - Off-peak - Low Demand Season	USD/kWh	0,60	0,60	0,60	0,40	0,40	0,40	0,40	0,20	0,20	0,20	0,20
Tariff - Standard - Low Demand Season	USD/kWh	0,60	0,60	0,60	0,40	0,40	0,40	0,40	0,20	0,20	0,20	0,20
Tariff - Peak - Low Demand Season	USD/kWh	0,60	0,60	0,60	0,40	0,40	0,40	0,40	0,20	0,20	0,20	0,20
Tariff - Off-peak - High Demand Season	USD/kWh	0,60	0,60	0,60	0,40	0,40	0,40	0,40	0,20	0,20	0,20	0,20
Tariff - Standard - High Demand Season	USD/kWh	0,60	0,60	0,60	0,40	0,40	0,40	0,40	0,20	0,20	0,20	0,20
Tariff - Peak - High Demand Season	USD/kWh	0,60	0,60	0,60	0,40	0,40	0,40	0,40	0,20	0,20	0,20	0,20
Time of Day tariff structure?	Yes/No	No	No	No	No	No	No	No	No	No	No	No
Tariff - Grid Electricity	USD/kWh	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22
Avoided transmission and distribution infrastructu	kW											
Avoided T&D infrastructure (CAPEX)	USD/kW											
Avoided T&D infrastructure (OPEX)	%CAPEX/a											
Cost of avoided downtime	USD/a											

Example business cases (full input definition)

Energy Storage System

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
ESS Cost Profile	-	Lead Acid Small Scale	Lead Acid Small Scale	Lead Acid Small Scale	Li-ion Small Scale	Li-ion Small Scale	Li-ion Small Scale	Li-ion Small Scale	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale
CAPEX: Battery System	USD/kWh	367	367	367	620	620	620	620	158	158	158	158
CAPEX: PCS (Inverters)	USD/kW	-	-	-	-	-	-	-	64	64	64	64
CAPEX: EMS (control system)	USD/kW	-	-	-	-	-	-	-	56	56	56	56
CAPEX: Balance of System	USD/kW	-	-	-	-	-	-	-	160	160	160	160
CAPEX: Civil works	USD/kWh	-	-	-	-	-	-	-	37	37	37	37
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	-	-	-	-	-	-	-	68	68	68	68
CAPEX: Transport and Insurance	USD/kWh	73	73	73	305	305	305	305	5	5	5	5
CAPEX: Taxes & Fees	USD/kWh	-	-	-	-	-	-	-	5	5	5	5
CAPEX Power	USD/kW	-	-	-	-	-	-	-	348	348	348	348
CAPEX Energy	USD/kWh	440	440	440	926	926	926	926	205	205	205	205
CAPEX Total	USD/kWh	440	440	440	926	926	926	926	292	292	336	336
OPEX: O&M	USD/kW/a	10	10	10	10	10	10	10	10	10	10	10
OPEX: Capacity Maintenance	USD/kWh/a	-	-	-	-	-	-	-	-	-	-	-
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	1	1	1	1	1	1	1	1	1	1	1
OPEX Power	USD/kW/a	10	10	10	10	10	10	10	10	10	10	10
OPEX Energy	USD/kWh/a	1	1	1	1	1	1	1	1	1	1	1
OPEX Total	USD/kWh/a	5	4	3	3	3	3	3	3	3	5	5
Degradation Option	-	Lead Acid Small Scale	Lead Acid Small Scale	Lead Acid Small Scale	Li-ion Small Scale	Li-ion Small Scale	Li-ion Small Scale	Li-ion Small Scale	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale
Capacity Augmentation Option	-	ale - MiniGrid Replacement at 5yrs	ale - MiniGrid Replacement at 5yrs	ale - MiniGrid Replacement at 5yrs	le - MiniGrid Replacement at 10yrs	le - MiniGrid Replacement at 10yrs	le - MiniGrid Replacement at 10yrs	le - MiniGrid Replacement at 10yrs	Li-ion Utility Scale Scheme A	Li-ion Utility Scale Scheme A	Li-ion Utility Scale Scheme A	Li-ion Utility Scale Scheme A
Roundtrip Efficiency (AC)	%	70,0%	70,0%	70,0%	88,0%	88,0%	88,0%	88,0%	89,0%	89,0%	89,0%	89,0%
Maximum SoC	% SoC	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Minimum SoC	% SoC	40%	40%	40%	0%	0%	0%	0%	0%	0%	0%	0%
Auxiliary load	kW/kWh	0	0	0	0	0	0	0	0	0	0	0
Self Discharge	%/day	0,2%	0,2%	0,2%	0,1%	0,1%	0,1%	0,1%	0,1%	0,1%	0,1%	0,1%
ESS spatial requirements	m2/MWh	0	0	0	0	0	0	0	0	0	0	0

Solar PV Plant

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
PV generation Profile	-	enya - Monoperc Rooftop East-West	Kenya - Monoperc Fixed Tilt	Nigeria - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt	Kenya - Monoperc Fixed Tilt
Solar PV Cost Profile	-	Fixed Tilt MonoPerc	Rooftop	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc	Fixed Tilt MonoPerc
Solar+BESS Coupling	-	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled	AC Coupled
CAPEX	USD/kWp	2.825	2.825	2.825	2.825	2.825	1.500	1.500	991	991	991	991
OPEX	USD/kWp/a	18	18	18	18	18	18	18	12	12	12	12
Degradation	%/year	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%	0,55%
PV Plant Yield (by Generation Profile)	kWh/kWp/a	1.607	1.682	1.601	1.682	1.682	1.682	1.682	1.682	1.682	1.682	1.682
PV Plant Loading Factor	kWp/kW-AC	1,28	1,27	1,27	1,27	1,27	1,27	1,27	1,27	1,27	1,27	1,27
PV spatial requirements	m2/MW	-	-	-	-	-	-	-	-	-	-	-

Wind Farm

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Wind generation Profile	-	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)
CAPEX	USD/kW	7.500	7.500	7.500	7.500	7.500	7.500	7.500	7.500	7.500	7.500	7.500
OPEX	USD/kWp/a	180	180	180	180	180	180	180	180	180	180	180
Degradation	%/year	1,60%	1,60%	1,60%	1,60%	1,60%	1,60%	1,60%	1,60%	1,60%	1,60%	1,60%
Wind Farm Capacity Factor	%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Wind spatial requirements	m2/MW	-	-	-	-	-	-	-	-	-	-	-

Thermal Plant

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Plant Type	-	Small Diesel Generator	Small Diesel Generator	Small Diesel Generator	Small Diesel Generator	Small Diesel Generator	Small Diesel Generator	Small Diesel Generator	Medium Speed Diesel Generator	Aeroderivative Gas Turbine	Medium Speed Diesel Generator	Aeroderivative Gas Turbine
Fuel type	-	Diesel fuel	Diesel fuel	Diesel fuel	Diesel fuel	Diesel fuel	Diesel fuel	Diesel fuel	Diesel fuel	Natural gas	Diesel fuel	Natural gas
N-1 level of reliability?	0 / 1	0	0	0	1	1	1	1	1	0	1	0
CAPEX	USD/kW	183	183	183	183	183	183	183	900	1.100	900	1.100
OPEX Fixed	USD/kW/a	25	25	25	25	25	25	25	20	15	20	15
OPEX Variable	USD/kWh	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005
Fuel Price Scenario	-	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Diesel Fuel Price Scenario Med	Gas Price Scenario Med	Diesel Fuel Price Scenario Med	Gas Price Scenario Med
Base Fuel Price in 2021	USD/GJ	20,18	20,18	20,18	20,18	20,18	20,18	20,18	20,18	6,36	20,18	6,36
Diesel: Conversion to Liters	USD/L								0,77	0,24	0,77	0,24
Fuel Price addition A (taxes, subsidies, etc.)	%	+20%	+20%	+20%	+20%	+20%	+20%	+20%	+20%	-	+20%	-
Fuel Price addition B (transport cost, etc.)	USD/GJ	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	6,00	2,00	6,00
Diesel: Conversion to Liters	USD/L								0,08	0,23	0,08	0,23
Total Fuel Price in 2021	USD/GJ	26,22	26,22	26,22	26,22	26,22	26,22	26,22	26,22	12,36	26,22	12,36
HR Degradation	%/year	0,10%	0,10%	0,10%	0,10%	0,10%	0,10%	0,10%	0,10%	0,10%	0,10%	0,10%
Baseload HR	kJ/kWh	10.000	10.000	10.000	10.000	10.000	10.000	10.000	8.000	10.700	8.000	10.700
HRCF polynomial constants	a	0,3869	0,3869	0,3869	0,3869	0,3869	0,3869	0,3869	-1,0636	-2,1582	-1,0636	-2,1582
	b	-0,1658	-0,1658	-0,1658	-0,1658	-0,1658	-0,1658	-0,1658	2,5305	4,9762	2,5305	4,9762
	c	-0,5630	-0,5630	-0,5630	-0,5630	-0,5630	-0,5630	-0,5630	-2,0399	-4,3677	-2,0399	-4,3677
	d	1,3420	1,3420	1,3420	1,3420	1,3420	1,3420	1,3420	1,5731	2,5497	1,5731	2,5497
Ideal Load Factor	%	80%	80%	80%	80%	80%	80%	80%	100%	100%	100%	100%
Minimum Load	%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Start-up fuel consumption	GJ/start/MW											
Thermal spatial requirements	m2/MW											
Specific CO2 emisions	kgCO2/GJ fuel	74	74	74	74	74	74	74	74	56	74	56

Balance of Mini Grid System

Description	Unit	A-1	A-2	A-3	B-1	B-2	B-3	B-4	C-1	C-2	C-3	C-4
Grid Supply Connection Cost	USD/kW	-	-	-	-	-	-	-	100	100	100	100
Grid Supply Connection Capacity	kW	-	-	-	-	-	54	54	-	-	-	-
Grid Supply Connection Cost	USD	-	-	-	-	-	-	-	-	-	-	-
Tariff - Grid Connection	USD/kW/a	-	-	-	-	-	-	-	50	50	50	50
Grid Supply Connection Cost	USD/a	-	-	-	-	-	-	-	-	-	-	-

A.13. Business Cases - D to E

Example business cases (full input definition)

Business Case

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Business Case	-	Avoided T&D expansion (utility scale)	Avoided T&D expansion (utility scale)	Hybrid RE+Storage plants (utility scale)	Hybrid RE+Storage plants (utility scale)						
Category		Utility	Utility	Utility	Utility						
Examples		solving local grid constraints to defer or avoid investments in new transmission & distribution assets	Defer or avoid investments in new transmission & distribution assets and avoiding new thermal plants by reducing peak demand	avoiding new thermal plants to provide power during high demand hours	avoiding new baseload thermal plants						
Reference scenario (BAU)		T&D Investment	T&D + Generation Investment	Diesel	Gas						
Grid		On-Grid	On-Grid	On-Grid	On-Grid						
Type		Green-field	Green-field	Green-field	Green-field						

Active revenue streams:	Unit	D-1	D-2	E-1	E-2						Last business case
Energy Sales	on/off	-	-	-	-						
Avoided Fuel Consumption	on/off	-	-	1	1						
Avoided Grid Import	on/off	-	-	-	-						
Avoided Generation CAPEX	on/off	-	1	1	1						
Avoided T&D CAPEX	on/off	1	1	-	-						
Avoided Grid Connection Charges	on/off	-	-	-	-						
Avoided downtime	on/off	-	-	1	1						

Project capacity definition

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Load Profile	-	Avoided T&D expansion (reduce peak)	Avoided T&D expansion (reduce peak)	Hybrid RE+Storage Peaker Plant (South Africa)	Hybrid RE+Storage Baseload Plant (South Africa)						
Annual energy demand	MWh	43.800,0	43.800,0	470.850,0	810.300,0						
Maximum load	kW	20.000,0	20.000,0	100.000,0	100.000,0						
Minimum load	kW	-	-	-	80.000,0						
Average load	kW	5.000,0	5.000,0	53.750,0	92.500,0						
Grid Electricity Output Profile	-	Avoided T&D expansion (reduce peak)	Avoided T&D expansion (reduce peak)	Grid Electricity Output Profile - No Grid	Grid Electricity Output Profile - No Grid						
Maximum supply	kW	-	-	-	-						
Minimum supply	kW	-	-	-	-						
Average supply	kW	-	-	-	-						
Battery Energy Storage Energy Capacity	kWh	80.000	80.000	700.000	600.000						
Battery Energy Storage Power Capacity	kW	20.000	20.000	100.000	100.000						
Solar PV Plant Capacity	kWp			250.000	200.000						
Wind Farm Capacity	kW	-	-	-	125.000						
Thermal Plant Unit Capacity	kW	-	-	3.500	50.000						
Thermal Plant Number of Units	#	-	-	29	2						
Thermal Plant Total Capacity	kW	-	-	101.500	100.000	-	-	-	-	-	-
BAU Thermal Plant Unit Capacity	kW	-	20.000	3.500	50.000						
BAU Thermal Plant Number of Units	#	-	1	32	3						
BAU Thermal Plant Total Capacity	kW	-	20.000	112.000	150.000	-	-	-	-	-	-

Major project techno-economic parameters

Financial

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Reference year	year	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021
Discount rate	%/year	5,0%	5,0%	7,0%	7,0%						
Starting year (year 0 / construction)	-	2021	2021	2021	2021						
Project lifetime	years	25	25	25	25						
Development cost	% of total CAPEX	10,0%	10,0%	12,5%	12,5%						
Grant funding	USD	-	-	-	-						
Debt share	%	60%	60%	70%	70%						
Debt tenor	years	10	10	10	10						
Debt interest rate	%	5,0%	5,0%	8,0%	8,0%						
Minimum Debt Service Coverage Ratio	Factor	1,20	1,20	1,20	1,20						
Equity share	%	40%	40%	30%	30%	100%	100%	100%	100%	100%	100%
Tax credits (on CAPEX)	%	0,0%	0,0%	0,0%	0,0%						
Tax rate	%	20,0%	20,0%	20,0%	20,0%						

Commercial

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Tariff - Off-peak - Low Demand Season	USD/kWh	-	-	0,15	0,13						
Tariff - Standard - Low Demand Season	USD/kWh	-	-	0,15	0,13						
Tariff - Peak - Low Demand Season	USD/kWh	-	-	0,15	0,13						
Tariff - Off-peak - High Demand Season	USD/kWh	-	-	0,15	0,13						
Tariff - Standard - High Demand Season	USD/kWh	-	-	0,15	0,13						
Tariff - Peak - High Demand Season	USD/kWh	-	-	0,15	0,13						
Time of Day tariff structure?	Yes/No	No	No	No	No						
Tariff - Grid Electricity	USD/kWh	0,06	0,06	0,06	0,06						
Avoided transmission and distribution infrastructur	kW	20.000	20.000								
Avoided T&D infrastructure (CAPEX)	USD/kW	150	150								
Avoided T&D infrastructure (OPEX)	%CAPEX/a	2,0%	2,0%								
Cost of avoided downtime	USD/a			2.564.250	3.841.200						

Example business cases (full input definition)

Energy Storage System

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
ESS Cost Profile	-	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale						
CAPEX: Battery System	USD/kWh	158	158	158	158						
CAPEX: PCS (Inverters)	USD/kW	64	64	64	64						
CAPEX: EMS (control system)	USD/kW	56	56	56	56						
CAPEX: Balance of System	USD/kW	160	160	160	160						
CAPEX: Civil works	USD/kWh	37	37	37	37						
CAPEX: Design, Studies, Permits, Testing, etc.	USD/kW	68	68	68	68						
CAPEX: Transport and Insurance	USD/kWh	5	5	5	5						
CAPEX: Taxes & Fees	USD/kWh	5	5	5	5						
CAPEX Power	USD/kW	348	348	348	348	-	-	-	-	-	-
CAPEX Energy	USD/kWh	205	205	205	205	-	-	-	-	-	-
CAPEX Total	USD/kWh	292	292	255	263						
OPEX: O&M	USD/kW/a	10	10	10	10						
OPEX: Capacity Maintenance	USD/kWh/a	-	-	-	-						
OPEX: Other (royalties, fees, land lease)	USD/kWh/a	1	1	1	1						
OPEX Power	USD/kW/a	10	10	10	10	-	-	-	-	-	-
OPEX Energy	USD/kWh/a	1	1	1	1	-	-	-	-	-	-
OPEX Total	USD/kWh/a	3	3	2	3						
Degradation Option	-	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale	Li-ion Utility Scale						
Capacity Augmentation Option	-	Li-ion Utility Scale Scheme A	Li-ion Utility Scale Scheme A	Li-ion Utility Scale Scheme A	Li-ion Utility Scale Scheme A						
Roundtrip Efficiency (AC)	%	89,0%	89,0%	89,0%	89,0%						
Maximum SoC	% SoC	100%	100%	100%	100%						
Minimum SoC	% SoC	0%	0%	0%	0%						
Auxiliary load	kW/kWh	0	0	0	0						
Self Discharge	%/day	0,1%	0,1%	0,1%	0,1%						
ESS spatial requirements	m2/MWh	0	0	0	0						

Solar PV Plant

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
PV generation Profile	-	South Africa - Bifacial Tracker	South Africa - Bifacial Tracker	South Africa - Bifacial Tracker	South Africa - Bifacial Tracker						
Solar PV Cost Profile	-	1-axis Tracking Bifacial	1-axis Tracking Bifacial	1-axis Tracking Bifacial	1-axis Tracking Bifacial						
Solar+BESS Coupling	-	AC Coupled	AC Coupled	AC Coupled	AC Coupled						
CAPEX	USD/kWp	2.853	2.853	1.113	1.113						
OPEX	USD/kWp/a	18	18	10	10						
Degradation	%/year	0,55%	0,55%	0,55%	0,55%						
PV Plant Yield (by Generation Profile)	kWh/kWp/a	2.468	2.468	2.468	2.468						
PV Plant Loading Factor	kWp/kW-AC	1,05	1,05	1,05	1,05						
PV spatial requirements	m2/MW	-	-	-	-						

Wind Farm

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Wind generation Profile	-	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)	Wind Profile A (South Africa)						
CAPEX	USD/kW	7.500	7.500	7.500	1.708						
OPEX	USD/kWp/a	180	180	180	40						
Degradation	%/year	1,60%	1,60%	1,60%	1,60%						
Wind Farm Capacity Factor	%	43%	43%	43%	43%						
Wind spatial requirements	m2/MW	-	-	-	-						

Thermal Plant

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Plant Type	-	Heavy-duty Gas Turbine	Heavy-duty Gas Turbine	Medium Speed Diesel Generator	Heavy-duty Gas Turbine						
Fuel type	-	Natural gas	Natural gas	Diesel fuel	Natural gas						
N-1 level of reliability?	0 / 1	0	0	0	0						
CAPEX	USD/kW	800	800	900	800						
OPEX Fixed	USD/kW/a	12	12	20	12						
OPEX Variable	USD/kWh	0,004	0,004	0,005	0,004						
Fuel Price Scenario	-	Gas Price Scenario Med	Gas Price Scenario Med	Diesel Fuel Price Scenario Med	Gas Price Scenario Med						
Base Fuel Price in 2021	USD/GJ	6,36	6,36	20,18	6,36						
Diesel: Conversion to Liters	USD/L	0,24	0,24	0,77	0,24						
Fuel Price addition A (taxes, subsidies, etc.)	%	-20%	-20%	-	-						
Fuel Price addition B (transport cost, etc.)	USD/GJ	0,50	0,50	4,00	6,00						
Diesel: Conversion to Liters	USD/L	0,02	0,02	0,15	0,23	-	-	-	-	-	-
Total Fuel Price in 2021	USD/GJ	5,59	5,59	24,18	12,36						
HR Degradation	%/year	0,10%	0,10%	0,10%	0,10%						
Baseload HR	kJ/kWh	9.900	9.900	8.000	9.900						
HRCF polynomial constants	a	-3,0525	-3,0525	-1,0636	-3,0525						
	b	7,4360	7,4360	2,5305	7,4360						
	c	-6,2228	-6,2228	-2,0399	-6,2228						
	d	2,8394	2,8394	1,5731	2,8394						
Ideal Load Factor	%	100%	100%	100%	100%						
Minimum Load	%	30%	30%	30%	30%						
Start-up fuel consumption	GJ/start/MW										
Thermal spatial requirements	m2/MW										
Specific CO2 emisions	kgCO2/GJ fuel	56	56	74	56	56	56	56	56	56	56

Balance of Mini Grid System

Description	Unit	D-1	D-2	E-1	E-2	User Input 1	User Input 2	User Input 3	User Input 4	User Input 5	Last business case
Grid Supply Connection Cost	USD/kW	100	100	100	100						
Grid Supply Connection Capacity	kW	-	-	-	-						
Grid Supply Connection Cost	USD	-	-	-	-						
Tariff - Grid Connection	USD/kW/a	-	-	50	50						
Grid Supply Connection Cost	USD/a	-	-	-	-						

APPENDIX B. FOSSIL FUEL GENERATOR VALUE CHAIN

B.1. Small scale fossil fuel generators

In this section we address the value chain of the small-scale fossil fuel generators, which make up a large proportion of energy generation in rural Africa. The regional focus here is that of Sub-Saharan Africa with some country specific examples used.

B.1.1. General Description

The very high penetration of fuel generators across Africa has historically been a response to the lack of transmission infrastructure in rural areas and a low quality of service from the national grid. A 2019 report by A2EI[41] estimates that in Nigeria there are between 22 million and 60 million generators in use in the domestic and MSME sector alone. Although there is variation from market to market, the energy service quality challenge exists across the continent. It is estimated that as much as 75% of fossil fuel generators are operated at sites that are already grid connected.[42] This implies that the weak grid market is significantly larger than the off-grid market.

Figure 50: A hairdresser on Remba Island in Lake Victoria running his hair clippers from a small petrol generator

Most of the generators being used across Africa are small imported petrol generators. These will usually consist of a small, two-stroke, single cylinder, manually started, air-cooled engine with basic electronics to provide a 220-240AV output. There will be a small fuel tank above the engine and a metal frame to protect and house the whole assembly. The generator will generally be small enough to be lifted and moved by hand, be on wheels or built into a small trolley. For most applications this mobility is key. The generators will be wheeled out whenever the grid goes down or a customer arrives at the hair salon (for example).

[41] *Access to Energy Institute, Putting an End to Nigeria's Generator Crisis: The Path Forward June 2019*
[42] *IFC, 2019, The Dirty Footprint of the Broken Grid (link)*

Figure 51: A petrol generator in rural Nigeria runs a water pump

These small ubiquitous generators benefit from sharing much of their technology with other wide-spread machines, particularly small motorcycles, and outboard marine engines. This means that the know-how to operate and repair them is also widespread and the fuel supply chains are shared, active, and established. A large proportion of these generators will be powered by fuel delivered via informal supply chains for the ‘last mile’. Their affordability means that these smaller petrol-powered generators are found in urban on-grid and rural off-grid areas alike.

Figure 52: A boat supplies passenger transport and fuel to Remba Island, Lake Victoria

Larger output diesel powered generators are used for larger critical loads (such as hospitals), on high value sites (such as safari lodges) or in high density applications such as apartment buildings in urban centres. Large, static diesel generators are also used by mini grid developers to bring down the levelized costs of energy whilst being able to ensure continuous services. Larger containerised units are also used by utilities as a (relatively) rapidly deployable supply to make up for regional shortfall in centralised grid supply. At this utility-scale, it is not unusual to find multiple containerised generation units connected, however for most applications single generators will be used. It is typical to find the grid support generators being provided as a service by a private company. For example, the UK company Aggreko was employed by the Kenyan government KenGen to provide grid support services in the western part of the country. The 30MW diesel plant sold energy into the grid at the relatively high price of $0.49 per kilowatt hour.

Figure 53: The site of Aggreko's 'emergency power' plant in Western Kenya

At the larger scale (>20kVA), single generators will often be housed in a built-for-purpose building with integrated exhaust systems and fuel storage. Most diesel generators will include built-in electronic starter systems, and many will be configured to start automatically in the case of a grid outage. Generators are especially well suited for this purpose because of their fast start-up and ramp-up times. Start-up to full load can be as fast as 10 seconds.

Diesel generators will also be used on hybrid mini grids to supplement a solar PV system. These generators will most likely be used seasonally with more use taking place at times of the year when the solar irradiation is lower or during seasons of agricultural harvest (for example) if the mini grid is being used to power agricultural processing.

Figure 54: An example of a generator waiting installation for a rural mini grid

B.1.2. Key Indicators

Generators are made up of at least nine parts, which includes the engine, alternator, fuel system, voltage regulator, battery charger, cooling system, lubrication system, assembly frame and control panel. Generators used in rural mini grids and captive power sites are typically powered by diesel, while small mobile units used in households and small business are generally powered by petrol. Dual fuel (most commonly a combination of gas and diesel) and multi-fuel generators (gas, diesel, petrol or HFO) are uncommon in these markets. HFO generators are only used at utility-scale or very large industrial captive power sites such as mines. Petrol generators, constituting the largest share of the market in Sub-Saharan Africa in terms of units sold have small power capacities, typically not exceeding 10 kVA. Generators larger than 10 kVA are generally diesel powered, although this is a crude threshold given that overlap does exist. Generators running at 3,600 RPM are considered high-speed generators and the majority of these are configured with petrol engines. Low speed generators typically run at less than 1,800 RPM and the majority of these are powered by diesel. Again, overlap is not uncommon. Smaller generators provide single phase AC output and larger ones generate three phase AC output, with the size threshold at approximately 10 – 20 kVA. Efficiency depends on generator size and engine loading. Typical efficiencies for diesel generators between 20 kW and 200 kW are presented in Figure 55. Note that diesel generators are more efficient than their petrol counterparts.

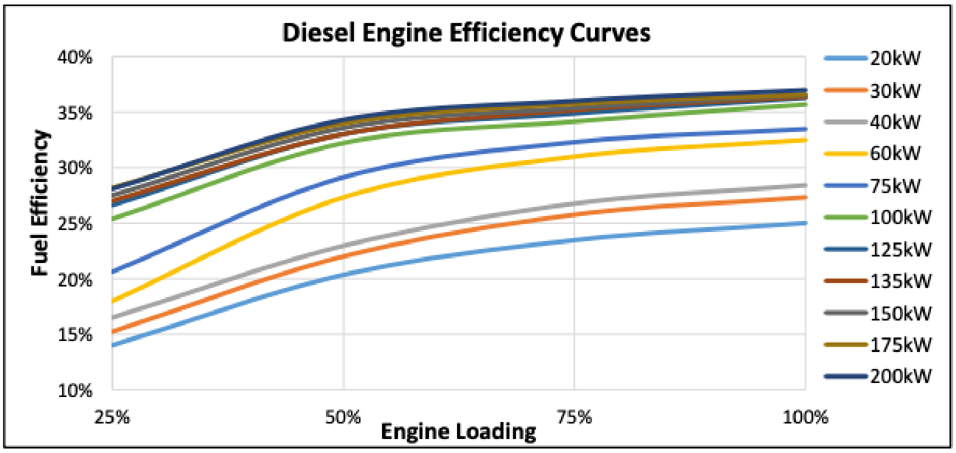


Figure 55: Typical diesel generator efficiencies[43]

The backup generator fleet across the developing world is estimated to be 450 GW.[44] While this large fleet is instrumental in plugging the gaps left by unreliable and non-existent grids, they have a variety of negative environmental and health consequences. Their contribution to climate change through carbon dioxide emissions is well documented and their nitrogen dioxide, sulphur dioxide and carbon monoxide emissions cause a variety of negative health impacts.

Electricity from fossil fuel generators can be as much as four times the price of grid power,[45] and is heavily influenced by fuel cost and in turn fuel subsidies. On average, governments in Sub-Saharan Africa subsidise diesel with an amount equal to 0.61% of gross domestic product (GDP) and petrol with an amount equal to 0.81% of GDP.[46,47] Fuel cost also differs depending on where in a country it is accessed. Transportation costs can add a significant price premium, especially in areas with low quality transportation infrastructure. As a result, retail fuel prices in inland areas can be approximately 5-15% higher than prices in coastal areas or close to capital cities.[48] At the most rural sites (typically mini grids), prices can be even higher due to the cost of transporting fuel beyond small towns and into the last mile. Levelized cost of energy of diesel-only mini grids range between \$0.89/kWh - \$1.28/kWh, while hybridisation with solar can bring this range down to \$0.49/kWh - \$0.68/kWh.[49]

[43] *Ireland, G. Techno-economic modelling of hybrid renewable mini grids for rural electrification planning in Sub-Saharan Africa, 2017 (link)*
[44] *IFC, The Dirty Footprint of the Broken Grid, 2019 (link)*
[45] *McKinsey & Company, Brighter Africa - The growth potential of the sub-Saharan electricity sector, 2015 (link)*
[46] *TFE Africa analysis based on IMF data*
[47] *Sudan has been excluded from the analysis due to its unusually high fossil fuel subsidies. The country subsidises diesel to the extent of 29.07% of GDP and petrol with 12.79% of GDP*
[48] *TFE Africa analysis based on data from national fuel cost tables*
[49] *Sustainable Energy for All, 2020, State of the Global Mini grid Market Report, (link)*

B.1.3. Value Chain

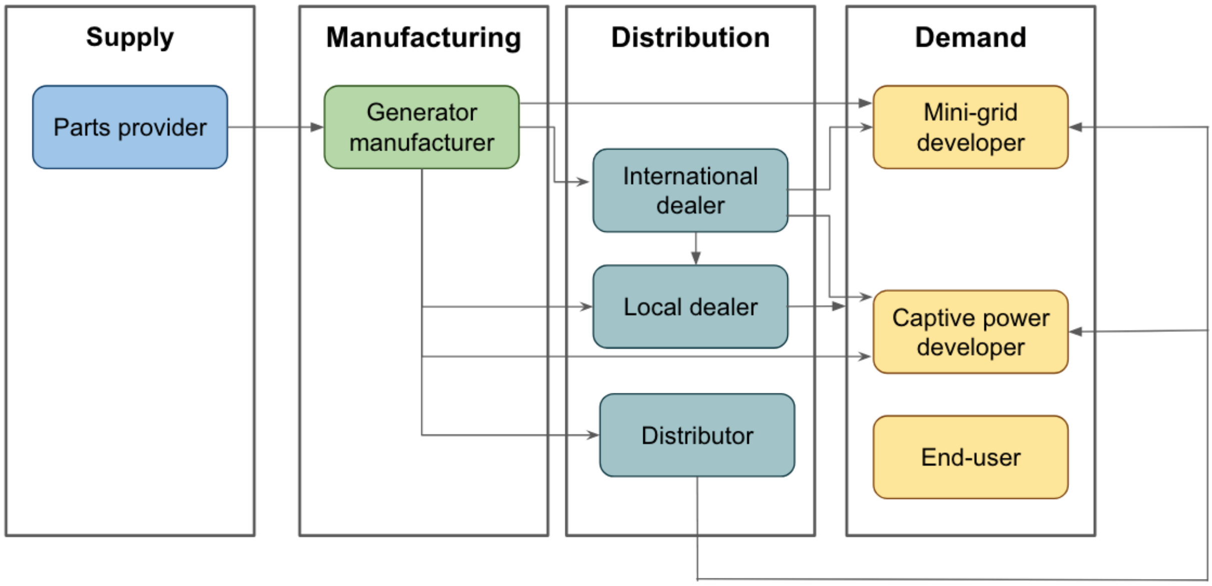


Figure 56: Supply chain dynamics of fossil fuel generators

Manufacturing

Generator manufacturing from scratch is not common in Sub-Saharan Africa. Thus, most generators used across the region are imported as finished products or as components which are then assembled. China is the leading manufacturer of diesel generators used in Sub-Saharan Africa.[50] Total imports from all countries of origin, in terms of MW, vary widely by country. Data from 2017 shows that Nigeria imported a total diesel generator fleet of 2,534 MW, but other countries lagged far behind. The other two larger generator markets (barring South Africa), Kenya and Ghana, imported 426 MW and 173 MW respectively, while smaller markets such as Rwanda and Botswana were limited to 17 MW and 6 MW respectively.[51] Unsurprisingly, Nigeria is also one of the largest petrol generator markets in the world. In 2019, the country was the second largest export market for Chinese petrol generators – a total of 1.45 million units was imported into the country from China.[52]

Genset manufacturers (for example MPMC) typically use generic components to produce generators and couple these with recognised generator engine manufacturers such as Perkins, Mitsubishi, Kholer and John Deere. As an example, SDMO uses both John Deere and Kholer engines in their generators. Other companies such as Deutz and Caterpillar are more vertically integrated and use in-house manufactured engines in the production of generators. A wide range of alternator brands are used by the major generator manufacturers and includes Mecc Alte, Marelli Motors and Linz Electric.

Most of the largest generator and engine manufacturers have sales offices and manufacturing facilities situated around the world, including Cummins, Wärtsilä, John Deere and Perkins. Yet despite this global spread, most of the manufacturing often still takes place in China. For example, in 2019, 40% of Cummins' manufacturing took place in China alone. Companies such as MPMC manufacture exclusively in China while others such as Deutz have manufacturing facilities in Europe and North America only.

Several multinational generator manufacturers have also opted to set up subsidiaries in major African markets. These subsidiaries typically come in the form of retail or wholesale facilities that hold stock that comes from the company's

[50] *African Review, Is the genset market going to turn in 2018? 2018 (link)*
[51] *Bloomberg New Energy Finance, Solar for businesses in Sub-Saharan Africa, 2019 (link)*
[52] *Kent Power, Overview of China's Generator Set Exports in 2019, 2020 (link)*

manufacturing facilities in China, Europe, or North America. For example, Himoinsa set up its first facility in South Africa in 2016,[53] while major brands such as Aggreko, CAT and Deutz have multiple outlets across the region.

Shipping and procurement

The mini grid sector is still in its infancy and project pipelines are often erratic. As a result, mini grid developers often do not meet the order volumes required for direct purchases from manufacturers, nor do they have the funding or appetite to hold large stocks of generators. This is despite the fact that developers often prefer to use similar brands and similar sized generators across most of their sites, giving rise to the potential to purchase generators in bulk and enjoy economies of scale. Developers prefer similar brands and similar sized generators because the benefits of standardising maintenance often outweigh the benefits of optimally sizing generators. Consequently, mini grid developers procure generators through a combination of international wholesale dealers and domestic dealers dependent on project scale and pipeline.

Captive power and mini grid developers alike tend to enjoy better pricing when buying from international suppliers compared to local suppliers. For example, research shows that a generator can be purchased at $350 per kVA from an international wholesale supplier in China but will cost $580 per kVA when bought from local dealers in Kenya, Tanzania or Uganda, equal to a local dealer mark-up of 40%. Yet, despite this lower cost, developers often must resort to buying from local dealers. Project pipelines tend to be sporadic and as a result equipment orders must be made on an ad-hoc basis. Bulk procurement from international dealers or directly from manufacturers would be a way to circumvent this, but aggregation of orders becomes difficult if the developer does not have a pipeline consisting of a sufficient number of projects. This remains an issue for developers in both market segments, as many have not yet reached the scale required to practice bulk procurement. Trends do however indicate that as captive power and mini grid markets grow in the region, developers are increasingly growing towards the level required to take advantage of scale economies.

Wholesale supply is limited to capital cities and some larger towns with limited supply outside the metropolises. Generators are typically purchased outright, as both international and domestic suppliers tend to be hesitant to offer credit terms. Developers are only availed limited terms by some international suppliers, for example as 30% deposit and 70% on shipping. This only marginally assists with cash flow.

Lead times of generator orders from international manufacturers is relatively short compared to lead-acid and lithium-ion batteries. Manufacturing lead times tend to be 4-6 weeks and shipping approximately 8 weeks.[54] These relatively short lead times suit project development timelines, provided that the developer does in fact have the necessary scale to buy directly from international manufacturers. In such cases, developers tend to purchase complete generator units as opposed to purchasing components and assembling in-house. In most countries across the region, generators are taxed[55] the same, irrespective of whether they are bought assembled or as components.[56] Across the region, fossil fuel generators are occasionally exempt from import duties, but are typically subject to standard VAT rates. For example, generators are exempt from import duties in Kenya, but subject to duty rates of 5% in Nigeria. VAT rates of 16%, 7.5% and 15% apply in Kenya, Nigeria, and South Africa respectively. In South Africa, generators are subject to a 20%, 18%, 16% or 0% import duty depending on the origin.

According to our research, when importing from international wholesalers, mini grid and captive power developers usually request cost, insurance, and freight (CIF) terms and compare this with 3rd party logistics costs found by in-house logistics teams for Free on Board (FOB). This demonstrates the difference between some developers opting to import goods and others procuring equipment through domestic wholesalers instead. Generators are transported through traditional shipping routes through the major African ports such as Mombasa, Dar es Salaam, Lagos, and Cotonou and then by truck to developer warehouses and project sites. Major ports in Sub-Saharan Africa are notoriously time-inefficient, with cargo dwell time in Mombasa and Dar es Salaam amounting to 11 and 14 days

[53] *Wilkinson, R., 2017, Generator giant to expand its Southern Africa network, (link)*
[54] *Indicative based on interviews*
[55] *Referring to value added tax and import duties*
[56] *Some exceptions do exist, for example, the Southern African Customs Union applies a 20% import duty on assembled generating sets and a 0% duty on components*

respectively.[57] The average dwell time in ports across Sub-Saharan Africa is 16 days. When considering all types of ports of entry, World Bank data shows that the median lead time to import goods from all types of port of dispatch (border) to destination in Sub-Saharan Africa is 6.8 days, which is more than that of South Asia (4.3 days) and South America (5.2 days).[58] It follows that mini grid and captive power developers in Sub-Saharan Africa are disproportionately affected by inefficient logistics infrastructure.

Minimum quantities per order are usually based on container volume. In the case of a 20 ft container, this translates to approximately six 10 kVA units. Logistical challenges typically only arise on small island sites where ports and boats are small and can't handle the weight and size of prefabricated systems. In such scenarios, developers must send components and assemble generators on site. This challenge may present an opportunity for lighter and more modular technologies such as lithium-ion batteries as the same issue persists with generator refuelling and maintenance.

Assembly & Integration

There are minimal alterations done to generators by mini grid and captive power developers. Most generators can be purchased pre-configured to different local country voltages. Alterations are limited to adding remote monitoring capabilities, custom exhaust systems and increasing fuel tank size. Fuel tank sizes are increased to allow developers (especially mini grids) to match refuelling to bi-annual routine maintenance. In the case of a 12 kVA diesel generator which comes standard with a 60l tank, developers often add an additional 1000l external tank, effectively increasing capacity almost 18-fold. The major challenge in this case is fuel theft.

Operations and maintenance

Mini grid developers typically maintain generators through an in-house operation and maintenance (O&M) team which covers reactive, corrective, and periodic maintenance. The O&M team in addition conducts remote system monitoring. Surveyed developers are looking to begin outsourcing generator maintenance as these skills are widely available given the proliferation of generators and the ease of skills transfer from the automotive industry. Specialisation gains through outsourcing generator maintenance to specialist companies or agents has the potential to reduce generator maintenance costs for mini grid developers.

Typical generator maintenance (irrespective of whether deployed at a mini grid or captive power site) occurs after 250 operational hours or three months (whichever comes first). Maintenance is cumbersome and costly in comparison to batteries and involves general cleaning, changing oil, changing air filters, changing oil filters, refuelling, and performing leakage inspections. These activities, as well as other O&M tasks can add expenses of approximately 10-20% on top of fuel costs.[59]

A key difference between mini grid and captive power generator life cycles is the nature of O&M. In the captive power market, O&M is dependent on the type of client and structure of the captive power contract. In the case of energy service companies (ESCOs) and clients with signed O&M contracts, the developer maintains generators in a similar manner to that of mini grids. Most clients opt for O&M contracts, however there are some rare cases where clients prefer to use their in-house technical teams in a hope to reduce OPEX costs. These are typically manufacturing and mining firms which have existing technical teams for other machinery at the same sites.

Re-use and recycling

Generator life expectancy mainly depends on operating conditions, frequency of maintenance and fuel and oil quality. In addition, a generator that only operates for a small number of hours per year will last much longer than one that operates near constantly, all else being equal. Table 22 indicates estimated life expectancy of generators distinguished by rated capacity and engine type.

[57] *The World Bank, Why does cargo spend weeks in Sub-Saharan African ports? 2018 (link)*
[58] *The World Bank & Turku School of Economics, Lead time to import median case (days), 2018 (link)*
[59] *IFC, The Dirty Footprint of the Broken Grid, 2019 (link)*

Table 22: Average estimated life expectancy of small- and medium scale generators[60]

Generator type	Rated capacity (kW)	Estimated lifetime (hours)
High-speed (3600 RPM) air-cooled petrol	1 - 10	250-1,000
High-speed (3600 RPM) air-cooled diesel	4 - 20	6,000 - 10,000
Liquid-cooled diesel	7 - 10,000	20,000 - 80,000

Generators operating in third generation mini grids and commercial small-scale captive power projects have not yet reached their end of life and as a result best practices on the re-use and recycling of generators have not emerged yet.

Value Chain Dynamics

A key consideration of the small-scale petrol generator value chain is its informality. Due to the similarity of technology built into these generators and other common machines such as motorcycles and outboard marine engines, expertise required for operations and maintenance is available from the most well-established commercial workshops in urban centres to the smallest of deep rural workshops. As a result, operations and maintenance of small-scale generators are typically done locally. Fuel supply to these small-scale generators are also often done informally (see Figure 52).

Larger, diesel-powered generator value chains are typically more formalised as these systems are more often used in facilities with more complex processes (e.g. manufacturing), more intensive energy demand and higher reliability requirements. Engines and other components are typically purpose built for generator use cases.

On the manufacturing front, the past few years have seen many fossil fuel generator companies make inroads into the energy storage industry. Energy storage companies Younicos and Greensmith have respectively been acquired by Aggreko and Wartsila, while Rolls-Royce made a large investment in Qinous. Traditionally generator-focused companies are now also operating hybrid back-up power systems. For example, Aggreko has been operating its first solar plus storage system, hybridised with a diesel generator. The 7.5MW solar plant, backed up with a 22MW diesel generator, is powering the Bisha copper and zinc mine in Eritrea. This illustrates the increasing market importance of battery energy storage solutions specifically in the context of distributed systems and the gradual de-prioritisation of the generator market relative to BESS. It remains to be seen whether this will lead to a gradual consolidation of value chains across BESS and generators.

B.1.4. Sub-Saharan Africa Perspective

Relative Market Size

Estimates of generator fleet sizes across Sub-Saharan Africa vary widely. However, in comparison to other developing regions, Sub-Saharan Africa is the largest regional user of fossil fuel generators with 9% of annual electricity consumption coming from generators. This is far higher than the 2% of the second largest consumer, South-Asia.[61] Installed capacity of back-up generators in Sub-Saharan Africa is twice the installed capacity of the grid.[62] Generators account for 15% of gasoline and 22% of diesel consumption in Sub-Saharan Africa.[63] The total value of generator fleets across Sub-Saharan Africa is roughly estimated at $15.7 billion.[64]

West Africa is by far the largest regional market in Sub-Saharan Africa, with generators accounting for 40% of total electricity consumption, four times that of East Africa. Nigeria is a strong contributor to this statistic, with the most

[60] *HOMER Pro, 2021, Generator lifetime, 2021 (link)*
[61] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*
[62] *Ghandi, D., 2019, Deployment and use of back-up generators in Sub-Saharan Africa, (link)*
[63] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*
[64] *TFE Africa analysis based on IFC data*

generators in Sub-Saharan Africa.[65] In 2019, half of all available power in Nigeria was generated by back-up generators.[66] In terms of generators per 100 people, South Africa ranks first, followed by Angola and Nigeria.[67]

In terms of numbers of units, small petrol generators are the most prevalent type of generator in Sub-Saharan Africa. Medium and large diesel generators (> 60 kW) however represent the largest share of installed capacity in the region.[68]

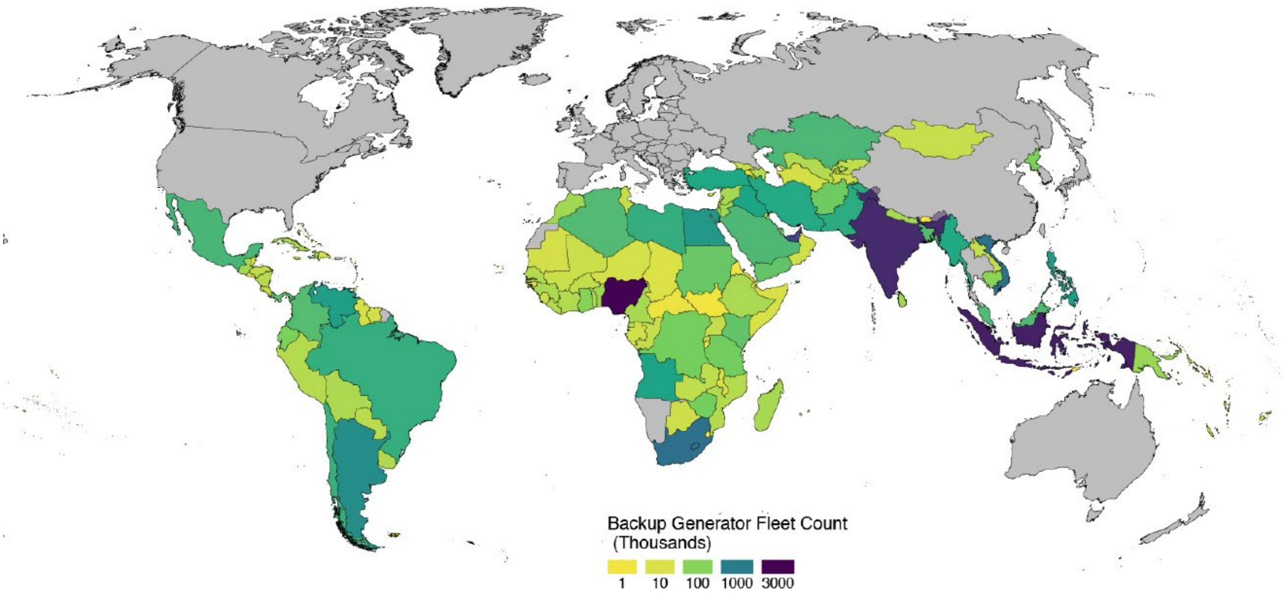


Figure 57: Global generator fleet by country*[69]*

Despite the increasing market importance of BESS, the fossil fuel generator market has continued to grow. In 2018, the African market for diesel generators grew by 3%, with Nigeria growing at 2%.[70] It is worth noting that the Africa-wide average is increased by North African countries that experienced faster growth than Sub-Saharan Africa. For example, over the same period, Algeria experienced 7% growth.

Major & Key Players

[65] *Exact fleet sizes in numbers of units are not provided because estimates vary too widely*
[66] Bloomberg New Energy Finance, 2019, Solar for businesses in Sub-Saharan Africa, (link)
[67] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*
[68] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*
[69] *IFC, 2019, The Dirty Footprint of the Broken Grid, (link)*
[70] *The African Review, 2019, Africa's genset demand bouncing back, (link)*

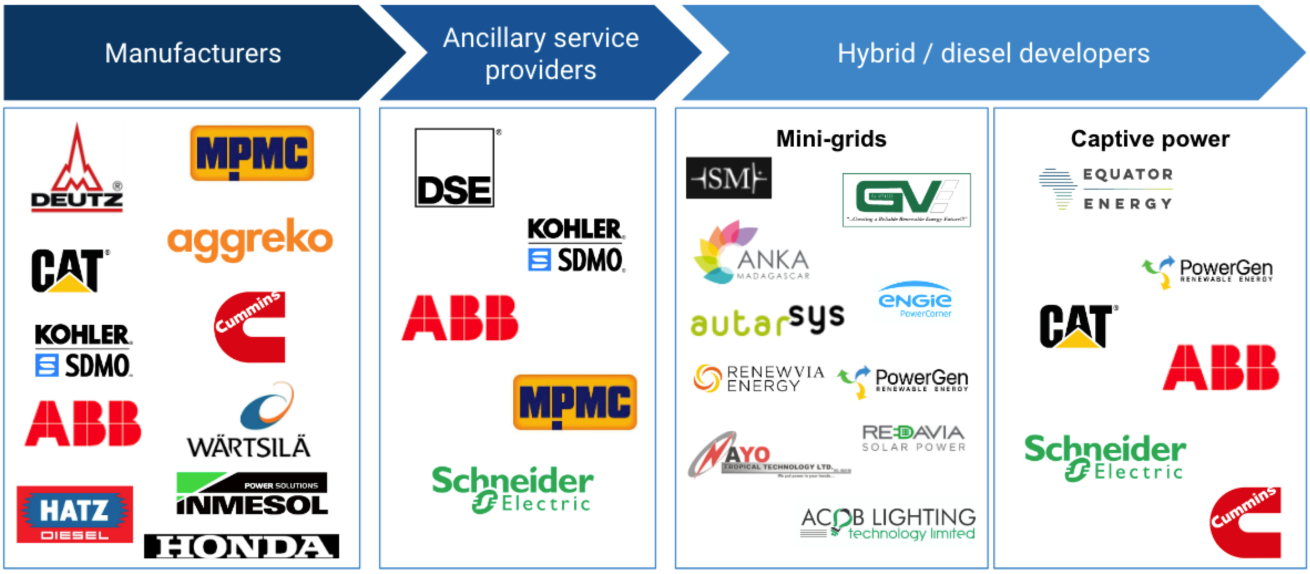


Figure 58: Main players along the generator value chain (indicative)

B.2. Gas Turbines

B.2.1. General Description

For utility-scale power generation, gas turbines are the main power generation technology used in much of the world due to the availability of relatively low-cost natural gas fuel and the low emissions that can be achieved. Gas turbine power plants come in two main configurations: open (or simple) cycle and combined cycle.

a) **Open (or simple) cycle gas turbine (OCGT) power plant**: In this configuration the gas turbine is connected to a generator and this is the only source of electricity production, similar to the schematic shown in Figure 59. The main benefit of this configuration is the flexibility and fast response time of the plant. The power output can be quickly ramped up or down to meet demand or grid requirements, though not as quick as diesel generators can. The downside is a relatively low thermal efficiency of about 30-36% (depending on the size and design).

b) **Combined cycle gas turbine (CCGT) power plant**: In this configuration the gas turbine hot exhaust gasses are used to produce steam in a heat recovery steam generator (HRSG), and that steam drives a separate steam turbine and generator. This process is illustrated in Figure 60. The main benefit of a CCGT power plant is the high thermal efficiency of up to 61%. This comes at a cost of lower flexibility as the steam cycle cannot respond quickly as that causes thermal stress on the equipment. This makes this configuration ideal for relatively constant (base) load operation at a large scale.

The complexity of the combined cycle plant is much higher, resulting in much longer construction periods (several years instead of weeks or months for packaged open cycle turbine units. The higher complexity also requires a more skilled workforce to operate and maintain the plant.

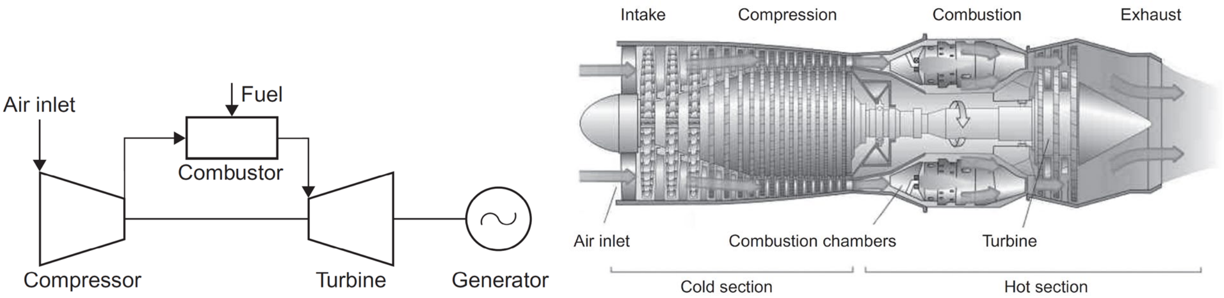


Figure 59: Gas turbine for power generation simplified schematic and example cross-section

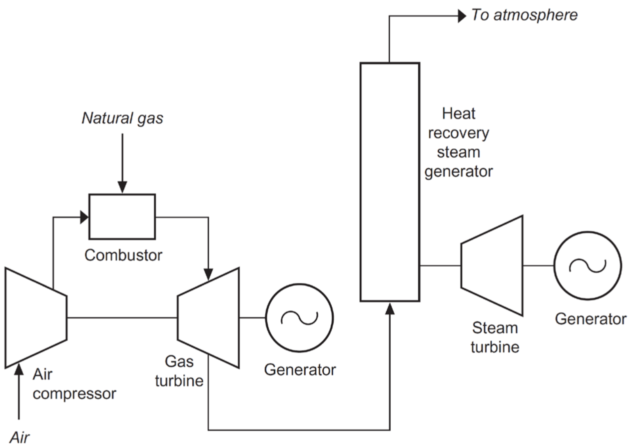


Figure 60: Combined Cycle Gas Turbine power plant simplified schematic

B.2.2. Key Indicators

The focus of this report is on open cycle gas turbines, as these are often used for peaking operation (short duration power output to meet peaks in demand) and have a lower efficiency that allows for more savings by the alternative BESS (+ renewables) power supply.

Gas turbines depend on the availability of natural gas fuel (pipelines), as the alternatives of LNG (liquified natural gas) or diesel fuel oil are much more expensive. Availability of natural gas is very limited in most of Sub-Saharan Africa, which is one of the main reasons gas turbines are used relatively little compared to most OECD countries.

One main benefit of open cycle gas turbine plants is that they can be constructed in only a few months if needed, when based on packaged gas turbine units, when permits and fuel supply are already arranged. The footprint of the turbine is small, for a 20 MW industrial gas turbine an area of about 10x20 m could be sufficient. An example of a large industrial gas turbine is shown in Figure 61. These characteristics make gas turbines an interesting option when (flexible) power is needed quickly.

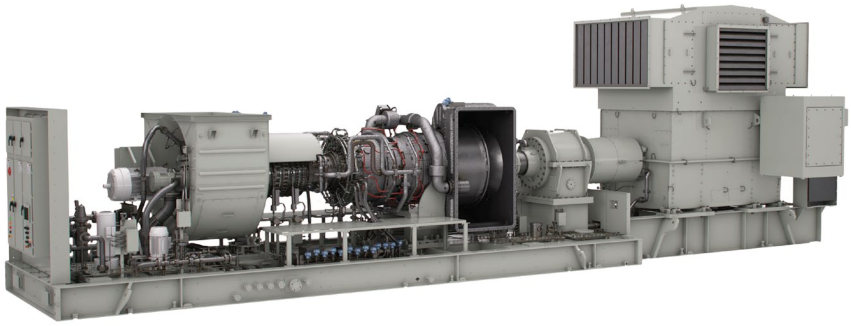


Figure 61: Example 23 MW Industrial gas turbine and generator package

Gas turbine performance

There are two main characteristics that describe the performance of gas turbines: power output (MW) and heat rate (kJ/kWh) or efficiency (%). The heat rate (HR) is the amount of fuel energy (in kJ, at lower heating value) needed to produce one kWh of electricity. Efficiency is the inverse of the HR: amount of electrical energy produced divided by the fuel energy input (both in kJ). To illustrate this, a HR of 3,600 kJ/kWh would mean an efficiency of 100% (3,600 kJ electricity / 3,600 kJ fuel), while a HR of 10,000 kJ/kWh would mean an efficiency of 36% (3,600 kJ electricity / 10,000 kJ fuel).

In general, the heat rate of turbines improves with their capacity, as larger turbines can be designed with lower thermal losses and the use of higher performance (and more expensive) materials is justified as these costs can be spread over a larger energy output. To give an indication of the expected HR for different gas turbines capacities:

- Small scale industrial turbines (several MW): 12,000 kJ/kWh (~30% efficiency)
- Larger industrial turbines (~20 MW): 10,700 kJ/kWh (~34% efficiency)
- Utility-scale units ("F" and "H" class, >200 MW): 9,000 kJ/kWh (~40% efficiency)

The power output and heat rate provided are normally valid for 100% load (base load) at ISO conditions (15 °C, 60% relative humidity, ambient pressure of 1 bar). In practice actual conditions will be different and the performance of the gas turbine will deviate from the reference performance. The main parameters to consider are:

1. **Ambient temperature**: higher inlet air temperature reduces power output and increases heat rate (reduces efficiency) as the air going into the compressor is less dense, reducing the mass flow (and associated power output with about 0.7% per °C) and increasing the energy required for compression (increasing HR with about 0.2-0.3% per °C). This is illustrated in Figure 62.

2. **Ambient pressure**: lower inlet air pressure reduces power output as the air density is lower and the mass flow is reduced, but the heat rate stays constant.

3. **Load factor**: the heat rate increases (efficiency decreases) when a gas turbine is operated below 100% load. An example is shown in Figure 63. This shows the hight impact of operating at lower load and the cost of flexibility: when operating at 50% of rated capacity the heat rate can increase by more than 20%.

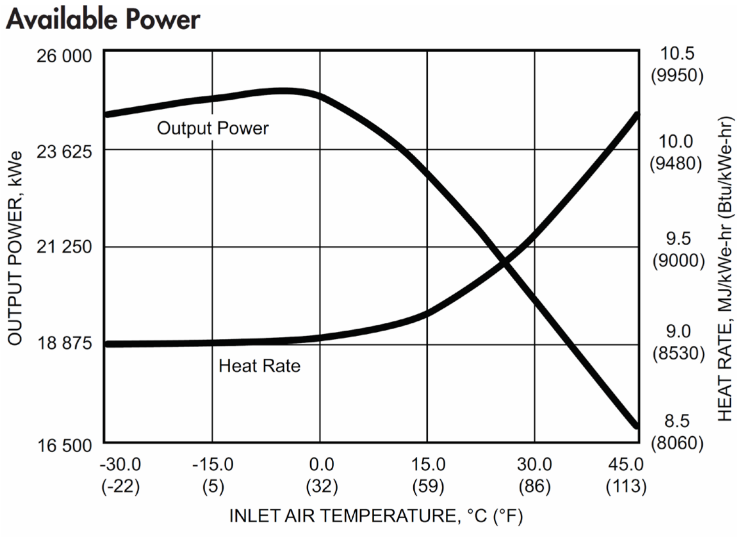


Figure 62:Industrial gas turbine power and HR vs ambient temperature

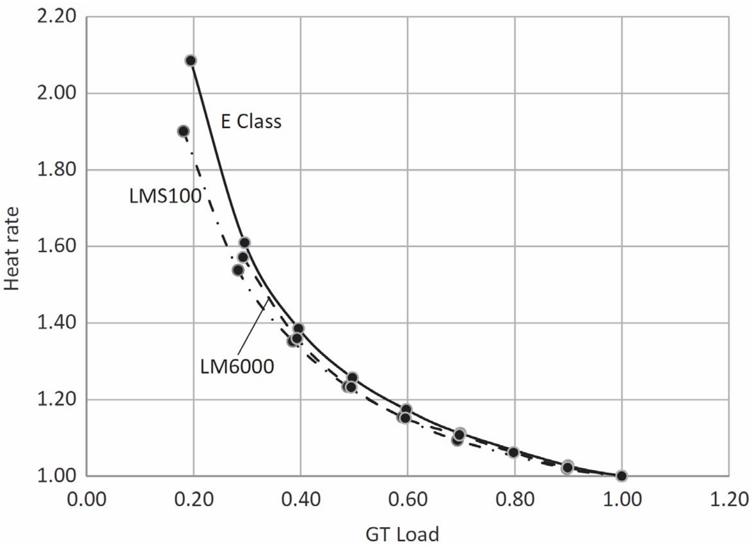


Figure 63: Impact of gas turbine load factor on HR example

Combined heat and power

A main benefit of gas turbines is that the hot exhaust gases can be used to provide steam for industrial processes as well, producing energy not only as electricity but also as usable heat. This configuration sits somewhere in-between the open cycle and combined cycle plant, as it has a heat recovery steam generator (HRSG) like the combined cycle plant, but not the steam turbine-generator. The steam generator can operate at a lower steam pressure, matching the require steam temperature of the industrial process. The combined heat and power efficiency ($\frac{Electricity+heat\ produced}{Fuel\ heat\ content}$) can be much higher and can even exceed 90% (when low temperature heat is needed).

This study will not focus on combined heat and power applications, as these are already very efficient applications of fossil fuels and these are difficult to replace by energy storage (which is electricity only).

Maintenance considerations

Maintenance is based on periodic inspections (and replacement of parts) that can be categorised as follows (from minor to major maintenance, with example intervals in hours of operation and starts[71]):

- Combustion Inspection (CI, interval: 12,000 hours or 800 starts): relatively short disassembly inspection of fuel nozzles, liners, transition pieces, crossfire tubes and retainers, spark plug assemblies, flame detectors, and combustor flow sleeves.
- Hot Gas Path (HGPI, interval: 24,000 hours or 1200 starts): examine those parts exposed to high temperatures from the hot gases discharged from the combustion process.
- Major Inspection (MI, interval: 48,000 hours or 2400 starts): examine all the internal rotating and stationary components from the inlet of the machine through the exhaust.

These maintenance intervals are influenced (reduced) by several factors, including fuel used (gas, diesel, HFO), (fast) starts, trips and high ramp rates.

These are important aspects of gas turbines, as these illustrate where energy storage can play an important role:

d) Allow gas turbines to operate closer to full load and at their lowest heat rate (maximum thermal efficiency)

e) Gas turbine specific fuel consumption is higher in regions with higher ambient temperatures, making energy storage and renewables more competitive

f) Avoid start/stop behaviour and reduce ramp rates to reduce maintenance costs

The main gas turbine manufacturers acknowledge this and started offering different energy storage products to augment their gas turbine offerings (e.g. GE, Siemens, Solar Turbines).

B.2.3. Value Chain

Manufacturing and supply

The gas turbine manufacturing market is very concentrated and a handful of suppliers are projected to have over 96% of the market (by value) as is illustrated in Figure 64.The main suppliers are:

- GE Energy: 46%
- Siemens: 22%
- MHPS (Mitsubishi Power): 16%
- Ansaldo Energia: 6%
- Mitsubishi Heavy Industries (MHI): 3%
- Solar Turbines: 3%
- Others: <4%

[71] GE GER 3620P, Jan. 2021, Heavy-Duty Gas Turbine Operating and Maintenance Considerations

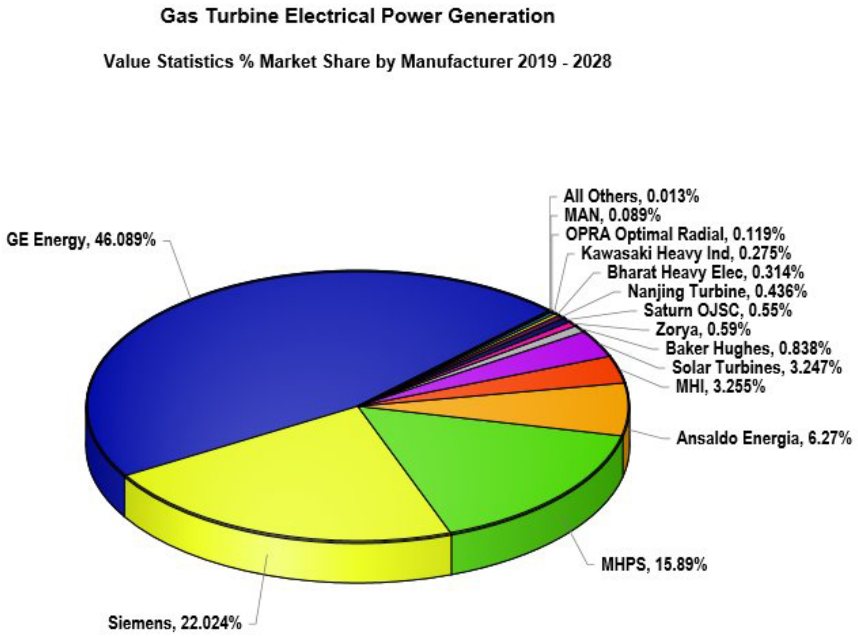


Figure 64: Gas turbine market share by manufacturer forecast[72]

About 80% of the market value is in large-scale turbines (unit capacities >70 MW), utilised in centralised combined cycle power plants, as is indicated in Figure 65. Where battery storage is much more likely to compete directly with gas turbines is for smaller scale units often used as captive power at industrial sites or for distributed generation in remote/isolated areas. Although both General Electric and Siemens also produce turbines for these smaller capacity applications, the smaller scale suppliers produce for this market exclusively and have a relatively larger market share. The main suppliers for the smaller (<15 MW) turbines are Solar Turbines (owned by Caterpillar), followed by MAN and Kawasaki.

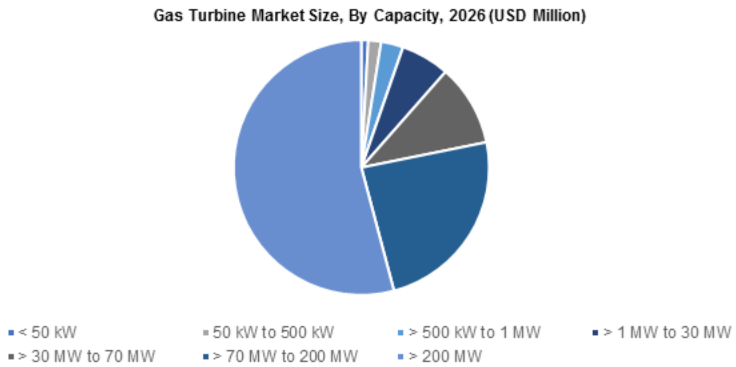


Figure 65: Gas turbine market split by unit capacity[73]

Assembly and Integration

In most cases the OEM (original equipment manufacturer) is also responsible for shipping and installing the equipment on site, or their licensee. Separate EPC (engineering, procurement, and construction) contractors are sometimes used, though they would still depend heavily on the OEM for the main power island part. Civil works (buildings, foundations, roads, etc) and the grid connection (transformers, switchgear, cables, overhead lines) may be done locally or be provided by other international suppliers.

[72] *Worldwide Gas Turbine Report, www.turbomachinerymag.com*
[73] *Global Market Insights, www.gminsights.com*

Operations and maintenance

Gas turbines require qualified operational and maintenance staff to ensure safe and reliable operation of the plant and to supervise the daily maintenance work. Often the manufacturer provides the main maintenance services (maintenance inspections: CI, HGPI, MI) as part of a long-term service agreement (LTSA). The manufacturer would provide the main expert staff to supervise, and the local O&M team would support and carry out much of the work. Having staff available with the right qualifications can be a barrier for gas turbine-based projects.

Decommissioning

Gas turbine-based power plants are very compact and most of the equipment materials can be recycled (mainly steel). Especially if the plant operated on natural gas, the risk of soil contamination would be minimal. For gas turbines operating on diesel fuel or heavy fuel oil there would be a risk of more significant restoration efforts to remove any oil contamination from the soil.

Value Chain Dynamics

The gas turbine value chain is characterised by a very limited number of international suppliers and after procurement the owner is locked in a long-term relationship with the selected supplier. This makes it important to consider the long-term local presence of the manufacturer to ensure a sufficient level of technical support over the project lifetime.

B.3. Diesel Power Plants

B.3.1. General Description

Throughout Africa, utilities make use of thermal power plants. In some cases, the plants are designed only for burning liquid diesel fuel, others operate only on gas, but the growing trend is engines that can utilise both gas and diesel, as seen in Figure 66.

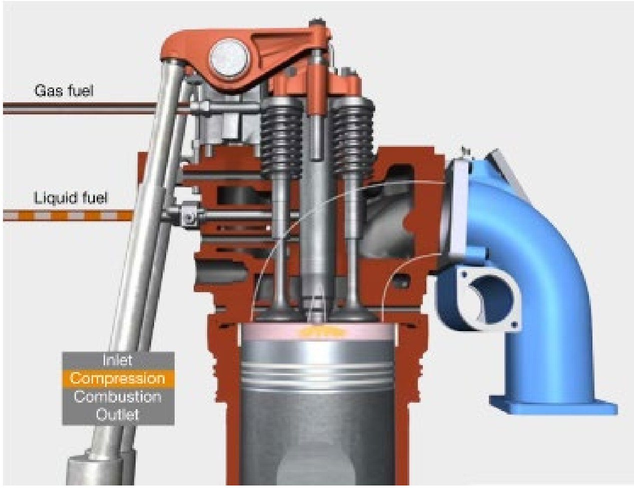


Figure 66: Gas-Diesel combustion engine

Liquid fuel generators make power available anywhere, anytime. Proven long-term reliability makes these engines suitable for stationary and floating baseload, and for stand-by applications.

In Gambia, the multinational company MAN Energy Solutions has secured a contract to supply two of its 9L51/60 engines for a newly built power plant in Brikama, the second largest city in the Gambia. This plant will supply 18Mw, accounting for 20% of energy supply in the country. Overall, the country will then be relying on diesel power plants for 42MW or a third of their capacity[74]. This is an example of a small power plant, but there are much larger diesel power plants in Africa.

In Ghana, there are three power plants that either run on pure diesel fuel or a combination of natural gas and diesel. These plants range in size from 230MW to 340MW[75]. In South Africa, where the utility, ESKOM provides 95% of the power in the country making up 42% of the power in Africa, Diesel power plants are increasingly used for peaking plants. In 2019 when the utility could not provide enough power to meet demand, due to failing plants, the utility spent R7.5 billion on diesel to avoid “load shedding”, but still ended up rationing power for 46 days[76].

B.3.2. Key Indicators

Generally, the engines designed for liquid fuel operation can make use of either crude oil, heavy (residual) fuels and distillate diesel oils. Renewable fuels include vegetable oils, animal fats and second-generation biofuels (such as biomass-to-liquid fuels). The engines for heavy fuel oil (HFO) and diesel fuel power plants have an extraordinary robust design that makes them highly reliable.

The various liquid fuels can be defined as follows:

LIGHT FUEL OIL

[74] *18MW Diesel Power Plant Installed in The Gambia - Green Building Africa*
[75] *List of power stations in Ghana - Wikipedia*
[76] *Eskom needs R1 billion a week from government to keep the lights on in 2021 (businessinsider.co.za)*

Light fuel oils or diesel oils are high value distillates that have traditionally been used to fuel diesel engine power plants, both for stand-by operation and baseload applications. The use of light fuel oils in baseload applications has decreased since it has become possible to use cheaper lower grade fuels. There are, however, certain applications, such as backup power plants, and installations on islands and in arctic conditions, where light fuel oil is still the preferred alternative.

HEAVY FUEL OIL

Heavy fuel oils are blended products based on the residues from refinery distillation and cracking processes. They are black viscous liquids which require heating for storage and combustion. Heavy fuel oils are used for diesel engines in power plant and marine applications.

CRUDE OIL

Crude oil is a highly complex mixture of hydrocarbons and other components. The flash point of crude oil is low, typically below the ambient temperature. Crude oil can also be used as fuel in power plants with diesel engines, for example in oilfield power production. Another application is for pumping stations located along a crude oil pipeline, where fuel from the pipeline can be used for the prime movers.

LIQUID BIOFUELS

Liquid biofuels are derived from biological material and can be produced from a variety of carbon sources. Common liquid biofuels approved for use in Wärtsilä engines include oils from various oilseeds, such as palm oil, palm stearin, rape seed oil, sunflower oil and jatropha oil. Liquid biofuels can also be of non-vegetable origin, i.e. oils or fats from fish, poultry, and animals. Refined biofuel qualities, such as trans-esterified biodiesel or hydrogenated renewable diesel, can also be used.

FUEL-WATER EMULSIONS

An oil-in-water type emulsion is one way of utilising the residue coming from a refinery as fuel in a diesel power plant. By making an emulsion with water the viscosity is dramatically reduced, enabling it to be pumped at ambient temperature in warm countries. Using it in the diesel engine requires only a fraction of the heating needed for heavy fuel oil.

Because liquid fuels are more expensive than natural gas, these engines are often designed for duel fuel capabilities. The gas-diesel engine can be switched instantly from gas to liquid fuel mode operation. The liquid fuel can be light fuel oil, heavy fuel oil or crude oil. In this case, the process is the same as the conventional diesel process. In fuel sharing mode, when both fuels are used, the ratio between liquid and gas fuel can be controlled and varied during operation. The operating window for the fuel sharing mode is 30-100% load, and the gas/liquid fuel ratio can vary according to the fuel sharing window. This process can tolerate big variations in the gas quality and is especially suitable for low quality gas, such as associated gas in oil fields.

Diesel power plants are reliant on availability of their fuels, which are subject to varying costs and logistics. This means that the fuel costs for these plants are high, which is why they are typically only used as peaking plants.

B.3.3. Value Chain

Manufacturing and supply

The manufacturing of diesel engines that provide utility scale power is done in-house and there are 10 companies that control most of the market share [77]. These are: Action, Aggreko, Atlas Copco, Caterpillar, Cummins, FG Wilson, Himoinsa, Kirloskar and Manlift Group.

Operations and maintenance

The large suppliers of these plants, like MAN Diesel & Turbo and Wärtsilä have their own O&M service packages to ensure reliability and performance of the units. These contracts are typically entered into with customers such as independent power producers (IPP), captive power plant operators, and baseload plant owners. These solutions are also suitable for balancing power plants, peaking/ intermediate plants, and utilities. They aim to maximise the productive lifetime of the installation and the return on investment. The solution is always tailored to the specific needs of the customer, including performance and lifecycle cost guarantees.

There are often multiple different maintenance agreements that can be entered into. These different options provide flexibility in terms of contract length, down time experienced, on-site support, spare stock supplies, availability, commitments, training etc.

Decommissioning

The decommissioning process for diesel generator-based power plants is relatively straight-forward as the equipment is compact and most of the equipment material is steel that can be recycled. The main concern would be soil contamination due to oil spills around the generation equipment or fuel distribution and storage facilities. For utility-scale power plants this issue is much more manageable than distributed remote generators.

Value Chain Dynamics

Similar to gas turbines, there is a limited number of large diesel generator suppliers and most equipment is imported to SSA. This means the owner/operator would continue to depend on these suppliers during the operation of the plant and a sufficient (ongoing) local presence of the supplier would be important to ensure the likelihood of adequate support over the plant lifetime. Compared to smaller scale diesel generators, outsourcing major maintenance to 3rd party maintenance companies is difficult, as the large-scale diesel generators often require specific spare parts and tools from the OEM.

[77] *Top 10 genset manufacturers and distributors - - Construction Week Online*

APPENDIX C. DESCRIPTION OF BUSINESS CASES

C.1. Mini Grid

C.1.1. Introduction

The history of mini grids is usually described as consisting loosely of four generations of mini grid. The first generation are the small-sized mini grids with isolated generation and distribution networks that pre-date the centralisation of energy systems in countries such as the United States and the United Kingdom. Second generation mini grids are those typically found in developing countries today. They tend to be built by local communities or by a utility company and service a very small area, usually a single village. These mini grids tend to rely on older generation technologies such as diesel generators and mini-hydro systems and will use traditional metering infrastructure if any metering is done at all. Informal second generation mini grids will usually charge a flat fee for service or rely on manual meter checking and post-paid fees collected in-person.

The World Bank's Energy Sector Management Assistance Program (ESMAP) estimate that most of the 19,000 mini grids they have identified worldwide fall into this category. Second generation mini grids will have little or no battery capacity. Several development finance organizations like the UNDP have projects to hybridise these systems across Africa, adding PV and BESS capacity to diesel-based systems.

Figure 67: Kenyan micro-hydro system powering a school, a few shops, and a few homes

Third generation mini grids are typically built by the private sector and are characterised by using renewable electricity generation, smart meters, and modern energy storage technologies. These systems have proliferated as the costs of the enabling technologies have fallen, the business models have evolved, and regulation has been put in place to allow grid operators to charge cost-reflective tariffs.

A tentative fourth generation of mini grids is emerging. These are typically characterised as being intentionally embedded in a value chain, enabling increased or improved agricultural processing[78] or production (for example), but also include weak or under-grid mini grids. The importance of productive energy users to the revenues of a mini grid operator is significant, and often underestimated. Increasingly, efforts to stimulate productive uses of energy on mini

[78] *Many non-agricultural value chains are also suitable for mini grid energy provision. The Jumume Keymaker model first trialled in Tanzania for example is built around the fish cold chain and linking rural fisherfolk directly to buyers in the capital.*

grids are forming the focus of much development finance institution funding and being integrated into the business models of private developers.

To stimulate local economies, the best productive uses to support are those for which there is a significant market already. In these cases, there is already local knowledge and technical experience with the crop and increased production can easily be absorbed into an existing supply chain. In some cases, there might be significant potential for the stimulation of a new value chain, but generally this requires more upfront technical assistance and investment.

Detailed analysis of national value chains and the selection of mini grid sites in locations where there is an obvious energy/agricultural processing symbiosis is becoming increasingly important to mini grid project design. However, this affects more than the business model; it can have a significant impact on the technical design of the mini grid and the balance of generation to storage capacity. Most productive activities will take place during the day when the sun is shining. This means that PV generation capacity will often need to be increased to meet this increased direct demand and provide sufficient extra energy to store in the BESS for night-time usage.

Falling technology costs,[79] improving business models (for example through productive uses and value chain integration), improving regulation and innovations in finance mean that mini grids are proliferating, and the sector forecasts continued exponential growth. A recent report from the African Mini grid Developers Association describes mini grid connection growth rates of 161% in 2017 and 267% in 2018.[80] As of 2019, the top mini grid market in Sub-Saharan Africa in terms of number of mini grids being planned is Senegal, with 1,217 projects in the pipeline. Senegal is followed by Nigeria and Tanzania with 879 and 501 projects respectively.[81]

In many developing economies, mini grids are increasingly being included in energy or electrification strategies exclusively on the basis of the least-cost criterion (only applied where they are cheaper than the national grid or cost effectively provide higher Tiers of Service than solar-home-systems). More recently, an increasing understanding of the impact that energy access has on rural economic development is meaning that mini grids are becoming an integral part of rural industrialisation strategies.

C.1.2. Customer Profile

Mini grids in Sub-Saharan Africa typically take the form of isolated rural systems servicing bottom-of-the-pyramid customers. Off-takers include households, public facilities like schools and healthcare facilities, commercial/productive users such as shopkeepers, bars and hair salons, primary manufacturers such as welders and carpenters and agricultural processing like maize millers. Most of the connections will be relatively low consumption household connections that use the energy for lighting, mobile phone charging and possibly one or two appliances like televisions or fridges. Their use will be primarily at night. Most of the energy will be consumed by a small number of high use customers. These provide most of the mini grid operator revenue and will typically be a commercial or productive use of energy like a grain mill or a hair salon. The energy usage of these customers will generally take place during the day.

In some cases, the principal energy consumer will be an off-taker such as a mobile telecommunication tower. The predictable energy use of an anchor load like this can be beneficial to the financial profile of the mini grid operator. The arrangement also benefits the telecom tower operator as energy costs will often be lower than with a remote diesel-powered tower and the availability of power will usually be guaranteed in the off-taker contract.

Mini grids in Sub-Saharan Africa are traditionally seen to be a solution for deep rural locations where the main grid could never go, however as mini grid costs come down, the zone where mini grids are the best option (least cost or highest quality of energy service) grows ever larger and ever closer to grid connected areas. In fact, there are increasing numbers of so-called under-grid mini grids emerging, notably in Nigeria. Nigeria has a privatised, unbundled model where distribution companies (DisCos) are granted franchise areas to buy energy from the national grid and resell it. In

[79] *According to research from the Rocky Mountain Institute and AMMP, the LCOE of mini grids can be 60% lower in 2030 than in 2019. (link)*
[80] *AMDA Benchmarking Report, https://shellfoundation.org/app/uploads/2020/08/AMDA-Benchmarking-2020.pdf*
[81] *The World Bank, 2019, Mini grids for half a billion people, (link)*

the more rural parts of the franchise area the quality of service plummets. Many end-users receive only two hours of electricity every day and revenue collection is minimal (covering approximately 35% of costs).[82] As a result the DisCo is not incentivised to maintain or invest in these communities and the service continues to deteriorate. These 'weak-grid' areas do not provide a foundation to support flourishing mechanised agricultural processing. Enter the mini grid operator who leases the distribution infrastructure from the DisCo, installs smart meters and takes on the job of revenue collection and customer management. They resell national grid electricity when available and electricity from their mini grid (which is connected to the same network) when it is not.

In the weak-grid scenario, the mini grid operator benefits from a lower LCOE and a vibrant, diversified, partially industrialised market with a considerably better customer profile (in terms of willingness and ability to pay for services) than most rural villages. The DisCo benefits from lower management fees and considerably better revenue collection leading reduced financial losses[83] and the end users benefit from lower overall energy costs.[84]

C.1.3. Technical Profile

There are approximately 2,160 mini grids currently operating across Sub-Saharan Africa.[85] The majority of mini grids in the region are powered completely by diesel generators or hybridised with solar.[86] Information from our database of 373 operational rural mini grids across 15 countries in Sub-Saharan Africa indicates that for these hybrid systems, the rated capacity of the fossil fuel generators typically makes up 60% of the total installed capacity which ranges from 10kW to more than 3MW. Although some mini grid funders will demand 100% renewable energy generation is used, most commercial mini grids will include a diesel generator. This is a decision usually based on the capital requirements of providing uninterrupted service continuously with solar and battery-based systems. It is almost always more cost effective to use a fossil fuel powered generator to provide electricity through outlier events like unusually low sun or unusually high energy demand.

Typically, the generator will be centrally located at the mini grid energy hub. In many cases the generator will start automatically when required. The AC output of the generator will be connected through the power management equipment (and routable to the batteries as necessary) to the main distribution system along with all the other generation assets.

By far the most common energy storage technology is lead-acid battery based, either deep cycle, sealed, AGM or gel. Units are manufactured to be 2V or 12V and arrays are usually configured to be 24V or 48V. Popular brands include Hoppecke, Trojan and BAE Secura. Some African countries have domestic battery manufacturers but often the cost savings are balanced out by low-quality products. Most mini grid compatible battery manufacture is carried out by companies whose main market is the automotive industry. An example from Kenya is ABM, established in 1963 by the UK-based Chloride Group to produce batteries for several British manufacturers including Chloride, Oldham, Lucas, and Dunlop. By 2018 they had produced 1,000,000 batteries.

The use of other battery chemistries such as lithium-ion is increasing, but this has typically been limited by a lack of local availability. Our research has suggested that most lithium-ion batteries are installed on C&I projects rather than on rural mini grids. The use of other technologies is very uncommon. Only mini grid system in Uganda uses vanadium flow batteries and another site in Madagascar uses a zinc-air system.

Under-grid or weak-grid mini grids are of particular interest to the battery storage industry as their main function can be characterised as 'supply smoothing'; energy from the grid is stored when available and made available to off-takers when the grid is down. The size of the required storage asset is a function of the demand, but also the availability of the

[82] *Graber et al., 2018, Under the Grid: Improving the Economics and Reliability of Rural Electricity Service with Undergrid Mini grids, (link)*
[83] *Reduced annual losses of $3 million in the Nigerian example (reduction by 60%)*
[84] *Paying $0.15 per kWh less than they had been before the introduction of the under-grid mini grid*
[85] *Sustainable Energy for All, 2020, State of the Global Mini grid Market Report, (link)*
[86] *The World Bank, 2019, Mini grids for half a billion people, (link)*

grid. Many of these systems will include a PV array to supplement the supply, but this will be much smaller than in a stand-alone mini grid.

In regulated markets, these weak-grid mini grids require more complex agreements to be in place than is usually required for off-grid mini grids. In Nigeria for example where these grids are showing great promise, a tripartite agreement is required between the central utility, the local DESCO and the mini grid operator. The attraction of these sites to mini grid developers stems from the increased density of semi-urban sites leading to lower distribution costs, established, often commercial energy demand, vibrant local economies, and the lower costs of sourcing kWh than on a stand-alone mini grid.

Typical Mini grid configuration

Although various 'exotic' models have been trialled,[87] to leverage the economies of scale from centralising equipment, most mini grids will have a single central energy 'hub' situated next to the solar array and diesel generator (if used). This hub will be a building or customised shipping container housing the BESS, inverters, remote monitoring equipment and all other electronic supply control systems. The installed capacity of mini grids is usually measured by the PV generation capacity and can vary from a few hundreds of kilowatts to multiple megawatts.[88]

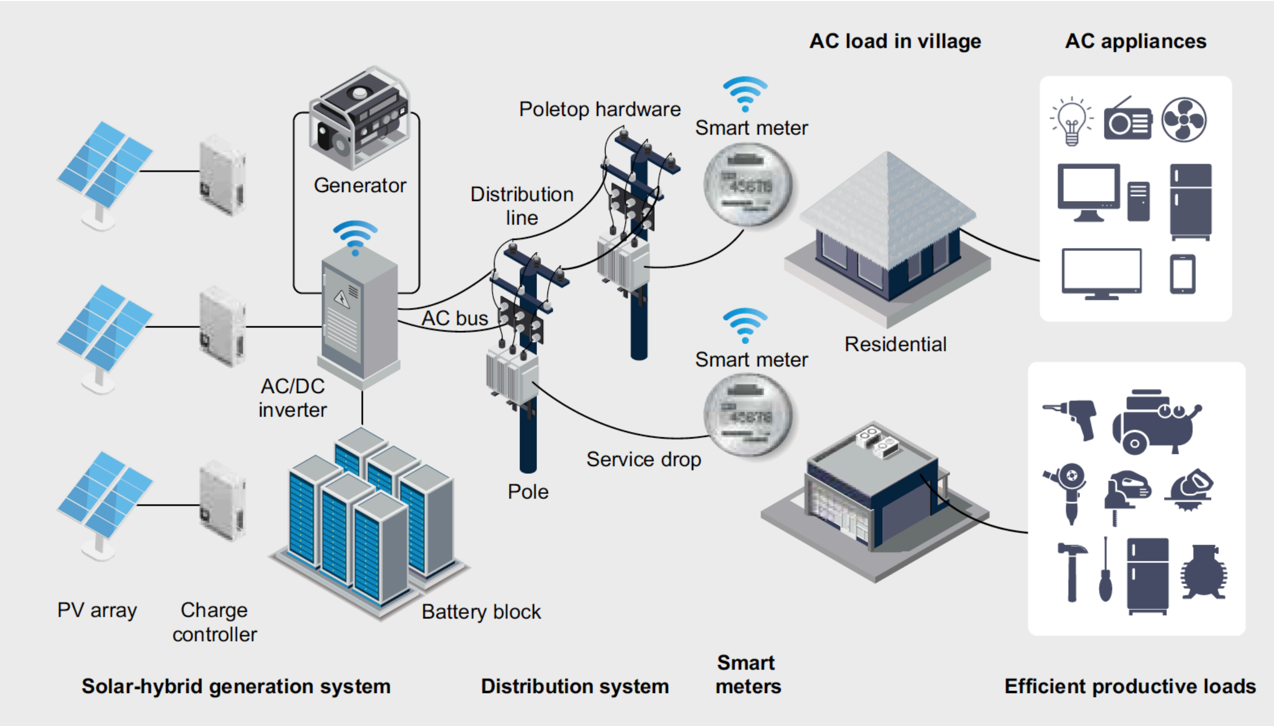


Figure 68: Typical third generation mini grid configuration[89]

Distribution from the energy hub will typically be done using standard poles and cables. In fewer cases, underground distribution is opted for. In larger grids, high voltage distribution will be stepped down using transformers closer to points of supply. The 'service drop' or last-meter connection to consumers will usually take place through a meter, either a standard utility meter or a smart meter in more sophisticated grids. As mini grids get more advanced, payments for electricity are shifting from in person collection, to pay-as-you-go systems. Service providers specialising in billing and revenue collection have emerged over the past decade and include Solaris Offgrid, Paygee and Angaza. These, in turn

[87] *For example the small DC-based nano grids of Devergy which connected separate nodes of solar and battery masts in a village 'mesh'*
[88] *Nuru is currently constructing a 1.3MW solar hybrid site in Goma, DRC*
[89] *The World Bank, 2019, Mini grids for half a billion people, (link)*

can be delivered through a variety of means, from scratch card systems in places with no internet coverage or using mobile money integrated PAYG smart meters such those offered by SteamaCo and SparkMeter.

Most mini grids will be designed to provide continuous power, but a number of models have been trialled that provide a limited number of hours of service every day.[90] Because of the higher LCOE of energy provided at night, limiting the number of night-time hours of service reduces required BESS capacity. This reduces the project capital costs and leads to lower tariffs. The availability of power is one of the factors that define the EMAP Multi-Tier framework for mini grids. The highest Tier 5 services need to be available at least 23 hours per day.

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3[b]	TIER 4	TIER 5
Capacity	Power capacity ratings (W or daily Wh)	Less than 3 W	At least 3 W	At least 50 W	At least 200 W	At least 800 W	At least 2 kW
		Less than 12 Wh	At least 12 Wh	At least 200 Wh	At least 1 kWh	At least 3.4 kWh	At least 8.2 kWh
	Services		Lighting of 1,000 lmhr per day	Electrical lighting, air circulation, television, and phone charging are possible			
Availability[a]	Daily Availability	Less than 4 hours	At least 4 hours		At least 8 hours	At least 16 hours	At least 23 hours
	Evening Availability	Less than 1 hour	At least 1 hour	At least 2 hours	At least 3 hours	At least 4 hours	
Reliability		More than 14 disruptions per week			At most 14 disruptions per week or At most 3 disruptions per week with total duration of more than 2 hours"	(> 3 to 14 disruptions / week) or ≤ 3 disruptions / week with > 2 hours of outage	At most 3 disruptions per week with total duration of less than 2 hours
Quality		Household experiences voltage problems that damage appliances				Voltage problems do not affect the use of desired appliances	
Affordability		Cost of a standard consumption package of 365 kWh per year is more than 5% of household income			Cost of a standard consumption package of 365 kWh per year is less than 5% of household income		
Formality		No bill payments made for the use of electricity				Bill is paid to the utility, prepaid card seller, or authorized representative	
Health and Safety		Serious or fatal accidents due to electricity connection				Absence of past accidents	

Figure 69: The ESMAP Multi-Tier Framework for Measuring Access to Electricity

Breakout box: Under-grid mini grids - an emerging application of energy storage

Across Sub-Saharan Africa, millions of people only have intermittent access to electricity despite having a grid connection. These are commonly known as "under-grid" communities. At these locations, under-grid mini grids can play an important role in ensuring 24/7 energy availability in the community, and, if connected to the main grid, increase the reliability of the grid. In February 2020, a commercial under-grid mini grid was commissioned at Mokoloki community, Ogun state, Nigeria. Previously, the community only had four hours of electricity per day. The 100kW solar, 278kWh lead-acid battery storage and 88kW diesel backup mini grid now offers customers reliable electricity supply, with residential customers paying a flat rate per kWh and commercial and agricultural customers paying time-

[90] *See Black Star Energy in Ghana http://energicitycorp.com/black-star-energy/*

of-use rates. The Nigerian case further illustrates the importance of having suitable regulations in place - Nigerian mini grid regulations provide clear guidelines for the development of under-grid mini grids. These include the signing of a tripartite contract between the distribution licensee, mini grid developer and the connected community, permit application processes and tariff calculation guidelines. The emergence of under grid mini grids presents a significant opportunity for energy storage in the mini grid space, especially when connected to the main grid. The cost of energy is lower for the operator because the generation system can be reduced in size and energy bought from the grid is often subsidised. Costs can be reduced further if the distribution system is shared with the utility. This frees up capital for increased storage system sizes.

C.1.4. Business Model Characteristics

There are three primary delivery models for mini grids in emerging economies. These are usually defined by asset ownership:

1. **Utility ownership:** The utility will build and operate the mini grid. These make up most of the mini grids currently operating in Africa and will most commonly be diesel powered with little or no BESS. These systems will often run at a financial loss.
2. **Co-operative ownership:** Owned and managed by a locally based co-operative.
3. **Private sector based:** Most of the mini grids currently being built are commercial, private sector based. The finance for these is often a blend of commercial, foreign capital and grant funding, occasionally in the form of subsidies.

The prevalence of these models is defined, primarily by the regulation specific to the country in question. There are many examples of hybrids of these models, for example a private company operating its assets that have been financed by and are owned by the utility.

The ownership structures of private sector mini grid projects are beginning to evolve. There is an emergence of increased specialisation through the separation between the role of developer and project owner (or even further, developer, EPC, owner, and O&M companies similar to an IPP). AssetCos and YieldCos purchase (refinance) operational mini grids from developers. The AssetCos and YieldCos become the project owners (entitled to mini grid revenues) whilst the developers continue to operate the mini grids at an agreed operation and maintenance fee. The capital injection allows mini grid developers to rapidly develop sites. Investors benefit from the separation of volatile development activities (such as R&D and construction) from stable operating and revenue generation activities.

It is likely that the provision of long term (cheaper) project capital coupled with the investor risk aversion of AssetCos and YieldCos will push developers to accelerate lithium-ion battery adoption and to increase the green mix of energy generation infrastructure.

C.1.5. Deploying Generators and batteries

As the mini grid industry matures, it is becoming increasingly clear that costs are influenced by the way generators and batteries are procured and then deployed to site. The Mini grid Innovation Lab in Kenya has recently found that buying mini grid components in volumes larger than individual mini grid developers are able to, confers significant cost-savings. Current estimates indicate that bulk procurement can reduce upfront capital expenditure by about 7-20%.[91] Although this kind of intervention is still exploratory, the mini grid industry differs from the other renewable energy technology-based business models discussed in this report in that targeted equipment deployment support programs are underway.

C.1.6. Operating generators and batteries

[91] *Cross Boundary Mini grid Innovation Lab, 2020, Study Design: Bulk Procurement, (link)*

Usually any routine operations such as refuelling a generator or topping up a battery electrolyte will be managed by on-site staff. However, any serious problems or complex maintenance is usually carried out by travelling technicians who might service multiple mini grid sites.

The business model of most modern mini grids relies on customers making pay-as-you-go payments for their energy services. As such, most are equipped with smart meters, located in areas with mobile network coverage and operated by companies familiar with remote operations. Alongside the smart meter-based data infrastructure used to monetise services is usually a separate data infrastructure to monitor the performance of all the energy generation, conditioning, and storage equipment. These systems can inform a remote operator if there is a problem with any piece of equipment such as a battery bank or generator so that a technician can be dispatched. Several companies have emerged that use the data from mini grids to predict upcoming failure before it happens. This enables targeted preventative measures that reduce potential system downtime. These companies include New Sun Road, AMMP and Ferntech and specifically cater for the mini grid sector.

C.1.7. End of Life Considerations

While most of the components that make up a mini grid will be exposed to the same end-of-life considerations as the same technologies applied to other business models and thus be subject to the general environmental, health and Safety considerations of the country of operation, mini grid operators do occasionally have to conform to requirements specific to their project. Much of the money used to fund mini grids and tip the business model towards viability comes from concessional and public sources and as a result often comes with conditions. USAID-funded projects, for example, must comply with USAID's environmental regulation, Title 22 of the Code of Federal Regulations Part 216 Agency Environmental Procedures.[92] This regulation includes sections discussing the potential impacts (direct, indirect, and cumulative) of each project. Of relevance here is the disposal of a mini grid's batteries. Despite this, the infancy of the mini grid industry has meant that very few mini grids have met the end of their useful life and as such, there has not been significant effort put into the practically realising mechanisms to safely decommission or dispose of mini grid equipment.

C.1.8. Policy Aspects

Favourable policies and regulations are of crucial importance for the development of any mini grid industry. Nigeria has some of the most advanced mini grid specific regulations[93] in the region and the vibrant domestic sector is a testament to the positive impact that these regulations have had. The mini grid sub-sector ideally requires its own set of regulations because the operating conditions differ significantly from other forms of energy supply, let alone other forms of decentralised energy supply. The risks of mini grid operations (and in turn investment risk) increase significantly if operating conditions are not clarified. Two factors that are of importance are the tariffs that operators can charge to their customers, and what happens when the national grid encroaches on a mini grid site. These two sets of provisions can severely impact a mini grid's business model. If the national grid encroaches on a mini grid site, the mini grid operator should be given the choice to either sell the assets to the utility or to connect the mini grid to the national grid (provided that the mini grid has been designed to grid-compliant standards) or operate as an independent power producer. Regulations should at least also prescribe the service quality expected from developers and operators[94] and clear permitting and licensing procedures.

Beyond mini grid specific considerations, a wide array of broader regulations also has an effect. In some countries, especially countries where mini grid specific regulations are not in place, mini grid operators must conform to distribution grid codes, rural electrification acts, renewable energy acts and tariff codes. The unconsolidated nature of these laws and regulations can often result in a cumbersome process as a developer aims to fulfil all regulatory requirements.

[92] https://www.usaid.gov/our_work/environment/compliance/22cfr216
[93] *For example allowing mini grid developers to charge a cost-reflective tariff. In Nigeria this is calculated using the standardised MYTO tariff calculator*
[94] *Performance standards should take into account that mini grids are often located in deep rural areas with little to no internet connectivity. This means that the operator will likely not have sophisticated remote monitoring infrastructure and will thus not be able to report on detailed metrics such as voltage variations. Manual checks would be more appropriate in such cases*

AMDA estimates that the average time for a mini grid to get all the required licenses and regulatory approval in Africa is over a year. This is a serious constraint on the industry.

As is the case with all energy supply market segments, mini grids are also subject to a wide range of importation and taxation regulations. Developers often must deal with complex importation rules set by regulatory agencies and national revenue authorities. Some exemptions are only afforded to larger companies which meet stringent requirements. There is scope to ease the process of importing goods - this is especially true for smaller developers who currently are not privy to certain exemptions. Ensuring compliance is not only a cumbersome task, but also an expensive one, despite recent efforts from governments to remove import duties on renewable energy components. A TFE Africa analysis of import duties charged by 15 countries across Sub-Saharan Africa indicates that the majority have exempted duties on solar panels, but less so on BESS. The average import duty applied to BESS in the subset of countries is 22%.[95] More countries tend to apply value added tax to solar modules and BESS as compared to import duties, with only six of the 15 countries exempting solar panels from VAT and four exempting BESS from VAT. Of those that do charge VAT, the average VAT rate on solar modules is 15%, and 16% on BESS.

C.1.9. Future outlook

238 million households across Sub-Saharan Africa still need electricity access if universal access is to be achieved by 2030. Approximately half of this population, 111 million households, are estimated to be best served by mini grids.96 While the current pace of electrification indicates that this target will not be reached, a number of promising trends are suggesting that the pace of deployment can increase significantly over the next five to ten years.

Cost reductions in generation and storage improving the business case

Cost reductions of mini grid components within the mid and long term (5 and 10 years) will continue to improve the business case of these projects and in turn accelerate deployment. Between 2010 and 2018, component costs fell by 62-85%.97 During this period, the cost of lithium-ion batteries fell by 85%. These cost reductions have meant that the upfront investment required for mini grids have fallen from approximately $9,000/kW in 2010 to $3,900 in 2018.98 These trends are expected to continue in the mid and long term. By 2030, Bloomberg New Energy Finance expects the cost of solar PV modules to fall to $140/kW from the 2018 baseline of $230/kW.99 Similarly, the cost of lithium-ion battery packs in mini grid settings is expected to drop from $598/kWh to $62/kWh by 2030, while PV inverters will drop from $264/kW to $58/kWh.100 These and other cost reductions will further bring upfront capital costs of mini grids down by an approximate 22%, which in turn improves the risk-return profile and attracts investors to the sector.

Fuel cost volatility and more calls for reductions of fossil fuel subsidies will coincide with continued cost reductions of battery energy storage systems over the next decade. Thus, it is anticipated that back-up supply will increasingly be provided by battery energy storage systems and decreasingly by fossil fuel generators.

Increased efficiencies in project development and procurement

The mini grid sector in Sub-Saharan Africa has only recently started to show its first signs of scale-up. For most of the past decade, developers have been focusing on testing business models and experimenting with different ways to increase efficiency and decrease costs. This has led to the proliferation of several solutions that now aid developers in selecting suitable sites faster and cheaper, estimating energy demand and willingness to pay in a more accurate manner and collect revenues more efficiently. These solutions leverage several technology advances, including high-resolution satellite imagery, artificial intelligence, and mobile communications. For example, a recent report by Village Data Analytics (VIDA) indicated how the most promising sites in a given area of interest can be selected with the use of

[95] *Countries that have exempted BESS from import duties have been excluded from the calculation. Six of the fifteen countries have exemptions*
[96] *Sustainable Energy for All, 2020, State of the Global Mini grid Market Report, (link)*
[97] *The World Bank, 2019, Mini grids for half a billion people, (link)*
[98] *The World Bank, 2019, Mini grids for half a billion people, (link)*
[99] *BNEF, 2018, Powering the last billion, (link)*
[100] *The World Bank, 2019, Mini grids for half a billion people, (link)*

satellite imagery and AI algorithms at a fraction of the time spent with extensive surveys.[101] These tools are projected to become increasingly automated over the next decade as more data is digested and lessons are learned from experience. They have already brought site preparation costs down from an average of $30,000 per site to $2,300[102] and this trend is expected to continue. The result is that developers will continuously be able to reduce costs and increase deployment speed leading up to 2030.

As has been noted earlier in this chapter, developers are currently not able to practice bulk procurement. Yet, as the sector scales up and more sites are developed, economies of scale emerge, and an increasing number of developers will be able to procure components in bulk and benefit from cost savings. The continued scale-up of the sector will also bring an increasing degree of specialisation in service delivery across the mini grid value chain. During the sector's infancy years, developers were vertically integrated, taking responsibility for all tasks from site identification to project operations. There is now a variety of service providers that specialise in specific tasks, which increases efficiency and brings down costs for all operators involved. Examples include Nithio for customer creditworthiness scoring, Village Data Analytics for site selection, Odyssey Energy Solutions for portfolio management, HOMER for site design, AMMP, New Sun Road and Ferntech for remote monitoring and specialist mini grid meter manufacturers SteamaCo and SparkMeter.

Finally, standardisation is likely to become widespread as the sector matures. Standardised site designs and components will enable bulk procurement and ease portfolio management and investor due diligence efforts because of similarities between projects. Importantly, standardisation of distribution design with consideration of national distribution grid codes will support developers in building grid-ready mini grids. This reduces the risk of main grid arrival and break the divide between the main grid and mini grids.

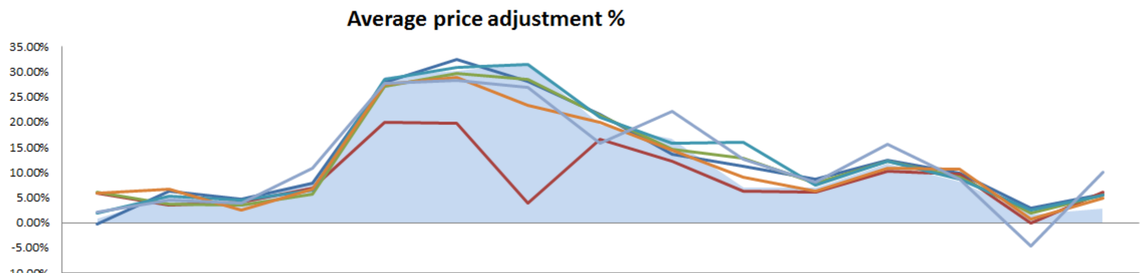
[101] *Village Data Analytics & PowerGen Renewable Energy, 2020, Improved mini grid site selection in West Africa using VIDA, (link)*
[102] *The World Bank, 2019, Mini grids for half a billion people, (link)*

C.2. Captive and Behind-the-Meter Applications

C.2.1. Introduction

The captive power market is experiencing unprecedented growth across Sub-Saharan Africa, mainly driven by unreliable grid electricity supply, high grid tariffs and falling renewable energy and energy storage costs. Fewer than half (43%) of Africans have a reliable electricity connection.[103] A large proportion of electricity generation, transmission and distribution infrastructure in many African countries such as South Africa and Zimbabwe is legacy pre-independence infrastructure and was designed for a small ruling class population. Since independence this infrastructure has been weakening under the pressure of growing populations, rapid urbanization, cable theft, poor maintenance, mismanagement, corruption and ordinary wear and tear. Line losses in Sub-Saharan Africa are on average 16%, compared to 9% in other developing regions.[104] In Nigeria, a typical business owner will experience power outages on average for at least 239 hours out of 720 hours in a month.[105] In Southern Africa, the South African utility, ESKOM, has been struggling to meet demand for more than a decade and the supply shortfall is expected to worsen in the coming years. This negatively affects energy security in the whole region, as many neighbouring countries buy electricity from ESKOM. Furthermore, droughts have exacerbated supply shortfalls in countries with hydro-dominant energy mixes, such as Zambia and Zimbabwe.

Captive power systems can play an important role in weak grid areas of economically vibrant countries - these trends have been observed in Nigeria, South Africa, Ghana, and Kenya. In these settings, the systems play an important role in ensuring continuous power supply to counter unreliable central supply. This is especially important for critical infrastructure such as data centres/IT servers, banks, and hospitals. Ever increasing grid tariffs are also forcing many businesses across Sub-Saharan Africa to resort to captive power generation. This is especially the case in countries such as Ghana and Senegal, where low voltage commercial customers pay as much as \$0.18/kWh and \$0.25/kWh respectively.



	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
Average standard tariff increase(Excld NPA and Int'l)	0.85%	5.15%	3.92%	8.18%	28.98%	30.15%	31.60%	19.50%	16.66%	6.92%	7.05%	11.70%	8.18%	1.62%	2.82%
Local-authorities	-0.36%	6.22%	4.62%	7.90%	27.89%	32.38%	28.17%	21.51%	13.68%	11.13%	8.66%	12.42%	9.80%	2.86%	5.77%
Residential	5.80%	3.56%	4.14%	6.76%	19.88%	19.76%	3.86%	16.64%	12.31%	6.17%	6.11%	10.26%	9.70%	-0.04%	6.05%
Commercial	6.14%	3.68%	3.58%	5.75%	27.20%	29.60%	28.45%	21.45%	14.59%	12.86%	7.86%	12.23%	9.02%	1.98%	5.44%
Mining	1.95%	5.35%	4.41%	6.47%	28.49%	30.84%	31.50%	20.93%	15.88%	16.00%	7.52%	12.22%	8.70%	2.48%	5.44%
Agriculture	5.79%	6.58%	2.52%	6.61%	27.47%	28.80%	23.33%	19.94%	14.37%	9.02%	6.36%	10.83%	10.54%	0.76%	4.91%
Traction	2.06%	4.55%	3.93%	10.75%	27.75%	28.36%	27.01%	15.83%	22.08%	12.65%	8.13%	15.50%	8.64%	-4.62%	10.07%

Figure 70: Eskom tariff increases for various sectors 2005-2019[106]

In response, many industries are resorting to on-site generation. While diesel generation has been the standard option for industries with higher power demand and petrol generation for small-scale industries, solar and storage is

[103] *Afrobarometer, 5 Dec. 2019, "Accessible, reliable power still in short supply ... https://afrobarometer.org/sites/default/files/publications/Dispatches/ab_r7_dipstachno334_pap11_reliable_electricity_still_out_of_reach_for_most_africans.pdf.*
[104] *IEA, 2019, Africa Energy Outlook, (link)*
[105] Access to Energy Institute, #StopGuessing, 2020, (link)
[106] *https://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Historical%20average%20prices%20and%20increase_v20200115_13h00_no%20links_External.xlsx*

increasingly becoming a viable option in the face of volatile fuel costs and declining renewable energy and battery costs. As of 2019, Nigeria already had 20MW of on-site solar projects.[107] LCOE of C&I solar in Nigeria, Kenya and Ghana ranged between $0.06 and $0.21/kWh in 2019 in cases where the grid is relatively reliable. Due to the rate of solar and battery cost reductions, it is highly likely that these figures have decreased since 2019. In Nigeria specifically, the cost of solar plus storage ranges between $0.12/kWh and $0.20/kWh.[108]

C.2.2. Customer profile

Captive power customer profiles differ from industry to industry in terms of energy demand and external motivating factors. The most important factors influencing energy storage and generator purchasing decisions are grid quality, the critical nature of loads, energy demand and access to capital.

Industries with critical loads such as telecoms, data centres and healthcare have a high prevalence of energy storage and generator back-up as uninterrupted service and power quality is high priority. There are many anecdotes of customers indicating willingness to pay a premium for uninterrupted energy supply - a study in Ghana for example found that firms would be willing to pay 12.6% more for uninterrupted electricity supply.[109] Batteries are typically in use in captive power applications with low to intermediate energy demand, with the vast majority of high energy demand applications still opting for industrial generators, often combined with renewable energy without battery storage.

This is a function of industries having trust, knowledge and expertise in incumbent generator technology, low availability of suitable battery replacements and high battery CAPEX costs. For example, across Africa, mining represents 20% of installed diesel generator capacity as these facilities must resort to on-site generation in the face of grid shortages. Yet, diesel generation is typically very expensive due to high fuel costs. An IRENA study for example indicated that the LCOE of electricity generation from diesel generators at mines in Africa amounts to an average of $0.29/kWh, and that hybridisation can be an effective strategy in reducing these costs.[110] Progress has been made in this regard already, as the mining sector accounts for more than a third of the C&I solar market in Sub-Saharan Africa.[111] Solar in mines is typically hybridised with diesel.

Industries with low access to affordable capital often opt for generators and lead-acid batteries, whilst industries with high access opt for advanced battery technologies, typically lithium-ion. This is mainly due to the high upfront costs of battery systems, in particular lithium-ion. This present trend is likely to change in the future with upfront costs of battery systems falling (see section 1.8) and captive power developers' efforts to work around high upfront costs with energy-as-a-service or lease-to-own business models (see section 1.3).

Breakout box: Electric Micro Mobility - an emerging application of energy storage

Africa's last mile transportation landscape is characterised by a lack of long-term urban planning coupled with poor and disconnected public transport and logistics systems. This results in constant congestion, costly transportation and long goods and passenger travel times. A host of African micro mobility start-ups have recently been formed to tackle these challenges. These start-ups include Zembo (Uganda), Ampersand (Rwanda), Awa Bike (Nigeria), Gura Ride (Rwanda) and Mobility for Africa (Zimbabwe). Similarly, some mini grid developers such as Powerhive are exploring the use of electric mobility charging as an anchor load and productive use of energy. These companies are active in urban and rural as well as passenger and logistics markets.

There are two dominant electric micro mobility business models in use: Owner operated/pay per use, and lease to own battery swapping services. Owner operated systems/pay per use sell a service instead of vehicles. This

[107] *Bloomberg New Energy Finance, 2019, Solar for businesses in Sub-Saharan Africa, (link)*
[108] *Bloomberg New Energy Finance, 2019, Solar for businesses in Sub-Saharan Africa, (link)*
[109] "For utilities in developing countries, revenue collection can be ...." 12 Jan. 2021, Accessed 31 Mar. 2021, https://energyeconomicgrowth.org/blog/utilities-developing-countries-revenue-collection-can-be-challenging-and-covid-19-could-be
[110] *IRENA, 2015, Africa 2030: Roadmap for a renewable energy future, (link)*
[111] *Bloomberg New Energy Finance, 2019, Solar for businesses in Sub-Saharan Africa, (link)*

is proving to be successful as passengers and delivery companies already pay high amounts for transportation in the same per use manner and many cannot afford to purchase vehicles outright. This leaves the burden of ownership and maintenance to businesses who can access capital to pay for the vehicle purchases and efficiently maintain the vehicles.

In lease-to-own with battery swapping services, the vehicle is sold on credit, while the battery is sold as a service. This model ensures that customers can afford the vehicles while the business maintains a long-term revenue stream. This strategy is popular in models that attempt to convert fossil-fuel motorcycle taxi operators in favour of electric motorcycles.

In both models, long term ownership and OPEX of batteries remain with the businesses. As businesses have access to capital, an overwhelming majority opt for lithium-ion technologies due to their lower OPEX and total cost of ownership in comparison to lead-acid batteries.

Case Study: Powerhive

Powerhive, a renewable energy mini grid company developer partnered with FCDO on a pilot programme bringing electric vehicles (EVs) to rural Western Kenya. For the pilot, Powerhive brought in a total of 33 EVs including electric 3 wheeled tricycles (tuk-tuks) and electric motorcycles (boda-bodas) to mini grid sites in Kisii, Western Kenya.

"Under a battery-swap model, Powerhive is able to earn revenue by charging EV batteries at the company's network of distributed solar power stations, making it easy for drivers to adopt EVs even if they don't have access to their own electricity source. Battery charging revenue can augment direct electricity sales, reducing payback periods and making mini grid assets bankable" - Powerhive.[112]

Breakout box: Data centres - A rapidly growing captive power application

International investors are rushing to fund a boom in the African cloud computing market, as the proliferation of smartphones and mass adoption of business software on the continent leads to soaring demand for data centres to power the technology.[113] Localisation of data storage improves connection speeds, while it is increasingly being mandated by governments that certain types of local data should be hosted domestically. Despite doubling in capacity in the past three years, Africa currently accounts for less than 1 percent of total available global data centre capacity, despite being home to about 17 percent of the world's population.[114]

Not only is the sector poised for exponential growth, it is extremely power hungry, requires uninterrupted supply and is sensitive to power quality. Cooling demand, a large component of energy demand in data centres is notably high in Africa given high ambient temperatures across the continent. Data centres have become more energy efficient in large part due to improvements in power efficiency and shifts towards cloud computing, however they continue to consume up to 3% of all global electricity production, and roughly ten times more per square metre than the average office.[115]

[112] *"On A Mission to Find An Electric Motorcycle That Will Usher in ...." 5 Jul. 2019, Accessed 21 Dec. 2020,* https://medium.com/frontier-technologies-hub/on-a-mission-to-find-an-electric-motorcycle-that-will-usher-in-kenyas-ev-revolution-6089e8847818
[113] *"Africa's cloud computing boom creates data centre gold rush ...." 2 Mar. 2020, Accessed 1 Apr. 2021,* https://www.ft.com/content/402a18c8-5a32-11ea-abe5-8e03987b7b20
[114] *"Africa's cloud computing boom creates data centre gold rush ...." 2 Mar. 2020, Accessed 1 Apr. 2021,* https://www.ft.com/content/402a18c8-5a32-11ea-abe5-8e03987b7b20.
[115] *"Data centres – the world's greatest energy guzzlers | Aurecon.", 1 Apr. 2021,* https://www.aurecongroup.com/thinking/insights/data-centres-for-the-digital-age/data-centres-the-worlds-greatest-energy-guzzlers

"*We have to fundamentally build our own power-generating capability to get a level of reliability and consistency, so that is a capital cost in itself.*" - Tunde Coker, Managing Director of Rack Centre, which connects to over three dozen data centre operators across West Africa, including Orange, MTN and Airtel.

Amazon, primarily for its web service AWS, has earmarked 26 utility-scale wind and solar energy projects totalling 3.4GW of electricity production capacity, bringing its total investment in renewable energy in 2020 to 35 projects and more than 4GW of capacity. This projection equates to the largest corporate investment in renewable energy in a single year. These new projects will make Amazon the largest-ever corporate purchaser of renewable energy in Africa.[116] In East Africa, Mettle Solar and Distributed Power (DPA) have announced a joint investment into a solar power and plan to power the largest data centre in Nairobi, Kenya.

[116] *"Amazon to decarbonise global operations with 26 new utility-scale ...." 15 Dec. 2020,Accessed 1 Aprr. 2021,* https://www.smart-energy.com/renewable-energy/amazon-to-decarbonise-global-operations-with-26-new-utility-scale-projects/

Table 23: Summary of prominent captive power applications

Applications	Grid connection	Use of battery storage	Critical load	Access to Capital	Motivation	Detail
Telecom Towers (MNO operated)	Good	Limited	Yes	High	-Uninterrupted service -Carbon emission targets	-Limited emergency battery back-up -High security vulnerability
	Weak	Intermediate	Yes	High	-Reduced TCO -Carbon emission targets	-Battery backup -High security vulnerability
	No	High	Yes	High	-Reduced diesel OPEX -Reduced maintenance costs - Carbon Emission Targets	-Solar-Battery-Diesel hybrid solutions -High security vulnerability
Telecom Towers (TowerCo operated)	Good					There is limited usage of TowerCos on good grid
	Weak	Limited	Yes	High	-Reduced diesel OPEX	-Battery backup -Capital constraints (short payback period requirements) -Threat of grid improvement inhibiting factors -High security vulnerability
	No	Intermediate	Yes	High	-Reduced diesel OPEX	-Solar-Battery-Diesel hybrid solutions -Capital constraints (short payback period requirements) -Threat of grid expansion inhibiting factor - High security vulnerability
Telecom Towers (ESCO operated)	Good and Weak					There is limited usage of ESCOs on good grid
	No	High	Yes	High	-Price p/kW relative to PPA	-Solar-Battery-Diesel hybrid solutions -ABC mini grids -High security vulnerability
Lodges/ Hotels	Good	Limited	No	Medium	-No strong motivation for battery storage	
	Weak	Limited	No	Medium	-Limited battery storage for uninterrupted power supply of critical operational infrastructure	

Applications	Grid connection	Use of battery storage	Critical load	Access to Capital	Motivation	Detail
	No	High	No	High	-Reduced OPEX, -Carbon emissions targets, -Preservation of the environment, -Reduced noise pollution, -Remoteness of locations (safaris and island resorts) -Green Image	-Solar-Battery-Diesel hybrid solutions -High margin business
High Value Agriculture	Good and Weak	Limited	No	High	-Reduced OPEX -Carbon emissions targets (of big buyers and industry (certification) associations) -Green image	-High value agriculture has prioritised grid access and often subsidised (commercial) electricity prices -Solar irrigation systems often use gravitational energy storage -Use of renewable energy peak load shaving
	No					Limited large scale off-grid high value agriculture
Mining	Good and Weak	High	No	High	-Reduced OPEX -Uninterrupted service	-Large scale mining has prioritised grid access and often subsidised (commercial) electricity prices, -Use of renewable energy peak load shaving, -predominant use of industrial scale generators
	No	Intermediate	No	High	-Remote and Off-grid operation	-Large scale off-grid mining actively lobby for grid connection prioritization as part of mining contracts
Data Centres	Good and Weak	High	Yes	High	-Uninterrupted service -Power quality -Reduced OPEX	-High levels of battery usage as uninterrupted Power Supply top priority, category includes Data as a Service Centres and private business data centres (i.e. Banks)
	No					Limited number of off-grid data centres
Education	Good					Limited usage of batteries on good grid facilities
	Weak	Intermediate	Yes	Low	-Reduced OPEX -Uninterrupted service	-Capital limiting factor, -Growing usage in "flagship" and private facilities

Applications	Grid connection	Use of battery storage	Critical load	Access to Capital	Motivation	Detail
	No	Limited	Yes	Low	-Reduced OPEX, -Uninterrupted service	-Capital limiting factor -Predominantly government and donor funded,
Traffic Lights	Good	Limited	Yes	Medium	-Uninterrupted Service	-Uninterrupted service top priority -Capital limiting factor -High security vulnerability - Government Funded
	Weak	Intermediate	Yes	Medium	-Uninterrupted Service	-Uninterrupted service top priority -Emerging application, capital limiting factor, -High security vulnerability -Government Funded
	No					Limited number of off-grid traffic lights
Solar Street Lights	Good					Limited usage of solar streetlights on Good grid
	Weak and No	Limited	Yes	Medium	-Reduced OPEX, -Uninterrupted Service	-Uninterrupted service top priority -Emerging application, capital limiting factor, -High security vulnerability -Government Funded
Health	Good	Limited	Yes	Low	-Reduced OPEX, -Uninterrupted Service	-Capital limiting factor -predominantly government and donor funded - growing usage in "flagship" and private facilities -high energy demand-predominant use of generators
	Weak	Intermediate	Yes	Low	-Reduced OPEX, -Uninterrupted Service	-Capital limiting factor -predominantly government and donor funded -growing usage in "flagship" and private facilities -high energy demand-predominant use of generators-battery usage for critical loads
	No	Intermediate	Yes	Low	-Reduced OPEX, -Uninterrupted Service	-Limited number of off-grid health facilities. -Capital limiting factor -predominantly government and donor funded

C.2.3. Technical Profile

Captive power systems are defined as being built for on-site consumption with no additional distribution infrastructure and can be configured as grid tied or off-grid. Grid-tied systems are typically configured with a transfer switch that is either manually operated or automated to switch on when the grid becomes unavailable. Our database of 322 off-grid and grid tied sites across the continent shows that installed capacity varies widely from small to medium applications from less than a kilowatt or hundreds of kilowatts supplying residential and commercial (mobile telecom towers, restaurants, safari lodges, shopping malls) loads to systems of more than 30MW serving mines and manufacturing facilities.

Larger systems tend to be diesel generation dominated with CAT and Wärtsilä being leading manufacturers and have little to no battery storage. As the total installed capacity decreases, so does the proportion of installed diesel while the amount of installed PV and storage capacity increases. Although the use of lithium-ion based systems is increasing, with emerging brands including Tesla, SimpliPhi, Pylontech, Freedom Won, LG Chem, BYD BBOX and Tesvolt, the dominant chemistry is still lead-acid.

AC or DC coupling refers to the way energy generation technology is coupled or linked to an energy storage or battery system. There are two main types of system configurations use in captive power systems:

1. Off-grid DC coupled systems and grid tied DC coupled Hybrid Systems
2. Off-grid AC coupled systems and grid-tied AC coupled battery Systems

Due to its maturity, DC coupled systems are the most common type of off-grid system. Developers have extensive experience with this configuration. In addition, this configuration offers high battery charging efficiency, great modular flexibility and it is cost effective for smaller systems (residential and commercial applications).

AC coupled systems are most used in grid tied applications with a high energy demand during the day such as schools and malls. AC coupled systems have an advantage over DC coupled systems in applications with large PV arrays. This is due to the fact that using string solar inverters which operate with higher DC voltages (up to 600V or higher) allows for large solar arrays to be easily installed at lower cost and complexity compared to DC coupled systems requiring multiple MPPT charge controllers.[117]

AC coupled batteries or simply ‘AC batteries’ are a relatively new evolution in battery storage for grid connected homes and allow batteries to be easily AC coupled to a new or existing solar installation. This technology is not common across the continent. AC batteries consist of lithium battery modules, a battery management system (BMS) and inverter/charger all in one compact, simple unit (complete system). These systems are designed exclusively for grid-tied applications as the (transformerless) inverters are typically not powerful enough to run a process off-grid and incapable of managing surge loads of many appliances.[118]

C.2.4. Business model characteristics

There are three main business models in use, out-right ownership, lease to own and Energy-as-Service/Product-as-Service. Large systems are typically designed, installed, and maintained by EPCs while smaller (solar home systems) are often sold and maintained through a network of distributors. In an outright ownership model, the developer sells and often installs the energy system. The customer can opt for a separate operation and maintenance agreement or to maintain the technology themselves. Operation and maintenance agreements are often paid monthly with cover lapsing in the event the customer fails to pay for the service. Operation and maintenance agreements often include on-going remote monitoring, periodic check-ups, and on-call assistance in the event of system failure. Businesses that have in-

[117] *"Which configuration should be more preferred AC or DC coupled for ...." 8 Sep. 2020, Accessed 5 Feb. 2021,* *https://www.researchgate.net/post/Which-configuration-should-be-more-preferred-AC-or-DC-coupled-for-PV-battery-storage-systems*
[118] *"Which configuration should be more preferred AC or DC coupled for ...." 8 Sep. 2020, Accessed 5 Feb. 2021* *https://www.researchgate.net/post/Which-configuration-should-be-more-preferred-AC-or-DC-coupled-for-PV-battery-storage-systems*

house technical teams (e.g. factories and mines) at times opt to maintain technology in house to reduce costs, contain (downtime) risk and increase operational efficiency.

Lease-to-own systems follow a similar path as that of out-right ownership. EPCs themselves, often in partnership with financial institutions, offer technology on credit to customers. The technology is owned by the EPC and is transferred to customers after credit is paid off through fixed instalments (usually 12-36 months). This model is ideal for individuals or institutions who are unbanked, where banks have poor credit terms and where banks fail to accurately price technology risk. Lease-to-own models often make operation and maintenance agreements mandatory in a bid to protect the technology, which acts as collateral. After the transfer of technology, the maintenance agreement is often no longer mandatory. These models often have better collateral asset recovery mechanisms relative to ordinary banks. For solar home systems, pay-as-you-go technology (PAYG) is commonly used. In these cases, customers pay a small deposit for a solar system to be installed in their homes. They then make smaller regular payments over time, usually through a mobile payment system, to pay for either the energy used or ownership of the system. Major financial institutions such as Barclays, OikoCredit, ABSA, FNB, Nedbank, Bamboo Finance and DBSA all offer credit to support this model. There are innovative cases where corporations finance systems on behalf of their own employees. Solarus is for example collaborating with a hotel in South Africa to roll out the Hotel Staff MPower Project. In this project, the hotel will finance the up-front installation costs of the systems to up to 600 employees' homes. The employees repay the cost of the installation at an affordable monthly rate to the hotel.[119]

Energy-as-Service and Product-as-Service (such as Cooling-as-Service, Towercos etc) is an emerging business model. These companies shift the cost of technology ownership from end-consumers to the company. These companies often can access long term credit at more competitive rates than typical African consumers or businesses. As a result, they typically opt for lithium-ion technology over lead-acid batteries (typically used by African consumers and businesses) due to their higher operational efficiency (across multiple sites) and lower LCOE (at their cost of capital).

C.2.5. Deploying Generators or Batteries

Captive power deployments are similar to mini grid deployments. However, captive power projects tend to be bespoke in nature and at times have stringent timelines. This project structure makes it difficult to combine projects, purchase equipment directly from manufacturers, gain from bulk procurement and obtain economies of scale.

There is an emerging trend of an increasing number of developers who are serving both mini grid and captive power markets. This is likely because their core technologies are similar, and skills are easily transferable across these market segments. This trend is driven by a desire to increase market share and attain greater economies of scale.

Captive power projects have the additional complexity of having reduced control over the project environment. Project environments differ from client to client. Installations must be modelled to fit into clients' schedules. In the case of backup systems, the design and installation is largely influenced by the architecture of existing energy infrastructure, which is the opposite of the greenfield nature of a typical mini grid site.

C.2.6. Operating Generators or Batteries

Small scale generator users are often enticed to buy larger systems even if it means that the systems are oversized. This decision is often made because of the longer life expectancy offered by larger systems (see Table 1, chapter 3). Early evidence however seems to indicate that larger generators used in small-scale captive power settings run with lower load factors as compared to smaller generators. A recent study conducted by the Access to Energy Institute found that generators above 6kW used in open air markets in Nigeria had load factors of as low as 4.5%.[120] Conversely, load

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[119] *"Switching on finance for off-grid energy - GSB Business Review Online.", 5 Feb. 2021, http://www.gsbbusinessreview.gsb.uct.ac.za/switching-finance-off-grid-energy/*
[120] *Access to Energy Institute, Data Release #2, 2020, (link)*

factors of generators less than 4kW ranged between 15.6% and 23%. The study reported an average load factor of 18.3% across all generators monitored.[121]

Monitoring battery operation

Battery monitoring systems (BMS) monitor and calculate the state of charge (SOC) of each individual cell in a battery to determine if there is uniform charge across all the cells. This is done to ensure that individual cells do not become overstressed. The SOC indication is also used to determine the end of the charging and discharging cycles. Over-charging and over-discharging are two of the leading causes of battery failure. The BMS ensures that cells stay within the desired depth of discharge (DOD) operating limits. Lead-acid batteries are typically more susceptible to higher levels of degradation due to over-charging and over-discharging relative to lithium-ion battery technology. It is imperative that lead-acid battery depth of discharge does not fall below a determined threshold and that there is enough energy to fully charge before discharging. Poorly designed systems can drastically reduce the expected lifespan of batteries. BMS systems in addition measure temperature. Temperature control is another factor which needs to be well managed. Ensuring sufficient cooling has shown to substantially increase the expected lifetime of a lead-acid battery.

C.2.7. End of Life Considerations

End of life considerations of generators and batteries within the captive power sector are largely influenced by the technology ownership structure. In the case of outright ownership, end of life considerations are determined primarily by the customer's own disposal policy, as well as policies applicable to the customer's industry as a whole. The EPC has limited control over the end-of-life considerations. However, EPCs have started to offer their customers a service in which the EPC takes responsibility for decommissioning. For example, EPC Muhanya Solar in Zambia collects decommissioned lead-acid batteries from clients and non-clients for both re-use and recycling. Muhanya receives a payment from re-use and recycling companies for batteries collected. In the re-use scenario, fees are determined by resale value, while lead value determines the fee in the recycling scenario. In the case of lease to own and energy-as-service/product-as-service models, the EPC is typically responsible for the dealing with end-of-life considerations. The benefit of recycling must be weighed against the cost and logistical challenge of collecting material from scattered sites of varying remoteness and size. Environmental guidelines also play a role in how the company disposes of decommissioned generators and batteries in this ownership model.

C.2.8. Policy Aspects

In many countries, off-grid, on-site captive power projects successfully operate without extensive regulation. However, grid connected systems are typically regulated more closely. At the basic level, most countries in the region have standard regulations in place that allow private individuals or businesses to generate their own electricity. Such provisions are typically made in the national electricity codes under chapters dealing with private sector participation in the generation of electricity. Associated with the invitation to the private sector to generate electricity comes specifications on installation quality and permitting processes. Quality standards are typically made in stand-alone regulations or as part of regulations dealing with quality standards. As an attempt to boost the captive power market, some countries are opting to exempt projects below a certain size threshold from permitting. This removes a considerable administrative burden from many developers.

Countries that allow for the interconnection of captive power plants also have regulations that deal with net-metering, wheeling and feed-in tariffs. These include for example Cote d'Ivoire, Ghana, Nigeria, South Africa, Tanzania, and Namibia, all in varying degrees. In some cases, such as in South Africa, each local government can have its own provisions, especially regarding feed-in tariffs. As a result, it might be more financially attractive to operate a grid-connected system in one part of the country than in another. Dynamic trade and pricing of electricity between grid connected captive power operators is not commonly provided for in regulations, mainly because the infrastructure required for this next frontier of decentralised energy supply is still out of reach in most Sub-Saharan African countries.

[121] *The study monitored a total of 216 smart meters connected to small scale generators across Nigeria*

As is the case with mini grid developers, captive power developers are also affected by several wider market regulations. These mainly include technical standards pertaining to the installation, grid interconnection requirements, tariff codes, import processes and taxation.[122] Distribution codes often also apply to interconnected captive power projects, despite the absence of distribution infrastructure in the system itself. This is because many countries prescribe conditions for interconnection of captive power systems in their distribution grid codes.

C.2.9. Future outlook

Power grids across the region struggle to meet existing energy demand. Extensive investment in power system rehabilitation, upgrade and expansion is thus required not only to meet existing demand, but also future demand. One in two people added to the world population between present day and 2040 are set to be African, and the continent will become the world's most populous region by 2023, overtaking China and India.[123] This will coincide with a rapidly emerging middle class. The IEA estimates that energy demand in Sub-Saharan Africa (excluding South Africa) will increase at an average annual rate of 6.5%, the highest of all regions worldwide.[124] This translates to an increase in average per capita consumption from 185 kWh to 430 kWh by 2040. Energy demand from industry and services sectors specifically will more than triple by 2040.[125] Failure to address supply shortfalls will further weaken grid reliability and incentivise households, businesses, and factories to adopt their own energy supply in the pursuit of energy security. Even in countries with stable grids captive power systems will remain attractive, for purposes such as peak shaving. Furthermore, businesses' increased focus on sustainable energy in corporate social responsibility initiatives and pressure from national and international emission reduction programmes will likely further propel the renewable energy captive power market.

The degree to which potential customers adopt captive power systems in the future also depends on cost trends, all of which are pointing downward. As Figure 71 shows, the cost of battery systems in behind-the-meter applications is expected to decline significantly up to 2030 and beyond. This is especially true for the two most used batteries in the small-scale captive power market today – lead-acid and lithium-ion. Project economics will be improved even further when cost reduction of one of the most common captive power generation technologies in the form of solar PV is considered. These are estimated to fall to $140/kW by 2030.[126]

[122] *For a detailed discussion of import duties and VAT on renewable energy components, see section 5.8.*
[123] *"Africa Energy Outlook 2019 – Analysis - IEA." 8 Nov. 2019, Accessed 31 Mar. 2021, https://www.iea.org/reports/africa-energy-outlook-2019*
[124] *IEA, 2019, Africa Energy Outlook, (link)*
[125] *IEA, 2019, Africa Energy Outlook, (link)*
[126] *BNEF, 2018, Powering the last billion (link)*

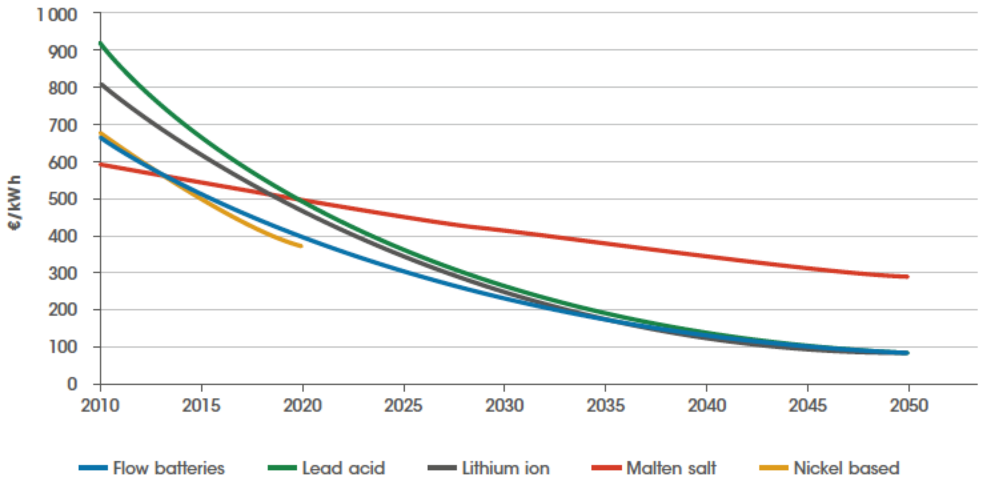

Figure 71: Projected cost reductions of battery systems in behind-the-meter applications[127]

Another factor that may support the economics of captive power systems with storage is the call for governments to reduce fossil fuel energy subsidies and introduce cost reflective tariffs. It's estimated that only 19 of 39 utilities in Sub-Saharan Africa earn sufficient revenue to cover operational expenses, while virtually none are able to cover capital expenditures from revenues.[128] The introduction of higher grid tariffs will make the grid less competitive with captive power solutions.

Cost reductions and rising grid tariffs will invariably improve the business case of captive power solutions and allow developers to increase the size of storage capacity of the energy systems. The impending introduction of support schemes such as net metering will further ease operating conditions. Yet, a barrier to widespread adoption of net metering has been and continues to be old grid infrastructure which needs to be upgraded to allow for bi-directional electricity flow. As in-country energy markets continue to develop, the captive power market segment is also set to benefit from greater proportion of local component manufacturing. This will see greater employment, greater skills transfers, shorter lead times and reduction in costs, in particular transport costs.

There has been a dramatic increase in financial inclusion in the past decade, however the real gains are likely to come in the medium term as millions of Africans access financial services for the first time owing to digital financial services offered through smart devices. Financial institutions will as a result be able to better assess creditworthiness, leading to increased access to consumer credit. In turn, this will help breach the affordability gap and accelerate adoption of captive power systems. On the supply side, the finance sector's increasing understanding of small-scale energy projects will likely see more credit available in the captive power sector. These facilities will be underpinned by the pledged billions earmarked for the energy sector by large multilateral funds such as the Green Climate Fund (GCF).

[127] *IRENA, 2019, Innovation landscape brief: Behind-the-meter batteries, (link)*
[128] *IEA, 2019, Africa Energy Outlook, (link)*

C.3. Off-Grid Industrial Facilities

Since 2011, Africa has seen linear growth with regards to off-grid electrification. In a 2018 report by IRENA, it is reported that the population served from off-grid generated power increased from 2 million people in 2011 to 52 million people in 2016[129] .Figure 72 shows how the majority of these off-grid systems were for the most basic of human needs, such as lighting. Benjamin Attia, a Senior Research Analyst at Wood Mackenzie, says in a 2020 report: "The market for off-grid renewables holds a lot more promise beyond lighting unlit households or reducing costs and fuel variability for remote, diesel-dependent industries; it represents a fundamental and dramatic evolution in the utility business model towards customer-centricity." Thus, there are opportunities to provide power to commercial and industrial users, with mini grids in many cases being more dependable than relying on a national grid. This leaves the potential for creation of local jobs in poor communities.

Figure 72: Population served by and capacity of off-grid renewable energy solutions in Africa

Many large-scale industrial plants and complexes produce their own electricity for two reasons: 1) local electricity production is cheaper than electricity from the grid; and 2) reliability and the need for uninterrupted power supply is a priority. In many cases, electricity is produced in a combined heat and power plant (CHP). Several African countries, such as Tanzania, Kenya, Uganda and Cameroon, have significant technology knowledge and agriculture-industry experience in CHP co-generation and gasification technologies and their utilisation in agriculture-industries for power self-generation and sales of excess power to the grid or surrounding mini grid area. Solar PV systems are commonly integrated into existing industrial plants to reduce the LCOE, especially during power outages when the PV system is integrated with a Diesel generator.

Falling PV prices and a lack of reliability in the grid is spurring sales of on-site solar to business customers in Sub-Saharan Africa. A report entitled "Solar for Businesses in Sub-Saharan Africa" finds that the commercial and industrial (C&I) solar sector in Sub-Saharan Africa is growing not because of regulatory support – as has been the case in many developed economies – but because of economics. On-site solar power is cheaper than the electricity tariffs paid by commercial or industrial clients in 7 out of 15 markets in Sub-Saharan Africa (excluding South Africa) studied by BNEF. As of November 2018, developers built a record number of 74MW serving business customers directly, offering them cheaper power than the grid. Kenya, Nigeria, and Ghana installed 15MW, 20MW, and 7MW respectively as of November 2018.Currently, most systems that serve industrial clients are grid-tied, but with ever decreasing cost of

[129] *IRENA, 2018, Off-grid Renewable Energy Solutions*

BESS and PV, and the increasing cost of grid electricity, the market for off-grid industrial systems could well see continued growth into the future.

C.3.1. Customer Profile

Industrial facilities, typically characterised by manufacturing, processing, and assembling of goods, are prevalent in all major cities in Sub-Saharan Africa. These facilities are typically designed for production schedules requiring constant electricity demand 24/7. Furthermore, the processes of industrial facilities are often adversely affected by power outages as it can lead to product or material getting stuck in parts of the plant which requires a labour and time intensive reset before the process can be continued. An example would be plastics that needs to be held at a constant temperature to prevent setting of the material.

Figure 73: Industrial cheese packing facility

Due to these needs for consistent and constant electrical supply, the weak and unreliable grids of Africa force some businesses to create their own off-grid electricity supply to have more control on their operations. Distributed renewables – mainly solar PV, increasingly combined with battery storage – now have highly convincing economics against costly and polluting distributed diesel for commercial and industrial demand applications. Data shows a total pipeline of more than 500 MW of commercial and industrial solar under development in Sub-Saharan Africa[130].

In Africa, the mining industry Globally, nearly 3.5 GW of renewable energy capacity is operational or under development for powering mining applications, nearly half of which will power mines already off the grid or those looking to improve on unreliable grid power[131].

C.3.2. Technical Profile

Industrial loads typically range from 0.5MW for small factories or processing plants up to 20MW or more for large mining operations or heat intensive furnaces. Most industrial facilities will fall under 5MW load.

Historically, these larger loads were exclusively served by diesel generators, typically run in parallel to allow for units to switch off and on as the load requires to save on fuel costs. With reducing costs of renewables and BESS and with

130 WoodMac: Nearly $470M Invested Into Off-Grid Energy Access Companies Last Year | Greentech Media
131 Off-grid energy key to power growth in emerging markets | Wood Mackenzie

increasing pressure on companies to offset their carbon footprint, more and more large industrial clients are turning towards renewables for their off-grid plants.

With space constraints playing a role for industrial facilities in urban areas, Wind-based energy production is not common. Typically, industrial off-grid facilities will make use of Rooftop and ground-mount solar, integrated with a BESS and a diesel generator to create a small mini grid that can always provide power.

In cases where the reimbursements are not fixed but either pay-as-you-go or PPA based, a billing-class energy meter is typically installed at the output of the grid forming inverter, which acts as the main source of energy to the load. This meter can be connected to a router that can then upload the energy production data to an online platform.

C.3.3. Business Model Characteristics

Per unit of electricity delivered, off-grid solutions cost more for the end user if the alternative is a connection to a well-managed and efficient national grid. However, in the case of some of the poorest and remote communities in Sub-Saharan Africa, where grid connection is not feasible, off-grid renewable electricity is often not only the cheapest but, in many cases, the only option available. Even where off-grid (solar home systems or mini grids) is the only option for a community, the up-front costs are still often a major barrier. Businesses face a credit challenge in many African countries due to high and fluctuating interest rates and a customer base, particularly those in more remote locations, who have uncertain and very low incomes. All of this makes lending a challenge and returns uncertain. To get around these challenges businesses in Sub-Saharan Africa must be innovative in trying to ensure they have the best possible business models for uptake and growth of the sector. Figure 74 shows how the cost of solar was in 2019 already less expensive than grid power in many countries in Sub-Saharan Africa.

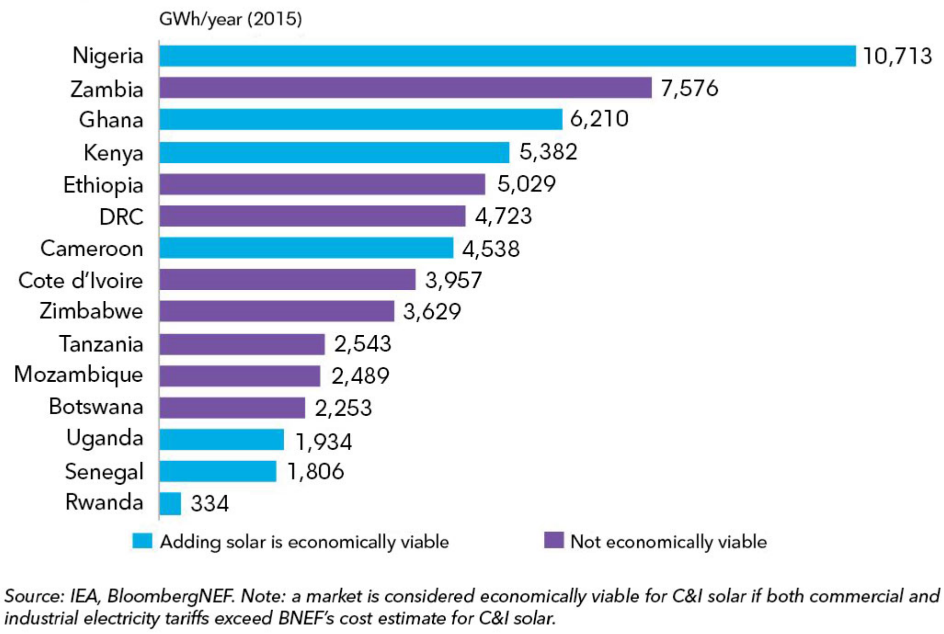

Figure 74: C&I power demand in Sub-Saharan Africa

The success of pay-as-you-go is also going beyond household ownership and being adapted for use in mini grids with businesses now adapting the model to serve other rural and off-grid sectors. A range of other commercial and industrial uses for off-grid electricity from supermarkets to mining also have potential.

The commercial and industrial business model also provides a secure customer for the mini grid developer, creating regular income and leaving open the opportunity for additional services and access to be provided to the local community from excess energy supplies.

For off-grid systems which are developed for one customer directly and only serves a single building, standard PPA models can be utilised to bill the client monthly, either based on power used or produced. In most instances structuring the PPA around the power produced, rather than consumed, will lead to the asset reflecting as a liability of the *generator* or *seller* of the energy. In the case of PPA agreements the contract can be flexible in terms of the duration, with anything from 5 to 25 years as viable options. The starting tariff per kWh and its annual escalations are other variables to the contract that will determine the returns for the developers.

For the mining industry, there is a misalignment in commercial structure between the mining and energy industries that makes negotiating cost-effective renewable contracts difficult. For example, 20-year power purchase agreements - the predominant contracting mechanism used by renewable energy developers - are not well aligned with the life-of-mine projections and the energy flexibility required for off-grid mine operations. For off-grid mines, each mine requires its individual solution, considering mine management and existing infrastructures. It may be considered easier to switch to renewables for grid connected mines: PPAs could be more flexible on the basis that, should the mine shut down, the IPP would be able to sell power to the rest of the grid. But even on the grid, things are not as easy as they seem. First, miners must wait until their current contract expires before they can change providers. And secondly, the integration of renewable energy into national grids must be approved by local governments.

O&M contracts can also be included to guarantee a level of energy production and to uphold technical specifications and warrantees.

One downside to the increasing number of services and activities off-grid electricity companies are involved in is the complexity of these organisations who simultaneously can be handling technology development, distribution, operations and maintenance, and finance. Alongside this complexity within operation, small start-up companies are also often working across larger and more markets than you would expect companies of a similar age and scale in other markets, often setting up projects across multiple regions and countries in Sub-Saharan Africa. As a result of this complexity feedback from businesses and investors suggests that the sector could to go through a period of disaggregation which could result in increases in efficiency, specialisation, and profitability. In turn, this makes the proposition for prospective investors simpler to understand and risk-assess.

C.3.4. Deploying Generators or Batteries

Projects of this scale will typically be run a in a closed tender or direct contact with an experienced EPC. In both cases the EPC will procure the hardware from their preferred supply chains, which typically will be a local distributor or in some cases directly from the supplier. On this scale, procurement lead times will vary from 4-12 weeks, but could be as long as 6 months if the BESS is more than 1MW and needs to be manufactured to site specific specifications. It is common to see up to 50% payments due on contract signature to fund the procurement and design.

Installation will typically be conducted by the appointed EPC and the design will require sign off from a professional engineer. In some cases, the BESS or generators will be installed and commissioned by the supplier and only the connection and necessary switch gear will fall under the scope of the EPC. Upon full system commissioning the final payment will be payable in most instances of an outright purchase deal and in the case of a PPA, the commissioning will typically trigger the start of the contract payments.

Fully off-grid operations are very sensitive to the design of the plant sizing, to ensure continuity in times of underperformance by the Solar array. The sizing of the BESS will typically be designed to provide power for a typical day in the winter or rainy season. Weather anomalies are not designed for, as this can increase the size of the BESS to double what is otherwise required. This shortfall is picked up by an integrated generator that is called upon by a system controller.

The growing renewable energy industry has largely been focused on electricity production and grid integration over the last decade, and technology solutions designed for other industrial processes are still nascent. While wind, solar and other renewable technologies have established solid track records, there is limited experience in their integration into on-grid and off-grid mining sectors. Other energy service technologies, such as the expanding energy storage and advanced control markets, are becoming more common within the utility sector; however, the associated technical and financial models are still largely untested within the mining industry[132].

C.3.5. Operating Generators or Batteries

The operation of off-grid energy assets is primarily focused on the maintenance of the system to ensure reliability and performance. A comprehensive O&M contract is required to service the hardware and often also to meet warranty and financial requirements.

Fossil fuel-based systems usually have scheduled maintenance intervals based on hours of operation and is conducted by a trained technician or by an appointed service technician from the supplier. For renewable systems the contract and maintenance process can be more complicated.

Because of cycles in commodity prices, the mining industry values flexibility, or the ability to ramp down or cease production at a mine site if the mineral market price becomes unprofitable to keep the mine in operation. This has traditionally favoured fossil fuel generators for off-grid operation. However, with declining capital costs for renewable systems and more flexibility offered in the form of pay-as-you-use PPAs, future operations at mines will rely more and more on renewable energy.

Especially for off-grid or edge-of-grid applications, there is an expanded opportunity to employ multi-technology microgrid systems, which can confer a resiliency benefit not only to the mine but to the larger community. A mine site could act as an anchor customer to such a microgrid and local communities could benefit from an additional, reliable source of energy (provided that the community and mine site are in close enough proximity to minimise wiring costs). Policy and regulations are often key in facilitating microgrids, so this is another area where engagement with governments can be critical.

C.3.6. End of Life Considerations

The end of life considerations of the BESS for off grid applications for industrial facilities are like a lot of the other business cases in this report. Unique perhaps to off-grid applications, are the fact that the energy supply through the BESS is often necessary for the functioning of the site. In this case, proper planning is required to either have a supplementary strategy where additional BESS capacity is added over time to allow for continuous operation beyond the initial design's end of life. Alternatively, a replacement installation will have to be planned as this will in most cases result in down time of the facility.

Already addressed in other subsections in this chapter is how the life of mine impacts off grid renewable projects. There is a drive from developers of BESS and Solar technology to focus on creating deployable and movable products and systems that could potentially be moved to other locations. In the case of a mine reaching end of life, the protocol to close out the mine will be vastly more complicated that the removal or recycling of the BESS or other energy assets. In the case of fossil fuel generators used on site, it will simply be moved to another location or sold.

C.3.7. Policy Aspects

The traditional electric utility business is ripe for disruption. As energy access markets evolve and scale, off-grid energy provision will have increasingly significant impacts on power demand, grid extension and modernization investments, the siting of new generation sources, and future carbon emissions reduction pathways. Private investment is stepping into the gap, targeting the 'lost' customers who are ill-served by the grid. Lack of grid access is particularly acute in Sub-Saharan Africa, where incumbent utilities are the most cited obstacle to the growth and maturity of the electricity sector.

[132] Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches NREL

A study in 2020 by BloombergNEF concluded that the two biggest challenges that need to be overcome for mini grids to scale up and realise their potential. First, rural customers in need of electricity access often have limited power demand and sometimes lack the ability to pay. Second, there is a general lack of policies and regulations to support mini grids.

The collaborative efforts between the mining industry, energy industry, international organization, and host governments will be needed to create supportive policy and regulation support to scaling renewables. For example, large systems could be installed that can be shared between miners and communities; this kind of investment will require clear mechanism supported by policy and regulations[133].

Policies that need to be addressed are wide-ranging and need to be tailored to meet the needs of the new off-grid sector which has several different characteristics. It is also the role of Governments to be able to ensure that should the industry begin to grow, clearer standards are set which will both attract investors who can assess investments against clear regulations as well as being robust enough to protect the consumer. Figure 75 shows some of the considerations a Government should make in setting policy frameworks for off-grid electricity access[134].

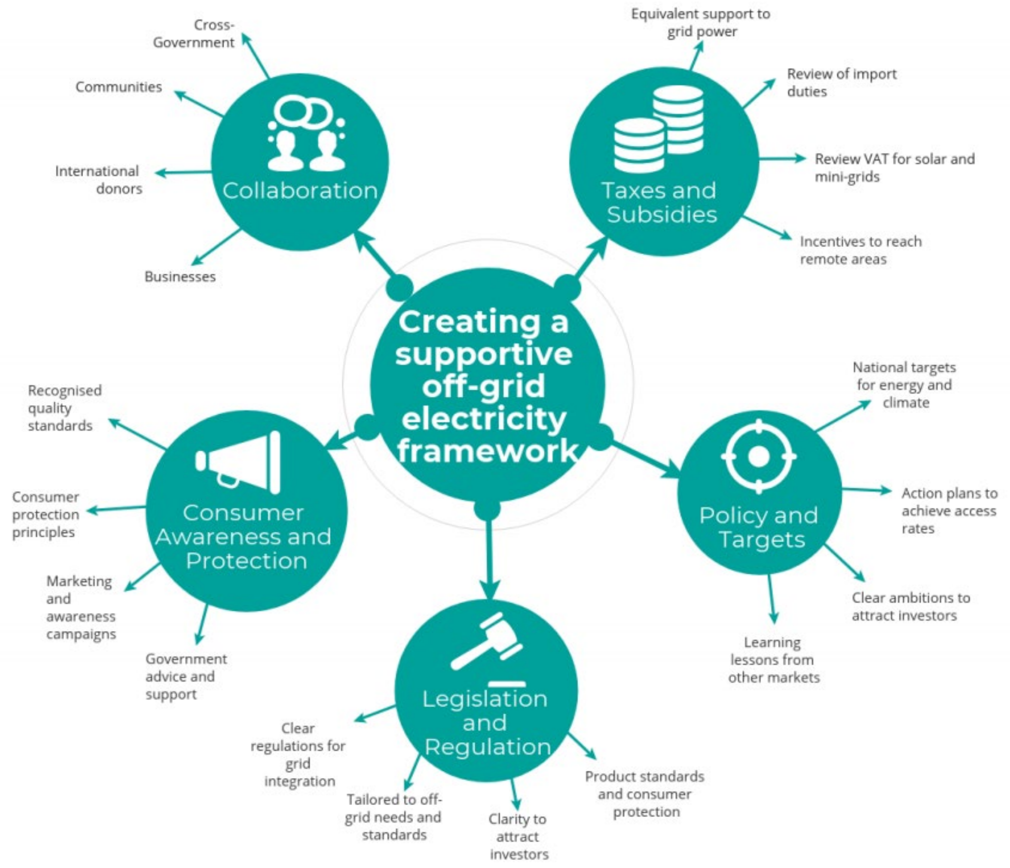

Figure 75: Towards creating a supportive off-grid electricity framework

As recent as in 2018 the technical director of Anglo American mentioned that apart from issues regarding the size of projects, some countries in Africa have policies in place that do not allow them to go off-grid completely[135]. In South Africa, where the adoption of off-grid projects have been held back by the national energy regulator of south Africa (NERSA), due to a bottle-neck in the processing of applications, there has of recent times been some good news regarding policies and regulation pertaining to embedded generation as well as off-grid projects [136]. Large industrial

[133] *Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches NREL*
[134] *Report (sun-connect-news.org)*
[135] *Anglo Using 'Digital Twins', Robotics to Boost Mining: Q&A | BloombergNEF (bnef.com)*
[136] *De Ruyter urges greater industrial policy integration with renewables roll-out (engineeringnews.co.za)*

consumers in south Africa were not allowed to have more than 1MW of generation capacity on site, but this has also recently been adjusted to increase the licence-exemption cap from 1 MW to 50 MW. This will allow mining companies and other large industrial customers to make greater use of renewable energy, even if still connected to the national grid (for the time-being).

C.4. Avoided T&D Expansion

Sub- Saharan Africa, a region known for its significant wealth in natural resources is amongst the fastest emerging markets in the world. But falls well short from other similar growing markets when it comes to economic prosperity.

In fact, there exists a direct correlation between economic growth and electricity supply, and if Sub-Saharan African countries need to see faster economic growth, then they must focus on developing its power sector. There are three aspects of power sector supporting national development of any economy - availability, accessibility, and affordability. In the case of Africa, accessibility is a major concern.

It is pertinent to note that only 35-40% of the total population in Africa has access to electricity[137]. A primary cause for such poor quality of supply and low electrification rates lies with weak power networks. Addressing these challenges will require new approaches to development and funding into the power transmission sector of the country.

Since a large funding gap is already affecting Sub-Saharan Africa's power sector, solutions are being looked at where Bess solutions can be implemented to add stability to grids and avoid unnecessary capex. Figure 76 shows how BESS can be integrated at every level of the grid, but to avoid the large costs associated with the infrastructure upgrades of transmission and distribution (T&D), BESS can play a big role and is already doing so globally.

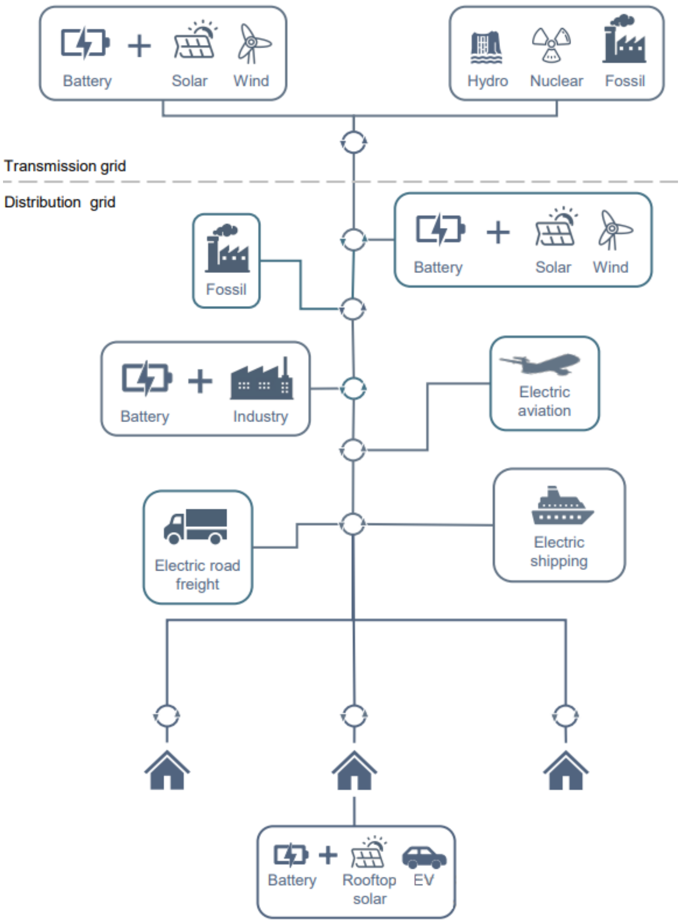

Figure 76: Batteries can be integrated at every level of the grid

Internationally, storage programmes have been launched in the USA, Europe, and China. The USA programme in California is called the Self-Generation Incentive Programme (SGIP) and in 2013 set a target of 1,3 GW of storage by

[137] [Africa Power Transmission Market 2019-2025 (globenewswire.com)]

2020. The majority (85%) of this is utility-based with the balance being customer facing. The European Union has approved plans to inject €200 million into a programme to develop battery storage manufacturing capacity (Energy Storage News, 14 Nov 2017), in addition to €150 million already allocated.

Demand is expected to rise more than eleven-fold by 2025 (from 10 to 117 GWh per annum) by 2025. China is expected to trail only the US by 2022 in demand for battery energy storage (4 GW/10 GWh vs. 8 GW/21 GWh).

Storage systems located in the distribution network can provide all the services as transmission-sited storage, in addition to several services related to congestion and power quality issues. BESS interconnected to the transmission system can provide a broad range of ancillary and transmission-related services. These systems can be deployed to replace or defer investments of peaking capacity, provide operating reserves to help respond to changes in generation and demand, or they can be used to defer transmission system upgrades in regions experiencing congestion from load or generation growth. In principle BESS applications to the grid will only replace fossil fuels in the case where it is integrated with renewables.

C.4.1. Customer Profile

When looking at the business case of avoiding T&D expansion, the customer is the utility company that services that area of grid.

In cases where the utility company is deregulated, the primary customer would be the entity operating and overseeing the infrastructure development of the transmission of electricity. In cases, where the utility fulfils all the roles of generation, transmission, and distribution, like ESKOM, then they are the only customer that stands to benefit.

C.4.2. Technical Profile

The assets implemented to avoid T&D expansion are typically BESS systems with or without renewable sources like Solar or Wind. Fossil fuel generators typically are not used for this purpose. The electricity grid’s transmission and distribution infrastructure must be sized to meet peak demand, and thus can vary widely from one location to the next. Typically, these systems are connecting to 11kV or 33kV connections and are sized upwards from 1MW up to 100MW.

Payment or reimbursement of these assets are seldom only from one function. Globally the trend is to make use of the various functions that BESS can deliver; a term called value stacking. The contract will have to be set up to reflect how the different functions will be reimbursed, but in principle electricity meters are installed at the output of the inverter and read in conjunction with the BESS software to establish discharge times, MWh throughput and other important characteristics that determines the asset’s performance.

C.4.3. Business Model Characteristics

Storage systems located in the MV distribution network can provide several services to the grid, some of which can be provided in parallel, or stacked, to add more value with the same energy storage asset. The following are the main services that can be provided, more information is included in Appendix C.4:

1. (Fast) Frequency Response / Spinning Reserve capacity / Frequency Containment Reserve
2. Frequency Regulation / Regulating Reserves
3. Investment avoidance or deferral for (local) infrastructure upgrades (by solving grid congestion issues)
4. Investment avoidance or deferral for generation capacity (by reducing grid peak load and need for new generation capacity)
5. Emergency local power supply during power outages
6. Power Quality improvement (including voltage control)

Storage systems connected to the transmission system (HV) can mostly provide the same services. However, emergency power supply and improving power quality would often not be possible due to the limited BESS power capacity compared to the transmission system capacity. Grid connection costs are normally much higher when connecting to the transmission system, as the transformers, switchgear and cabling rated for HV have much higher costs.

The first two services, providing two different grid frequency-based (power) services, are well-established applications for BESS around the world, and are currently the main application where BESS outperforms existing thermal power plants. The main issue is that the market rules or competitive tender specifications should consider the characteristics of BESS projects:

- Contracts should be long-term (ideally 10 years or more) to allow for the projects to be bankable based on providing just this service (compared to thermal plants that provide this service in addition to energy production
- There should be clear limits on how much the BESS can be used daily and annually, to ensure that degradation is manageable and avoid excessive capacity maintenance agreement costs

This project focusses on the more energy-based type of grid services, especially deferred or avoided investment in new transmission & distribution assets or new generation capacity.

The electricity grid's transmission and distribution infrastructure must be sized to meet peak demand, and thus can vary widely from one location to the next. Typically, these systems are connecting to 11kV or 33kV connections and are sized upwards from 1MW up to 100MW. An example layout of the system is illustrated in Figure 77.

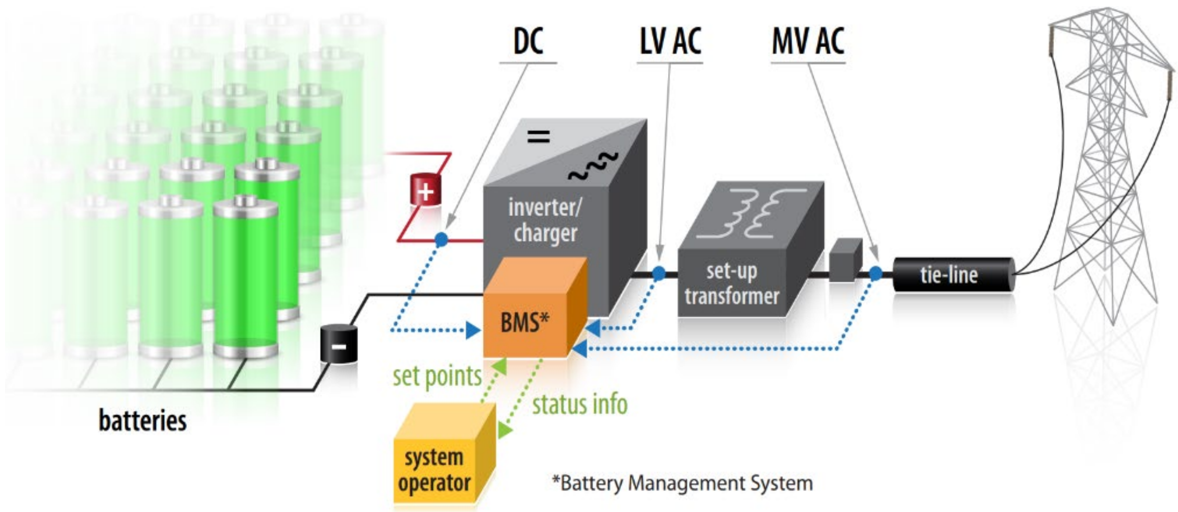

Figure 77: Key components of BESS interconnected at the transmission substation level.

In cases where the utility company is deregulated, the primary customer would be the entity operating and overseeing the infrastructure development of the transmission of electricity. In cases where the utility fulfils all the roles of generation, transmission, and distribution, such as the South African utility, ESKOM, then they alone stand to benefit.

The assets implemented to avoid T&D expansion are typically stand-alone BESS systems connected at a critical substation. By combining BESS with solar and/or wind (based on resource and land availability) charging from the grid can be minimised.

Payment or reimbursement of these assets are seldom only from one function. Globally the trend is to make use of the various functions that BESS can deliver; a term called value stacking. The contract will have to be set up to reflect how the different functions will be reimbursed, but in principle electricity meters are installed at the output of the inverter and read in conjunction with the BESS software to establish discharge times, MWh throughput and other important characteristics that determines the asset's performance. In the modelled business cases two options are reviewed:

c) BESS that is used in the morning and evening peak hours to reduce demand, allowing the demand to be met while avoiding investment in a new transformer and overhead line investment in the distribution grid (Case D-1)

d) Same as in a), but the reduction in peak demand also allows avoiding investing in new generation capacity to meet the annual peak demand (Case D-2)

Other potential revenue streams that are not included in the current business cases, but could be considered, are:

- **Arbitrage**: energy discharged during peak hours would be of a higher value/tariff than energy charged during off-peak hours. This would require a time-of-use tariff or market with varying prices during the day, this is not available in most SSA countries
- **Frequency response/regulating reserve**: during the off-peak hours the BESS could provide power-based grid services. This would require a dynamic grid services market or very flexible grid services contracts, this is not available in most SSA countries (or anywhere outside of the US)
- **Emergency local power supply**: depending on the local grid layout, the BESS could supply emergency power during power outages. However, the value of this service would be difficult to determine and translating the added value for the end-users to revenues for the BESS project/distribution company would be difficult
- **Power Quality improvement**: the BESS could be a source of both active and reactive power, allowing better control of the power quality in the distribution grid. This would bring benefits to the end-users. However, the value of this service would again be difficult to determine and translating this added value to revenues for the BESS project/distribution company would be difficult

C.4.4. Deploying Generators or Batteries

A typical BESS installation that can function in front of the meter on utility-scale are usually starting at 5MW size and can range up to 1000MW. A typical BESS consists of various components as seen in Figure 78.

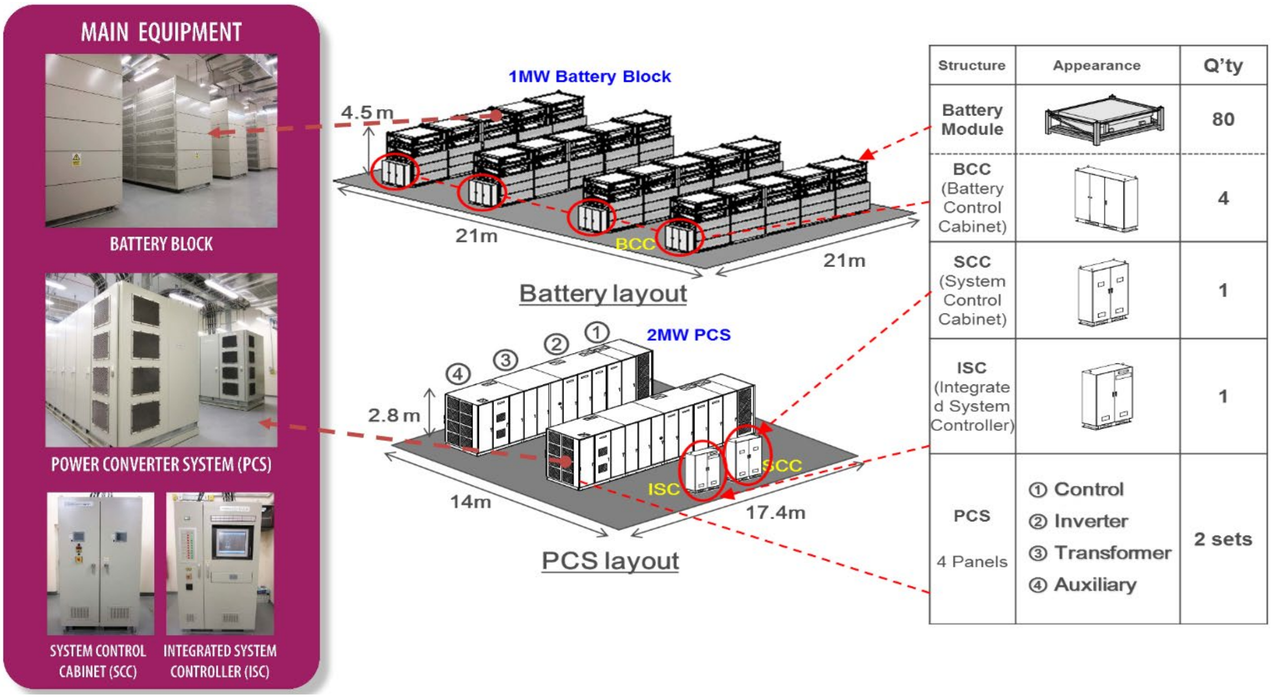

Figure 78: Typical large BESS components

These systems typically connect either to a 11kV feeder or to a 33kV feeder. In some cases, it could be as large as a 132kV feeder, but this is less common. Figure 79 shows how the BESS connects to the grid of at 11kV connection point.

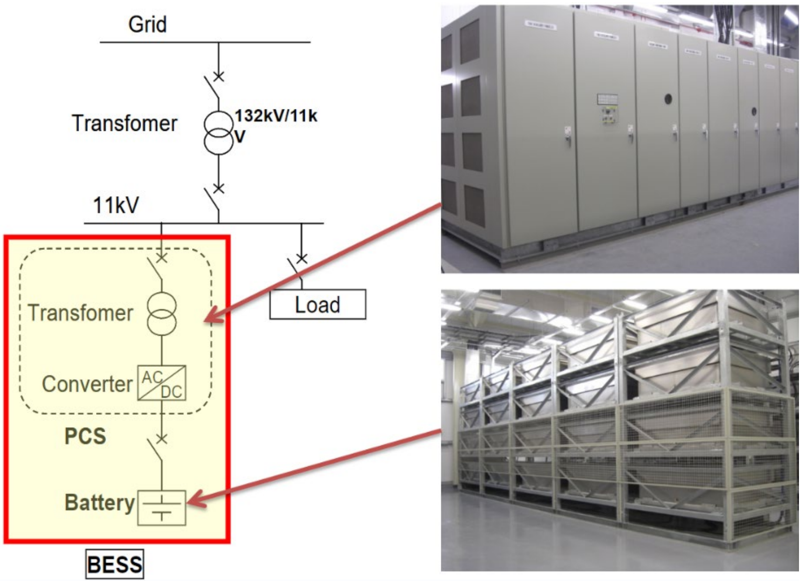

Figure 79: SLD of a typical BESS connected to 11kV feeder

C.4.5. Operating Generators or Batteries

Because there is so little operating history with this new asset class, financial models incorporate many parameters and assumptions that are not informed by historical operating experience. This lack of data and transparency introduces operational and economic risk to stakeholders. Asset managers, whether part of an owner's internal team or contracted, are tasked with overseeing the economic dispatch of the storage systems, managing the O&M contractor's field service work, and characterizing and managing operational risk. Asset managers need complete transparency into the commercial deployment and operations of the energy storage system.

The O&M contractor, or operator, is responsible for the safe monitoring and maintenance of the energy storage system equipment. The skill set required to operate and maintain solar and wind power operating equipment is easily adapted to maintaining a battery storage system. Operators are not generally responsible for the commercial deployment (scheduling) of the energy storage system on the grid, though they need visibility of past and upcoming dispatch schedules of the equipment to plan their work and monitor the warranty. O&M contractors need insights into the operating condition of the equipment and the ability to respond to alerts and safely service the equipment.

The buyers of the energy and ancillary services provided by BESS assets are typically electric utilities via an RA contract or power purchase agreement (PPA). Off-takers may have direct operational control of the energy storage asset and be able to perform discharge cycles on the asset to meet economic or operational control requirements[138].

C.4.6. End of Life Considerations

While many developers and owners are gaining experience deploying and operating grid-connected energy storage systems (ESS), few have yet to manage ESS facilities at the end of a system's life. But ESS owners, operators and developers may be able to apply some of the lessons learned from the auto industry's experience as it confronts the task of managing an increasing stock of used Lithium-ion (Li-ion) batteries from electric vehicles (EVs)[139].

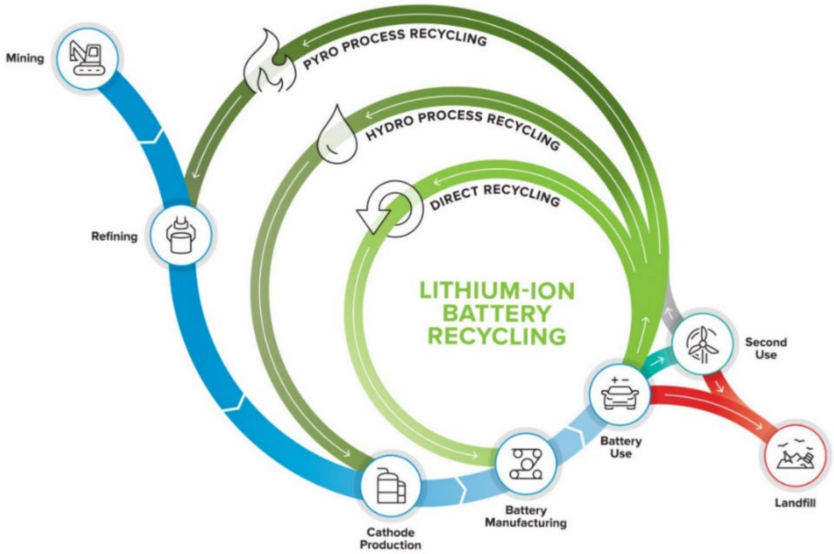

Figure 80: Circular Economy Pathways for EV Batteries[140]

Both grid-connected ESS and EVs rely on Li-ion batteries, and the phenomenal growth in Li-ion applications creates stress along the entire value chain–from mining raw material inputs, such as lithium and rarer elements, to manufacturing and disposition of the batteries once they reach the end of their useful lives. This linear depiction of material and energy use in the economy – from extraction of natural resources to production, use, and disposal – may present significant environmental consequences as the volume of battery production increases. An alternative model has emerged that instead attempts to mimic nature in the way inputs are used in production of goods, which upon reaching the end of their useful lives are then reused and/or recycled as inputs again. Such "circular economy" concepts are prevalent in the debates surrounding how to best manage the Li-ion battery life cycle.

For the vast majority of stationary ESS installations, the end of life represents a planning decision rather than an unexpected moment. Operating a Li-ion battery ESS under prudent safety guidelines and adhering to codes and standards helps prevent significant accidents or failures and thus extends its useful life. In the absence of catastrophic failure, owners generally have discretion on when to remove a Li-ion battery ESS from service. The effective lifespan of

[138] *Energy Storage Systems: Operational Challenges for Asset Managers and Operators - Power Factors % (pfdrive.com)*
[139] *End-of-Life Management of (energystorage.org)*
[140] *ReCell; Argonne National Laboratory*

the ESS can also sometimes be extended with enhanced maintenance and replacement activities. Li-ion battery-based ESS are inherently modular, being composed of individual battery cells assembled into modules (packs, trays, or assemblies), arrayed in racks, connected into various control systems, and enclosed in containers. Individual cells, modules and even entire racks can be replaced as needed (when, for example, one degrades unusually quickly compared to other components that maintain performance). Where economic, overall ESS performance can be maintained at acceptable levels by selectively refreshing individual components, thus extending the overall economic lifetime, and deferring the retirement of the facility. Currently, the validation to ensure that a mixture of old and new battery cells or modules can work together effectively can be costly, although those costs will likely fall as operating experience accumulates. Extending the effective lifetime of a durable asset is consistent with circular economy benefits as it reduces both virgin material input requirements as well as potential waste, although at some point performance, safety and economic considerations will dictate decommissioning.

C.4.7. Policy Aspects

Regulatory barriers to market entry are a stifling point for many Utility-scale BESS projects. Simply put there is a lack of rules and regulations to clarify the role of BESS.

Although storage may be technically able to provide essential grid services, if no regulations or guidelines explicitly state that storage can provide these services, utilities and market operators may be unwilling to procure services from BESS. Furthermore, without a guarantee that services provided by a BESS project will be compensated, storage developers and financing institutions may be unwilling to make the necessary capital investments. Federal Energy Regulatory Commission (FERC) Order 841 addressed this issue in U.S. wholesale markets and directed market operators to develop rules governing storage’s participation in energy, capacity, and ancillary service markets. Among other requirements, the rules must ensure open and equal access to the market for storage systems, taking into consideration their unique operating and technical characteristics (FERC 2018).

Additionally, restrictions or lack of clarity around if and how storage can be used across generation, transmission, and distribution roles acts as a barrier.

The variety of different services storage can provide often cuts across multiple markets and compensation sources. For instance, frequency regulation may be compensated in a wholesale market, but transmission or distribution investment deferrals may be compensated as a cost of service by the utility or system operator. In some jurisdictions, providing services across different compensation sources is restricted by regulation. Limiting the services batteries can provide based on where the service is provided or how it is compensated can influence how often they are utilised and whether they remain an economic investment.

C.5. Hybrid Solar and Wind Plants

C.5.1. Customer Profile

In most cases battery energy storage systems are used to provide short-duration power (for several hours), but in this business case the aim is to replace dispatchable thermal power capacity by a combination of solar PV, wind and BESS (potentially augmented with back-up generators). The first large scale application has been seen in the emergency power tender in South Africa: the Risk Mitigation Independent Power Producers Procurement Programme (RMIPPPP). The aim of this program is to obtain dispatchable power while avoiding excessive fuel costs and (CO_2) emissions. The initial results of the tender show that different combination of solar, wind and BESS can be competitive with conventional power plants at utility-scale. The added benefit of renewables and storage-based power plants is the predictability of future costs, as there is no need to procure and import volatile priced fossil fuels.

C.5.2. Technical Profile

The RMIPPPP tender mentioned in the previous subsection specified dispatchable (baseload) power from 05:00 in the morning to 21:30 in the evening, as this is the period of the day that there are generation shortages or when older (inefficient) diesel fuel power plants have to be utilised at high marginal costs of generation to meet demand.

This concept is likely to be applied in some form in other countries in SSA, where there is an aim to increase renewable energy generation, but security of supply also needs to improve to support economic growth. There will likely not be a need for full baseload output, as demand changes over the time of day, but there is a need for predictable or reliable power capacity that can be dispatched (scheduled) by the central grid operator.

C.5.3. Business Model Characteristics

This business case is still in its infancy so the effectiveness still needs to be proven and in time the details will be further improved. This business model works best as a competitive IPP tender, where developers offer competitive solutions based on minimum functional specifications. The main optimisation seems to be in the feasibility stage when the tender requirements are determined: important balance between flexibility for the off-taker and affordability of the solution. Too stringent requirements put high risks on the developer and result in over-designed solutions with associated high costs and resulting tariffs. The detailed requirements determine the amount of energy storage required to achieve a certain flexibility and availability of power output. As energy storage does not produce energy itself, additional storage capacity results in higher costs per kWh delivered to the grid. When continuous baseload power is required day and night, hybrid solar, wind and storage plants cannot provide this competitively yet. But the minimum functional specifications should be that the reliability and dispatchability required for the power system are met to justify the premium compared to more straight forward solar and wind take-or-pay based tenders with rock-bottom LCOEs.

The likely best payment structure is a combination of a fixed available capacity-based payment and a variable energy delivered-based payment, as that best reflects the value of the project for the offtaker and allows the IPP to best manage their dispatch risks.

Another approach is to offer a bonus payment for energy output during peak hours (e.g. in the evening starting at sunset), to encourage solutions that better meet peak demand. But this is difficult to get right for several reasons, including:

a) The right amount of bonus payment for peak kWh is difficult to determine and keeps changing

b) There is no guarantee the entire duration of the peak is reduced, instead of only the first few hours, leaving the same overall peak demand later in the evening

With increasing renewables penetration and (slower) changes in demand (e.g. through adoption of HVAC), the shape of the demand curve also changes over time. This requires some flexibility for the offtaker to define what hours of the day they want to ensure power output. From the developer/IPP point of view, this increases their risk as it is difficult to predict what the exact dispatch and payments will be.

C.5.4. Deploying Generators or Batteries

The main reference for dispatchable hybrid solar and wind plants in Africa is the RMIPPPP (emergency power tender) currently running in South Africa. This tender shows the complexity of procuring truly technology agnostic dispatchable generation capacity, as technical functional specifications quickly limit the (economically) feasible technologies. But the process so far shows that hybrid plants can compete with fossil fuel plants under certain conditions and a competitive tender-based procurement approach seems to be the most effective. The two main drivers that determines the optimum amount of energy storage compared to thermal generator capacity are:

- **Technical**: the requirements on the timing and duration of continuous baseload power output
- **Economic**: the (projected) fuel prices and/or CO_2 emissions costs included in the evaluation metrics

Procuring, installing, and commissioning BESS at utility-scale power plants is in general much more straight forward than thermal generators, as the interfaces and foundation requirements are much simpler for BESS. The main complexity is the hybrid plant control system (advanced energy management system, EMS) that optimises the dispatch of the different generation units and BESS (dis)charging. There are several suppliers of these control systems that have sufficient operational experience to reduce the risk of communication and control issues between the different assets, the larger suppliers including Siemens, Emerson, GE, and ABB. This risk should be managed more closely when the supplier has less operational experience.

C.5.5. Operating Generators or Batteries

Having a large-scale centralised plant makes managing operation and maintenance much more straight forward. Compared to thermal generators the BESS requires very little maintenance or operational staff, as there are no moving parts (besides HVAC equipment) and operation is automated. The same considerations discussed in the previous section on utility-scale BESS for avoiding T&D expansion apply for BESS at hybrid power plants. One main difference is that there would be a need for accurate continuous forecasting of solar and wind output for the next hours and day-ahead. Based on the forecasted production, the BESS dispatch and state-of-charge can be managed.

C.5.6. End of Life Considerations

Managing the re-use and recycling of BESS equipment from large-scale centralised plants is much easier than remote distributed systems. The same end of life considerations discussed in the previous section on utility-scale BESS for avoiding T&D expansion apply for BESS at hybrid power plants.

C.5.7. Policy Aspects

As discussed in the previous sub-sections, the specific requirements of the functional specifications/technical requirements of the tender determine most of the BESS feasibility. Policy measures can further support the feasibility and deployment of BESS in several ways:

- Exemption of BESS equipment from import duties
- Direct investment support/subsidies (grants) or tax incentives/accelerated depreciation
- Dedicated funding (loans) for BESS projects to improve the bankability
- Ensure the grid code requirements are relevant for BESS (and hybrid plants)
- Streamlined permit processes for BESS (and hybrid plants), reflecting the low environmental impact of BESS

APPENDIX D. BATTERY ENERGY STORAGE TECHNOLOGIES

D.1. Lead-acid

Valve regulated lead-acid (VRLA) and flooded type lead-acid are the two main types of lead-acid battery designs. Flooded is the conventional battery design involving a liquid electrolyte. In the VRLA design, a special absorbent material (gel or AGM – absorbent glass mat) immobilises the electrolyte and provides many desirable properties to the battery. The design of the individual positive and negative electrodes is either in the form of flat sheets or concentric tubes. Each design has its own advantages and disadvantages with tubular batteries exhibiting longer cycle life and flat plate batteries, higher power density, despite being made of identical materials.

The SMF (sealed maintenance free) VRLA batteries have extensively been used for emergency supply in power plant applications. Despite being universally accepted in the market, conventional lead-acid batteries face several technical obstacles in large scale adoption as utility-scale BESS. Their relatively low energy density, inflexible C-rates, high thermal runaway in times of partial cycling and relatively low cycle life owing to active sulphation, lead to a very narrow window wherein their adoption becomes practical.

Table 24: Typical performance characteristics for lead-acid and advanced lead-acid batteries

Parameter	Lead Acid	Advanced Lead-Acid
Power Rating	Fully scalable	Up to 100 MW
Discharge at Rated Power	Generally < 1 hour	15 minutes to 4 hours
Round Trip Efficiency	70% - 80%	75% - 90%
Response Time	Milliseconds	Milliseconds
Self-Discharge per day	0.1% - 80 kWm^3	0.1% - 0.3% per day
Power Density	50 – 80 kWhm^3	50 - 80 kWm^3
Energy Density	10 – 400 kWm^3	10 – 400 kWhm^3
Cycle Life	200 to 1,800 cycles	2,200 – 4,500 cycles
Depth of Discharge	~50%	~50%
System Lifetime	3 – 15 years	3 – 15 years
Cost, power	200 – 600 $/kW	300 – 600 $/kW
Cost, energy	50 – 400 $/kWh	500 – 1,150 $/kWh
Actual cost/performance varies by construction and manufacturer.		

Scientists have known for years that sulphate accumulation prevents the classic lead-acid battery from delivering sustained performance. Partial charge and ageing are the main culprits because the negative lead plate is not sufficiently scrubbed. The advanced lead-carbon (ALC) battery solves this by adding carbon to the negative plate (cathode).

Compared to some Li-ion equivalents, ALC is low cost, operates at sub-freezing temperatures and does not require active cooling. However, ALC is heavier and larger and thus its energy density becomes laborious for large installations. Colder operating temperatures will yield a little extra life, but they will also lower the capacity of lead-acid cells. High temperatures by contrast yield higher capacity, but they have a detrimental effect on life expectancy. Unlike regular lead-acid batteries, lead-carbon can operate at between 30% - 70% state-of-charge without becoming sulphated due to the presence of carbon in the anode.

Despite having a very low energy-to-weight ratio and a low energy-to-volume ratio, lead-acid batteries can supply high surge currents, which means that the cells have a relatively large power-to-weight ratio. Large-format lead-acid designs are widely used for storage in backup power supplies in cell phone towers, high-availability settings such as hospitals, and stand-alone power systems. Applications for a stationary ESS will favour advanced lead-acid. Advanced lead-acid batteries are increasingly being considered for transportation applications[141] and have been used to regulate frequency in utility-scale grid applications.

Maintenance requirements for lead-acid batteries are more onerous than for many newer technologies, and include float charging, equalisation charging, water replacement, and cell post maintenance. A voltage also needs to be continuously applied to the already-charged battery to maintain a small current and prevent self-discharge. The external parts of lead-acid batteries (terminals, lugs, connectors) are also prone to corrosion resulting from chemical reactions and limited box ventilation.

Decommissioning and disposal of battery components, especially some lead compounds, is critical as many of these are highly toxic. Exposure to even small amounts can cause chronic brain and kidney damage. While lead-acid battery recycling is effectively practiced in most parts of the world, Africa's hot climate can significantly decrease the life of lead batteries thereby increasing recycling requirements. The total end-of-life volume for lead-acid batteries in Africa in 2016 was 1.23 million tonnes, equating to more than 800 000 tonnes of lead that require processing[142].

The risks, costs and barriers associated with lead-acid batteries are well understood, and the maturity, availability and relative low cost continue to make it an attractive alternative. Advances in the technology are also improving performance measures and addressing issues, however for many applications other battery technologies may outperform or provide lifecycle costs.

Advantages & disadvantages of lead acid batteries

Advantages:

- Low CAPEX
- Operates at sub-freezing temperatures
- Does not require active cooling
- High power/weight ratio
- Can supply surge currents

Disadvantages:

- Relatively low energy density
- Inflexible C-rates
- High thermal runaway in partial cycling
- Active maintenance requirements
- Prone to self-discharge
- Hix toxicity of lead makes battery disposal difficult

[141] *Cooper, A; Moseley, P, Advanced Lead-acid Batteries – the Way forward for Low-Cost Micro and Mild Hybrid Vehicles, (Link)*
[142] *The deadly business - Findings from the Lead Recycling Africa Project (Link)*

D.2. Li-ion

Li-ion batteries are the most common category of rechargeable batteries and used in a vast range of applications including portable electronics, battery Electric Vehicles (EVs), aerospace, and large-scale stationary applications. At its most basic level, a Li-ion cell contains a cathode (positive electrode), an anode (negative electrode), an electrolyte, all of which is held within a container (typically a pouch or cylindrical cell). The chemical process by which energy is stored, involves lithium-ions moving from the negative electrode to the positive electrode during discharge and back when charging – this reversible reduction-oxidation reaction (redox) chemically stores electrical energy for use later.

A "lithium-ion" battery is the umbrella term referring to any electrochemical energy storage system which uses Li-ions as the charge carrier between the cathode & anode. There are many types of Li-ion battery, usually differentiated by the chemical structure of the cathode material. Common cell chemistries include lithium cobalt oxide ($LiCoO2$), lithium iron phosphate ($LiFePO4$), lithium-ion manganese oxide battery ($Li2MnO3$, or LMO) and lithium nickel manganese cobalt oxide ($LiNiMnCoO2$ or NMC/NCM). The anode material is generally graphite, however there are some alternatives such as lithium titanate (LTO) or graphite with silicon additives. Changes in the chemistry of the cathode and anode gives rise to variations in properties such as specific energy, specific power, cycle lives, cost, safety, and thermal stability. Figure 81 shows a schematic of a Li-ion battery with the different components.

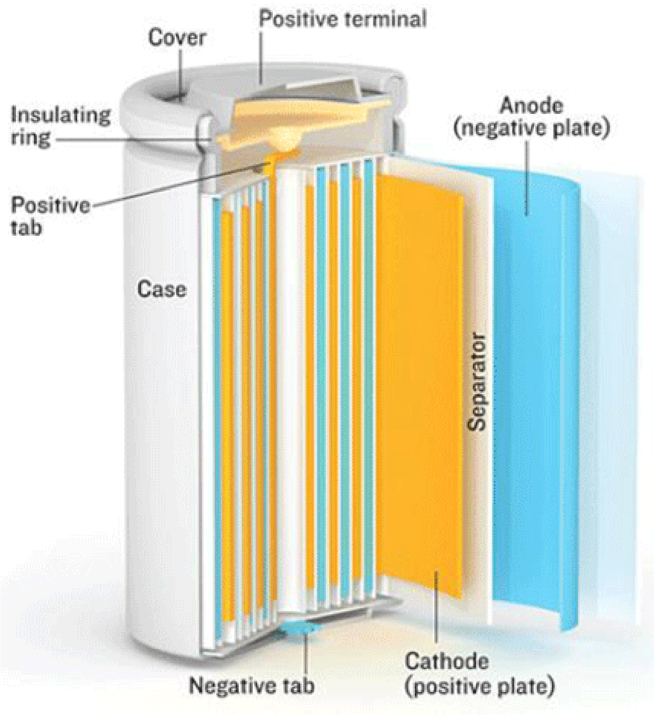

Figure 81: Lithium-ion cell schematic

Chemistries

This section provides a short description of some commonly used Li-ion chemistries in stationary grid scale applications; NMC, LFP & NCA. However, recent trends in grid scale storage deployments have begun to move away from NCA and NMC chemistries and pivot towards LFP based cells. The key driver for this shift is the lower cost and potential safety benefit of LFP cells which have a higher thermal runaway temperature and lower likelihood of catching fire.

NMC – Lithium Nickel Manganese Cobalt Oxide

NMC is still one of the most popular choices for utility-scale ESS. Variation in the ratios of Ni-Mn-Co allows the system characteristics to be tailored to specific applications. Increasing the share of nickel favours higher specific energy, while also improving thermal stability and cycle life. Alternatively, increasing the share of manganese favours higher specific power. Therefore, NMC batteries exhibit balanced overall performance in specific power, safety, thermal stability, lifespan, and cost, while they excel in terms of specific energy (in the range of 140-200Wh/kg). NMC batteries are well suited to stationary industrial applications which require good loading capabilities, long life, safety, and dependable service. Some prominent manufacturers include LG Chem, Kokam, Panasonic & Samsung.

LFP – Lithium Iron Phosphate

The main benefits of LFP are low cost of cells, high current rating, long cycle life, good thermal stability, safety, and durability. Additionally, it can tolerate a large SOC window while maintaining a constant voltage – this implies consistent performance even at low SOC. Another advantage of the LFP chemistry is that it relies on abundant, eco-friendly materials. The use of metals such as cobalt & nickel in other Li-ion chemistries is responsible for a significant environmental impact when considering the full life cycle. While LFP batteries can handle the stress of prolonged high voltage better than other Li-ion systems, they have a lower nominal voltage which reduces the specific energy (in the range of 90-140Wh/kg). Due to the high thermal stability of LFP cells in comparison to other Li-ion chemistries, many recent installations have used LFP to reduce the associated fire risk. In particular, many BYD systems (using LFP cells) have been installed in the UK in recent years. CATL and Narada are also well-established manufacturers of LFP cells.

NCA – Lithium Nickle Cobalt Aluminium

NCA has similarities with NMC in that it displays excellent specific energy (in the range of 200-250Wh/kg) with reasonably high specific power and cycle life. However, it is inferior to NMC in terms of safety, stability, and cost. Utility-scale applications centre around high energy functions such as backup and load shifting. This is the chosen chemistry by Tesla for its EVs (it is noted than Tesla plan to move away from this technology in favour of cobalt free cells. Typically, NCA blends consist of 80% Ni, 15% Co and 5% Al. This relatively low reliance on cobalt is an advantage due to the negative impacts associated with cobalt extraction. However, nickel extraction also has a significant environmental impact that must be taken into consideration. Tesla are a prominent supplier of this technology in stationary applications. Their Megapack offering utilises Panasonic 21700 cylindrical NCA cells. However, it is noted that it is possible to purchase the Megapack with CATL LFP cells as an alternative.

Advantages & disadvantages

Advantages:

- Highly modular and scalable
- High energy per unit volume (high energy density) when compared to other energy storage technologies, potentially allowing for a more compact design or a smaller footprint
- Fast response times
- Low maintenance
- Li-ion systems typically demonstrate higher efficiency than other technologies
- Gaining experience and references in terms of the number of projects globally

Disadvantages:

- Fire and safety risk under abuse conditions e.g. mechanical abuse, short circuit, over-charge, or exposure to high temperature

- Constructed using elements such as Nickel, Cobalt and Manganese which are linked to either environmental or human rights concerns
- Lower cycle life than some alternative technologies
- Performance degradation due to calendar aging and cycling
- End of life recycling of lithium-based batteries can be complex and costly

Performance metrics

This section provides a summary of some typical figures seen for key Li-ion performance metrics. Table 25 shows a high-level comparison of NMC, LFP and NCA chemistries. Table 26 shows some general performance parameters seen for Li-ion projects. These figures are not specific to any one chemistry, therefore, in some cases a range of values is specified to account for the variability/uncertainty.

Table 25: Summary of key parameters for NMC, LFP and NCA cells

Parameter	NMC	LFP	NCA
Specific Energy (Wh/kg)	140 – 200	90 – 140	200 - 250
Cycle Life (100% DOD)	>5,000[143]	>6,500[144]	500 – 3,000
Self-discharge		2% - 3% per month	
DC RTE (%)	93% - 96%	92% - 94%	93% - 96%
Durability in high temperatures	Low	High	Low
Nominal cell voltage (V)	~3.7	~3.2	~3.6
Advantages	High energy density	Safety and Power	High energy density
Disadvantages	Lower safety	Degradation at higher temperature	Low cycle life Lower safety

[143] https://www.mdpi.com/1996-1073/10/12/2107/pdf
[144] https://www.mdpi.com/1996-1073/10/12/2107/pdf

Table 26: General performance characteristics of Li-ion BESS

Parameter	General Li-ion performance metric
DC RTE (%)	~92% - 96%
AC RTE at output terminals of PCS (%)	~90% - 92%
Full site AC RTE at POC, including auxiliary loads (%) [guaranteed by BESS supplier]	~84% - 89% (for a reference test cycle. During operation, this depends on cycling rate, ambient conditions, electrical equipment used, site electrical design etc.)
Response time (for initial response, time until start of ramp up)	Within ~ 50 ms – 100 ms of an instruction signal, including any communications latency. The initial response requirement for Dynamic Containment Reserve in the UK is 250 ms.
Response time (time until full power response)	Within ~150 ms – 250 ms of an instruction signal, including any communications latency (full power response within 150 ms is very difficult to achieve, but it is required for services in certain markets, eg: DS3 services in Ireland).
End of Life (EOL) state of health (SOH)	Typically defined around 65% - 70% SOH depending on the manufacturer, in some cases it can be as low as 50%.
Cycle Life (100% DOD)	This depends on the exact system, but typically in the range of 4,000-7,000 cycles. This figure can be increased/decreased based on how well the system is maintained, the cycle rate, depth of discharge (DOD) for each cycle etc.
Lifetime (years)	8-15 years for approximately 1 – 2 cycles/day
Safety	Fire safety remains a concern, consideration must be given to appropriate sizing of the thermal management system and fire detection/suppression systems
Charge/Discharge characteristics	Li-ion systems are generally capable of provided a flat charge/discharge curve (constant power) across a wide SOC range within the specified optimal operational temperature range. Tapering of charge/discharge power can occur at very high or low SOC (>95% or <5%, exact figures depend on the specific system) and when the cell temperatures fall outside the optimal range
Auxiliary Loads	The auxiliary loads for a typical site are highly variable based on the ambient conditions and the required cycling rate. DNV therefore cannot specific a "typical" auxiliary load figure.
Self-discharge	2% - 3% per month
DOD or usable capacity range (%)	Typically, 80% DOD to 85% DOD (Note: 80% DOD results in usable capacity range from 10% - 90% SOC)
Ambient operational temperature range (°C)	~ -20°C to 40°C
Cell optimal operational temperature range (°C)	~ 20°C to 30°C

D.3. Sodium Sulphur

Molten sulphur acts as cathode within a sodium sulphur battery, molten sodium acts as anode and the electrolyte is sodium alumina. The principle of operation is the same as that of Li-ion batteries - the difference in electrolytic potential of two electrodes establishes the flow of an electric current when connected across a load.

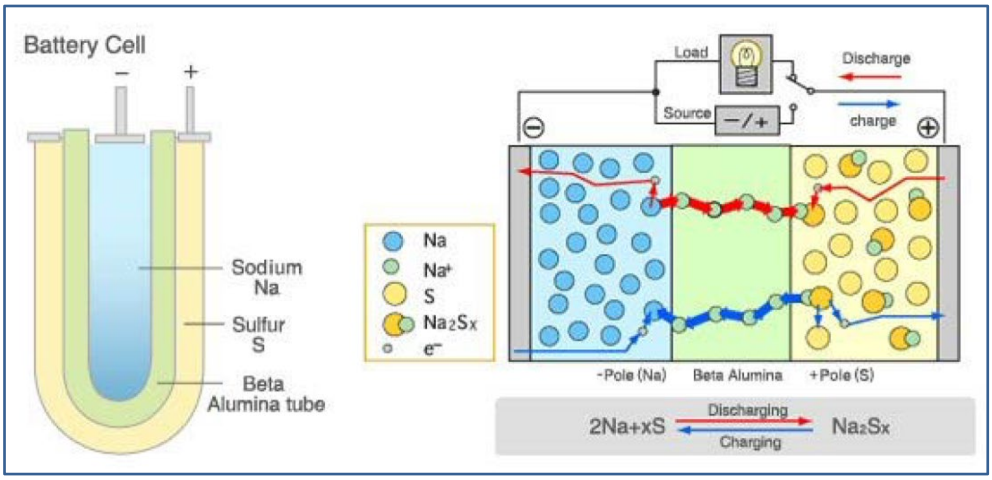

Figure 82: Sodium Sulphur batteries

The inclusion of the term “molten” alludes to the battery operating temperature. NaS batteries store electricity through a chemical reaction which takes place at 300 °C or above. At lower temperatures the chemicals become solid and reactions cannot occur. The high operating temperature makes the NaS batteries suitable for larger applications supporting the electric grid, but not for personal electronic devices or vehicles. Further, due to elevated temperature and violent reactivity of pure sodium when exposed to water, the system can present a safety hazard if damaged. NaS batteries are a mature technology, and the system cost has generally levelled off.

D.4. Redox Flow

Technology: Redox flow batteries are a form of electrochemical storage which releases energy through a reaction between two chemical compounds dissolved in electrolytes. Unlike conventional batteries, flow batteries store the electrolytes in separate tanks which flow into a cell (or membrane stack) and the ion exchange occurs through the cell membrane. The energy capacity of the battery is a function of the volume of electrolyte, therefore by changing the size of the tanks the energy capacity of the system can be increased or decreased. The power rating of the system is dependent on the number of stacks of cells. As with Li-ion batteries, redox flow batteries can be constructed with different chemistries. The most common chemical compositions include vanadium (VRB) and zinc-bromine (ZnBr). Other, but less mature, technologies of redox flow batteries include those deploying organic, metal hydride and semi-solid electrolytes.

Application: Redox flow battery technology is generally less mature than Li-ion batteries, however there are several promising grid-scale trials and initial commercial systems. Its applications for stationary electricity storage overlap largely with those of Li-ion, i.e. from fast responding ancillary services to energy shifting over multiple hours. There are a few factors that render redox flow batteries as a promising solution for storage systems that require 6-8h (or more) of storage duration. These factors are a long cycle life, promise of low marginal cost to increase energy capacity, and absence of degradation. Commercial uptake has – to date – been slow due to the higher cost, low volumetric energy density and low efficiency (65-75%) when compared to Li-ion. Systems up to 100 MW are however operational, with deployment spanning more than 50 projects globally.

D.5. Ni-MH

A nickel metal hydride battery (NiMH or Ni–MH) is a type of rechargeable battery. The chemical reaction at the positive electrode is similar to that of the nickel–cadmium cell (NiCd), with both using nickel oxide hydroxide (NiOOH). However, the negative electrodes use a hydrogen-absorbing alloy instead of cadmium. NiMH batteries can have two to three times the capacity of NiCd batteries of the same size, with significantly higher energy density, although much less than lithium-ion batteries.

Figure 83: Modern Ni-MH rechargeable cells

Research on nickel-metal-hydride started in 1967; however, instabilities with the metal-hydride led to the development of the nickel-hydrogen (NiH) instead. New hydride alloys discovered in the 1980s eventually improved the stability issues and today NiMH provides 40 percent higher specific energy than the standard NiCd.

Nickel-metal-hydride is not without drawbacks. The battery is more delicate and trickier to charge than NiCd. With 20 percent self-discharge in the first 24 hours after charge and 10 percent per month thereafter, NiMH ranks among the highest in the class. Modifying the hydride materials lowers the self-discharge and reduces corrosion of the alloy, but this decreases the specific energy. Batteries for the electric powertrain make use of this modification to achieve the needed robustness and long lifespan.

About 22% of portable rechargeable batteries sold in Japan in 2010 were NiMH.[13] In Switzerland in 2009, the equivalent statistic was approximately 60%.[14] This percentage has fallen over time due to the increase in manufacture of lithium-ion batteries: in 2000, almost half of all portable rechargeable batteries sold in Japan were NiMH.

NiMH cells are often used in digital cameras and other high-drain devices, where over the duration of single-charge use they outperform primary (such as alkaline) batteries.

NiMH cells are advantageous for high-current-drain applications, largely due to their lower internal resistance. Typical alkaline AA-size batteries, which offer approximately 2600 mAh capacity at low current demand (25 mA), provide only 1300 mAh capacity with a 500 mA load. Digital cameras with LCDs and flashlights can draw over 1000 mA, quickly depleting them. NiMH cells can deliver these current levels without similar loss of capacity.
Applications:

1. Consumer electronics
2. Early generation EVs (Li-ion have replaced them in this market)

D.6. Zinc Electrolyte Batteries

A new, little-known BESS using zinc electrolyte chemistry has recently been developed by Eos Energy Storage that shows significant promise in reduced costs and cycle life with little degradation of capacity over time. The core of the Eos energy storage systems is the Eos Znyth (zinc hybrid cathode) battery technology, shown in Figure 84. It employs inexpensive, widely available materials within a robust, scalable design to achieve long life and extremely low cost.

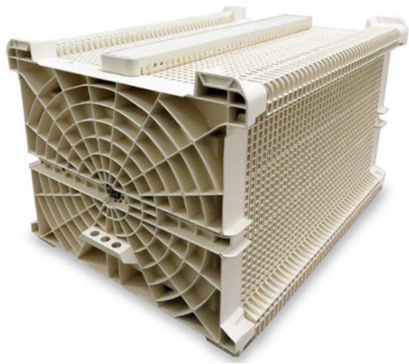

Figure 84: Deployed Eos batteries (left) and architecture of the Eos Znyth (right)

The battery is designed to last 5,000 cycles for a 15-year calendar life, with no subcooling or pumps required. It can achieve high energy efficiencies with up to 80% efficiency in 100% depth of discharge applications. With 3-12 hours of discharge capability, immediate response time, and modular construction, the Eos systems can be scaled and configured to reduce cost and maximise profitability in utility, commercial and industrial, and military market segments.

Another benefit is that of safety. The battery is constructed from non-flammable aqueous electrolyte which has no flashpoint and is non-hazardous and non-corrosive when shipped.

The O&M costs each year are projected to be 1.5% of the total installed capital cost. While the optimal ambient operating temperature range is wide, from 45 degrees Celsius down to – 45 degrees Celsius, a cold weather blower package may be provided by an integrator to allow operation at even lower temperatures. According to the company, Eos Aurora does not require fire suppression and, absent extreme environments, does not require a HVAC system. Eos offers extended warranties for the DC system for 5, 10, 15 and 20 years. A warranty may be purchased to ensure 80% or 100% of nameplate capacity at the end of project life.

Zinc Redox Batteries

The zinc bromine (ZnBr) battery utilises similar flow battery technology as the previously discussed VRB. Due to this, it shares many of the same advantages: little to no claimed degradation over time (both in use and in the fully discharged state), high energy density, 100% DOD, and easily scalable. The ZnBr consists of a zinc-negative electrode and a bromine-positive electrode, separated by a micro-porous separation. Solutions of zinc and a bromine complex compound are circulated through the two compartments. In a ZnBr the electrodes serve as substrates for the reaction. During charging, zinc is electroplated at the anode and bromine is evolved at the cathode. When not cycled, there is a potential for the zinc to form dendrites that can degrade capacity or damage the battery components. To prevent this, the battery must be regularly and fully discharged.

The response time for this technology is thought to be inadequate for fast-response applications; this should be verified on a case by case basis as new system designs may be able to improve on this limitation. ZnBr is a promising technology for balancing low-frequency power generation and consumption. However, cycle life tends to be less than that of VRBs and the toxicity of bromine is a concern. These systems are in the initial stages of commercialisation but are being produced by multiple manufacturers.

D.7. Emerging BESS technologies

The future of BESS technologies is predominantly centred around innovation of Li-ion chemistries. This innovation is however wide-ranging:

- Incremental improvement of performance and cost of Li-ion batteries already found in smartphones, cars and stationary storage applications by improved cell design, better manufacturing practices and better control or management of the battery cells.
- Development and discovery of new materials and recipes to improve the components of Li-ion batteries, such as the anode, cathode, separator, and electrolyte.
- Shift in recipes to improve sourcing, cost, safety or general performance of Li-ion batteries, such as the shift to nickel-rich cathodes for automotive applications (reducing or avoiding cobalt) and increasing adoption of lithium iron phosphate (LFP) for stationary storage in 2020.
- Design of battery pack or module layout, material, form factor and protection system on both performance and cost, with a trend to pack design specific for applications (stationary storage, home storage, electric vehicles, heavy duty vehicles, marine/shipping, drone/flight, portable, etc.).
- Research and development of more disruptive rather than step change battery technologies, including solid state Li-ion, metal Li-ion, metal air, and low-cost redox flow electrolytes.

Technology readiness levels (TLRs) are a method for estimating the maturity of technologies during the acquisition phase of a program, developed at NASA during the 1970s. The TRL methodology – with minor adaptations – is also utilised by the US Department of Defence, European Space Agency, and the European Union's Horizon 2020 program. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology.

The below lists several emerging battery technologies that have the potential to make their mark on the rapidly developing battery technology space due to promises on performance and cost. Each technology includes an estimation on TRL. The below list is non-exhaustive, and these technologies are not discussed in further detail in this report due to their status as an emerging technology with several years of technology development and commercialisation efforts expected till market introduction for stationary storage.

LeydenJar – Silicon anode for Li-ion batteries

Most Li-ion batteries have a carbon-based anode. The specific energy capacity of a graphite anode is significantly lower than that of a silicon anode.

LEYDENJAR TECHNOLOGIES

Leyden Jar Technologies is developing a novel 100% silicon anode. Moreover, they are developing a manufacturing process for their anodes that benefits from past experiences in the manufacturing of thin-film solar cells.

TRL: 4-5 (estimated)

Pros/Cons: Increased energy density expected (1,350 Wh/l achieved)

Innolith – Non-flammable electrolyte for Li-ion batteries

Most Li-ion batteries use a polymer electrolyte that enables the Lithium-ions to move from cathode to anode and back during discharging and charging. These polymers can – when a hazard occurs – contribute to thermal runaway and result in the release of toxic gasses.

INNOLITH

Innolith is developing a polymer electrolyte with no fire risk that is compatible with most current Li-ion cathode and anode chemistries but enables operation at higher voltages and capacities.

TRL: 4 (estimated)

Pros/Cons: Increased energy density expected, Potentially safer than conventional Li-ion

OCSiAl Group – Graphene nanotubes for Li-ion batteries

Most Li-ion batteries have a carbon-based anode. The specific energy capacity of a graphite anode is significantly lower than that of a silicon anode.

OCSiAl have developed proprietary graphene nanotube technology called TUBALL which are able to reinforce a Silicon oxide anode (with up to 90% Silicon) of Li-ion batteries. The graphene is said to reinforce the silicon and bridge any cracks that may form as the silicon 'swells' and 'shrinks' during charging and discharging.

TRL: 3-4 (estimated)

Pros/Cons: Increased energy density expected (OCSiAl expects 350 Wh/kg/1,300 Wh/)

Amprius – Silicon nanowire anode for Li-ion batteries

Most Li-ion batteries have a carbon-based anode. The specific energy capacity of a graphite anode is significantly lower than that of a silicon anode.

Amprius is developing silicon nanowires that can act as a (100%) silicon anode for Li-ion batteries. The use of nanowires is said to avoid damage to the anode as it 'swells' when it takes up lithium (at charging of the battery).

TRL: 3-4 (estimated)

Pros/Cons: Increased energy density expected.

Samsung Advanced Institute of Technology (SAIT) – Solid-State Battery

Researchers from SAIT published in 2020 initial results of prototype solid-state battery cell with an energy density of 900 Wh/l that lasted 1,000 cycles.

SAIT indicates their innovation lies in the use a silver-carbon layer on the anode, that prevents some of the chemical degradation.

TRL: 4-5 (estimated)

Pros/Cons: Increased energy density expected, Potentially safer than conventional Li-ion

Oxis Energy – Lithium Sulfur – Solid-State Battery

Oxis Energy is developing a battery with a Lithium-Sulfur cathode. Bullet and nail penetration tests of prototype cells indicate that no fire ensues, and the cell can continue to operate at reduced capacity.

Cycle life is limited at current, with Oxis Energy expecting to achieve 500+ cycles in a few years.

TRL: 4-5 (estimated)

Pros/Cons: Increased energy density expected, Potentially safer than conventional Li-ion

QuantumScape – Lithium Metal – Solid State Battery

Lithium metal batteries are best known as the “button cells” used in small electronics, e.g. kitchen scales and small remotes. These are non-rechargeable Li-metal batteries. Quantumscape is developing a solid-state battery with a lithium metal anode, whereas conventional Li-ion batteries use a carbon-based anode.

QuantumScape

QuantumScape targets Li-metal batteries that can be defined as batteries without a fixed anode, the Li-anode is formed during charge when the Li-ions move from the cathode to the anode. Quantumscape has made advancements on a ceramic solid separator, that is claimed to avoid the dendrite formation associated with Li-metal batteries. Dendrites are ‘spikes’ of the metal that can form and pierce the separator.

TRL: 4-5 (estimated)

Pros/Cons: Increased energy and power density expected, longer life forecasted. Safety of the novel solid separator is a potential concern.

Metal Air

Metal air batteries use oxygen (from the air) as the cathode material, i.e. current is sources from oxidation of a metal. Small and non-rechargeable zinc-air batteries have been in commercial use since the 1970. Nant Energie, formerly Fluidic Energy, developed rechargeable zinc-air batteries. Lithium-air batteries promise a much higher specific energy. Significant R&D is however required to develop Li-air batteries. Technological challenges include the formation of dendrites (spikes of metal), solubility of the Li-ion in suitable electrolytes, and overall stability.

About DNV

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