Rockefeller Foundation

RAPID COST BENEFIT ANALYSIS FOR DIESEL GENERATOR REPLACEMENT OPTIONS AND MODELLING OF GRID-INTEGRATED BESS

Final Report

APRIL 2022

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Rockefeller Foundation

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CONTENTS

TABLES

FIGURES

APPENDICES

EXECUTIVE SUMMARY

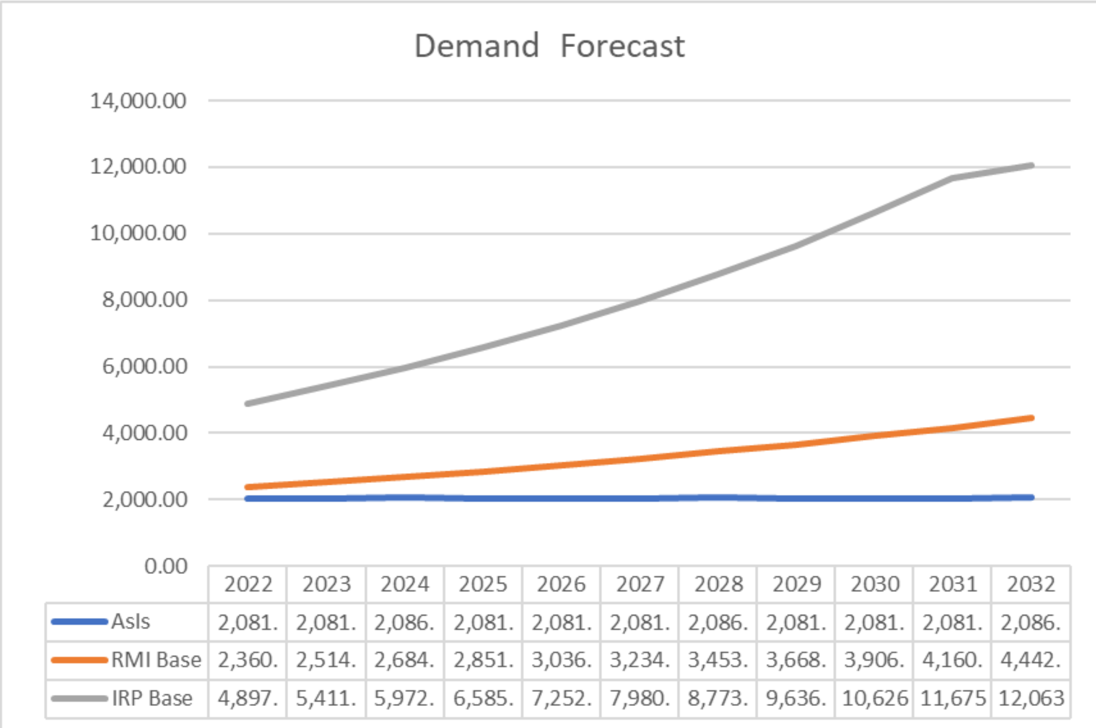
The primary objective of this project is to provide technoeconomic bases for decision making on replacement of diesel generators and provide inputs to Malawi's integrated resource plan with respect to the optimal deployment of grid-integrated battery energy storage systems (BESS) in the country.

Malawian power system currently consists of predominantly renewable energy sources (hydro generation as a bigger part and solar generation as a smaller part) which covers more than 95% of total generation on annual basis. The remaining part comes from the diesel power plants, whose role primarily is for peak demand covering.

Although the total annual share of diesel generation is quite low (2-5%), almost half of total system costs (that includes fixed and variable operational (and maintenance) costs) come from the fuel costs. Given that the IRP expansion plan foresee significant level of new renewable sources, the objective is replacing the diesel generators with more competitive technology as soon as possible and that way reduce the total system costs.

What will be the best choice depends on how the candidate will respond to the fundamental inputs that drive the change: demand and hydrology.

The following figure shows different demand projections that were used in analyses.



Hydrology pattern that was used in this study has been created based on historical record in the recent decade, although the wider historical record shows quite large variability and no periodical behaviour. Based on recorded inflows the following table was created

	Mean Monthly flows (m³/s)	Nkula – monthly capacity factor (%)	Tedzani– monthly capacity factor (%)	Kapichira– monthly capacity factor (%)
January	140.7	45.4	38.7	52.1
February	143.2	46.2	39.3	53
March	149.6	48.3	41.1	55.4
April	165.1	53.3	45.4	61.1
May	160.5	51.8	44.1	59.4
June	180.2	58.1	49.5	66.7
July	181.1	58.4	49.8	67.1
August	181.1	58.4	49.8	67.1
September	196.7	63.5	54	72.9
October	210.2	67.8	57.7	77.9
November	220.3	71.1	60.5	81.6
December	220.3	71.1	60.5	81.6

Candidates that were considered in our analyses were divided in two groups:

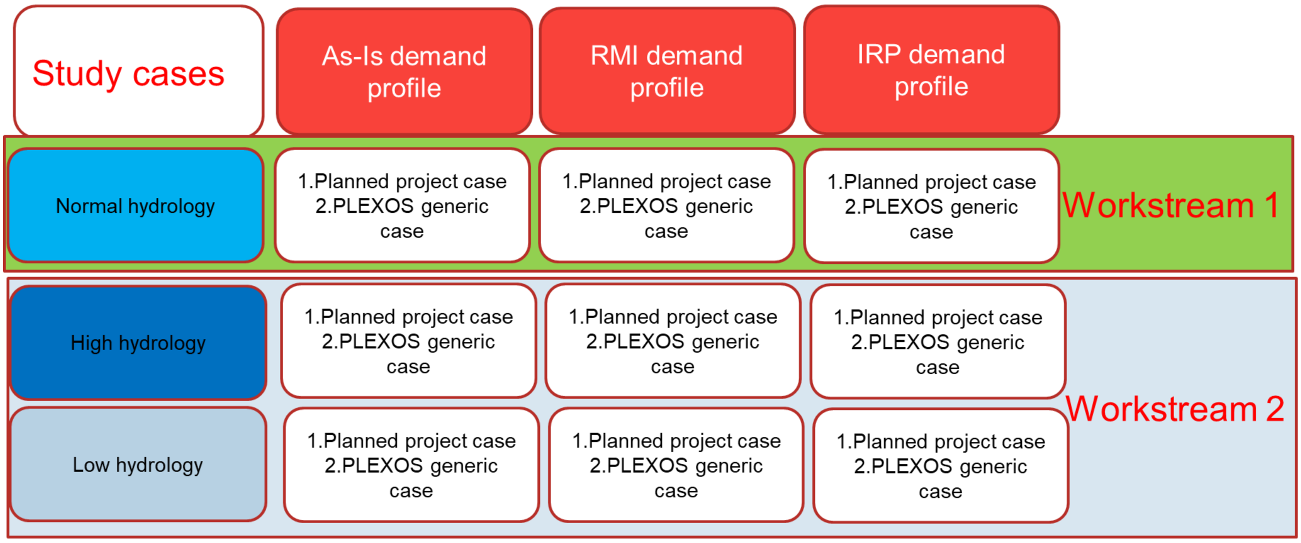
- Projects that figure in existing plans (and have some level of agreement)
- Generic candidates which will be a result of an optimization process

The following table represent a pipeline project list:

Project Name	Capacity	Expected Year for COD
Wind Power plant candidate 1	13MW	>=2024
BESS candidate 1	240MWh (60MW battery)	2023
Hydropower, Wovwe upgrade	4.5MW	>=2025
Solar Power Plant candidate 1	10MW (Scalable to 20MW) + battery	>=2024
50MW CCGT	50MW	>=2024
Solar Power Plant candidate 2	20MW	2022
Solar Power Plant candidate 3	21MW	2022
Solar Power Plant candidate 4	20MW	>=2024
Solar Power Plant candidate 5	40MW	>=2024
Solar Power Plant candidate 6	50MW	>=2025
Solar Power Plant candidate 7	20MW	>=2024
Solar Power Plant candidate 8	50MW	2024
Wind Power Plant candidate 2	50MW	>=2025
Hydropower Project candidate 2	41MW	>=2026

Hydropower Project candidate 3	350MW	2028
Hydropower Project candidate 4	261MW	>=2027
Hydropower Project candidate 5	210MW	>=2027
Geothermal Power Plant candidate 1	To be based on FS	>=2028
Floating solar PV candidate 9	18MW	>=2026
LNG Project candidate 1	75MW	2025
Coal Project candidate 1	100MW	>=2026
Solar Power Plant candidate 10	34MW	>=2024
Wind Power Plant candidate 3	151.5MW	>=2026
Hydropower Project candidate 6	40.4MW	>=2028
Hydropower Project candidate 7	40.4MW	>=2028
Hydropower Project candidate 8	90MW	>=2030
Malawi-Mozambique Power interconnector	50MW (initial capacity for trading)	>=2023
400KV Zambia-Malawi Power interconnector		>=2024

In order to properly observe influence of the mentioned drivers, and to check optimality of the existing IRP pathway, several study cases were created, as shown in the following figure.



It should be noted that Workstream 1 considered just the normal hydrology, while the remaining cases will be considered in the Workstream 2 which could serve as a support for the IRP update.

Quick Cost-Benefit Analyses (CBA) is essentially composed of two parts:

1. Money wise CB evaluation as a result of the long term PLEXOS simulations
2. Other CB assessment that might impact the decision making

Long-term PLEXOS simulations result in essential answers:

- When is a certain candidate going to be built?
- How much are the total OPEX and CAPEX?
- What is the trend of levelized cost of electricity (LCOE) over the wanted horizon?

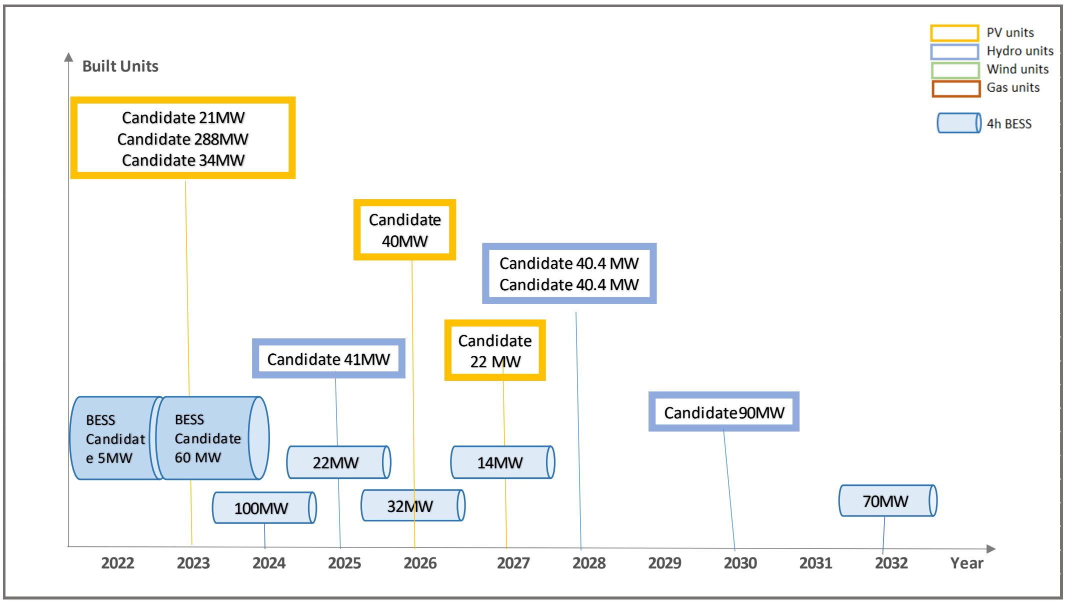
The main findings of these study cases are summarized in the following table

2032	Plexos generic case			Pipeline projects case		
	As Is	RMI based	IRP based	As Is	RMI based	IRP based
Installed Capacity [MW]	507.15	1993.15	7,818.55	508.15	1097.95	4,909.00
Generation [GWh]	2,092.56	4,553.74	12,630.00	2,092.58	4,469.12	12,208.00
BESS Installed Capacity [MWh]	32	3600	18324	20	952	7450
PV Installed Capacity [MW]	106	1542	7316	107	485	3606
Wind Installed Capacity [MW]	0	0	0	0	0	0
Hydro Installed Capacity [MW]	401.15	401.15	401.15	401.15	612.95	1173
Generation Cost [mil $]	0.68	27.75	62.4	0.676	4.612	26482
LCOE [$/MWh]	13.69	41.29	65.61	13.72	30.77	62.40
Average Cost [$/MWh]	0.32	6.09	3.48	0.32	1.03	2.39

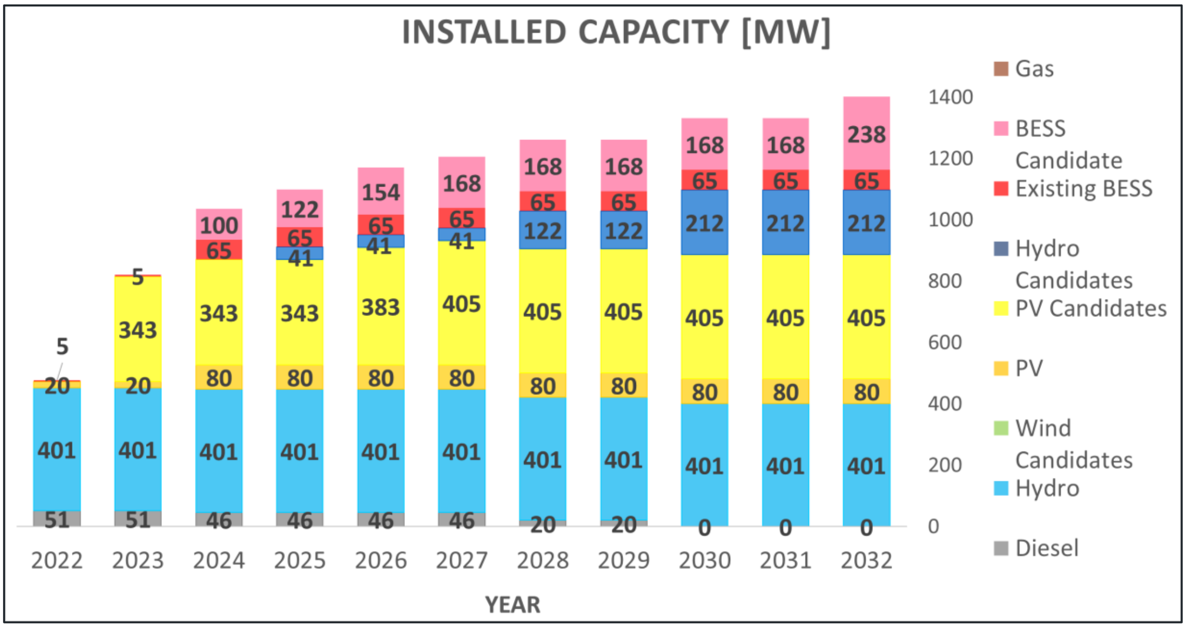
We believe that amongst all the study cases, the most representative is RMI based case which considers pipeline-based projects. It should be noted that pipeline-based projects include also generic PV and BESS candidates in addition to the already confirmed list.

The main outputs of this case are as follows:

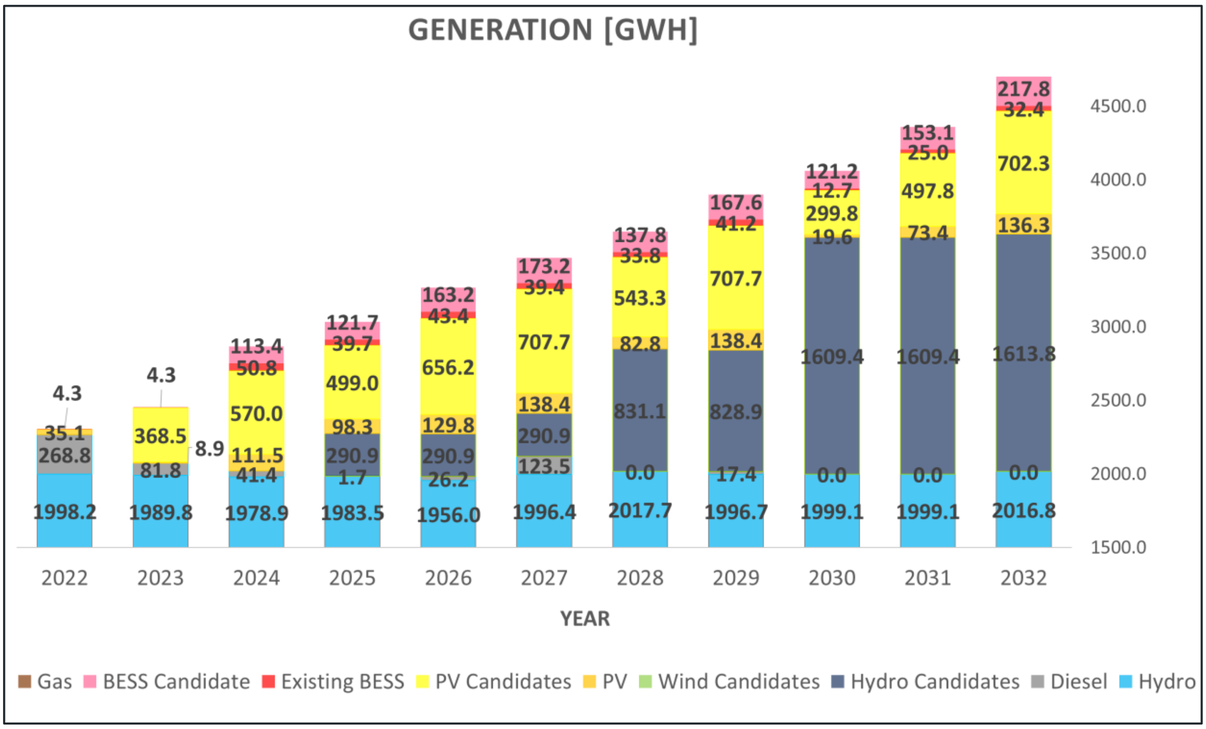
The expansion plan was illustrated in the following figure



Installed capacity shows generation facilities and BESS facilities



Annual generation is also presented for generators and BESS



The following table represents the total cost breakdown, which is an essential money-wise CB analyses

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0.00	21,657.21	21,657.21	94,049.35	1,692.62	95,741.97	117,399.18	2,302.04	51.00
2023	30,941.68	26,542.72	57,484.40	29,679.28	2,532.25	32,211.53	89,695.93	2,449.00	36.63
2024	30,941.68	32,861.13	63,802.81	15,534.99	3,979.23	19,514.22	83,317.03	2,701.80	30.84
2025	42,248.81	34,441.61	76,690.42	679.78	3,294.76	3,974.54	80,664.96	2,873.49	28.07
2026	45,406.12	34,841.61	80,247.73	10,528.27	4,469.34	14,997.61	95,245.34	3,059.13	31.13
2027	47,059.96	35,193.61	82,253.57	51,166.72	5,342.36	56,509.08	138,762.65	3,256.84	42.61
2028	68,769.80	37,294.26	106,064.06	0.00	3,443.20	3,443.20	109,507.26	3,474.90	31.51
2029	68,769.80	37,192.36	105,962.16	7,675.92	4,750.77	12,426.69	118,388.85	3,689.08	32.09
2030	92,951.55	39,835.80	132,787.35	0.00	1,756.59	1,756.59	134,543.94	3,927.89	34.25
2031	92,951.55	39,835.80	132,787.35	0.00	3,141.40	3,141.40	135,928.75	4,179.67	32.52
2032	92,951.55	39,944.94	132,896.49	0.00	4,612.15	4,612.15	137,508.64	4,469.12	30.77

The following table represents an overview of the main outputs over the horizon

Year	2022	2027	2032
Installed Capacity [MW]	472.55	973.15	1,097.95
Generation [GWh]	2,302.04	3,256.84	4,469.12
BESS Installed Capacity [MWh]	0	672	952
PV Installed Capacity [MW]	20	485	485
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	442.15	612.95
Generation Cost [mil $]	95.74	56.51	4.612
LCOE [$/MWh]	51.00	42.61	30.77
Average Cost [$/MWh]	41.59	17.35	1.03

In order to have a comprehensive look at costs and all the benefits, each case was accompanied by the CBA review table to point out all the implications that the case produces. The table was not associated with quantification factors for each issue, it is rather indicative.

	Costs	Benefits
Annualized Build Cost	Increased, caused by expansion (PV, BESS, Hydro)	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	High, but not as much as in case 2	
Wind penetration	no wind	
BESS contribution	Reasonable, much lower then in case 2, as hydro generation contributes a lot to overall system flexibility	Possibilities for other services: frequency regulation, reserve, voltage support, black start
Firm capacity of the system		hydro units provide sufficient firm capacity
Influence on operating reserve	Increase of spinning reserve requirements due to variable nature of soar	
Influence on system security		Given that BESS are high-performance facilities, security is expected to be just better
Environmental concerns		Reduced emissions
Social concerns		This pathway is more aggressive in RES penetration, that can cause benefit for society (job creation)

Conclusions and recommendations

1. The leading time for the new projects is the key issue for immediate action – although hydro candidates may represent the most competitive candidate, the precedence was given to solar in combination with BESS (in both generic case and the pipeline case) as it represents the fastest option and at the same time the most optimal.
2. Techno-economic assessment, done by PLEXOS, see a gradual reduction of diesel generation, replaced with renewable sources, and stepwise machine retirements. Indicative timeline for diesel retirement shows the following: Aggreko IPP – By the end of 2022, Remaining diesel gen – 3 units in 2024, and one unit later (at latest in 2028)-however if CCGT (50MW) is found to be a competitive candidate, all the remaining diesel units retire in 2024
3. All considered cases see the solar PV+BESS as an option for immediate action – installed capacity depends on the projected demand level
4. 4hour BESS are recommended as they can provide the sufficient firm capacity – which will together with hydro units ensure sufficient reserve margin
5. BESS are chosen by PLEXOS to help manage curtailed energy coming out of PV solar generation and shift that energy in periods without sun. It is not necessary to complement PV solar plant with the BESS as long as the system flexibility is sufficient as a result of other sources (hydro). This further means that BESS can be also used as stand-alone facilities. This is, in particular, important if BESS are foreseen to provide other services, such as voltage (and reactive) support –this will be considered in Workstream 2
6. If the expansion pathway sees just PV (or wind) as an option, then any new solar PV should be complemented with an appropriate BESS (size would depend on current power system conditions and is not a unique % of PV size). On the other side, if the expansion pathway sees also flexible hydro sources, then the PV power plant need not necessarily be complemented with additional BESS
7. For the longer time horizon, additional cases should be considered to include different hydrology pathways, and possibly new technologies (for seasonal storage). We further recommend keeping updating IRP on regular basis (every three years), in order to better capture the demand projections as the key driver

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1

INTRODUCTION AND OBJECTIVES

1 INTRODUCTION AND OBJECTIVES

1.1 BACKGROUND

The Global Energy Alliance for People and Planet (GEAPP) is supporting Malawi to achieve universal electrification based on renewables while ensuring inclusive economic growth and sustainable livelihoods. The GEAPP is committed to supporting a universal electrification agenda, covering both DREs and the grid-based energy transition, and has identified Malawi among high priority countries. There is a need for the country to rapidly expand its generation capacity, and an opportunity to capitalize on opportunities for early successes in this area and demonstrate a heavily renewable, least-cost pathway for providing affordable energy for underserved people and businesses throughout the country. This will displace the traditional thermal generation in the country's current integrated resource plan, and directly impact vulnerable populations in a country that has just 12% access to the electricity grid. A recent bankability analysis contracted by GEAPP laid out top priorities for attracting investment into the sector and was accepted by relevant government agencies. These priorities include updating the national integrated resource plan and supporting the utility on business planning, integration of DREs and battery systems, and grid extension. Key Electricity Sector Institutions are currently preparing for an update of the national integrated resource plan. In addition, there are decisions underway towards replacement of on-grid thermal generator systems. Grid-integrated battery storage systems may be able to play significant roles in both of these.

A range of institutions are active in the sector and aligning these groups for rapid decision-making will require technical analyses in support of the distribution utility (ESCOM), the single buyer unit (PML), and the Ministry of Energy (MoE). Supporting Malawi at this critical stage will require agile and highly specialized expertise in modelling of electricity grids and battery energy storage systems, to provide timely input and support decision making in the sector. In that respect, WSP was chosen to perform the studies and support stakeholders in this journey.

1.2 KEY OBJECTIVES

The primary objective of this assignment is to provide technoeconomic bases for decision making on replacement of diesel generators and provide inputs to Malawi's integrated resource plan with respect to the optimal deployment of grid-integrated battery energy storage systems (BESS) in the country

1.3 REPORT ORGANIZATION

This Report comprises the following sections:

- Section 1: INTRODUCTION AND OBJECTIVES– The general overview of the study is given.
- Section 2: DATA COLLECTED – Overview of the data collected from RMI and EGENCO at and after several meetings, including demand data, generation data and previous reports.
- Section 3: PLEXOS MODEL DEVELOPMENT– Review and harmonisation of the data collected, including used assumptions. Data collection together with data review and harmonisation is one of the key steps in this project.

- Section 4:METHODOLOGY – Overview of the methodology and assumptions used for execution of the studies.
- Section 5:ANALYSES – Techno–economic analysis for different cases.
- Section 6:CONCLUSIONS AND RECOMMENDATIONS – Summary of the conclusions reached in the previous sections is given.

2

DATA COLLECTED

2 DATA COLLECTED

Data collection of electricity demand, distribution system and power generation are recognised to be one of the most important steps for the successful execution of the study. Kick–off meeting was held on16th of December 2021 via web meeting. Within the next two months, WSP received input datasets by the Malawian project team by internet transfer.

In this section of the report a summary of data received from RMI and EGENCO has been reviewed.

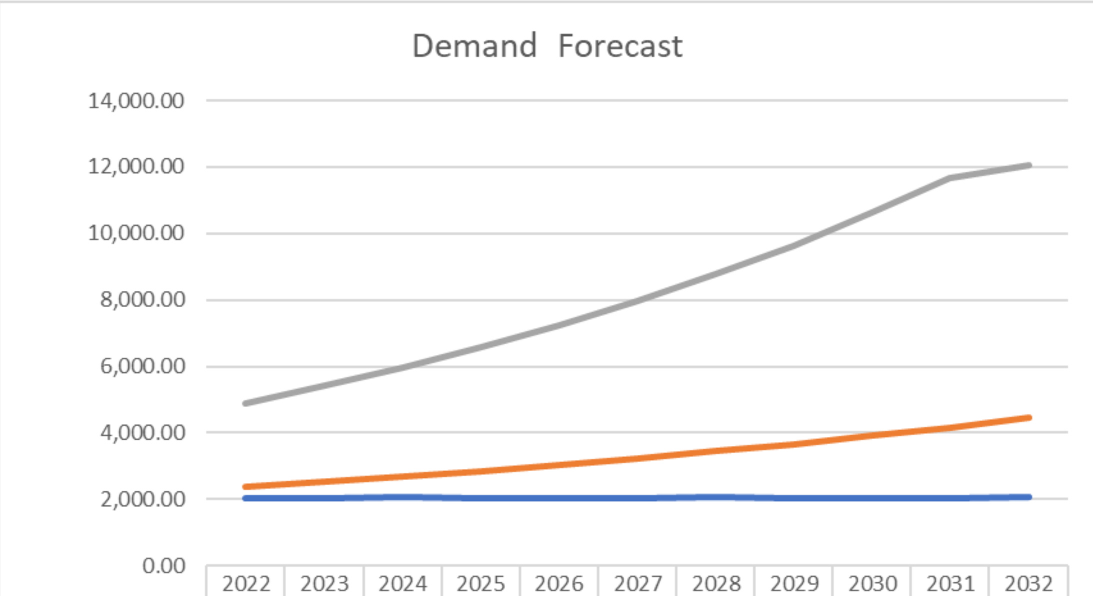
2.1 ELECTRICITY DEMAND

The demand forecast is the most important input which drives the expansion plans. The forecast depends on overall social, economic and even political tendencies. Given the demand forecast is not a part of our scope, we are going to use projections from two relevant sources:

- Documentation from the study done by Rocky Mountain Institute (RMI)
- Integrated Resource Plan (IRP)

These two projections will have been compared to each other along with the conservative projection – by which the demand remains unchanged over the 10-year horizon ahead.

The following figure shows different demand projections that will be used in analyses.



	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
AsIs	2,081.	2,081.	2,086.	2,081.	2,081.	2,081.	2,086.	2,081.	2,081.	2,081.	2,086.
RMI Base	2,360.	2,514.	2,684.	2,851.	3,036.	3,234.	3,453.	3,668.	3,906.	4,160.	4,442.
IRP Base	4,897.	5,411.	5,972.	6,585.	7,252.	7,980.	8,773.	9,636.	10,626	11,675	12,063

Figure 2-1 - Demand Forecast 2022 – 2032

Regarding the daily demand pattern, it is a reflection of the standard activities like in other countries, by which the peak demand is being reached in the evening hours, while the off-peak demand is being reached in the hight hours, as shown in the following figure.

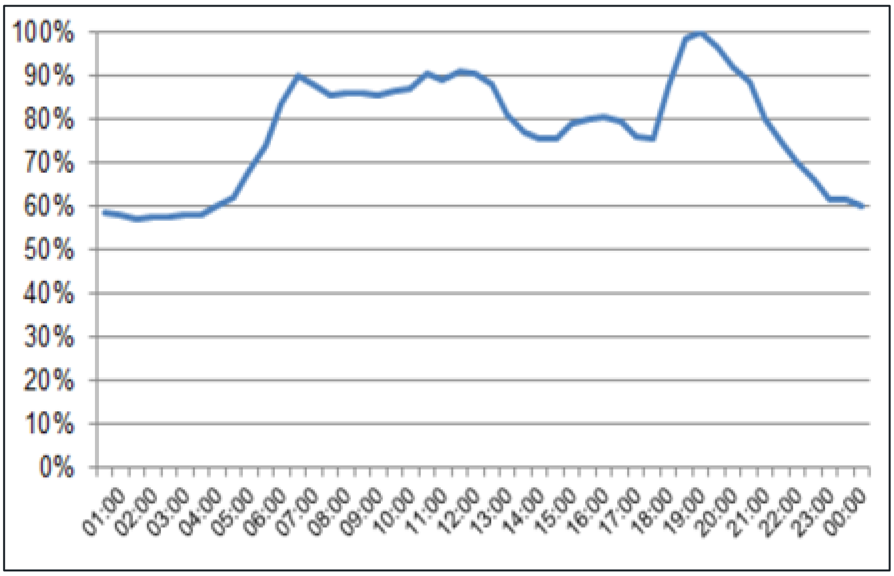


Figure 2-2 - Typical daily load pattern in Malawi

2.2 GENERATION DATA

Malawian power system is predominantly reliant on hydro power production, with over the 90% of annual energy coming out from hydro power plants. The most of the hydro power plants are concentrated along the Shire River, running as a cascade. Those are:

- Nkula A and B
- Tedzani (1, 2, 3 and 4)
- Kapichira

Remaining hydro power plants belong to another catchment areas and those are:

- Mulanje
- Muloza
- Vovwe

Besides hydro, there are five diesel generators, out of which four is owned by ESCOM while one runs as Independent Power Producer (IPP). The following table shows installed capacity of existing units.

Table 2-1 – Installed capacity of the Malawian power system

Technology	Generating unit	Installed capacity
Hydro Power Plant	Nkula A	35.1
Hydro Power Plant	Nkula B	100
Hydro Power Plant	Tedzani I	20
Hydro Power Plant	Tedzani II	20

Hydro Power Plant	Tedzani III	62
Hydro Power Plant	Tedzani IV	19.1
Hydro Power Plant	Kapichira	129.6
Diesel Power Plant	Mzuzu-Luwinga	6
Diesel Power Plant	Lilongwe A	5.4
Diesel Power Plant	Lilongwe B	20
Diesel Power Plant	Mapanga	20
Diesel Power Plant	Aggreko IPP	78
PV solar power plant (from 2022)	Golomoti	20
PV solar power plant (from 2024)	Salima	60

Along with the generation capacities, there is one Battery Energy Storage system Golomoti, 10MWh size, with 5MW maximum power. Another BESS is conceived to be connected in 2023, which is 240MWh size, with 60MW maximum power.

According to the historical record, almost complete annual generation come from the Hydro power plants, while just a couple of percentages (2-5%) come out of the diesel power plants.

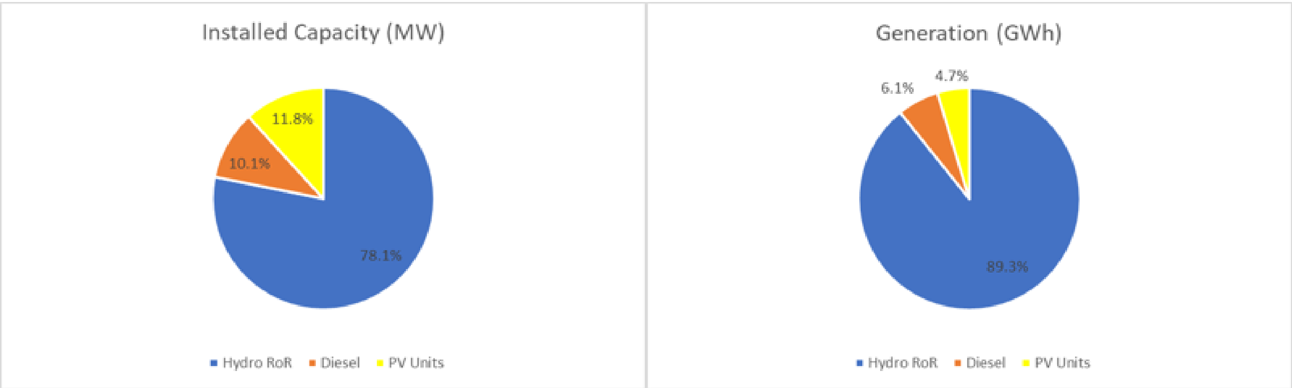


Figure 2-3 - Malawian power mix - installed capacity and annual generation

Diesel generating plants serve as pick plants and in some exceptional circumstances, so their annual production depends on hydrology and reliability of the hydro generators.

2.3 HYDROLOGY DEPENDENCY

Currently, the hydropower potential of Malawi relates to the river Shire outflowed from the Lake Malawi. Natural inflows for cascading power plants along the Shire river depend on Lake headwater level. This level had been changing over time, as shown in the following figure:

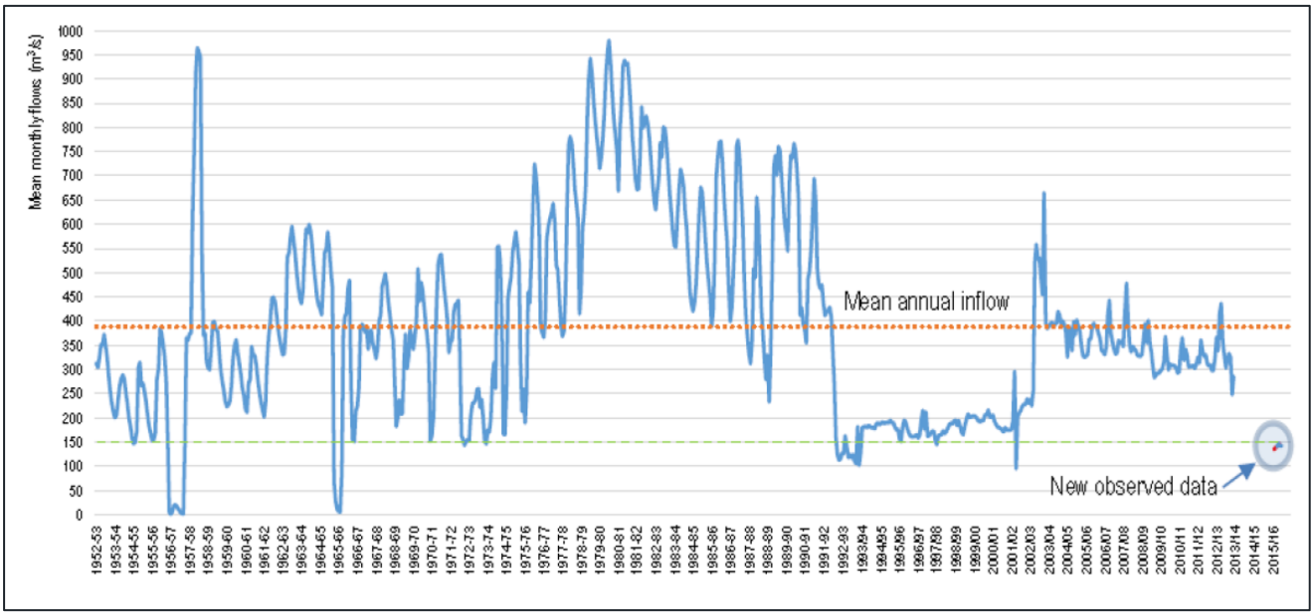


Figure 2-4 - Flow series recorded in period 1953-2016

Obviously, there is no pattern related to the season or any other periodical behaviour which could help alleviate the modelling work. Most importantly, all the planning activities, either medium-term or long-tern, are facing quite opposite drivers: inconsistent and unpredictable flows on one side and the need for sustainable and the most economical generation mix on another.

For the time being, there is no seasonal storage in Malawian power system which could help manage volatile flows and increase overall system flexibility.

On the short -term level, generation is constrained by cascade system peculiarities, such as:

- Natural inflows
- Total installed capacity of each power plant
- Turbine flows
- Tributary flows
- Catchment area (short-term reservoir capacity)
- Minimum stable level

Overall system flexibility on a daily level depends mostly on catchment areas of cascading power plants. Given that all the hydro power plants are run-of-river, their reservoirs are very small, with just a few hours ability. The following table shows storage capacities along the Shire cascading power plants.

Table 2-2 - Storage capacities along the Shire River

	Installed capacity (MW)	Max turbine flows (m^3/s)	Ratio Turbine flow/mean flow	Storage capacity (Mm^3/s)
Nkula	136	310	1.4-2.2	5
Tedzani	121	364	1.65-2.6	2

Kapichira	128	270	1.2-1.9	3

According to the flows recorded over the past several years, the mean monthly flows were calculated. Along with the mean flows, the following table shows monthly capacity factors for each plant.

Table 2-3 – Mean monthly flows and capacity factors

	Mean Monthly flows (m^3/s)	Nkula – monthly capacity factor (%)	Tedzani– monthly capacity factor (%)	Kapichira– monthly capacity factor (%)
January	140.7	45.4	38.7	52.1
February	143.2	46.2	39.3	53
March	149.6	48.3	41.1	55.4
April	165.1	53.3	45.4	61.1
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October	210.2	67.8	57.7	77.9
November	220.3	71.1	60.5	81.6
December	220.3	71.1	60.5	81.6

2.4 CANDIDATES

There is a wide range of candidates that can be selected for the comprehensive and thorough expansion activities, and they were all considered in a recent Integrated Resource Plan. The expansion plan is looking in the long-term horizon, typically 10 years and more.

For the medium-term horizon which covers 2-3 years, there is a need for the filtering, given the leading times for specific technologies to be completed. Thus, for Workstream 1, by which immediate actions for diesel replacement have to be proposed, we will be considering the feasible solutions:

- Projects that figure in existing plans (and have some level of agreement)
- Generic candidates which will be a result of an optimization process

With regards to planned projects (either IPPs or ESCOM driven), the main focus is on renewable sources such as Hydro power plants, PV solar power plants, Battery Energy Storages, but there is also one thermal based CCGT candidate. The following table shows the list of candidates that figure in existing plans and with whom a certain agreement/understanding was achieved.

Table 2-4 - Malawi On-grid Pipeline Projects

Project Name	Capacity	Expected Year for COD
Wind Power plant candidate 1	13MW	>=2024
BESS candidate 1	240MWh (60MW battery)	2023
Hydropower, Wovwe upgrade	4.5MW	>=2025
Solar Power Plant candidate 1	10MW (Scalable to 20MW) + battery	>=2024
50MW CCGT	50MW	>=2024
Solar Power Plant candidate 2	20MW	2022
Solar Power Plant candidate 3	21MW	2022
Solar Power Plant candidate 4	20MW	>=2024
Solar Power Plant candidate 5	40MW	>=2024
Solar Power Plant candidate 6	50MW	>=2025
Solar Power Plant candidate 7	20MW	>=2024
Solar Power Plant candidate 8	50MW	2024
Wind Power Plant candidate 2	50MW	>=2025

Hydropower Project candidate 2	41MW	>=2026
Hydropower Project candidate 3	350MW	2028
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Geothermal Power Plant candidate 1	To be based on FS	>=2028
Floating solar PV candidate 9	18MW	>=2026
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Hydropower Project candidate 6	40.4MW	>=2028
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Hydropower Project candidate 8	90MW	>=2030
Malawi-Mozambique Power interconnector	50MW (initial capacity for trading)	>=2023
400KV Zambia-Malawi Power interconnector		>=2024

Amongst generic candidates, we have selected the solar PV power projects and Battery Energy Storage Solutions (BESS) as project that might be practically feasible in considered horizon.

SOLAR POWER PLANTS

Benefits that come with the solar power plants are evident and well known, as they are mostly related to the nearly zero marginal costs. Operational and maintenance costs seem to be very low, so the only relevant component of total costs represents the build costs.

Build costs projection over the longer term is a challenging task because of the different aspects which must be taken into consideration

The installed cost of solar photovoltaics (PV) has fallen rapidly in recent years and is expected to continue declining in the future, thanks to different technology and market drivers. According to the IRENA, almost 60 % cost reduction for the electricity generated by the Solar is expected by 2025, while for example, Bloomberg New Energy Finance (BNEF) forecasts the same cost reduction, but by 2040.

According to the "*Future of Solar Photovoltaic – a global energy transformation paper*" (IRENA, 2020), rapid declines in installed costs and increased capacity factors have improved the economic competitiveness of solar PV around the world. The global weighted average LCOE of utility-scale PV plants is estimated to have fallen by 77% between 2010 and 2018, from around USD 0.37/kWh to USD 0.085/ kWh, while auction and tender results suggest they will fall to between USD 0.08/kWh and 0.02/kWh in 2030. By 2050, solar PV is expected to be among the cheapest sources of power available, particularly in areas with excellent solar irradiation, with 2050 costs in the range USD 0.014–0.05/kWh.

Given as total installation costs, PV projects would continue to decline dramatically in the next three decades, averaging in the range of USD 340 to USD 834/kW by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018.

Solar Power Plant efficiency

One of the challenging questions comes with the introduction of the solar trackers and is the extra solar power output worth the additional cost of a solar tracker?

Solar trackers can be categorized, based on which direction they move. A solar tracker can be either:

- Single axis solar tracker – which follows the position of the sun as it moves from east to west. These are usually used in utility-scale projects. A single axis tracker can increase production between 25% to 35%
- Dual axis solar tracker - not only tracks the sun as it moves east to west, but also follows it as it moves from north to south. Two axis trackers are more common among residential and small commercial solar projects that have limited space, so they can produce enough power to meet their energy needs

Solar trackers can greatly increase the cost of a photovoltaic solar installation, even doubling them. They are made up of moving parts, which means they are more likely to break. This would lead to higher maintenance costs.

Basically, the question is whether solar trackers are **worth the additional investment**?

In most cases, solar trackers are not worth the additional investment, even though they do produce more electricity. Because solar panels are cheaper than ever, it would cost less to install more solar panels than it would to include a tracking system.

BATTERY ENERGY STORAGE SYSTEMS

One of the most significant entities in shaping the future generation portfolio will be Battery Storage. Particularly, with an increase of PV solar penetration with inflexible generation pattern, its role becomes crucial. In the recent decade, a battery energy storage system has been constantly developing, increasing its technical capabilities on one side, and decreasing the costs on the others.

From the perspective of possible services that can provide, battery storage takes the top place in preferable technologies. Two basic services battery storages are being used for are:

- Energy arbitrage
- Ancillary services (primary, secondary and tertiary reserve, voltage support, black start capability)

Which service is going to be used depends on techno economic drivers that would lead to the least total system costs.

It should be noted that manifold service is possible as well, particularly in state-of-the-art BESS units. However, for the sake of this workstream, **energy arbitrage is a preferable** service due to its ability to smoothen the non-dispatchable nature of solar generation.

However, as an emerging technology, Battery storage systems have been becoming cheaper over time, so any longer-term projection should take into consideration an appropriate cost declining curve.
Similarly, like for PV cost projections, plenty of research papers were published with a goal to properly estimate investment costs for BESS, which would further facilitate strategic planning activities towards a clean energy future.
According to the “Electricity storage and renewables: Costs and Markets to 2030” (IRENA, 2017), **rapid declines** in installed costs in expected for the BESS, **up to 60%** in the next 15 years.
According to the “Cost Projections for Utility-Scale Battery Storage: 2020 Update” (NREL, 2020) the costs for utility-scale lithium-ion battery systems, with a focus on 4-hour duration systems are also foreseen to decline over the next 30 years.
According to the Bloomberg NEF researches, (BNEF’s Energy Storage Outlook 2019), further halving of lithium-ion battery costs per kilowatt-hour by 2030 is predicted.
It should be noted that 40% of the total costs represents the cells costs, while the rest is related to the equipment regardless of the cells size..
Based on the benchmarks mentioned above and for the techno economic analyses purpose, we have created a build cost curve for period 2021-2050, which is shown on the following figure:

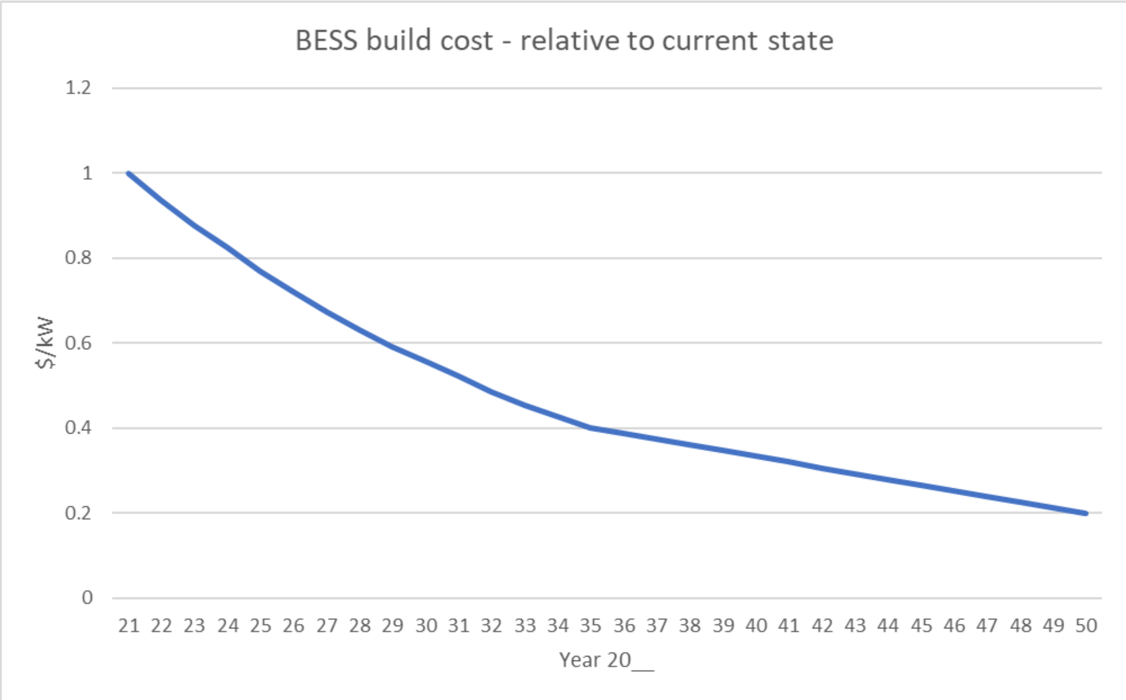

Figure 2-5 - BESS build cost projection up to 2050

It should be noted that BESS capacity degradation with increasing numbers of cycles was not taken into consideration as technology enhancements are continuously evolving from year to year, towards the instance when the degradation will not be an issue

2.5 PREVIOUS REPORTS

EGENCO provided following documents:

- Malawi Grid Capacity Study
- Integrated Resource Plan (IRP) for Malawi

3

PLEXOS MODEL DEVELOPMENT

3 PLEXOS MODEL DEVELOPMENT

3.1 INTRODUCTION

This section describes input data and assumptions used to build a PLEXOS model for Malawi Grid. The input data in this report will be reviewed for each of the components used in PLEXOS model, as listed below:

- Generators (conventional units and renewables)
- Fuel
- Demand
- Reserve
- Battery energy system storage (BESS)

As PLEXOS model primarily focuses on the production and techno-economic analysis, the transmission network is represented through a single node, to simplify the analysis conducted in PLEXOS. For detailed transmission network analysis, DigSILENT software will be used. PLEXOS model was developed from the beginning. All these planning data and parameters, including load forecast data have been processed in PLEXOS to develop generation model of Malawi Grid, which is then used as a long-term generation planning tool for 11-year period (2022-2032).

3.2 INPUT SYSTEM DATA

3.1.1 DIESEL GENERATOR MODELLING

Conventional generators modelled in PLEXOS are diesel generators. The data used for these generators consist of data provided by RMI and EGENCO and assumed data, based on previous PLEXOS models and experience. Five generators are modelled, and the parameters used in PLEXOS model are listed in Table 3-1

Table 3-1 - Diesel generators - PLEXOS properties

Property	Aggreko IPP	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
Max Capacity [MW]	78	5.4	20	20	6
Min Stable Level [MW]	15.6	0.66	1.6	1.6	1.2
Heat Rate [GJ/MWh]	9.919	9.919	9.919	9.919	9.919
Load Point [MW]	-	-	1.6	1.6	1.5
VO&M Charge [$/MWh]	5.58	5.58	5.58	5.58	5.58
FO&M Charge [$/kw/yr]	46.55	46.55	46.55	46.55	46.55
Min Up Time [h]	0.017	0.017	0.083	0.167	0.0667
Min Down Time [h]	0.083	0.083	0.083	0.067	0.067
Maintenance Rate [%]	7	7	7	7	7
Firm capacity [MW]	78	5.4	20	20	6

Mean Time to Repair [h]	5	5	5	5	5
Max Capacity Factor [%]	100	56	78	80	75

3.1.2 GAS UNIT MODELLING

Gas Unit is modelled by using parameters shown in Table 3-2.

Table 3-2 - Assumed parameters for Gas unit

Max Capacity [MW]	Heat Rate [GJ/MWh]	FO&M Charge [$/kW/yr]	VO&M Charge [$/MWh]	Technical Life [yr]
50	9.919	20	5.58	25
Min Stable Level [MW]	**Project Start Date**	**Min Up Time [h]**	**Min Down Time [h]**	**Economic Life [yr]**
20	01/01/2024	4	2	25

WACC was set at 10%, and the price of the gas was 27.778$/GJ.

3.1.3 HYDRO GENERATOR MODELLING

Data used for modelling hydro generators, consist of data provided by RMI and EGENCO and assumed data, based on previous PLEXOS models and experience. Hydro generation was modelled in two categories:

1) Existing units shown in Table 3-3 and Table 3-4
2) Candidate units which are confirmed to be built.

Existing Units:

Table 3-3 - Hydro generators Shire River – PLEXOS properties

Property	Kapichira	Nkula A	Nkula B	Tedzani I	Tedzani II	Tedzani III	Tedzani IV
Max Capacity [MW]	129.6	35.1	100	20	20	62	19.1
Minimum Stable Level [MW]	40	9	14	8	8	24	10
Efficiency Incr [MW/m^3/s]	0.47	0.4	0.45	0.33	0.33	0.33	0.33
Firm Capacity [MW]	129.6	35.1	100	20	20	62	19.1
FO&M Charge [$/kw/yr]	40.738	40.738	40.738	40.738	40.738	40.738	40.738
Load Point [MW]	64.8	9	18.14	8	8	29.26	18
Maintenance Rate [%]	7	7	7	7	7	7	7
Mean Time to Repair [h]	5	5	5	5	5	5	5
Max Release [m^3/s]	270	90	220	60	60	190	54

Table 3-4 - Hydro generators – PLEXOS properties

Property	Mulanje	Muloza	Wovwe
Max Capacity [MW]	8	3	4.35
Minimum Stable Level [MW]	0.25	0.15	1.45
Efficiency Incr [MW/m³/s]	-	-	12.8
Firm Capacity [MW]	8	3	4.35
FO&M Charge [$/kw/yr]	40.738	40.738	40.738
Load Point [MW]	8.2	-	1.45
Maintenance Rate [%]	2	2	7
Mean Time to Repair [h]	2	2	5
Max Capacity Factor Year [%]	47	-	74
Max Release [m³/s]	-	-	0.34

Table 3-5 - Max Capacity Factors for hydro generators

Max Capacity Factor Month [%]	Kapichira	Nkula A	Nkula B	Tedzani I	Tedzani II	Tedzani III	Tedzani IV	Muloza
January	52.1	45.4	45.4	38.7	38.7	38.7	38.7	52.1
February	53	46.2	46.2	39.3	39.3	39.3	39.3	53
March	55.4	48.3	48.3	41.1	41.1	41.1	41.1	55.4
April	61.1	53.3	53.3	45.4	45.4	45.4	45.4	61.1
May	59.4	51.8	51.8	44.1	44.1	44.1	44.1	59.4
June	66.7	58.1	58.1	49.5	49.5	49.5	49.5	66.7
July	67.1	58.4	58.4	49.8	49.8	49.8	49.8	67.1
August	67.1	58.4	58.4	49.8	49.8	49.8	49.8	67.1
September	72.9	63.5	63.5	54	54	54	54	72.9
October	77.9	67.8	67.8	57.7	57.7	57.7	57.7	77.9
November	81.6	71.1	71.1	60.5	60.5	60.5	60.5	81.6
December	81.6	71.1	71.1	60.5	60.5	60.5	60.5	81.6
January	52.1	45.4	45.4	38.7	38.7	38.7	38.7	52.1

Real limitations of the system are modelled within a generic constraint: Generation from these 10 hydro units must always be less than or equal to 270MW.

Confirmed Candidate Units:

Table 3-6 - Candidate units confirmed to be built

Property	HP Project candidate 2	HP Project candidate 3	HP Project candidate 4	HP Project candidate 5	HP Project candidate 6	HP Project candidate 7	HP Project candidate 8
Max Capacity [MW]	41	350	261	210	40.4	40.4	90
Minimum Stable Level [MW]	2.05	17.5	13.05	10.65	2.02	2.02	4.5
Firm Capacity [MW]	41	350	261	210	40.4	40.4	90
FO&M Charge [$/kw/yr]	40.738	39.716	39.716	39.716	39.716	39.716	39.716
Max Capacity Factor year [%]	81	64	41	59	76	76	99
Build cost [$/kW]	2720	2650	2650	2650	2650	2650	2650
Economic Life [year]	45	45	45	45	45	45	45
Technical Life [year]	50	50	50	50	50	50	50
Project Start Date	01/01/2025	01/01/2028	01/01/2027	01/01/2027	01/01/2028	01/01/2028	01/01/2029
WACC [%]	10						

3.1.4 SOLAR PV MODELLING

As shown in **Figure 3-1** - Solar Potential in Malawi, solar potential in Malawi is rather high with the GHI (Global Horizontal Irradiation) in the range from 1351-1716 kWh/m2.

Modelled PV plants are divided into three groups:

1) Existing units
2) Confirmed Candidate units
3) Generic 1MW Candidate

Existing Units:

Golomoti PV power plant is modelled in PLEXOS with the maximum capacity set at 10MW in the first quarter of the year and at 20MW starting from April 2022. Fixed O&M charge was set at 116 $/kW/year, Variable O$M were set at 5.5$/MWh and for the firm capacity of Golomoti PV, value of 4 MW was taken.

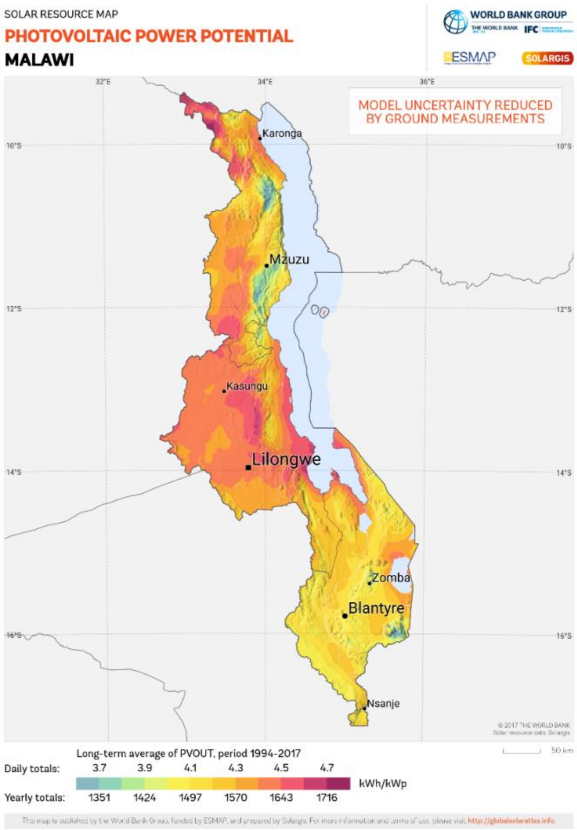

Figure 3-1 - Solar Potential in Malawi[1]

Confirmed Candidate Units:

Data for the PV units which are assigned project start date, is presented in the table below:

Table 3-7 - Modelled PV properties

Property	Candidate 3	Candidate 4	Candidate 5	Candidate 6	Candidate 7	Candidate 8	Candidate 10
Max Capacity [MW]	21	20	40	50	40	50	34
Firm Capacity [MW]	4	4	8	10	10	10	8.5
FO&M Charge [$/kw/yr]	16	16	16	16	10	16	16
Project Start Date	01/01/2022	01/01/2023	01/01/2024	01/01/2024	01/01/2024	01/01/2024	01/01/2023
Technical Life [yr]	25	25	25	25	25	25	25
Economic Life [yr]	20	20	20	20	20	20	20

[1] *© 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.*

Generic Candidate Unit:

Generic 1MW PV unit has a Project Start Date set at 01/01/2023.

Table 3-8 - Assumed PV parameters

Max Capacity [MW]	FO&M Charge [$/kW/yr]	VO&M Charge [$/MWh]	Technical Life [yr]	Economic Life [yr]	Firm Capacity [MW]	Max Units Built
1	16	5.5	25	20	0.2	9999

All PV power plants in the system, existing and candidate units, were modelled through Rating Factor property, which simulates the irradiance-dependent PV production capability. This was done by using data file "PV_Candidates.csv", which had been created using the capacity factor data for Malawi available on https://www.renewables.ninja/. Build costs and WACC associated with PV generation are shown in Table 3-9.

Table 3-9 - Assumed PV build cost

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Build Cost [$/kW]	800	768	736	704	672	640	608	576	544	512	480
WACC [%]	10										

3.1.5 WIND MODELLING

Wind potential in Malawi is high. Wind plants are divided into two groups:

1) Candidate units which are confirmed to be built.
2) Generic 1MW Candidate

Confirmed Candidate Units:

Data for the Wind units which are assigned project start date, is presented in the table below:

Table 3-10 – Modelled Wind properties

Property	WPP candidate 1	WPP candidate 2	WPP candidate 3
Max Capacity [MW]	13	50	151.5
Firm Capacity [MW]	3	10	30.3
FO&M Charge [$/kw/yr]	75.177	75.177	75.177
VO&M Charge[$/MWh]	5	5	5
Project Start Date	1/1/2024	1/1/2025	1/1/2025

Property	WPP candidate 1	WPP candidate 2	WPP candidate 3
Technical Life [yr]	25	25	25
Economic Life [yr]	20	20	20

Generic Candidate Unit:

Generic 1MW Wind unit has a Project Start Date set at 01/01/2025.

Table 3-11 - Assumed Wind parameters

Max Capacity [MW]	FO&M Charge [$/kW/yr]	VO&M Charge [$/MWh]	Technical Life [yr]	Economic Life [yr]	Firm Capacity [MW]	Max Units Built
1	75.177	5	25	20	0.2	100

All Wind candidate units were modelled through Rating Factor property. This was done by using data file "Wind Candidates.csv", which had been created using the capacity factor data for Malawi available on https://www.renewables.ninja/. Build costs and WACC associated with Wind generation are shown in Table 3-12.

Table 3-12 - Assumed Wind build cost

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Build Cost [$/kW]	2790	2582	2377	2188	2091	1998	1912	1832	1760	1692
WACC [%]	10									

3.1.6 FUEL MODELLING

The fuel used by the system diesel generators is Light Fuel Oil (LFO), and the fuel object in PLEXOS model was created based on fuel price escalation as a result of economy. Fuel is represented in PLEXOS with price which differs from year to year and is displayed in Table 3-13.

Table 3-13 - Fuel Prices by Year

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Fuel Price [$/GJ]	35.28	36.57	37.87	39.18	40.48	41.79	43.09	44.39	45.70	47.00	48.31

3.1.7 BATTERY STORAGE SYSTEM MODELLING

Modelled battery energy storage units are divided into two groups:

1) Confirmed Candidate units

2) Generic Candidate Unit

Confirmed Candidate Units:

Data for the BESS units which are assigned project start date, is presented in the table below:

Table 3-14 - Battery PLEXOS properties

Property	BESS candidate 2	BESS candidate 1
Capacity [MWh]	10	240
Max Power [MW]	5	60
Firm Capacity [MW]	4	48
Max SoC [%]	98	98
Min SoC [%]	10	10
Initial SoC [%]	90	90
Charge Efficiency [%]	94	94
Discharge Efficiency [%]	93	93
FO&M Charge [$/kW/yr]	116	116
End Effects Method	Free	Free
Project Start Date	01/04/2022	01/10/2023

Generic Candidate Unit:

Table 3-15 - Battery PLEXOS properties

Property	Generic BESS
Capacity [MWh]	4
Max Power [MW]	1
Firm Capacity [MW]	0.8
Max SoC [%]	98
Min SoC [%]	10
Initial SoC [%]	90
Charge Efficiency [%]	95
Discharge Efficiency [%]	95
FO&M Charge [$/kW/yr]	14
End Effects Method	Free
Project Start Date	01/01/2024
Max Units Built in a year	1000

Technical Life [year]	15
Economic Life [year]	10

Table 3-16 - BESS build cost

Year	2024	2025	2026	2027	2028	2029	2030	2031	2032
Build Cost [$/kW]	552	528	504	480	456	432	408	384	360
WACC [%]	10								

3.1.8 DEMAND MODELLING

Demand was modelled in three different scenarios:

- "As Is" – Increase in demand which can occur in the 11-year period was not taken into consideration.
- "RMI Based" – Increase of 6.5% per year was taken as per datafile provided by RMI.
- "IRP Based" – Increase in demand as per datafile from IRP for Malawi (given in Appendix), provided by EGENCO.

Max demand for each year is represented in **Figure 3-2** - Provided Demand Forecast Data.

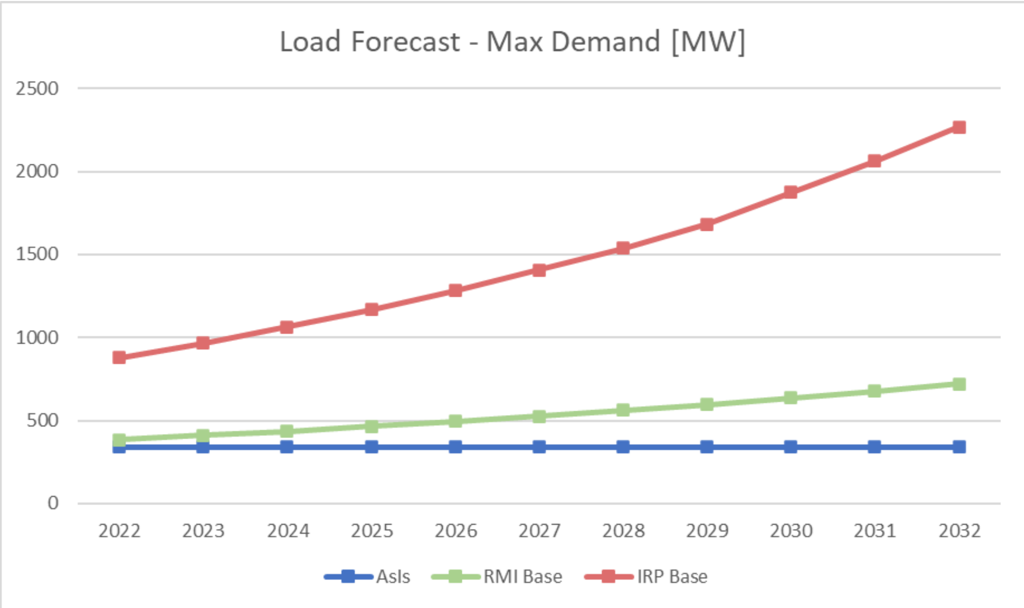

Figure 3-2 - Provided Demand Forecast Data

3.1.9 SYSTEM RESERVE MODELLING

Reserves in PLEXOS are modelled through reserve object. This object includes potential response from diesel and hydro generators. For reserve type, "raise" was used (spinning up reserve). Minimum reserve provision is assumed to be 32MW. In case of failing to meet reserve requirements, the penalty shortage price was set at 1000$/MW via VoRS property in PLEXOS.

4

METHODOLOGY

4 METHODOLOGY

In order to appropriately answer the fundamental question defined by this project, we should start with an essential goal which will be accompanied by a certain methodology.

And the essential goal could be defined as an efficient replacement of diesel generators as soon as possible while minimizing total system costs. To do that, a couple of issues should be properly considered:

1. Candidates as elaborated in section 2.4
2. Flexibility
    - How does the capacity factor for different technologies affect the overall flexibility?
    - How would the daily dispatch look like?
    - How to provide the firm capacity with different technologies?
    - How would new generation mix will affect the controllability?
    - How seasonal changes affect the overall flexibility?
3. Reliability
    - Hydrology – constant or changeable?
    - Solar irradiation and its variability
    - Wind and its variability

Along with these concerns, grid compatibility is of the great importance, but that will be done in the Workstream 2.

The **capacity factor** for the hydro units is being calculated based on predicted mean monthly inflows (see Table 2-3). Although the historical record shows no periodical changes of Liwonde inflows, by which a specific pattern could be assessed, our assumption will be basically made in accordance with the flows in the recent decade.

Therefore, for the purpose of this study, we will assume the ***NORMAL HYDROLOGY*** pattern as the most probable inflows based on the historical record in the past decade.

Detailed expansion plan for the longer time horizon should take into consideration extreme conditions of the hydrology – the dry season and the wet season.

The capacity factor for the PV solar power plants is the direct consequence of the irradiation in certain area and contrary to the hydro, there is quite a high level of predictability. The solar generation is being given as the annual pattern.

With reference to the firm capacity, let`s have a look at the existing Malawian capacity firmness. The following figure shows the total firm capacity with (bold red line) and without (dotted red line) diesel generators. As can be seen, the firm capacity which could ensure an appropriate level of reserve margin and keep the Loss of Load Probability acceptable, is sufficient.

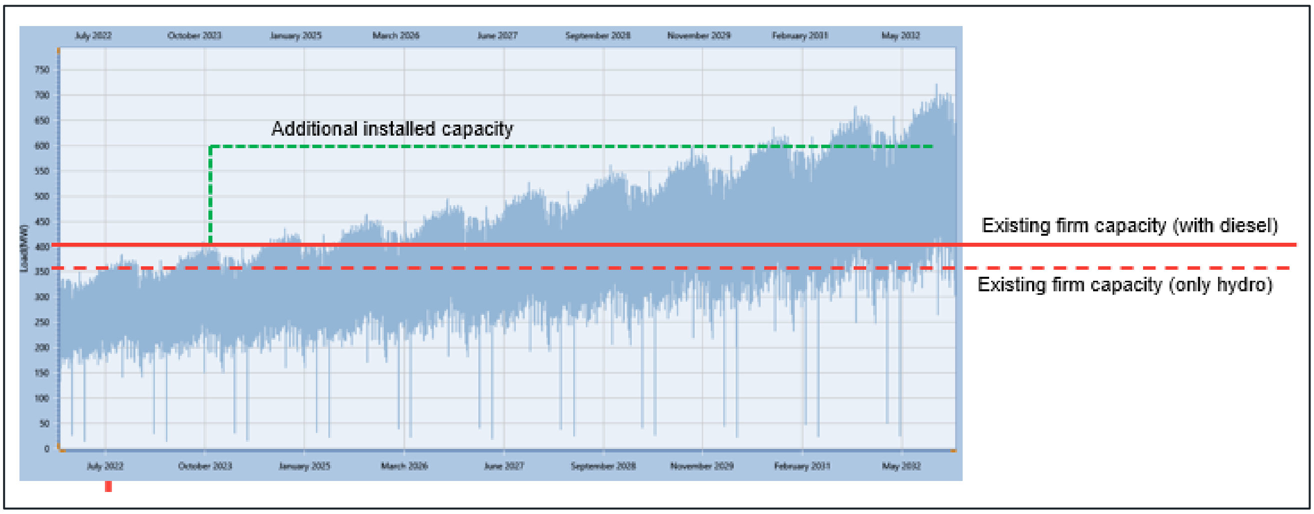

Figure 4-1 - Malawian firm capacity

For any new installed capacity which is primarily foreseen for the energy balancing, there is a raising question of how it contributes to capacity reserve margin. The answer is not unique, given the nature of the primal energy source of different technologies.

The **solar** power plant has an intermittent energy source and a very constant irradiance map (during the day), which means the system cannot rely on PV solar support in the evening peak regimes. This is the reason why the firm capacity for the PV solar power plants is usually **assumed zero** for the systems with the most common daily demand shape (where the peak hour is the evening hour). A similar conclusion can be drawn for the wind power plants given their intermittent nature.

The **firm capacity of the BESS** depends on the service it provides. Obviously, if BESS is foreseen to be used for the replacement reserve, the firm capacity would be almost 100%, but this service is not likely to be economical. If BESS is foreseen for the frequency regulation, the firm capacity depends on the storage autonomy. Most importantly, if BESS is foreseen to be used for energy arbitrage, it turned out that the firm capacity of BESS in that case, might be assumed quite high **(60%-80%)**[2]. This is basically understandable given the charge/discharge periods in the typical daily dispatch.

Controllability of the Malawian system in the case of different generation mixes will be basically demonstrated in PLEXOS analyses, by running short-term simulations on a daily basis, as the fundamental PLEXOS tasks are unit commitment and economic dispatch.

In order to be able to draw an adequate conclusion and help decision making for efficient replacement of the diesel generators, we have set several study cases, as presented in the following figure:

[2] According to the research by relevant authorities (IRENA, BNEF, NREL)

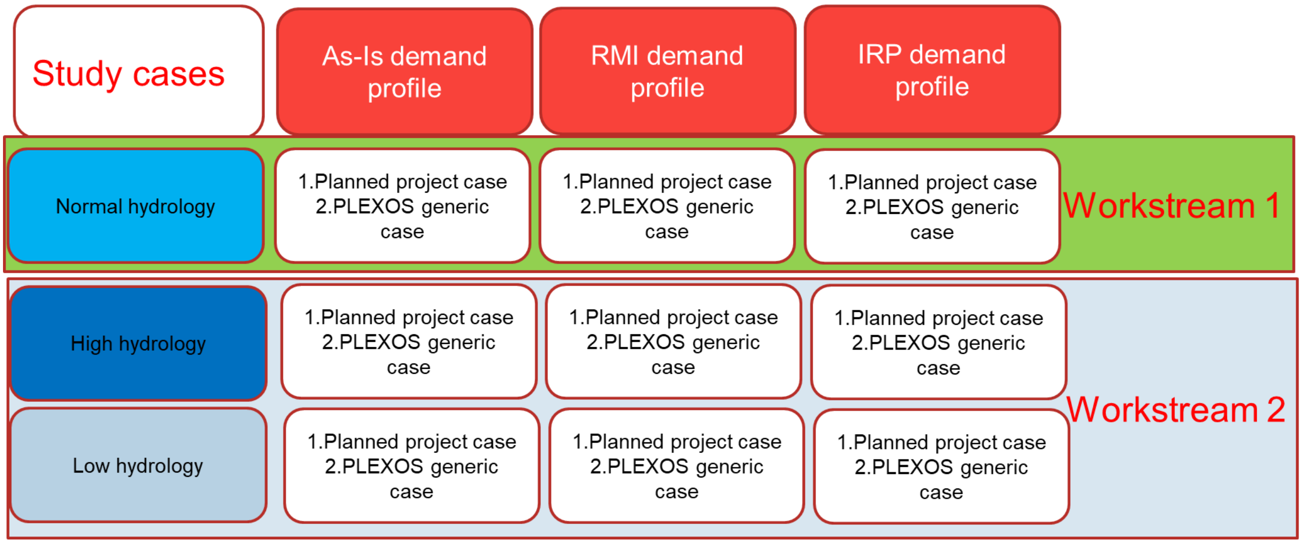

Figure 4-2 - Study cases selection

As mentioned earlier, for the quick cost-benefit analyses, a normal hydrology has been considered. However, further analyses that can serve as a support for the IRP update would require sensitivities on different hydrology, low and high.

Quick Cost-Benefit Analyses (CBA) will be essentially composed of two parts:

3. Money wise CB evaluation as a result of the long term PLEXOS simulations
4. Other CB assessment that might impact the decision making

Long-term PLEXOS simulations will result in essential answers:

- When is a certain candidate going to be built?
- How much are the total OPEX and CAPEX?
- What is the trend of levelized cost of electricity (LCOE) over the wanted horizon?

The cot breakdown for each case will be as follows:

Table 4-1 – PLEXOS output template – cost breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	A	B	C=A+B	D	E	F=C+D	G=C+F	H	I=G/H

Where:

- Annualized build cost represent investment on annual basis calculated on accordance wit assumed economic metrics (WACC and economic life)
- FO&M cost – fixed operational and maintenance costs – refer to the capacity
- VO&M costs – variable operational and maintenance costs– refer to the generation

In order to have a comprehensive look at costs and all the benefits, each case will be accompanied by the CBA review table to point out all the implications that the case produces. The table will not be associated with quantification factors for each issue, it is rather indicative.

Table 4-2 – CBA review table

	Costs	Benefits
Annualized Build Cost	Conclusions coming out from the Table 4-1	
Fuel Cost		Conclusions coming out from the Table 4-1
Levelized Cost [$/MWh]		Conclusions coming out from the Table 4-1
PV penetration	Assess the penetration level of intermittent sources – this may give a clue whether some specific issue might be of concern (e.g., system inertia)	Basically, benefits of intermittent sources are manifold, one of which is clean energy increase, which is not a big issue in Malawi given that almost whole Malawian generation is clean
BESS contribution		In respect of the flexibility increase and other services that represent a real added value
Firm capacity of the system	What does a new generation mix mean to the overall firmness?	
Influence on operating reserve	How does a new generation mix affect the reserve requirements?	
Influence on system security	Basically, the system security will be checked in the W2, here it indicates expectations	
Environmental concerns	How do new technologies influence the environment regarding emissions?	
Social concerns	What is the impact of considered pathway on society?	

PLEXOS analysis

The generation optimization studies using the PLEXOS state–of–the art power system simulation program have been performed for the purpose of this report. Techno–economic optimization and determination of the appropriate size of the generating and storage units is based on the carried-out analysis.

PLEXOS is an electricity simulation model which applies mathematical programming techniques including linear and mixed integer programming. Based on the extensive inputs about the existing system, future conditions, and characteristics of the electricity demand, existing and new power plants, the operation of the generation system is simulated, and optimal solutions are achieved for each considered case. PLEXOS model of Malawi Grid was developed from scratch.

Mentioned planning data and parameters, including load forecast data, have been processed in PLEXOS to develop generation model of Malawi Grid which is then used as long-term generation planning tool for 11-year Horizon (2022-2032). LT (long term) schedule is used to run dispatch.

Assumptions

Key assumptions made in this model are:

- ✓ Capacity factors for hydro generation were calculated based on mean monthly Liwonde inflows of for the normal hydrology 140-220m3/s
- ✓ No tributaries along the cascade
- ✓ No spillage
- ✓ PLEXOS model respects the minimum load (plant based)
- ✓ Declining cost curves for PV plants and BESS are based on relevant researchers worldwide (IRENA, BNEF, NREL)

Diesel Aggreko IPP unit was disconnected starting May 2022

5

ANALYSES

5 ANALYSES

PLEXOS analysis has been carried out for period 2022–2032 to determine optimal generation portfolio for efficient replacement of the diesel generators. Calculations have been done through several models and are split into several cases.

The goal of LT calculations is to determine expansion plan for defined period considering reliability criteria.

Six different cases have been analysed within LT Calculations for Malawi Grid in accordance with the Table 4-2, and they can be divided into two subgroups based on the generation implemented:

1. Generic PLEXOS Cases – Candidates for expansion are generic 1MW PV, wind and BESS units, and confirmed candidate units (PV, wind and gas). Hydro candidates for expansion are not included.
2. Planned Projects Cases – Candidates for expansion are confirmed candidate units (PV, wind, gas and hydro). Generic 1MW PV, wind and BESS units are not included.

Three simulations were performed for each of the subgroups, to reflect three different sets of received data for the demand profile.

Performed simulations are organized as per following table:

Table 5-1 - Simulations' overview

Generation/Demand	As Is	RMI Base	IRP Base
Generic Plexos Cases	1	2	3
Planned Projects Cases	4	5	6

5.1 PLEXOS LT (LONG-TERM) CALCULATIONS

Six different cases have been analysed within LT Calculations for Malawi Grid. Cases are as follows:

1) Generic Plexos Case + As Is demand profile
2) Generic Plexos Case + RMI Base demand profile
3) Generic Plexos Case + IRP Base demand profile
4) Planned Projects Case + As Is demand profile
5) Planned Projects Case + RMI Base demand profile
6) Planned Projects Case + IRP Base demand profile

1. GENERIC PLEXOS CASE + AS IS DEMAND PROFILE =>

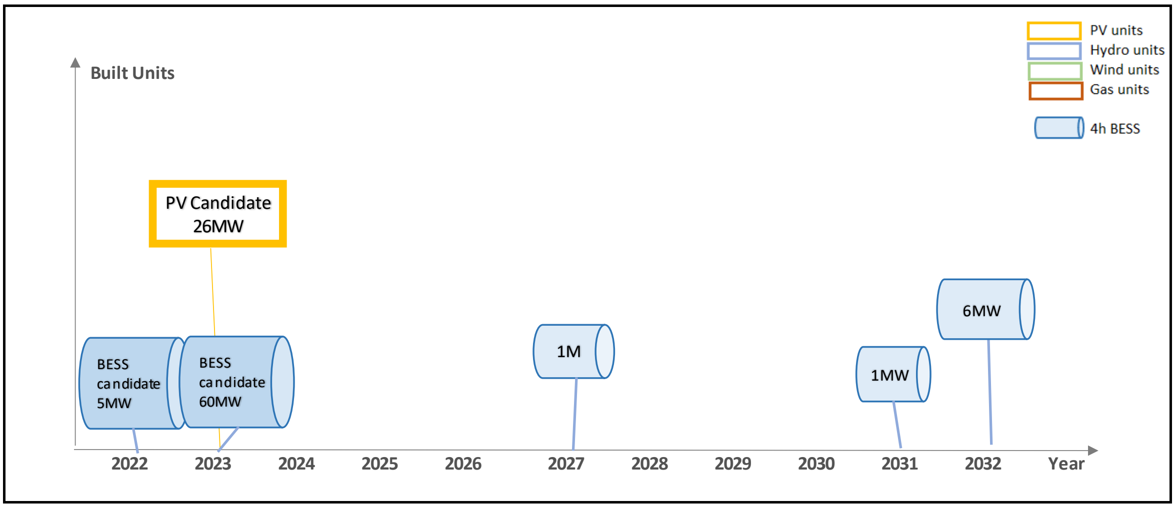

Figure 5-1 - Graphical overview of the system expansion

Table 5-2 - Built generating units

Built Generating Units			
RES	**Unit Name**	**Build Date**	**Capacity Built [MW]**
PV	Candidate	2023	26

Table 5-3 - Built Storage capacity

Built Battery Units			
Unit Name	**Build Date**	**Capacity Built [MW]**	**Capacity Built [MWh]**
Candidate BESS	2027	1	4
	2031	1	4
	2032	6	24
	TOTAL:	8	32

Table 5-4 - Retired Diesel units

Retired Units [MW]				
Year	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
2024	5.4	20	20	/
2032	/	/	/	6

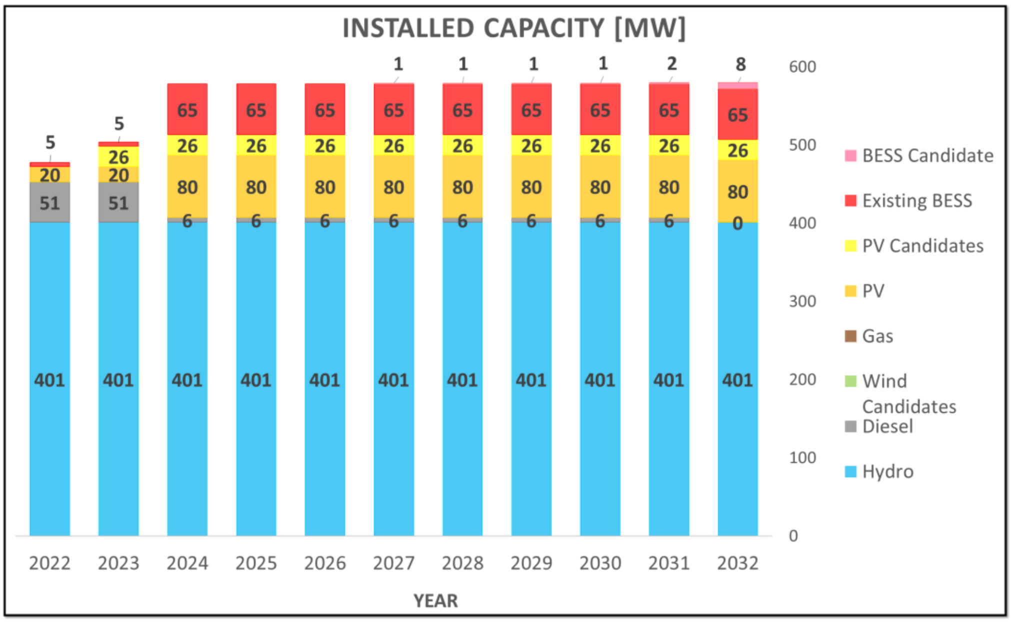

Figure 5-2 - Installed capacity for different technologies

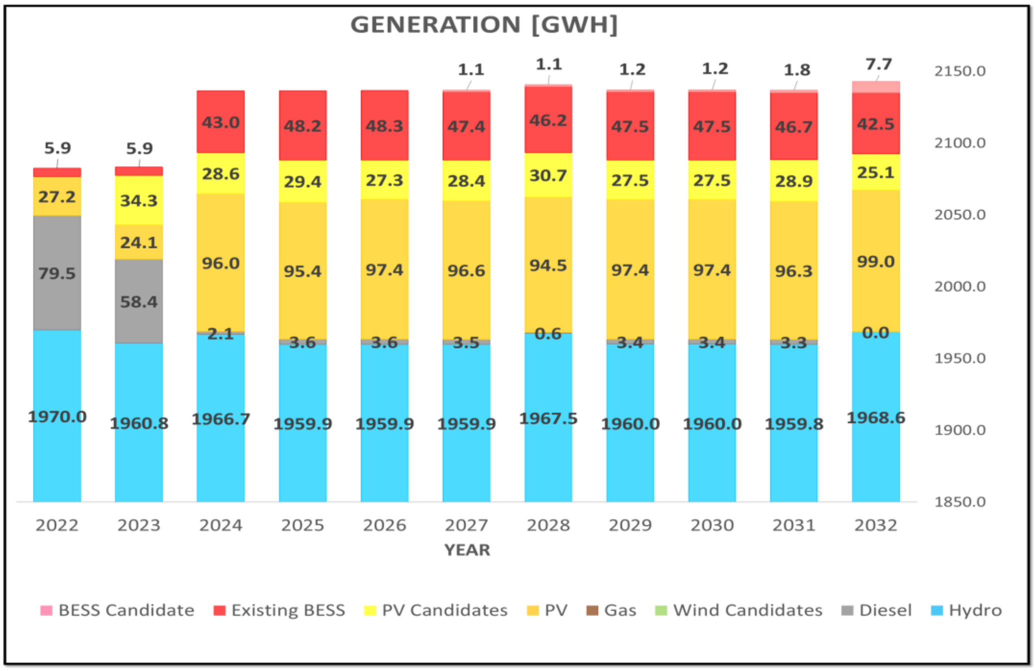

Figure 5-3 - Generation for different technologies

Table 5-5 - Cost Breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0	21,657.21	21,657.21	27,810.57	593.13	28,403.70	50,060.91	2,076.68	24.11
2023	2345.43	21,470.72	23,816.15	21,190.67	646.91	21,837.58	45,653.73	2,077.52	21.98
2024	2345.43	25,908.14	28,253.57	803.58	697.09	1,500.67	29,754.24	2,093.41	14.21
2025	2345.43	25,837.35	28,182.78	1,412.12	706.21	2,118.33	30,301.11	2,088.27	14.51
2026	2345.43	25,837.35	28,182.78	1,459.40	706.21	2,165.61	30,348.39	2,088.28	14.53
2027	2345.43	25,837.35	28,182.78	1,435.29	706.66	2,141.95	30,324.73	2,088.32	14.52
2028	2345.43	25,908.14	28,253.57	252.31	691.74	944.05	29,197.62	2,093.30	13.95
2029	2345.43	25,837.35	28,182.78	1,509.36	706.12	2,215.48	30,398.26	2,088.30	14.56
2030	2345.43	25,837.35	28,182.78	1,553.61	706.11	2,259.72	30,442.50	2,088.29	14.58
2031	2345.43	25,837.35	28,182.78	1,557.55	707.23	2,264.78	30,447.56	2,088.36	14.58
2032	2345.43	25,628.07	27,973.50	0.00	682.05	682.05	28,655.55	2,092.56	13.69

Table 5-6 - Overview of installed capacity and LCOE

Year	2022	2027	2032
Installed Capacity [MW]	472.55	513.15	507.15
Generation [GWh]	2076.68	2088.32	2092.56
BESS Installed Capacity [MWh]	0	4	32
PV Installed Capacity [MW]	20	106	106
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	401.15	401.15
Generation Cost [mil $]	28.4	2.14	0.68
LCOE [$/MWh]	24.11	14.52	13.69
Average Cost [$/MWh]	13.68	1.02	0.32

Table 5-7 - Cost Benefit overview for case 1

	Costs	Benefits
Annualized Build Cost	Constant, caused by modest expansion	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	Low (no demand growth), immediate action to replace the diesel production as the optimal solution	
Wind penetration	no wind	
BESS contribution	Low - Hydro facilities are flexible and able to handle power variability	
Firm capacity of the system		Existing hydro units (plus 4hour BESS) provide sufficient firm capacity
Influence on operating reserve		no
Influence on system security		no
Environmental concerns		Reduced emissions
Social concerns		As-Is pathway is conservative in its nature, so no big impact on social issues

This is a predominantly hydro based portfolio, where the hydro capacity factor is not more than 60%, which leaves sufficient room for the reserve.

2. GENERIC PLEXOS CASE + RMI BASE DEMAND PROFILE =>

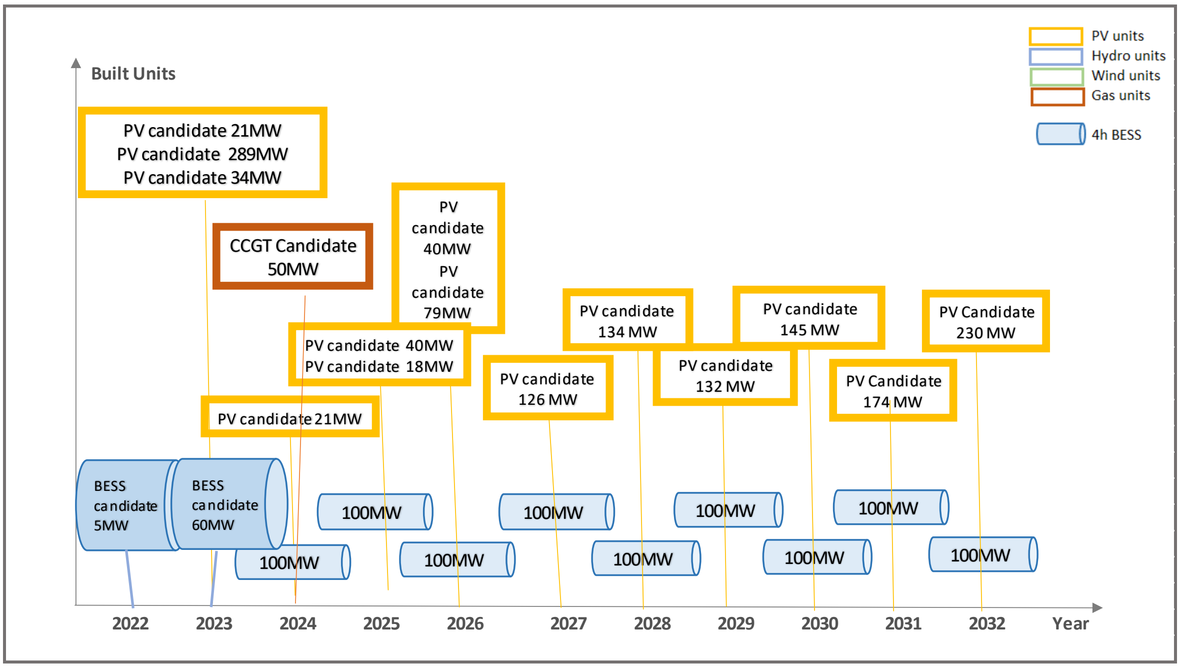

Figure 5-4 - Graphical overview of the system expansion

Table 5-8 - Built generating units

Built Generating Units				Total [MW]
	Unit Name	**Build Date**	**Capacity Built [MW]**	
PV	Kanengo	2026	40	**1462**
	Nkhotakota	2023	21	
	Candidate	2023	289	
	Candidate	2024	0	
	Candidate	2025	18	
	Candidate	2026	79	
	Candidate	2027	126	
	Candidate	2028	134	
	Candidate	2029	132	
	Candidate	2030	145	
	Candidate	2031	174	
	Candidate	2032	230	
	Voltalia	2025	40	
	Zomba_Changalume	2023	34	
Gas	Candidate	2024	50	**50**
			TOTAL:	**1512**

Table 5-9 - Built Storage capacity

Built Battery Units			
Unit Name	Build Date	Capacity Built [MW]	Capacity Built [MWh]
Candidate BESS	2024	100	400
	2025	100	400
	2026	100	400
	2027	100	400
	2028	100	400
	2029	100	400
	2030	100	400
	2031	100	400
	2032	100	400
	TOTAL:	900	3600

Table 5-10 - Retired Diesel units

Retired Units [MW]				
Year	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
2024	5.4	20	20	6

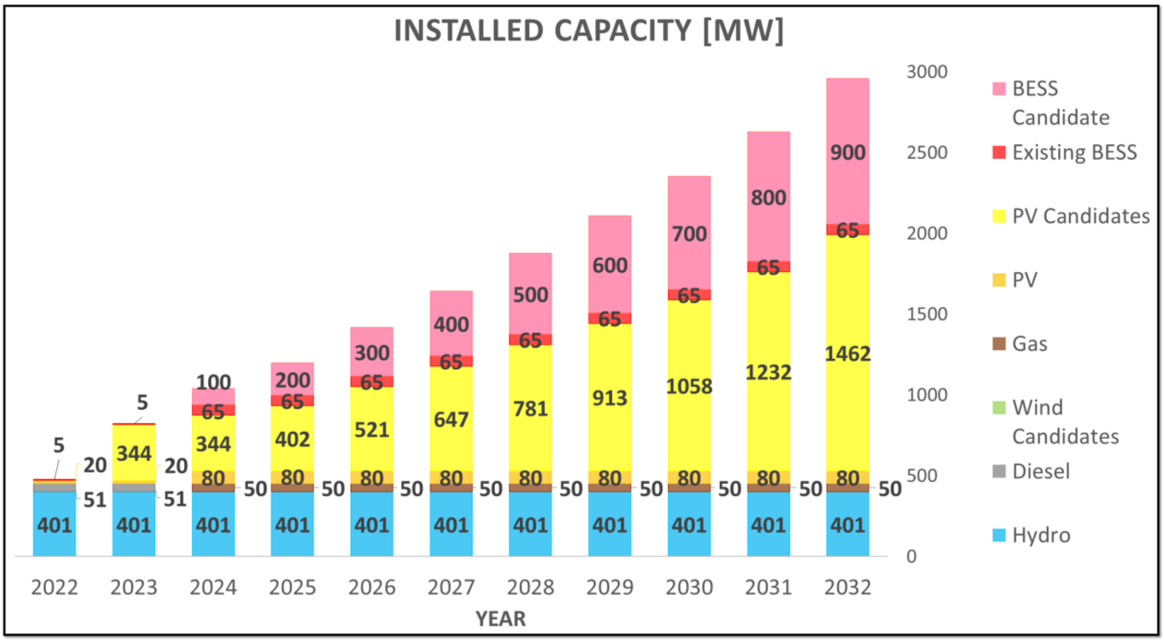

Figure 5-5 - Installed capacity for different technologies

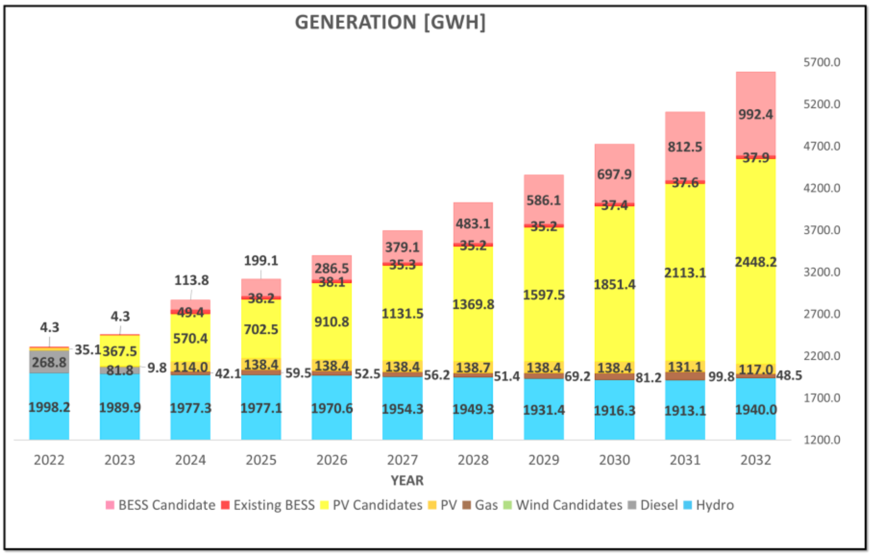

Figure 5-6 - Generation for different technologies

Table 5-11 - Cost Breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0.00	21,657.21	21,657.21	94,049.36	1,692.62	95,741.98	117,399.19	2,302.04	51.00
2023	31,031.89	26,558.72	57,590.61	29,677.74	2,531.57	32,209.31	89,799.92	2,449.00	36.67
2024	35,989.46	31,732.75	67,722.21	11,598.50	3,998.84	15,597.34	83,319.55	2,703.70	30.82
2025	40,785.57	32,334.05	73,119.62	16,403.38	4,956.80	21,360.18	94,479.80	2,877.44	32.83
2026	50,178.58	34,238.05	84,416.63	14,463.37	6,063.45	20,526.82	104,943.45	3,072.24	34.16
2027	59,650.52	36,254.05	95,904.57	15,474.52	7,297.80	22,772.32	118,676.89	3,280.40	36.18
2028	69,220.19	38,503.25	107,723.44	14,160.59	8,583.81	22,744.40	130,467.84	3,509.20	37.18
2029	78,150.88	40,510.05	118,660.93	19,073.56	9,933.29	29,006.85	147,667.78	3,736.43	39.52
2030	87,416.10	42,830.05	130,246.15	22,377.57	11,397.12	33,774.69	164,020.84	3,987.31	41.14
2031	97,880.34	45,614.05	143,494.39	27,506.81	12,900.32	40,407.13	183,901.52	4,257.13	43.20
2032	110,847.88	49,429.10	160,276.98	13,368.28	14,379.42	27,747.70	188,024.68	4,553.74	41.29

Even though all diesel units are retired in 2024, there are some fuel costs since the gas unit was built.

Table 5-12 - Overview of installed capacity and LCOE

Year	2022	2027	2032
Installed Capacity [MW]	472.55	1,178.15	1,993.15
Generation [GWh]	2,302.04	3,280.40	4,553.74
BESS Installed Capacity [MWh]	0	1600	3600
PV Installed Capacity [MW]	20	727	1,542
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	401.15	401.15
Generation Cost [mil $]	95.74	22.77	27.75
LCOE [$/MWh]	51.00	36.18	41.29
Average Cost [$/MWh]	41.59	6.94	6.09

Note that we did not include hydro power plants in generic PLEXOS pathway for two reasons:

- To better see the difference with case 5 (Planned Projects Case + RMI Base demand profile),
- We wanted to see an immediate action and the leading time for hydro projects is min 4 years.

Table 5-13 - Cost Benefit overview for case 2

	Costs	Benefits
Annualized Build Cost	Increased, caused by expansion (PV, Gas, BESS)	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing in first several years, then slightly increase
PV penetration	High (note that an annual capacity factor is appx 20%)	
Wind penetration	no wind	
BESS contribution	High, due to need for energy arbitrage	Possibilities for other services: frequency regulation, reserve, voltage support, black start
Firm capacity of the system		Existing hydro units along with the 4hour BESS provide sufficient firm capacity
Influence on operating reserve	Increase of spinning reserve requirements due to variable nature of solar	
Influence on system security		Given that BESS are high-performance facilities, security is expected to be just better
Environmental concerns		Reduced emissions
Social concerns		This pathway is more aggressive in RES penetration, that can cause benefit for society (job creation)

3. GENERIC PLEXOS CASE + IRP BASE DEMAND PROFILE =>

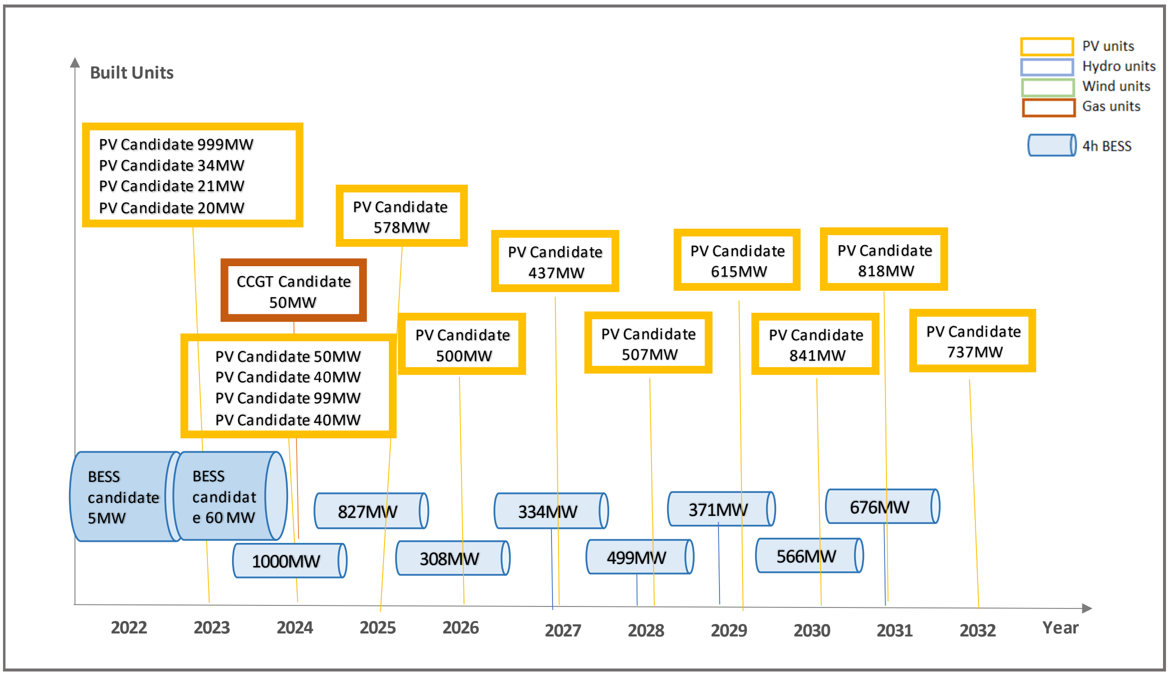

Figure 5-7 - Graphical overview of the system expansion

Table 5-14 - Built generating units

Built Generating Units				Total [MW]
	Unit Name	**Build Date**	**Capacity Built [MW]**	
PV	Bwengu	2024	50	**7236**
	Kanengo	2024	40	
	Nkhotakota	2023	21	
	Candidate	2023	999	
	Candidate	2024	999	
	Candidate	2025	578	
	Candidate	2026	500	
	Candidate	2027	437	
	Candidate	2028	507	
	Candidate	2029	615	
	Candidate	2030	841	
	Candidate	2031	818	
	Candidate	2032	737	
	Voltalia	2024	40	
	Monkey Bay	2023	20	
	Zomba_Changalume	2023	34	
Gas	Candidate	2024	50	**50**
			TOTAL:	**7286**

Table 5-15 - Built Storage capacity

Built Battery Units			
Unit Name	Build Date	Capacity Built [MW]	Capacity Built [MWh]
Candidate BESS	2024	1,000.00	4,000.00
	2025	827.00	3,308.00
	2026	308.00	1,232.00
	2027	334.00	1,336.00
	2028	499.00	1,996.00
	2029	371.00	1,484.00
	2030	566.00	2,264.00
	2031	676.00	2,704.00
	TOTAL:	4,581.00	18,324.00

Table 5-16 - Retired Diesel units

Retired Units [MW]				
Year	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
/	/	/	/	/

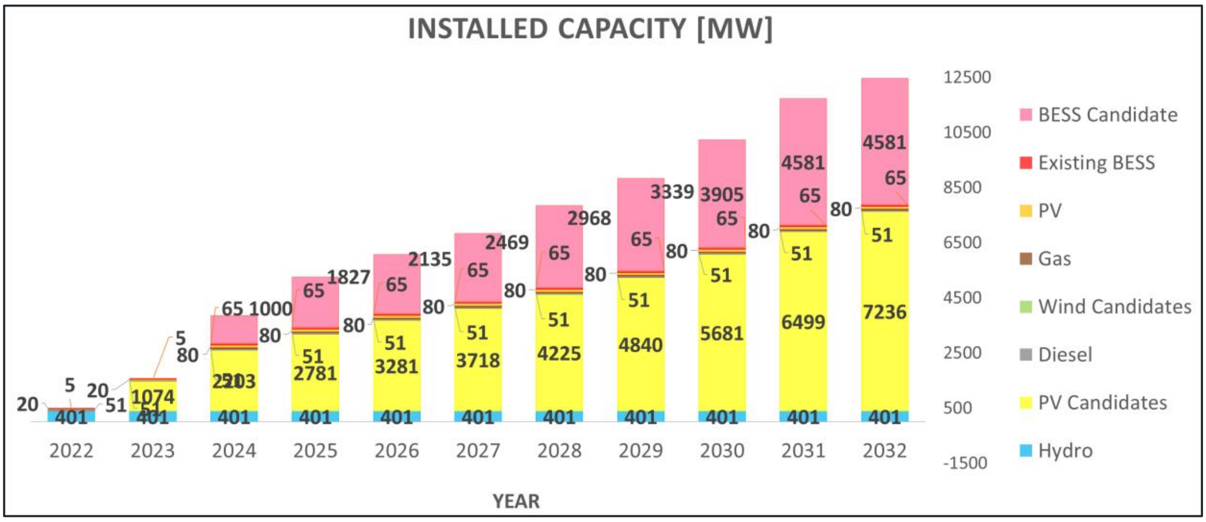

Figure 5-8 - Installed capacity for different technologies

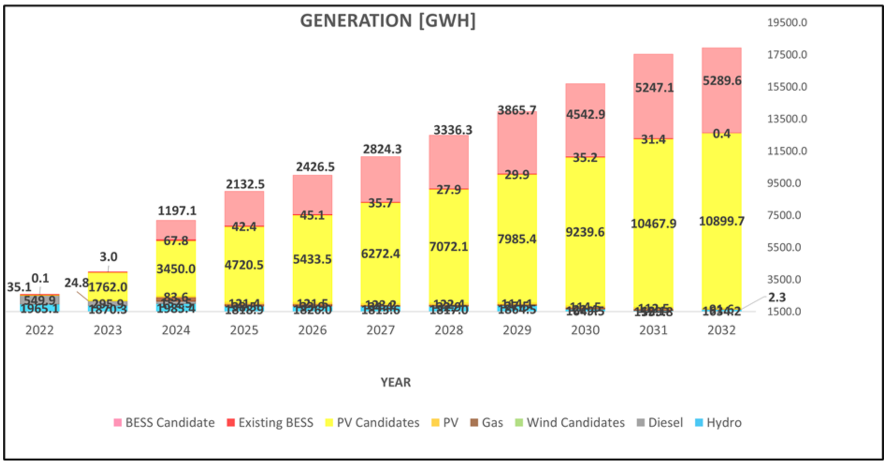

Figure 5-9 - Generation for different technologies

Table 5-17 - Cost Breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0	22,408.52	22,408.52	192,422.54	3,261.32	195,683.86	218,092.38	2,550.10	85.52
2023	96,884.46	38,818.72	135,703.18	107,320.34	11,478.51	118,798.85	254,502.03	3,956.06	64.33
2024	289,279.85	85,315.82	374,595.67	128,111.45	21,719.72	149,831.17	524,426.84	7,193.38	72.90
2025	408,139.33	105,908.72	514,048.05	46,004.78	27,473.99	73,478.77	587,526.82	8,986.94	65.38
2026	472,869.06	118,220.72	591,089.78	44,057.43	31,357.67	75,415.10	666,504.88	9,996.79	66.67
2027	531,811.51	129,888.72	661,700.23	26,488.22	35,615.38	62,103.60	723,803.83	11,149.99	64.92
2028	605,050.88	145,383.94	750,434.82	36,862.16	40,215.08	77,077.24	827,512.06	12,491.31	66.25
2029	672,743.31	160,020.72	832,764.03	30,543.54	45,073.91	75,617.45	908,381.48	13,954.06	65.10
2030	764,064.03	181,400.72	945,464.75	36,106.96	52,098.31	88,205.27	1,033,670.02	15,698.25	65.85
2031	855,504.10	203,952.72	1,059,456.82	34,450.30	58,843.31	93,293.61	1,152,750.43	17,535.34	65.74
2032	897,056.61	216,335.80	1,113,392.41	1,944.79	60,482.45	62,427.24	1,175,819.65	17,920.93	65.61

This pathway represents an extreme case from the current perspective, as the demand projection is very rapid. High levelized costs reflect the investment needs.

Table 5-18 - Overview of installed capacity and LCOE

Year	2022	2027	2032
Installed Capacity [MW]	472.55	4300.55	7,818.55
Generation [GWh]	2,550.04	8,290.00	12,630.00
BESS Installed Capacity [MWh]	0	9876	18324
PV Installed Capacity [MW]	20	3,800	7,316
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	401.15	401.15
Generation Cost [mil $]	195.68	62.1	62.4
LCOE [$/MWh]	85.35	64.92	65.61
Average Cost [$/MWh]	76.74	5.57	3.48

Table 5-19 - Cost Benefit overview for case 3

	Costs	Benefits
Annualized Build Cost	Increased, caused by expansion (PV, Gas, BESS)	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	Very High (note that an annual capacity factor is appx 20%)	
Wind penetration	no wind	
BESS contribution	Extremely High, due to need for energy arbitrage	Possibilities for other services: frequency regulation, reserve, voltage support, black start
Firm capacity of the system		Existing hydro units + lot of BESS provide sufficient firm capacity
Influence on operating reserve	Increase of spinning reserve requirements due to variable nature of solar	
Influence on system security		Given that BESS are high-performance facilities, security is expected to be just better
Environmental concerns		Reduced emissions
Social concerns		This pathway is more aggressive in RES penetration, that can cause benefit for society (job creation,,,,,)

This is an extreme scenario for which the system is clearly not well prepared.

Constraints from logistical point of view, feasibility, or any real build-up cap due to civil work constraints were not taken into consideration while performing this simulation.

The goal was avoiding unserved energy and reaching energy balance.

4. PLANNED PROJECT CASE + AS IS DEMAND PROFILE =>

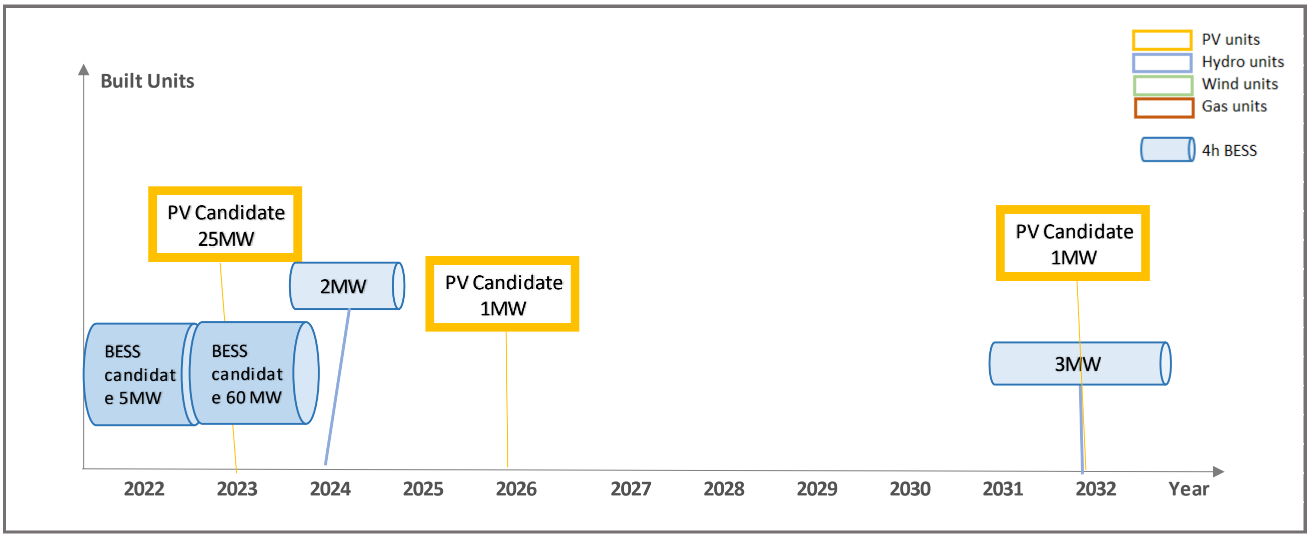

Figure 5-10 - Graphical overview of the system expansion

Table 5-20 - Built generating units

Built Generating Units			
RES	**Unit Name**	**Build Date**	**Capacity Built [MW]**
PV	Candidate	2023	25
	Candidate	2026	1
	Candidate	2032	1
		TOTAL:	27

Table 5-21 - Built Storage capacity

Built Battery Units			
Unit Name	**Build Date**	**Capacity Built [MW]**	**Capacity Built [MWh]**
Candidate BESS	2024	2	8
	2032	3	12
	TOTAL:	5	20

Table 5-22 - Retired Diesel units

Retired Units [MW]				
Year	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
2024	/	20	20	6
2032	5.4	/	/	/

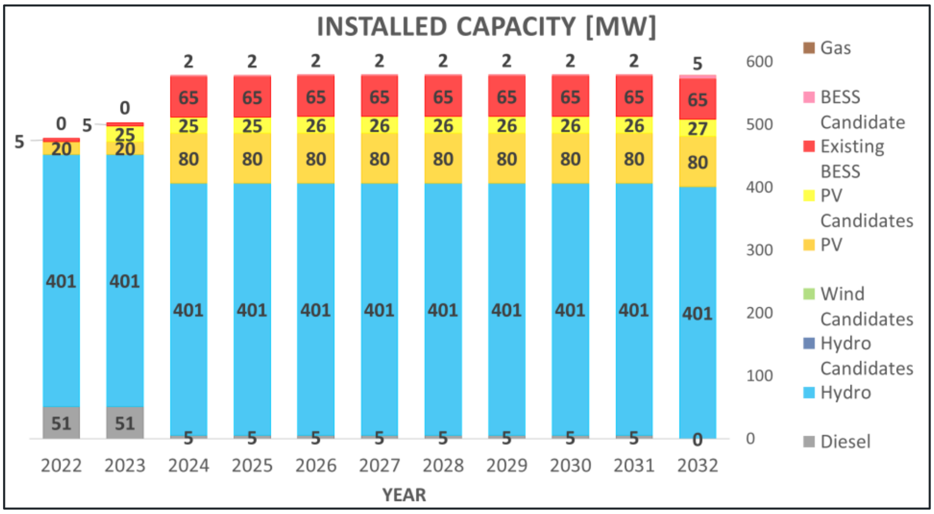

Figure 5-11 - Installed capacity for different technologies

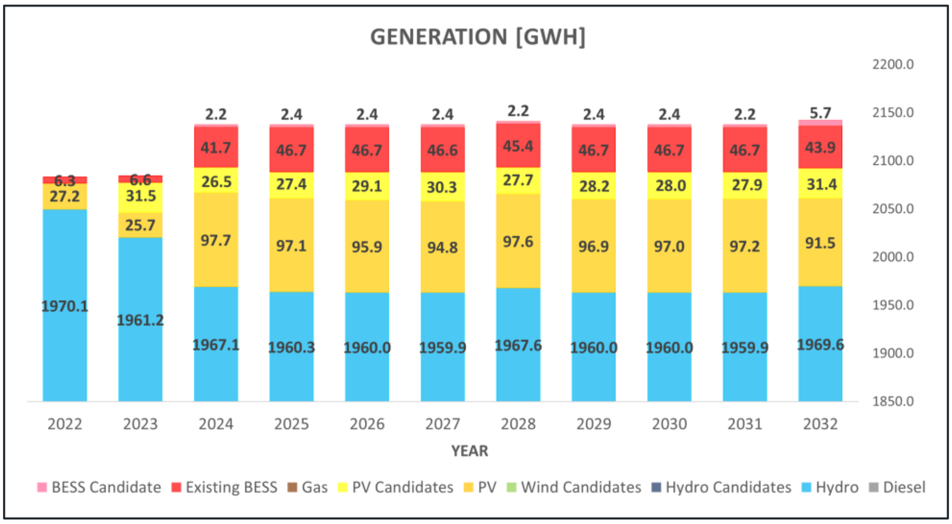

Figure 5-12 - Generation for different technologies

Table 5-23 - Cost Breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0.00	21,657.21	21,657.21	27,810.57	593.13	28,403.70	50,060.91	2,076.74	24.11
2023	2,255.22	21,454.72	23,709.94	21,458.52	644.93	22,103.45	45,813.39	2,077.62	22.05
2024	2,255.22	25,864.09	28,119.31	796.97	695.25	1,492.22	29,611.53	2,093.48	14.14
2025	2,255.22	25,793.42	28,048.64	1,390.52	704.27	2,094.79	30,143.43	2,088.31	14.43
2026	2,334.16	25,809.42	28,143.58	1,321.06	706.10	2,027.16	30,170.74	2,088.31	14.45
2027	2,334.16	25,809.42	28,143.58	1,370.51	706.51	2,077.02	30,220.60	2,088.34	14.47
2028	2,334.16	25,880.13	28,214.29	191.99	691.68	883.67	29,097.96	2,093.31	13.90
2029	2,334.16	25,809.42	28,143.58	1,448.62	706.09	2,154.71	30,298.29	2,088.31	14.51
2030	2,334.16	25,809.42	28,143.58	1,491.50	706.11	2,197.61	30,341.19	2,088.31	14.53
2031	2,334.16	25,809.42	28,143.58	1,546.60	706.78	2,253.38	30,396.96	2,088.36	14.56
2032	2,390.54	25,644.11	28,034.65	0.00	676.31	676.31	28,710.96	2,092.58	13.72

Table 5-24 - Overview of installed capacity and LCOE

Year	2022	2027	2032
Installed Capacity [MW]	472.55	512.55	508.15
Generation [GWh]	2,076.74	2,088.34	2,092.58
BESS Installed Capacity [MWh]	0	8	20
PV Installed Capacity [MW]	20	106	107
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	401.15	401.15
Generation Cost [mil $]	28.4	2.077	0.676
LCOE [$/MWh]	24.11	14.47	13.72
Average Cost [$/MWh]	13.68	0.99	0.32

Table 5-25 - Cost Benefit overview for case 4

	Costs	Benefits
Annualized Build Cost	Constant, caused by modest expansion	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	Low (no demand growth), immediate action to replace the diesel production as the optimal solution	
Wind penetration	no wind	
BESS contribution	Low - Hydro facilities are flexible and able to handle power variability	
Firm capacity of the system		Existing hydro units provide sufficient firm capacity
Influence on operating reserve		no
Influence on system security		no
Environmental concerns		Reduced emissions
Social concerns		As-Is pathway is conservative in its nature, so no big impact on social issues

5. PLANNED PROJECT CASE + RMI BASE DEMAND PROFILE =>

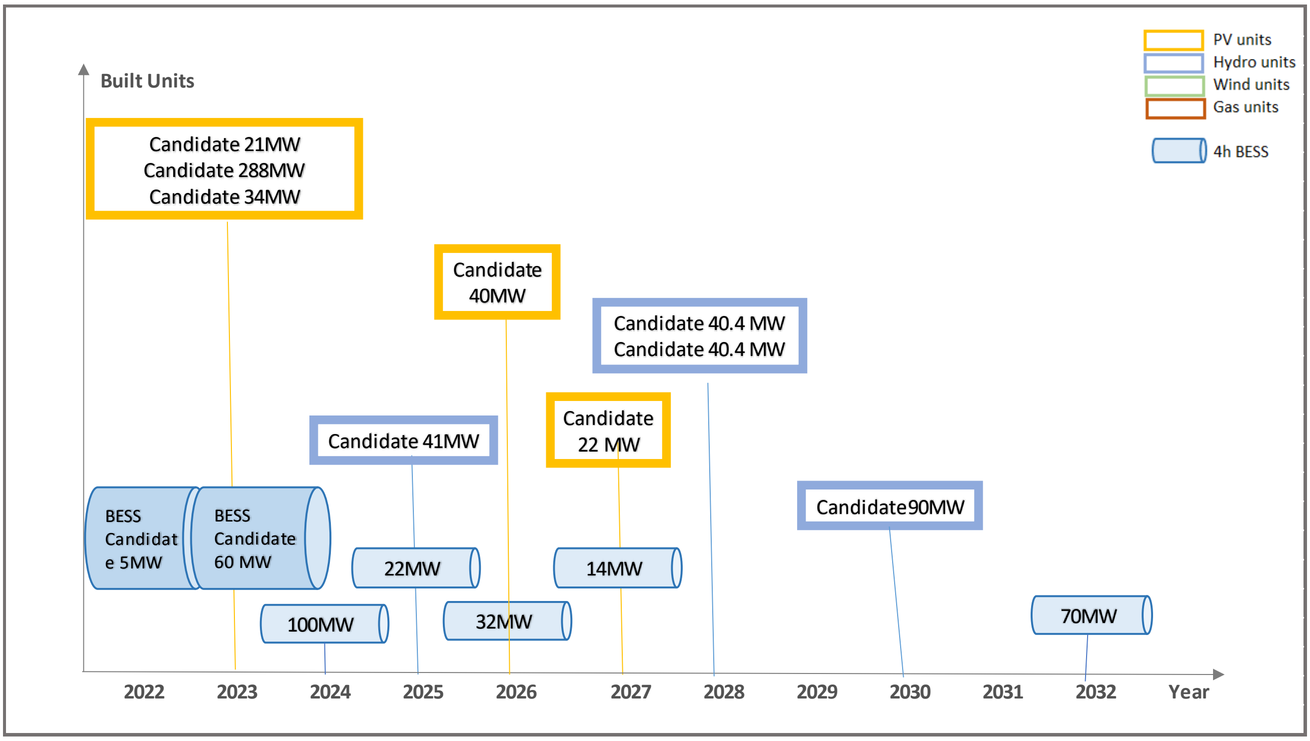

Figure 5-13 - Graphical overview of the system expansion

Table 5-26 - Built generating units

Built Generating Units				Total [MW]
	Unit Name	**Build Date**	**Capacity Built [MW]**	
PV	Nkhotakota	2023	21	**405**
	Candidate	2023	288	
	Candidate	2027	22	
	Voltalia	2026	40	
	Zomba_Changalume	2023	34	
Hydro	Chasombo	2028	40.4	**211.8**
	Chizuma	2028	40.4	
	Lower Songwe	2030	90	
	Mbongozi	2025	41	
			TOTAL:	**616.8**

Table 5-27- Built Storage capacity

Built Battery Units			
Unit Name	Build Date	Capacity Built [MW]	Capacity Built [MWh]
Candidate BESS	2024	100	400
	2025	22	88
	2026	32	128
	2027	14	56
	2032	70	280
	TOTAL:	238	952

Table 5-28 - Retired Diesel units

Retired Units [MW]				
Year	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
2024	5.4	/	/	/
2028	/	20	/	6
2030	/	/	20	/

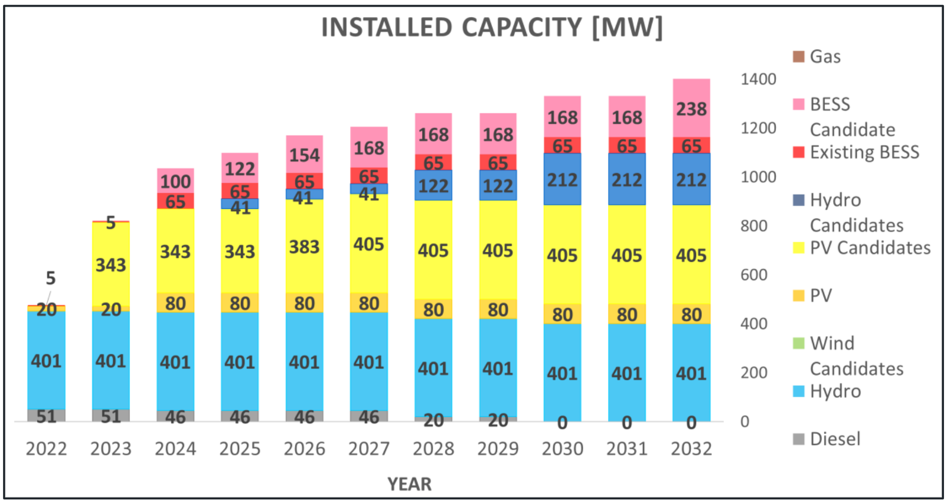

Figure 5-14 - Installed capacity for different technologies

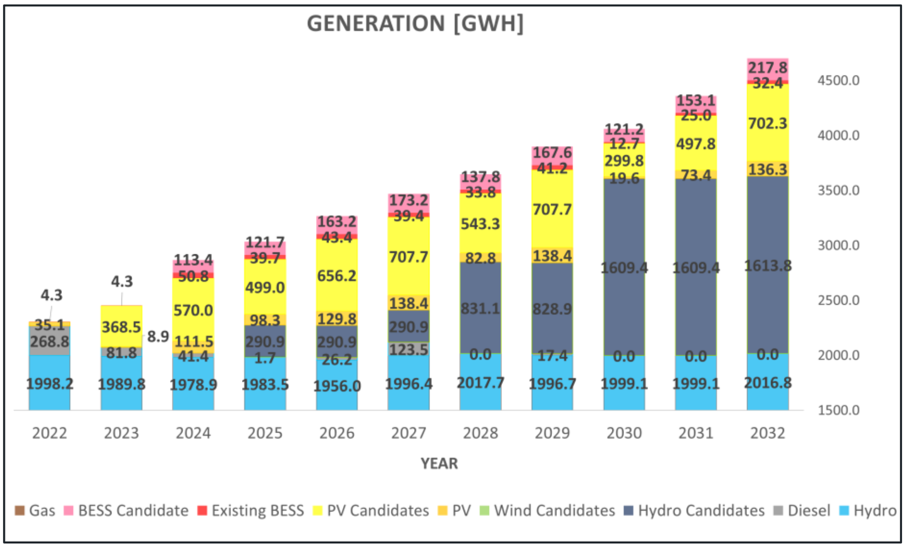

Figure 5-15 - Generation for different technologies

Table 5-29 - Cost Breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0.00	21,657.21	21,657.21	94,049.35	1,692.62	95,741.97	117,399.18	2,302.04	51.00
2023	30,941.68	26,542.72	57,484.40	29,679.28	2,532.25	32,211.53	89,695.93	2,449.00	36.63
2024	30,941.68	32,861.13	63,802.81	15,534.99	3,979.23	19,514.22	83,317.03	2,701.80	30.84
2025	42,248.81	34,441.61	76,690.42	679.78	3,294.76	3,974.54	80,664.96	2,873.49	28.07
2026	45,406.12	34,841.61	80,247.73	10,528.27	4,469.34	14,997.61	95,245.34	3,059.13	31.13
2027	47,059.96	35,193.61	82,253.57	51,166.72	5,342.36	56,509.08	138,762.65	3,256.84	42.61
2028	68,769.80	37,294.26	106,064.06	0.00	3,443.20	3,443.20	109,507.26	3,474.90	31.51
2029	68,769.80	37,192.36	105,962.16	7,675.92	4,750.77	12,426.69	118,388.85	3,689.08	32.09
2030	92,951.55	39,835.80	132,787.35	0.00	1,756.59	1,756.59	134,543.94	3,927.89	34.25
2031	92,951.55	39,835.80	132,787.35	0.00	3,141.40	3,141.40	135,928.75	4,179.67	32.52
2032	92,951.55	39,944.94	132,896.49	0.00	4,612.15	4,612.15	137,508.64	4,469.12	30.77

Table 5-30 - Overview of installed capacity and LCOE

Year	2022	2027	2032
Installed Capacity [MW]	472.55	973.15	1,097.95
Generation [GWh]	2,302.04	3,256.84	4,469.12
BESS Installed Capacity [MWh]	0	672	952
PV Installed Capacity [MW]	20	485	485
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	442.15	612.95
Generation Cost [mil $]	95.74	56.51	4.612
LCOE [$/MWh]	51.00	42.61	30.77
Average Cost [$/MWh]	41.59	17.35	1.03

Table 5-31 -Cost Benefit overview for case 5

	Costs	Benefits
Annualized Build Cost	Increased, caused by expansion (PV, BESS, Hydro)	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	High, but not as much as in case 2	
Wind penetration	no wind	
BESS contribution	Reasonable, much lower then in case 2, as hydro generation contributes a lot to overall system flexibility	Possibilities for other services: frequency regulation, reserve, voltage support, black start
Firm capacity of the system		hydro units provide sufficient firm capacity
Influence on operating reserve	Increase of spinning reserve requirements due to variable nature of soar	
Influence on system security		Given that BESS are high-performance facilities, security is expected to be just better
Environmental concerns		Reduced emissions
Social concerns		This pathway is more aggressive in RES penetration, that can cause benefit for society (job creation)

6. PLANNED PROJECT CASE + IRP BASE DEMAND PROFILE =>

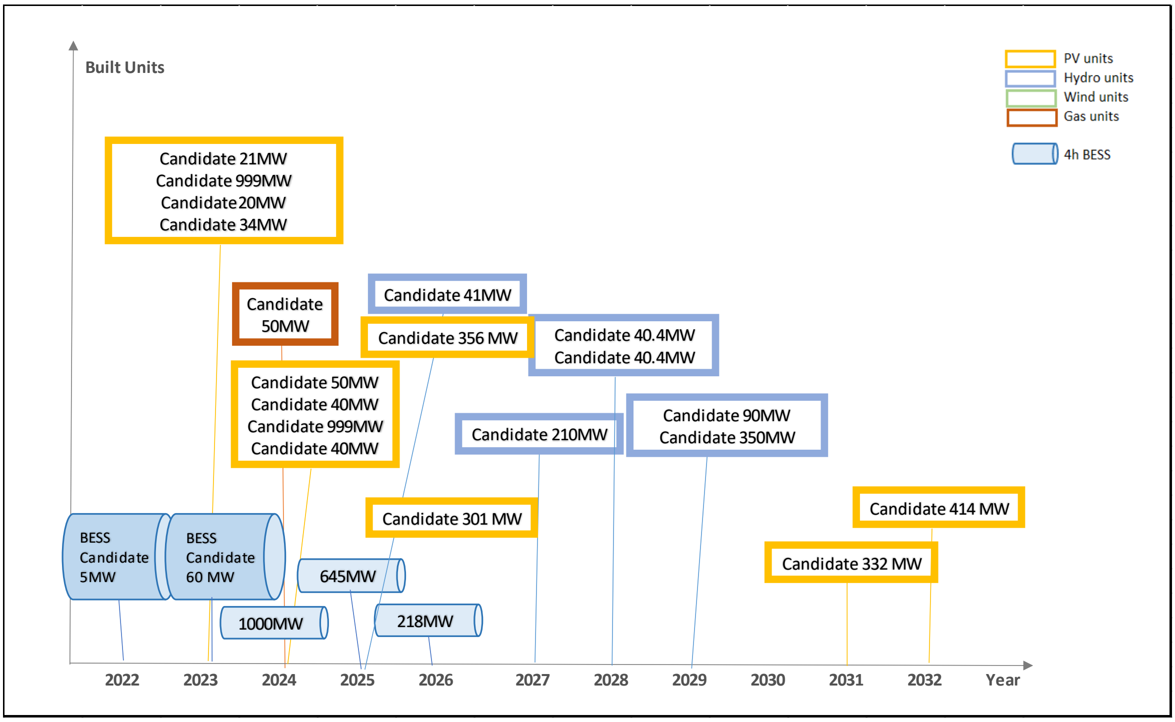

Figure 5-16 - Graphical overview of the system expansion

Table 5-32 - Built generating units

Built Generating Units				Total [MW]
	Unit Name	**Build Date**	**Capacity Built [MW]**	
PV	Bwengu	2024	50	**3606**
	Kanengo	2024	40	
	Monkey Bay	2023	20	
	Nkhotakota	2023	21	
	Candidate	2023	999	
	Candidate	2024	999	
	Candidate	2025	356	
	Candidate	2026	301	
	Candidate	2031	332	
	Candidate	2032	414	
	Voltalia	2024	40	
	Zomba Changalume	2023	34	
Hydro	Chasombo	2028	40.4	**771.8**
	Chizuma	2028	40.4	
	Kholombidzo	2027	210	
	Lower Songwe	2029	90	
	Mbongozi	2025	41	
	Mpatamanga	2029	350	
Gas	Candidate	2024	50	**50**
			TOTAL:	**4427.8**

Table 5-33 - Built Storage capacity

Built Battery Units			
Unit Name	Build Date	Capacity Built [MW]	Capacity Built [MWh]
Candidate BESS	2024	1,000.00	4,000.00
	2025	645.00	2,580.00
	2026	218.00	872.00
	TOTAL:	1,863.00	7,452.00

Table 5-34 - Retired Diesel units

Retired Units [MW]				
Year	Lilongwe A	Lilongwe B	Mapanga	Mzuzu-Luwinga
2032	/	/	/	/

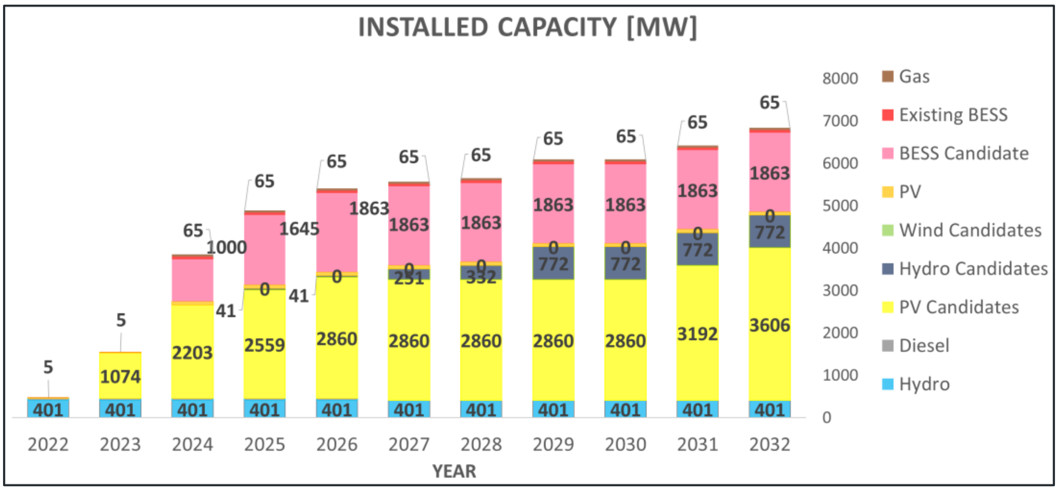

Figure 5-17 - Installed capacity for different technologies

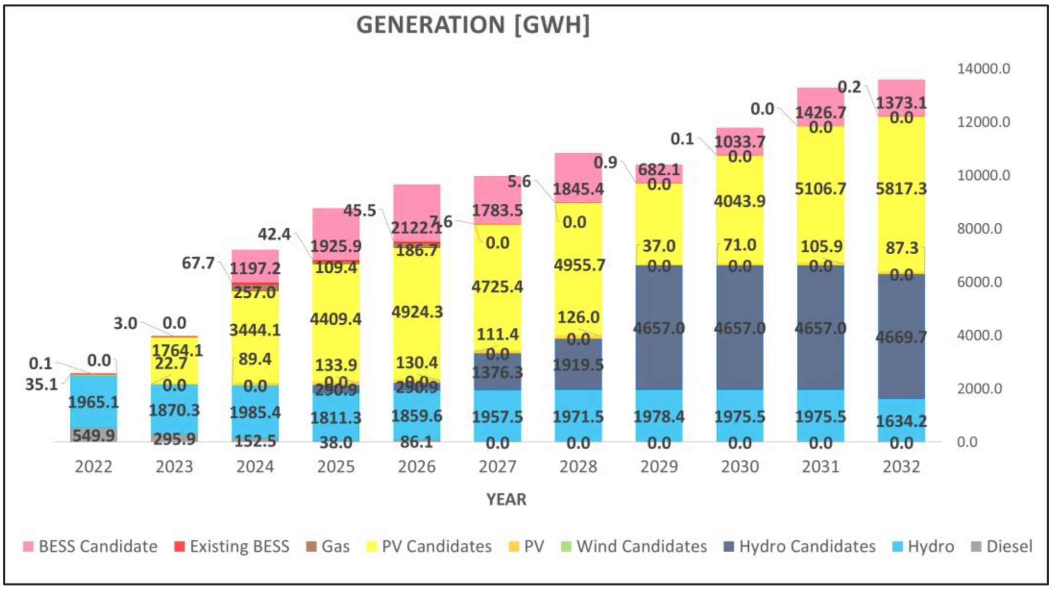

Figure 5-18 - Generation for different technologies

Table 5-35 - Cost Breakdown

Fiscal Year	Annualized Build Cost [$000]	FO&M Cost [$000]	Total Fixed Costs [$000]	Fuel Cost [$000]	VO&M Cost [$000]	Total System Costs [$000]	Total [$000]	Generation [GWh]	Levelized Cost [$/MWh]
2022	0	22,408.52	22,408.52	192,422.54	3,261.32	195,683.86	218,092.38	2,550.10	85.52
2023	96,884.46	38,818.72	135,703.18	107,320.34	11,478.51	118,798.85	254,502.03	3,956.06	64.33
2024	289,279.85	85,315.82	374,595.67	128,111.45	21,719.72	149,831.17	524,426.84	7,193.38	72.90
2025	385,449.75	101,478.98	486,928.73	44,898.16	25,810.04	70,708.20	557,636.93	8,761.08	63.65
2026	427,089.70	109,346.98	536,436.68	85,995.98	29,322.67	115,318.65	651,755.33	9,645.45	67.57
2027	483,513.80	115,294.67	598,808.47	0	26,602.22	26,602.22	625,410.69	9,961.71	62.78
2028	505,223.64	118,828.39	624,052.03	0	27,949.34	27,949.34	652,001.37	10,823.66	60.24
2029	623,445.55	135,978.76	759,424.31	0	16,891.12	16,891.12	776,315.43	10,389.44	74.72
2030	623,445.55	135,978.76	759,424.31	0	22,631.80	22,631.80	782,056.11	11,781.07	66.38
2031	643,411.81	141,290.76	784,702.57	0	28,669.60	28,669.60	813,372.17	13,271.79	61.29
2032	666,753.38	148,320.01	815,073.39	0	32,475.57	32,475.57	847,548.96	13,581.79	62.40

This pathway represents an extreme case from the current perspective, as the demand projection is very rapid. High levelized costs reflect the investment needs.

Table 5-36 - Overview of installed capacity and LCOE

Year	2022	2027	2032
Installed Capacity [MW]	472.55	3,642.00	4,909.00
Generation [GWh]	2,550.04	8,170.00	12,208.00
BESS Installed Capacity [MWh]	0	7450	7450
PV Installed Capacity [MW]	20	2,860	3,606
Wind Installed Capacity [MW]	0	0	0
Hydro Installed Capacity [MW]	401.15	652	1,173.00
Generation Cost [mil $]	195.68	57,762	26,482
LCOE [$/MWh]	85.35	62.78	62.40
Average Cost [$/MWh]	76.70	2.67	2.39

Table 5-37 - Cost Benefit overview for case 6

	Costs	Benefits
Annualized Build Cost	Increased, caused by expansion (PV, Gas, BESS)	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	Very High (note that an annual capacity factor is appx 20%)	
Wind penetration	no wind	
BESS contribution	Extremely High, due to need for energy arbitrage	Possibilities for other services: frequency regulation, reserve, voltage support, black start
Firm capacity of the system		Existing hydro units + new hydro units + lot of BESS provide sufficient firm capacity
Influence on operating reserve	Increase of spinning reserve requirements due to variable nature of solar	New hydro facilities will alleviate economic impact of increased requirements
Influence on system security		Given that BESS are high-performance facilities, security is expected to be just better
Environmental concerns		Reduced emissions
Social concerns		This pathway is more aggressive in RES penetration, that can cause benefit for society (job creation,,,,,)

This is an extreme scenario for which the system is clearly not well prepared.

Constraints from logistical point of view, feasibility, or any real build-up cap due to civil work constraints were not taken into consideration while performing this simulation.

The goal was avoiding unserved energy and reaching energy balance.

6

CONCLUSIONS AND RECOMMENDATIONS

6 CONCLUSIONS AND RECOMMENDATIONS

This analysis was aiming to provide a quick answer on what was an efficient way of replacing the diesel generators in the Malawian power system. It was supposed to answer on:

- When is the most optimally to retire existing diesel units?
- What those units will be replaced with?

These answers are of utmost importance to alleviate a decision making for the operational planning activities. Although the focus was supposed to be on a quick cost-benefit analyses, the wider context had to be taken into consideration, which includes the current IRP findings and a longer horizon (up to 2032).

Previous chapter considered several study cases and for each of them PLEXOS long term simulation resulted in optimal expansion for the period 10 years ahead. Given that any construction is complex and requires years to be completed, those practical constraints were also taken into consideration.

The leading time for the new projects is the key issue for immediate action – although hydro candidates may represent the most competitive candidate, the precedence was given to solar in combination with BESS (in both generic case and the pipeline case) as it represents the fastest option and at the same time the most optimal.

Although contribution of the diesel generation is not significant, the fuel costs are obviously high and tend to increase due to demand increase on one side and fuel price increase on another. In addition to this, build costs of renewable sources are continuously decline and become competitive more and more.

Techno-economic assessment, done by PLEXOS, see a gradual reduction of diesel generation, replaced with renewable sources, and stepwise machine retirements. Indicative timeline for diesel retirement shows the following: Aggreko IPP – By the end of 2022, Remaining diesel gen – 3 units in 2024, and one unit later (at latest in 2028)-however if CCGT (50MW) is found to be a competitive candidate, all the remaining diesel units retire in 2024

Both considered scenarios, pipeline project based and generic PLEXOS based, are composed of solar PV, wind, and BESS candidates

All considered cases see the solar PV+BESS as an option for immediate action – installed capacity depends on the projected demand level

As far as BESS are concerned, their main role should be for energy shifting. 4 hours BESS autonomy was considered the most practical option for the typical daily dispatch routine (based on experience from other projects worldwide). Typical daily dispatch would show that BESS are almost fully charged in peak demand periods. This indicates that BESS are able to contribute to capacity reserve.

4hour BESS are recommended as they can provide the sufficient firm capacity – which will together with hydro units ensure sufficient reserve margin

Overall system flexibility will be impacted by the higher penetration of intermittent renewable sources. For the time being and in the very near future as well, the flexibility will be attained by two essential sources:

- Existing hydro generation though constrained with cascading interdependencies
- BESS which figures as confirmed projects, such as Golomoti (5MW/10MWh) and Energy Storage Africa (60MW/240MWh)

Most commonly, BESS facilities come together with PV or Wind power plants to help manage the system in stiff regimes (when the generation overpass the demand). However, stiff regimes may happen in the system with a significant hydro contribution in periods with dramatic hydrological changes (rainy seasons, melting snow). These regimes require storage, seasonal for a longer-term, but also battery storage for short-term variations.

Therefore, the question of whether the BESS should operate as a standalone facility or complementary with PV solar facility, cannot be followed by a unique reply.

BESS are chosen by PLEXOS to help manage curtailed energy coming out of PV solar generation and shift that energy in periods without sun. It is not necessary to complement PV solar plant with the BESS as long as the system flexibility is sufficient as a result of other sources (hydro). This further means that BESS can be also used as stand-alone facilities. This is, in particular, important if BESS are foreseen to provide other services, such as voltage (and reactive) support –this will be considered in Workstream 2

If the expansion pathway sees just PV (or wind) as an option, then any new solar PV should be complemented with an appropriate BESS (size would depend on current power system conditions and is not a unique % of PV size). On the other side, if the expansion pathway sees also flexible hydro sources, then the PV power plant need not necessarily be complemented with additional BESS

Analyses in this workstream were done taking into consideration normal hydrology conditions, based on the historical record from the past several years. Having reviewed the longer historical horizon, significant variations were noticed, in particular variations of Liwonde inflows. Given that the Malawian power system is predominantly hydro based, it would be reasonable to analyze some exceptional circumstances which refer to the hydrology changes.

For the longer time horizon, additional cases should be considered to include different hydrology pathways, and possibly new technologies (for seasonal storage). We further recommend keeping updating IRP on regular basis (every three years), in order to better capture the demand projections as the key driver

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