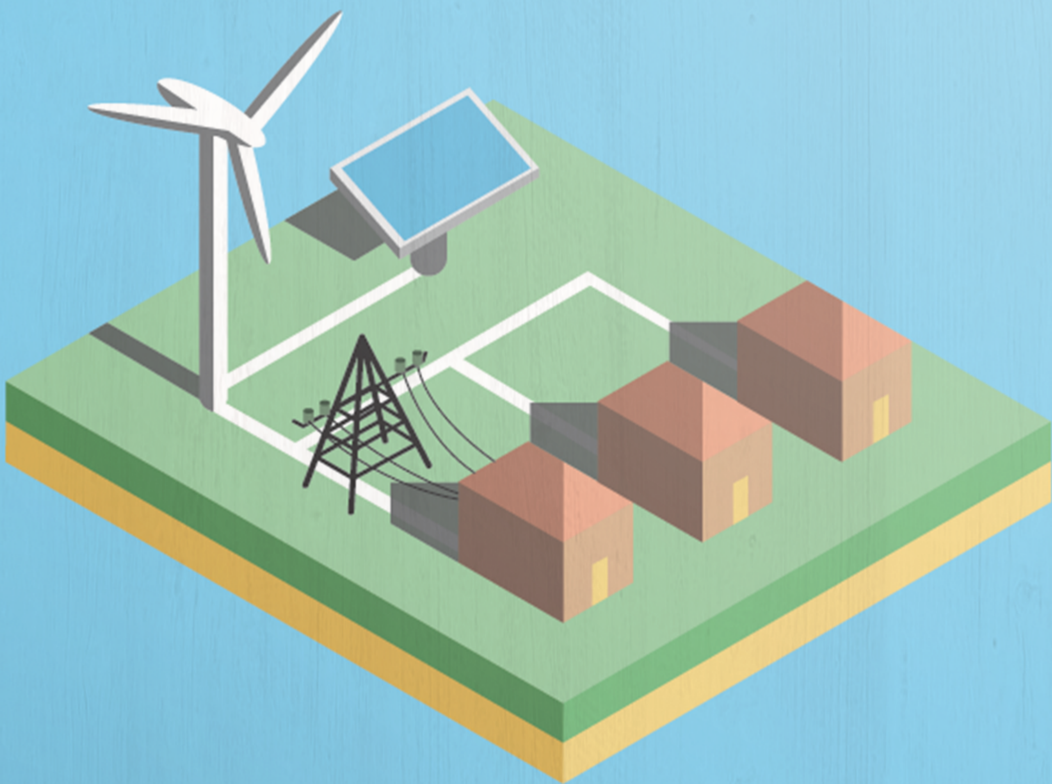
# INTEGRATION OF VARIABLE RENEWABLE ENERGY SOURCES

## *in the National Electric System of Zambia*



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# EXECUTIVE SUMMARY

Zambia is endowed with outstanding and diversified renewable energy sources, namely hydro, wind and solar. For many decades, the development of the electricity sector was based on the exploitation of hydro resources that made the electric power system dependent on water and particularly exposed to the climate change. The variable renewable energy sources (VRES), namely wind and solar, can be efficiently exploited in the power sector to improve energy diversification and strengthen both short- and long-term power system resilience, to cope with current and future water challenges related to climate change. However, the deployment of VRES generation shall be accurately designed to ensure sufficient security and reliability margins. The current study was focused on the integration of variable renewables into the Zambian electrical grid considering development scenarios until 2030. It provided the optimal VRES capacity, as a proper combination of wind and PV capacity, that can be installed in Zambia considering both technical and economic constraints (i.e. balancing resources, reserve requirements, generation fleet flexibility, security of supply, grid loadability and economic competitiveness of VRES technologies in the regional power pool). Both the electrical self-sufficiency of Zambia and the power trading opportunity on the competitive regional market have been analysed. In this framework, the generation fleet flexibility and the role of interconnections have been studied because they play a role of utmost importance to maximize VRES integration in Zambia, following the load pattern and dealing with the intermittency of VRES generation when a high penetration level is achieved.

The analyses clearly highlight that additional capacity from VRES can be integrated, on top of the projects already in the Country's pipeline. The operational flexibility ensured by the hydroelectric power plants allows 27% VRES penetration both in 2025 and 2030, even without power trading on the competitive market. An installed capacity up to 1,176 MW from PV and 1,200 MW from wind can be integrated by 2025; these capacities can be increased up to 1,376 MW from PV and 1,400 MW from wind by 2030. These optimal VRES capacities, in addition to the existing and committed programmable generation fleet (2,413 MW hydro and 370 MW fossil fuels power), are not enough to ensure the electrical self-sufficiency of Zambia, therefore, additional non-VRES flexible capacity (e.g. hydropower) shall be integrated to achieve this target (about 600 MW with 30% capacity factor by 2030). The exploitation of the network interconnections ensures high standards of security of supply also increasing VRES penetration up to 36%, both in 2025 and 2030. Economic benefits from power export are envisaged increasing the installed capacity up to 1,826 MW from PV and 1,900 MW from wind by 2030 (1,576 MW from PV and 1,600 MW from wind are the limits by 2025). The exploitation of network interconnections and the cooperation of the national electricity companies will play a key role in VRES exploitation and the optimal use of energy sources in southern Africa, improving system resilience in case of extreme climate conditions.

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## Introduction

Historically, the Government of the Republic of Zambia (GRZ) has focused on water exploitation in the electricity sector. Hydropower is the most important energy source for the Country and accounts for about 85% of total National installed capacity in the year 2019. However, the energy crisis of 2015/2016 pushed the GRZ to undertake a diversification process of the energy mix in the electricity sector. With the Vision 2030 and the Seventh National Development Plan 2017-2021, the GRZ aims to create a diversified and resilient electricity sector to sustain the National growth. In this regard, in 2017, the GRZ through the Ministry of Energy (MOE) launched the initiative "REFiT Strategy" to accelerate private investments in small and medium sized renewable energy projects to open the power sector ever more. So, the renewal process of the energy mix in the electricity sector is ongoing with the aim to achieve a utility-scale development of non-hydro renewable sources able to supplement the large hydro energy sources, which have been negatively affected by the climate change, and to increase the security of supply.

Zambia owns a high intensity of sunshine and a very good wind potential, besides being one of the most water-rich countries in Africa.

Concerning hydro resources, hydropower potential exceeds 6,000 MW, of which only 2,400 MW is exploited. The hydro potential exploitation is expected to achieve 3,150 MW by the end of 2020 when the Kafue Gorge Lower power plant will be completed. The hydro potential in Zambia results from six river basins with huge catchment areas that, however, are dealing with the effect of the climate change. The two major rivers in the Country, such as the Zambezi River (the fourth largest river system in Africa) and the Kafue River own most of the potential. 96% (2,300 MW) of the existing hydropower plants are along these rivers. Current small hydropower (≤20 MW installed capacity) stand at about 44 MW (0.7% of National hydro potential).

Thanks to its latitude near the equator, very high solar resources are present in Zambia. The average value of GHI (Global Horizontal Irradiation) exceeds 2,000 kWh/m2/year; GHI reaches 2,150 kWh/m2/ year in favourable regions. The sites with the highest solar irradiation are in the south-western areas of the Country while the irradiation decreases towards the northern and eastern areas (Fig. 1).

About the wind resources, Zambia was historically considered a low potential Country; only few wind measurements at 10 m AGL (Above Ground Level) were available until 2015. However, in 2015, The MOE and the World Bank launched a renewable energy wind mapping for Zambia in the framework of the Energy Sector Management Assistance Program (ESMAP). Meteorological data is collected at 80 m AGL at eight sites over a 2-year period and long-term estimations were processed to provide a high- resolution mesoscale wind atlas. Long-term wind estimations show an average wind speed at 130 m AGL between 7 and 8 m/s that joined with the fast improvements in turbine design and manufacturing (higher hub heights and larger swept areas than older technologies) highlight a very good wind potential in the Country. The locations with the highest wind speed are the eastern areas of the Country, but these are remote from the grid and correspond to areas with a low population density. Nevertheless, there are also locations with very good potential close to the grid, with higher population density in the area around Lusaka (Fig. 2).

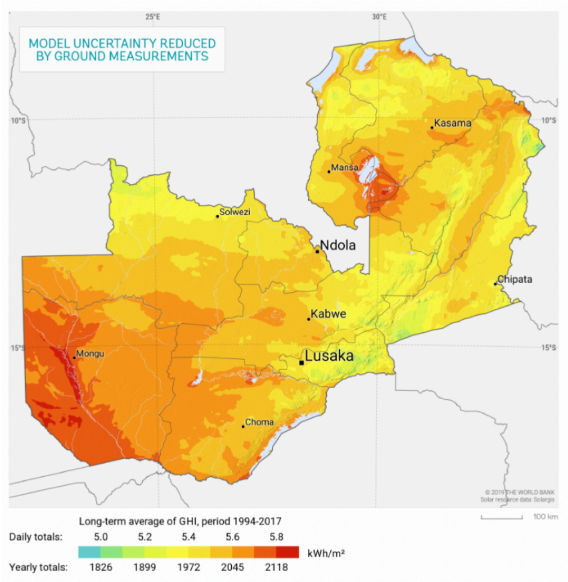



**Fig. 1. Global Horizontal Irradiation in Zambia (© 2019 The World Bank, Solar resource data: Solargis)**

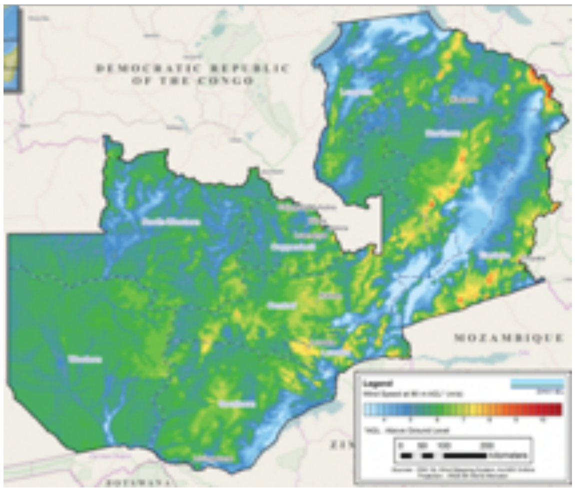



**Fig. 2. Mean wind speed at 80 m height above ground level m/s (source: The World Bank – ESMAP)**

This outstanding renewable energy potential can be efficiently exploited in the power sector to boost generation so to cope with the demand growth (CAGR 2019-2030 equal to 3.8%) and the lack of hydropower due to low rainfall, improving the security of supply both in short and long term.

Whilst hydro power is largely exploited in Zambia, photovoltaic (PV) power plants were only recently introduced, while wind power plants are still not developed. A wide deployment of variable renewable energy sources (VRES) requires proper integration strategies; it shall be accurately designed to ensure sufficient security margins and reliability levels. The exploitation of the generation fleet flexibility and the interconnections with the neighbouring countries becomes of utmost importance to follow the load pattern and for dealing with the variability of wind and PV generation.

The aim of this study is to estimate the optimal amount of VRES that can be integrated into the Zambian electric power system in the mid- and long-term (years 2025 and 2030), identifying possible criticalities and suggesting remedial measures concerning both the operation of the generation system and the network.

## The Zambian Power System

Zambia's total electricity generation in 2018 was equal to 15.9 TWh/year, out of which 92% for domestic demand and network losses, 8% for export. The peak power demand, excluding export, was about 2.2 GW.

Annex 1 depicts the generation capacity mix in 2019. The generation heavily relies on hydropower with 2,413 MW equal to 84.4% of total generation capacity. Additional 833 MW are expected within 2023, 750 MW of which are expected by the end of 2020 when Kafue Gorge Lower hydro project will be completed. Coal is the second electricity source with 265 MW maximum power equal to 9.3% of total generation capacity; 3.7% is from Heavy Fuel Oil power plants (105 MW) while only 2.6% of total generation capacity is from PV power plants (76 MW).

Concerning the interconnections with the neighbouring countries, the Zambian electric power system is currently interconnected with DRC, Malawi, Namibia and Zimbabwe for a total of about 1,250 MW and 1,000 MW net transfer capacity under import and export conditions respectively. Zambia is an active member of the Southern African Power Pool; i.e. the cooperation of the national electricity companies in southern Africa with the scope to optimize the use of available energy sources in the region and enhance energy exchange between countries facilitating the development of a competitive electricity market in the Southern African Development Community (SADC).

## Scenario

The study covers the period until 2030, with special focus on two target years: a mid-term year, 2025, and a long-term year, 2030.

A reference scenario named "Enhanced VRES deployment with normal water availability (ENH-NWA)" has been defined considering the following main assumptions:

- reference demand growth pattern and increasing firm export agreements with the neighbouring countries;
- average hydropower availability according to the historical data;
- programmable generation fleet (such as hydropower and fossil fuels plants) including only the existing and committed power plants. No candidates from non-VRES technologies were considered;
- high integration of wind and PV generation including the feasible additional capacity that does not affect the reliability, integrity and efficiency of the electric power system.

Two operating conditions were analysed for the reference scenario:

1. Isolated Country (ISO), analysing the possibility to guarantee the electrical self-sufficiency of Zambia increasing only VRES capacity and neglecting candidates from other energy sources (e.g. hydropower candidates). The optimal VRES capacity mix to meet the domestic demand and the firm export has been assessed neglecting power trading with the interconnected countries on the competitive market;
2. Interconnected Country (INT), analysing the opportunity to increase VRES integration exploiting the export capacity to the neighbouring countries and the power trading on the competitive market.

The Zambian generation system is closely dependent from hydropower and a very high exploitation of water for electricity sector will continue in the future. In this context, both long-lasting climatic changes and singular extreme natural events, which are becoming more frequent in the last decades, are expected to affect the security of supply. Starting from the reference scenario, additional analyses/ sensitivities have been performed to investigate the impact of the climate change on the operation of the electric power system and the VRES integration level. Two extreme weather conditions were simulated: firstly, low rainfall periods with a prolonged drought have been assumed simulating -33% hydropower availability compared to normal conditions, then also a wet year has been analysed assuming +44% hydropower availability compared to normal conditions.

Additional analyses at the target year 2022 have been performed by the Consultant at the end of the study with the aim to highlight a development plan for VRES in worst-case scenario for system development in the short term. Delays in transmission projects have been simulated to assess the VRES penetration comply with the current transmission network and generation facilities.

**Demand Forecast**

The demand forecast is based on ZESCO and CEC predictions. The total demand (domestic demand, firm export and transmission and commercial losses) expected by 2025 is about 24.4 TWh/year (CAGR +5.0% in 2019-2025) with a peak power demand of 3.5 GW. In 2030, the demand achieves 27.6 TWh/ year (CAGR +2.5% in 2025-2030) with a peak load equal to 3.9 GW (Fig. 3).

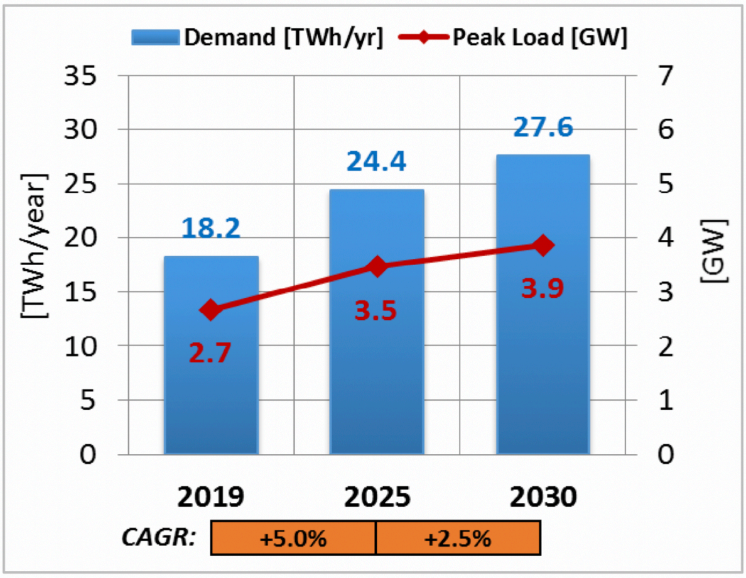



**Fig. 3. Demand Forecast of Zambia for 2025 and 2030, including losses and firm export**

Firm export was considered as part of the electricity demand because it is the result of firm contracts to supply electricity to some neighbouring countries or obligations such as the supply of electricity to towns on the border with Zambia. 200 MW firm export was considered with DRC, 100 MW with Namibia and 70 MW with Malawi (90% annual load factor), both in 2025 and 2030.

**Generation Mix**

The important demand growth and the shortage of hydropower due to the climate change shall be sustained by a diversified and robust power generation growth roadmap. For these reasons, an expansion plan of VRES generation was studied to meet the security of supply by providing, if any, information on the need for additional non-VRES generation to ensure the electrical self-sufficiency of Zambia.

The baseline generation mix includes only the existing and committed programmable generation fleet (such as hydropower and fossil fuels plants) and the existing VRES capacity (the PV power plants recently

put in service). Starting from this generation fleet, additional VRES power plants (projects in pipeline or VRES candidates) were included in the system finding the optimal VRES integration from technical and economic point of view. The study is not a least cost generation expansion plan by comparing the costs of VRES and non-VRES technologies (e.g. hydropower candidates). Therefore, no candidates from non-VRES technologies (e.g. hydropower candidates) were considered.

Annex 1 shows the programmable capacity considered in reference scenario 2025 and 2030, and the VRES estimated capacities.

3,146 MW hydropower capacity was assumed both in 2025 and 2030: 2,190 MW from hydro power plants with reservoir and 956 MW from run-of-river power plants (including the largest under-construction project in the Country, i.e. Kafue Gorge Lower for 750 MW, and the extension of smaller hydro power plants such as Lusiwasi and Chishimba Falls). While only 370 MW were assumed from conventional fossil fuel generation, i.e. the existing coal and heavy fuel oil power plants.

Referring to the above-mentioned generation scenario, the annual production expected from programmable power plants in the average year is about 18.3 TWh/year both in 2025 and 2030; 15.6 TWh/year are estimated from hydro power plants and 2.7 TWh/year are available from fossil fuel power plants. VRES generation has been integrated to achieve the supply-demand balance until the techno- economic viability requirements are met.

**Levelized Cost of Electricity from VRES Technologies**

An assessment of the levelized cost of electricity (LCOE) from wind and photovoltaic technologies has been performed proving an indication of their competitiveness. Capacity factors of wind and PV power plants have been considered together with the investment costs, operating costs and lifetime[1] of these technologies to provide a qualitative assessment of LCOE that was considered in the cost- benefit analysis (Fig. 4). A big reduction of LCOE from PV power plants has been assumed in the short term as effect of the Round 1 of GET FiT program in which 120 MW PV capacity was committed with a weighted average LCOE equal to 4.41 US$c/kWh (the lowest bid was 3.99 US$c/kWh).

[1] Lifetime has been assumed equal to the duration of PPAs that will be signed with the IPPs (Independent Power Producers); hence, 20 years instead of 25 years which is the typical lifetime of wind and PV power plants.

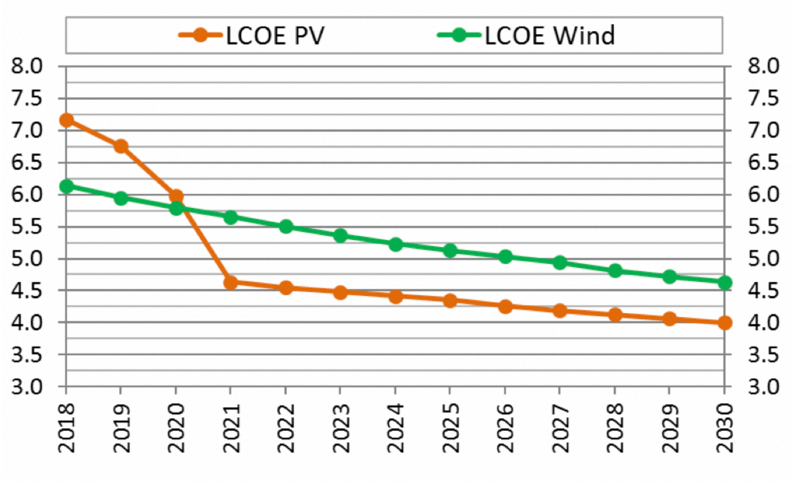



**Fig. 4. Forecast of the weighted average levelized cost of electricity from VRES technologies (US$c/kWh)**

## Interconnections

Zambia is involved in important interconnection projects in the framework of SAPP to improve the security of supply and the use of sources in Southern Africa regions (ZIZABONA project, Zambia- Mozambique project, Kolwezi-Solwezi project and Zambia-Malawi projects) and the power pools integration (Zambia-Tanzania-Kenya project to integrate the Southern African Power Pool and the Eastern Africa Power Pool). Additional 5,800 MW exchange capacity is expected in the long term. Fig. 5 shows the interconnection projects and the maximum net transfer capacities considered in the study. Interconnection projects follow the important development plan of the Zambian transmission network in which several internal reinforcements were planned by ZESCO to improve the adequacy and the system security.

The analyses have been carried out adopting a complete generation and transmission network model of the Zambian electric power system (330-220-132-88-66 kV); while an equivalent model of the neighbouring countries based on Zambian net transfer capacity and SAPP marginal clearing prices has been defined to simulate the power trading on the competitive market in the interconnected scenario.

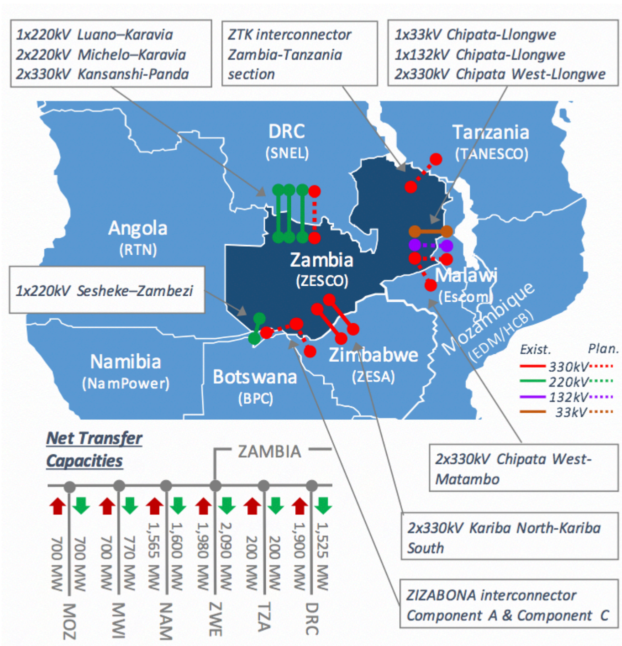



**Fig. 5 (right). Net Transfer Capacity expected between Zambia and the neighbouring countries in 2025 and 2030**

Several questions arise on whether the generation-transmission system of Zambia is suitable for integrating large amounts of VRES. The key questions to be addressed are:

- Is the VRES generation alone able to meet the demand for electricity maintaining high standards of security of supply?
- Are the Zambian hydro power plants sufficiently flexible to cope with the variability of wind and PV productions?
- Is the transmission network suitable to integrate additional VRES capacity?
- What is the role of the interconnections?
- Is there a cost opportunity in VRES investments to increase export towards the neighbouring countries where the electricity generation cost is higher?

Hence, an integrated approach has been developed for the in-depth analysis of technical and economic constraints that could have an impact on the enhanced deployment of wind and PV sources in the Zambian interconnected system.

## Methodology

The approach adopted to evaluate the optimal wind and PV capacities that can be installed in Zambia in 2025 and 2030 includes different phases in which, progressively, technical and economic constraints are integrated and analysed. Fig. 6 summarizes the integrated multi-phase approach applied. Starting from the data collection exercise and the setup of the reference scenarios (Task 1), a screening of the operating reserve constraints has been performed (Task 2), then the energy balance and economic constraints have been investigated (Task 3), closing with the analysis of grid constraints (Task 4).

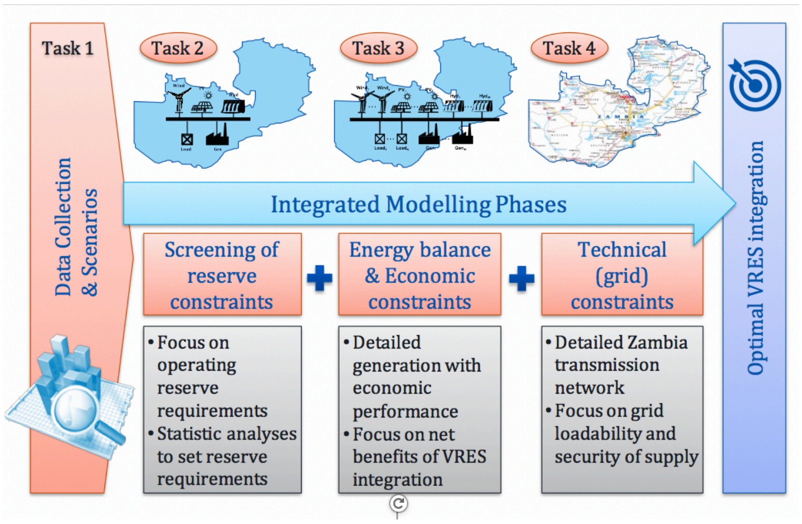



**Fig. 6. Scheme of the integrated multi-phase approach**

Task 2 allowed the assessment of the operating reserve requirements in presence of VRES generation. A hybrid approach combining probabilistic and deterministic methods has been developed for the dynamic sizing of the operating reserve. The main achievement of Task 2 was used to set-up the best market and reliability models to be used in the following tasks.

In Task 3, the simulation of the system operation on an hourly basis, with the optimal coordinated hydro- thermal dispatching performed to minimize the system costs, allowed to select the cost-effective VRES capacity mix that could be integrated in Zambia. A detailed model of the generation fleet allowed in-depth analyses of system operation considering both supply-demand and economic constraints. Finally, in Task 4, a grid impact study of the VRES capacity selected in Task 3 has been performed, examining the system adequacy and the grid loadability, to define the optimal amount from both a technical and economic point of view of wind and PV capacity that can be integrated in 2025 and 2030 in the Zambian electric power system, maintaining high standards of security of supply and improving the system resilience.

The analyses were performed through the application of state-of-the-art computational tools, developed by CESI, simulating the market mechanisms with a deterministic algorithm[2] and the system reliability with a probabilistic algorithm[3].

## Wind and PV Integration Outlook

The study clearly shown that additional capacity from VRES can be integrated in the Zambian electric power system, on top of the projects already in the Country's pipeline (Annex 2). The following wind and PV capacities can be installed in Zambia in the mid- and long-term without the exploitation of the interconnections (scenario with isolated Country):

- up to 1,176 MW from PV and 1,200 MW from wind in 2025;
- up to 1,376 MW from PV and 1,400 MW from wind in 2030.

+34% VRES installed capacity can be integrated both in the mid- and long-term scenarios exploiting the interconnections and the power trading in the competitive market (scenario with interconnected Country):

- up to 1,576 MW from PV and 1,600 MW from wind in 2025;
- up to 1,826 MW from PV and 1,900 MW from wind in 2030.

The above-mentioned capacity mixes allow to maximise the VRES penetration, resulting in an increase of the security of supply, and the economic benefits for the system. Due to the intrinsic features of the primary source, unlike wind, PV power production is concentrated in a limited number of hours and therefore it can benefit more of the hydropower flexibility. Consequently, PV technology is more affected by the lack of hydropower if low rainfall periods occurs. Therefore, despite PV technology is cheaper than wind technology, a balanced integration of both technologies is recommended since this diversification improves the system resilience.

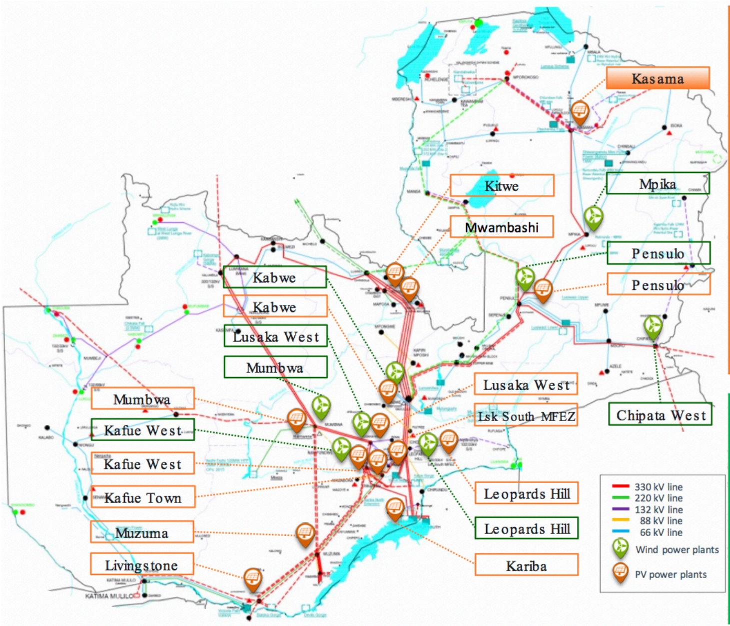
Annex 1 shows the generation capacity mix that could be achieved in Zambia in 2025 and 2030: VRES installed capacity attains 47% of the total generation fleet in 2025 and it grows up to 51% in 2030 interconnected scenario. The hydropower renewable capacity is estimated to decrease from 84% recorded in 2019 up to 48% in 2025 and 44% in 2030. Only 5% is the remaining non-renewable capacity assumed in the mid and long term.

[2] PromedGrid software for market modelling. See www.cesi.it
[3] GRARE software (Grid Reliability and Adequacy Risk Evaluator). See www.cesi.it/grare

A high share of VRES penetration (i.e. the share of energy demand that can be supplied by VRES power plants) and a well-balanced energy mix can be achieved both in the mid- and in the long-term scenarios reducing the dependency from hydropower and increasing the security of supply.

Without power trading on the competitive market, about 27% VRES penetration can be achieved both in 2025 and 2030; 10% from PV and 17% from wind power plants. Hydropower production (15.6 TWh/ year both in 2025 and in 2030) supplies 64% of the demand in 2025 and 56% in 2030. Up to 2.8 TWh/ year PV and 4.8 TWh/year wind productions are expected within the year 2030. The exploitation of the power trading on the competitive market can increases the VRES penetration up to 36% both in 2025 and 2030 (13% from PV and 23% from wind power plants). In 2030, PV and wind productions achieve 3.7 TWh/year and 6.5 TWh/year respectively. VRES production curtailments are negligible and not very frequent (0.25% of potential production is the maximum value recorded in a mid-term scenario).

The wind and PV power plants already in pipeline were assumed to be connected to the grid in the substations listed in Annex 2. The additional capacity was distributed in the system considering the locations with higher wind/solar potential and strength of the National grid. Fig. 7 shows the location of VRES projects and the wind and PV capacities that can be integrated at each substation in isolated (ISO) and interconnected (INT) scenarios. Such capacities comply with the Zambian reliability standards (network loadability) and they allow the maximum VRES energy integration at the target years, minimizing production curtailments due to network overloads or over-generation phenomena. The figures recommended for specific substations should be subjected to further detailed studies with the aim of with the aim of identifying any static, dynamic and power quality issue and providing countermeasures needed for the full integration of the recommended VRES capacities, completing in this way the integration analyses.




Max PV capacity [MW]

| S/S | 25-ISO | 25-INT | 30-ISO | 30-INT |
|---|---|---|---|---|
| Kabwe | 140 | 140 | 190 | 140 |
| Kafue Town | 40 | 40 | 40 | 40 |
| Kafue West | 100 | 150 | 100 | 150 |
| Kariba | 90 | 90 | 90 | 90 |
| Kasama | - | - | - | 50 |
| Kitwe | - | 100 | 100 | 100 |
| LeopardsHill | 150 | 200 | 150 | 250 |
| Livingstone | 50 | 100 | 50 | 150 |
| Lusaka West | - | 100 | 50 | 150 |
| Lsk South MFEZ | 76 | 76 | 76 | 76 |
| Mumbwa | 170 | 220 | 170 | 220 |
| Muzuma | 220 | 220 | 220 | 270 |
| Mwambashi | 40 | 40 | 40 | 40 |
| Pensulo | 100 | 100 | 100 | 100 |
| TOTAL | 1,176 | 1,576 | 1,376 | 1,826 |

Max wind capacity [MW]

| S/S | 25-ISO | 25-INT | 30-ISO | 30-INT |
|---|---|---|---|---|
| Kabwe | 150 | 200 | 200 | 200 |
| Kafue West | 100 | 200 | 100 | 250 |
| LeopardsHill | 250 | 300 | 250 | 300 |
| Lusaka West | 150 | 200 | 150 | 250 |
| Mpika | 100 | 100 | 250 | 250 |
| Mumbwa | 170 | 220 | 170 | 220 |
| Pensulo | 280 | 280 | 280 | 330 |
| Chipata West | - | 100 | - | 100 |
| TOTAL | 1,200 | 1,600 | 1,400 | 1,900 |

**Fig. 7. Wind and PV capacities that can be installed at each substation in the mid- and long-term**

**Security of Supply**

The quantitative evaluation of static reliability of the electric power system (adequacy) proved that a progressive deployment of VRES generation will not worsen the security of supply both in 2025 and 2030. Wind and PV installed capacities calculated in the isolated scenario improve the security of supply, but they are not enough to meet the Zambian reliability standards without power import from the neighbouring countries. Hence, since additional VRES capacity is not cost effective, additional non- VRES flexible capacity shall be integrated to achieve the electrical self-sufficiency of Zambia: 100 MW power plants with 48% capacity factor by 2025 and 570 MW power plants with 30% capacity factor by 2030.

No risk of energy not supplied resulted from the interconnected scenarios, since the suitable exchange capacity between Zambia and the neighbouring countries help to balance the variability of wind and PV productions meeting the demand.

## The Role of Hydropower

The great amount of hydroelectric generation, largely coupled with high capacity reservoir, owns a suitable operational flexibility that plays a key role in the development of wind and PV power production in Zambia. Climate change forces hydropower sector to cope with shorter rainy seasons and longer dry seasons. With the current generation mix, hydroelectric reservoirs must store huge volumes of water in short periods (the months earlier in the year) to make it available in the second half of the year (dry season) to meet the annual demand. A great seasonal stress of the reservoirs and the risk of lack of power at the end of the year arise, especially if consecutive dry years occur, as experienced in recent years. The integration of VRES, which peaking during the dry season when water availability is minimal, would reduce the reservoir's stress thanks to the good complementarity of hydro sources. On the contrary, VRES integration leads more stress in the daily operation of the hydro power plants with reservoir to cope with steeper ramps and deeper turn downs to meet the net load (load net of VRES production). Hydropower management must change from a demand-dependent approach to a VRES- dependent approach.

As highlighted in the average day 2030 (Fig. 8), without power trading on the competitive market (left side), a hydropower displacement from the daytime hours to the night hours is expected to make room to the wind and PV production. The integration of the Countries in the competitive market (right side in Fig. 8) allows a better integration of VRES and makes convenient the power import during the night, when the price of electricity in SAPP is low, and the power export during the daytime hours when the price in SAPP is higher than the price in Zambia. Import helps to meet the demand avoiding unserved energy, while export can allow the full exploitation of VRES avoiding production curtailments, mainly during the daytime hours. In this context, hydro power plants can operate to maximise VRES integration and the economic benefits of energy trade, exploiting the market price.

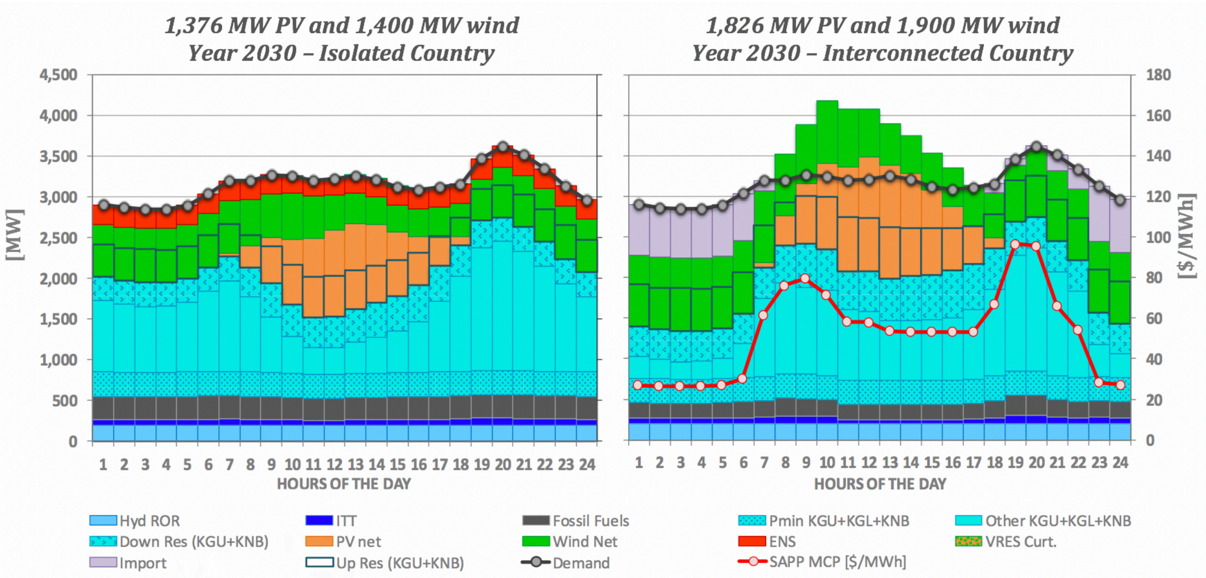



**Fig. 8. 24-h power balance in the average day 2030. Isolated scenario, including firm export, is compared with the interconnected scenario including power trading**

The Zambian generation system is closely dependent from hydropower and a very high exploitation of water for electricity sector will continue in the future. An energy diversification strategy in the electricity sector including technologies with low water use needs, such as wind and photovoltaic, could offer an important technical solution for Zambia that could strengthen both short- and long-term resilience of the power system and may face current and future water challenges related to climate change. VRES power plants are less impacted by climate change and they can face the lack of hydropower during drought periods. Additional VRES generation can be integrated under low rainfall scenario reaching about 40% VRES penetration in 2030. The lack of hydropower (-4.7 TWh/year in the dry year) can only be partially replaced by VRES generation; in fact, power import or additional programmable capacity is needed to meet the security of supply. On the contrary, under the wettest conditions (+6.8 TWh/year from hydropower), dispatch challenges with the neighbouring countries arise to avoid VRES production curtailments (up to 69% in 2025 and 37% in 2030) due to over-generation phenomena. The coordination with the neighbouring countries and the exploitation of the exchange capacity will be crucial to maximise the cost-effective use of resources both in Zambia and in SAPP.

## The Role of the Interconnections and the Transmission Grid

The interconnections among countries will play an important role in large-scale integration of VRES throughout southern Africa. The integration of the markets and an effective cooperation among the countries will lead to the maximization of VRES penetration and the best use of energy sources at regional level, not only on a national basis. Interconnections improve the flexibility of the systems to cope with the variability and uncertainty of VRES production, maintaining the security of supply and avoiding over-generation phenomena.

The exploitation of the interconnections and the energy trade on the competitive market would increase VRES penetration in Zambia (+9%). The additional VRES capacity joined with the flexibility of its hydro power plants would allow Zambia to take market opportunities in SAPP. As shown in Fig. 8 (right side) on a daily basis, Zambia could import more power at low price overnight to increase exports during the daytime when the price in SAPP is higher. Benefits result also on a yearly basis, as highlighted in Fig. 9. Zambia is a net exporter between March and September due to SAPP marginal prices greater than those in Zambia; while it is a net importer at the beginning and at the end of the year, mainly due to the lack of hydropower. Up to 2.9 TWh/year import and 2.8 TWh/year export are expected in 2030 on the competitive market (2.0 TWh/year import and 3.5 TWh/year export in 2025), i.e. energy trade net of firm export. Firm export leads to additional 2.9 TWh/year.

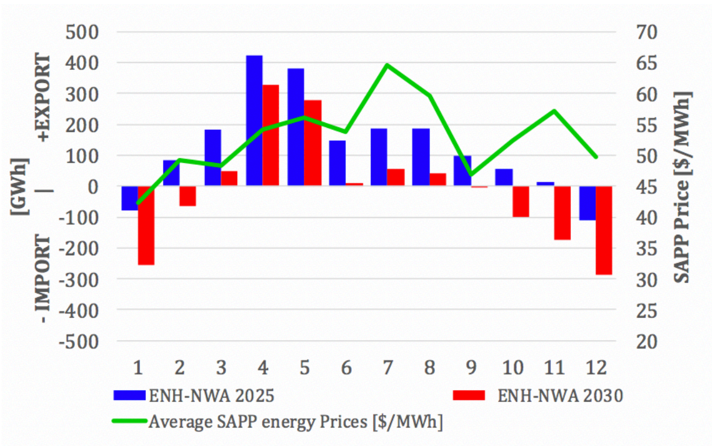



**Fig. 9. Monthly import-export energy trading on the competitive market**

Interconnections allow the exploitation of the renewable energy during both the wet years and the dry years to cope with the over-generation phenomena or lack of power. In the long-term scenario, +44% hydropower (+6.8 TWh/year) due to wet conditions leads to -80% import and +138% export; while -33% hydropower (-4.7 TWh/year) due to low rainfalls leads to +76% import and -64% export.

The system reliability impact study shown that the transmission network expansion plan outlined by ZESCO will allow the development of big amount of VRES generation both in the mid- and in the long-term. A few network reinforcements have been advised to avoid load shedding actions due to the demand growth, while no critical network overloads resulted from VRES power plants integration.

## Worst-case scenario in the short term

The role of transmission grid is crucial for the development of great amount of utility-scale PV and wind projects. The high number of request for connections of VRES projects at the beginning of a renewable energy development programme and the relatively short time to market of these projects often clash with the times for realization and the uncertainties of transmission projects. In this context, the integration of great amount of VRES could be very challenging in the short-term. For these reasons the maximum wind and PV installed capacity that could be installed by 2022 with the current transmission grid (i.e. the worst-case scenario for the system development) have been assessed, providing a set of feasible solutions[4].

The current electric power system in Zambia will be able to integrate all PV projects in pipeline by 2022 (660 MW) reaching 736 MW installed capacity from PV power plants, even without energy exchanges with the interconnected countries on the competitive market (Isolated Country). Furthermore, 130 MW wind installed capacity could be integrated without relevant over-generation problems or network overloads (scenario "Current Roadmap"). Alternatively, without wind projects in 2022, up to 956 MW from PV can be integrated in the isolated scenario, while up to 1,006 MW in the interconnected scenario (scenario "100% PV"). The maximum PV installed capacity shall be reduced if additional wind projects want to be integrated into the system by 2022. Up to 496 MW from PV and 260 MW from wind could be integrated in the isolated scenario, while up to 596 MW from PV and 260 MW from wind could be integrated in the interconnected scenario (scenario "Balanced VRES mix").

The VRES development plan 2020-2030 resulting from the study is shown in Annex 3.

## Conclusions and Recommendations

Thanks to the excellent solar and wind potential in the country, the reduction of VRES investment costs, the flexibility of the hydro generation fleet and the on-going interconnection projects, wind and PV technologies can play a key role to reduce the dependence on water of the Zambian electricity sector. An energy diversification strategy based on the exploitation of wind and solar potential supported by additional programable generation and/or the exchange capacity from the interconnection projects can strengthen both short- and long-term resilience of the power system and may face current and future water challenges related to climate change. The analyses clearly highlight that additional capacity from VRES generation can be integrated on top of the projects already in the Country's pipeline. 27% VRES penetration can be achieved without power trading on the competitive market, both in 2025 and 2030.

This optimal VRES integration results from 1,176 MW PV and 1,200 MW wind capacities in 2025 and from 1,376 MW PV and 1,400 MW wind capacities in 2030. However, additional non-VRES flexible capacity (e.g. hydropower) shall be integrated to achieve the electrical self-sufficiency of Zambia (about 600 MW maximum power with 30% capacity factor by 2030, in addition to the existing and committed non-VRES projects).

The existing and committed network interconnections with the neighbouring countries improve the flexibility of the system to cope with the variability and uncertainty of VRES production. Therefore, they can help Zambia to increase VRES exploitation maintaining high standards of security of supply and improving the system resilience in case of extreme

[4] The Lusaka Transmission and Distribution System Rehabilitation Project also had to be included in the model to meet the demand expected in 2022 (19.6 TWh/year, including domestic demand, T&C losses and firm export to DRC and Malawi). This is the minimum system reinforcement required by the target year to allow the security of supply in the Lusaka area and the better network performance.

climate conditions. VRES penetration levels up to 36% can be reached exploiting the power trading on the competitive market, both in 2025 and 2030. Up to 1,576MW from PV and 1,600 MW from wind capacity can be installed in 2025, while up to 1,826 MW PV and 1,900 MW wind capacities in 2030.

In the short term (2022) all PV projects included in the current roadmap could be integrated even if delays will occur in the transmission development plan. Up to 1,006 MW PV capacity could be achieved without any wind project, while it shall be reduced up to 596 MW if 260 MW wind capacity will be developed by 2022.

The achievements of the current study provided a preliminary estimation of the optimal wind and PV capacity that could be technically and economically integrated in the Zambian electric power system. Further static, dynamic and power quality analyses outside the scope of the current study are required and a specific feasibility study for each wind and PV project that will be integrated in the system is recommended.

Moreover, innovative strategies for the control and operation of VRES power plants are recommended to maximise VRES exploitation and maintain a secure operation of the electric power system. These strategies can counterbalance critical situations due to VRES intermittency, reducing the risk of production curtailments due to over-generation phenomena (i.e. when the generation available in the system is higher than the demand). Two actions should be considered during the VRES integration process to reduce the risks concerning the power system operation in presence of a big amount of VRES power plants:

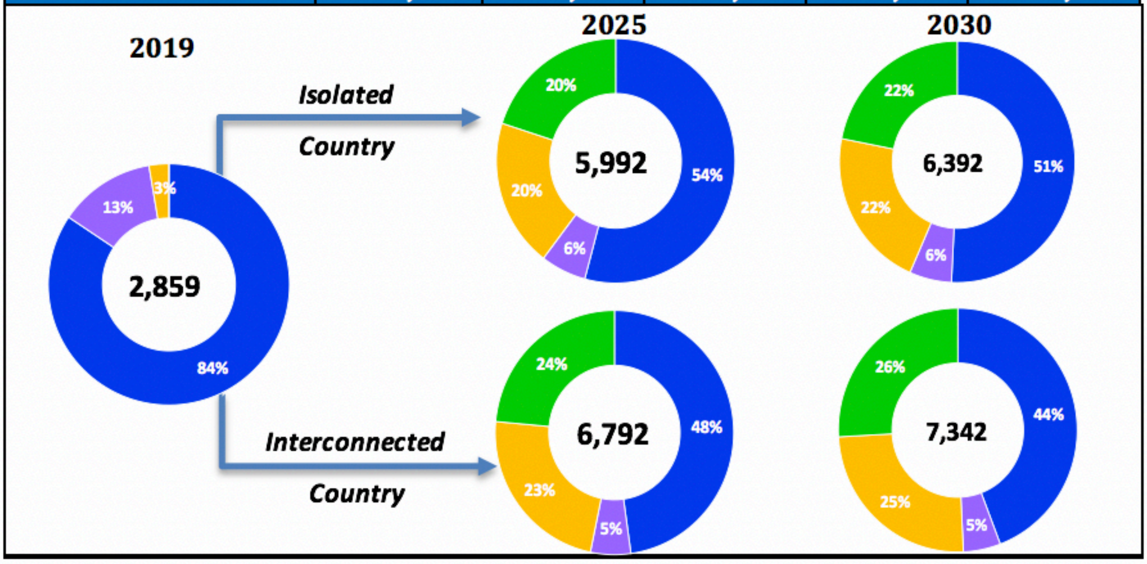
- A central control room for VRES power plants, with clusters of different plants, would allow a better forecast of generation lowering forecast errors and minimizing reserve need. A greater penetration of VRES generation is possible if the uncertainty of its prediction is reduced.
- Participation of VRES to ancillary services markets, for instance availability to decrease their production (downward reserve) to ensure the stability of the power system. In this way, VRES downward reserve can replace the hydro one.

These actions are usually addressed during the short-term and real-time operation of the power systems. Experiences in advanced markets with high VRES penetration show significant rooms for reducing VRES energy curtailments when appropriate real time control systems are put in place.

# Annex 1

Capacity mix in 2019 and estimated at years 2025 and 2030 in isolated (ISO) and interconnected (INT) scenarios with enhanced VRES deployment (MW)

| Source | | 2019 | 2025 ISO | 2030 ISO | 2025 INT | 2030 INT |
|---|---|---|---|---|---|---|
| | Hydropower | 2,413 | 3,246 | 3,246 | 3,246 | 3,246 |
| | Fossil | 370 | 370 | 370 | 370 | 370 |
| | PV | 76 | 1,176 | 1,376 | 1,576 | 1,826 |
| | Wind | - | 1,200 | 1,400 | 1,600 | 1,900 |
| Total | | 2,859 | 5,992 | 6,392 | 6,792 | 7,342 |




# Annex 2

PV and wind projects in the pipeline

| PV Project | Status | Pmax [MW] | Substation |
|---|---|---|---|
| Bangweulu | existing | 47.5 | LS-MFEZ |
| Ngonye | existing | 28.2 | LS-MFEZ |
| Bulemu West | committed | 20 | Kabwe |
| Bulemu East | committed | 20 | Kabwe |
| Solar one | committed | 20 | Kafue Town |
| Solar Two | committed | 20 | Kafue Town |
| Garneton North | committed | 20 | Mwambashi |
| Garneton South | committed | 20 | Mwambashi |
| Kanona | committed | 100 | Safal |
| Muzuma | committed | 100 | Muzuma |
| Green Field | committed | 50 | Leopards Hills |
| Globeleq project | candidate | 100 | Leopards Hills |
| MGC project | candidate | 100 | Mumbwa-Nambal |
| Hive project | candidate | 90 | Kariba North Bank |
| TOTAL | | 735.7 | |

| Wind Project | Status | Pmax [MW] | Substation |
|---|---|---|---|
| Serenje | candidate | 130 | Pensulo |
| TOTAL | | 130 | |

# Annex 3

VRES development plan 2020-2030

Different short-term paths to achieve the optimal VRES capacity mixes in 2025 and 2030 have been highlighted to provide a set of feasible solutions; within the range of solutions found in the short term, greater PV integration implies a lower wind integration and vice versa.