Eliminating energy poverty in Africa by integrating top-down and bottom-up electrification concepts, i.e. cross-border backbone networks & solar-hybrids

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***Abstract*—Driven by the negative consequences of human-caused climate change, the fundamental transformation of the power infrastructure from mainly fossil-based to renewables is an obvious need. Unsubsidized wind and solar PV have become the cheapest source of electricity generation in nearly all major economies and advanced electronics allow for highly efficient and flexible power delivery. To provide power to the 645 million people in Africa that presently do not have access, game-changing technology can be applied on large scale. As innovative concepts such as battery-backed solar-hybrids have become mature and reached market competitiveness, the comprehensive electrification of the continent will follow different principles than the ones previously applied. Instead of centralized large power stations, small and decentralized generating units are becoming increasingly important. Forecasts say that 60% of future electrification will take place through mini-grids and small stand-alone systems. Considering that modern mini-grids are already designed to interconnect on the transmission grid level, the coordinated steering of the two development trajectories – solar-hybrids and cross-border networks – raises a unique chance to eliminate energy poverty and to provide "energy for all" in Africa.**

***Index Terms*—Battery energy storage, energy poverty, HVDC, long-distance transmission, mini-grids, solar-hybrids**

I. Introduction

Electricity networks are subject to fundamental change and need to provide, over the long-term, the flexibility to integrate massive amounts of volatile distributed feed-in. On the power generation side, solar PV now plays a central role because of very low auction prices of 5 to 3 c€/kWh allowing the highest expansion rates of this technology in the world [1]-[4]. Mid-scale wind and solar generation can be compensated locally by battery-backed smart distribution networks and extensive supply and demand variations can be balanced by regional high-voltage transmission systems [5].

The overall growth in investment in grid infrastructure is correlated to the global electricity consumption that raised by 4% in 2018, according to the International Energy Agency (IEA) and increased grid performance due to fluctuating renewable power generation. Where Germany had around 1,000 power plants in 1990, today there are now more than 1.8 million individual producers on the network [6]-[8]. Considering the fundamental changes in the energy landscape in Germany (nuclear phase-out until 2022 and a current rate of renewable generation at 50%), there is no technical or economic barrier to transitioning the entire world to 100% clean and renewable energy. A basis for this will be a flexible and robust power network at acceptable cost.

The disruptive character of the global energy transition becomes present when considering the repeated appearance of the multiplication factor one thousand:

- a conventional power station had a design output in the order of 1 GW – today's wind turbines and solar power systems are often in the lower MW-range;
- the associated capital investment costs were in the billion Euro range – today, individual plants in the single-digit million range are possible; and
- the number of generation facilities has multiplied a thousand times in countries with a high share of renewable energy sources.

In terms of grid topology, the further electrification of Africa will follow different principles to those applied for example in Europe between 1950 and 2000. Instead of centralized large power stations, smaller and decentralized generating units are becoming increasingly important.

The paper is structured along an inductive reasoning approach starting after the introduction in Section II with an overarching description of the energy situation in Africa. In Section III, the characterises of cross-border backbone networks are outlined and the currently implemented 1,068 km interconnector project between Ethiopia and Kenya is described. Section IV follows with an outlook on the status quo and perspectives of solar-hybrids being completed with reference to an actual project in Nigeria being financed by the World Bank Group. To make full use of the elaborated fundamentals, Section V concentrates on leveraging synergies from the described top-down and bottom-up concepts. After providing the conclusion in Section VI, the paper closes with Section VII by summarising key recommendations.

II. The Energy Situation in Africa

The African continent is currently home to around 1.3 billion people. According to the latest figures from the African Development Bank (AfDB), around 645 million of these people have no access to electricity [9]. Annual electricity consumption in sub-Sahara Africa is currently about 180 kWh per capita. In Europe the figure is 6,500 kWh, making it 35 times higher. Cumulative installed power plant output in Africa comes to a sum of 168 GW – compared to over 200 GW in Germany alone.

On the basis of forecast population growth figures, the AfDB has set a target cumulative capacity figure of 330 GW for Africa by 2025. This means that transmission and distribution grid capacities need to be increased accordingly to improve cross-border electricity trading as a cost-effective way of balancing excess capacity in one region with demand peaks in another. Following this intention, three power pools were established in Sub-Saharan Africa: The West African Power Pool (WAPP), the Southern African Power Pool (SAPP) and the East Africa Power Pool (EAPP). Apart from technical challenges to be overcome, power pooling requires strong political agreements between the member states.

The International Energy Agency stresses that hybrid micro-grids – i.e. small stand-alone grids, e.g. with battery- or diesel-backed wind and solar electricity generation – will play a crucial role in the electrification of areas with no previous supply. Forecasts say that 60% of future electrification needed to reach the goal of energy for all by 2030 will take place through mini-grids and other small stand-alone systems [10].

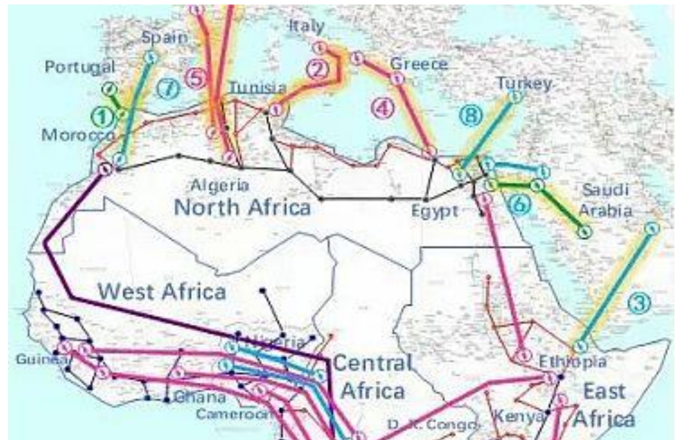
III. Cross-Border Backbone Networks

A. *Status Quo and Strategic Outlook*

Most of the existing power networks are fundamentally designed as a system of top-down radial transmission and distribution lines predicated on uni-directional energy flow from large centralized power plants to consumers [11]. Due to the increasing dynamics and complexities in operating modern electricity supply infrastructures, this grid architecture is becoming obsolete. In renewables-based power grids, the energy flow direction will be increasingly bi-directional. Depending on the extent of the wind and solar power development, this will also have an impact on the transmission grid level.

High-voltage direct current (HVDC) transmission is the solution for bulk energy transfer over large distances. With distances of over 700 km, overhead transmission lines using HVDC technology are more economical than in three-phase AC systems. For the same corridor width, an HVDC link can transmit 30 to 40% more power than an AC route. Furthermore, a DC link can also restrict the spread of disruptions between the connected three-phase AC grids and therefore prevent power outages. Apart from HVDC, in transmission network technology, a focus is put on flexible AC transmission systems and in distribution networks on Volt/VAR optimisation.

As loss-reduced long-distance power transmission across national borders is of key importance, it is worth looking at China which is the world's leading country when it comes to the construction and operation of ultra-high-voltage DC transmission lines. The most powerful system today (Changji-Guquan) operates with a voltage of ±1,100 kV and transmits 12 GW of power over a distance of 3,293 km [12], [13].



S/N	Project
1	Morocco-Portugal ±500 kV DC Project
2	Tunisia-Italy ±800 kV DC Project
3	Ethiopia-Saudi Arabia ±660 kV DC Project
4	Egypt-Greece-Italy ±800 kV Three Terminals DC Project
5	Algeria-France ±800 kV DC Project
6	Saudi Arabia-Egypt ±660 kV DC Project
7	Morocco-Spain ±660 kV DC Project
8	Egypt-Turkey ±660 kV DC Project
9	Algeria-France-Germany ±800 kV DC Project

Figure 1. A 2050-vision for Africa: 9 DC-channels of 54 GW capacity [14]

The largest utility company in the world, State Grid Corporation of China, is pursuing a bold vision with the development of a global power grid. Based on a multi-staged long-term clean energy strategy, the idea is to implement cross-border transmission lines, being subsequently extended by intra- and inter-continental links. In Fig. 1, the 2050-vision for Africa elaborated by GEIDCO (Global Energy Interconnection Development and Cooperation Organization) is shown.

A recent study by IEC has confirmed the principal technical feasibility of such supergrid structures using existing or soon to be market-ready ultra-high-voltage technology and latest IT concepts [15]. The main risks lie in political and regulatory circumstances. The time horizon is 2050 to 2070.

B. *Project Reference: ±500 kV HVDC link Ethiopia-Kenya*

Ethiopia currently has an installed hydropower output of approx. 3,800 MW, with the estimated potential for expansion of up to 45 GW [16]. The Grand Ethiopian Renaissance Dam is a hydropower project which is currently at the construction stage and will deliver 6,000 MW to make it the most powerful plant in Africa [17]. To make the electricity from Ethiopian hydropower plants usable for the entire region of East Africa, work is currently in progress on the completion of a US$1.26bn HVDC link between Ethiopia and Kenya. With a controllable transmission capacity of up to 2,000 MW, this will enable the alternating current grids in the two countries, which to date have been operated independently of each other, to be stabilized and the overall electricity generation costs to be reduced.

The Ethiopia-Kenya HVDC interconnector is in-line with the objectives of the East African Power Pool and is shown in Fig. 2 as a dotted line. In addition to the large-scale exchange of energy between the two countries, the objective is to raise the quality of the power supply in the region. Changes to the legal and regulatory framework were undertaken leading to a reduction in the cost of electricity and creating an attractive environment for investors with a view to promote further economic and social development.

In addition to logistical issues due to infrastructure which is often underdeveloped, the phased integration of such bulk energy power transfer systems in the national grids is a major challenge. The maximum transmission capacity of 2,000 MW exceeds the maximum consumption level ever recorded in Kenya of approx. 1,800 MW [18]. In the first few years, the transmission capacity of the HVDC system will be restricted via digital controller until further need of feed-in capacity.

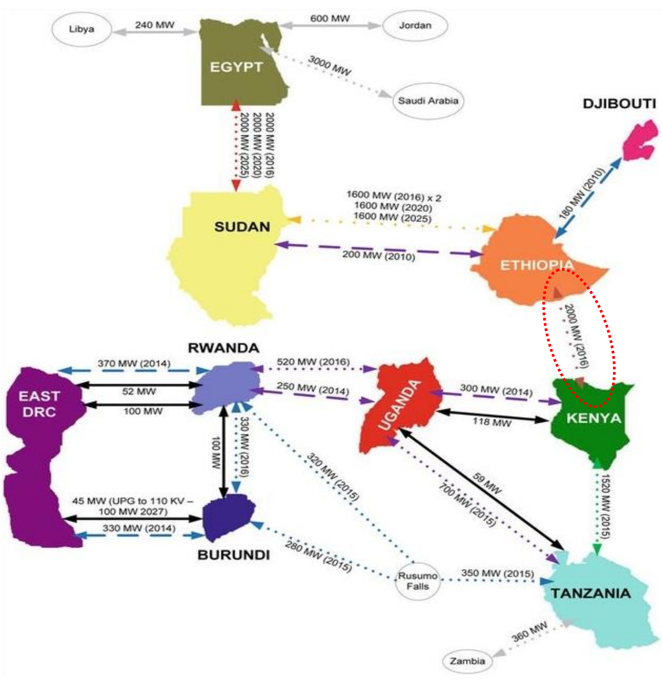


Figure 2. East African Power Pool with HVDC link Ethiopia-Kenya [18]

Tractebel Engineering (formerly Lahmeyer International) was commissioned for owner engineering’s consultancy and construction supervision by the state-owned power utilities Ethiopian Electric Power and Kenya Electricity Transmission Company. Consortium partners are the Italian consultancies CESI and ELC. Apart from supplying the core components for the HVDC systems (converter valves with light-triggered thyristors, transformers, smoothing reactors, protection and control systems, AC- and DC-filters), Siemens is responsible for the construction, installation and equipping of the buildings for the converter stations and the associated AC substations. The project is financed by the World Bank, the African Development Bank, the Agence Française de Développement and the States of Kenya and Ethiopia.

IV. Solar-Hybrids

A. *Status Quo and Strategic Outlook*

People living in rural and remote areas distant from the main electric grid, often confront unstable and unreliable electricity supply [19]. Due to regular power outages they rely on polluting diesel generators to supply electricity for every day needs. For such locations, decentralized mini-grid systems represent a viable solution in providing reliable electricity. Renewables-based mini-grids include generation capacity from 10 kW to over 100 MW.

Globally, at least 19,000 mini-grids are installed in 134 countries and territories supplying 47 million people. 1,500 mini-grids, mostly hydro- and diesel-powered, are located in Africa. On the same continent, another 7,500+ mini-grids are planned to go online over the next couple of years. By this measure, about 27 million people will be connected for an investment cost of US$12bn [20].

In the course of the Energy Storage Partnership (ESP), the World Bank Group has committed US$1bn to accelerate investments in grid-scale battery energy storage in developing countries to enable the increased usage of solar PV and wind power generation. With the investment, grid stability and power quality will be increased, and carbon emissions reduced. The bank financing is expected to mobilize another US$4bn in concessional climate financing and public and private investments. The program aims to finance 17.5 GWh of battery storage by 2025 – more than triple the 4 to 5 GWh currently installed in all developing countries.

The different generations of mini-grids are defined as [21]:

- First-generation mini-grid systems were introduced in the late 19th and early 20th centuries as the initial stages of electrification. They either formed the nucleus of larger centralized systems or were absorbed by the main grid as it expanded.
- Second-generation mini-grids are widespread in many low-income countries today. Most of them are inefficient small and isolated diesel- or hydro-based systems, primarily in rural areas that have not yet been reached by the main grid. During operation important knowledge could be gained on technical design, economies of scale, financial viability and regulatory frameworks.
- Third-generation renewable mini-grids – mainly solar-hybrids – are typically designed from the beginning to interconnect with the main grid. They are mainly owned and operated by the private sector and can provide early economic growth so that significant load already exists by the time the main grid arrives.

Recent cost reductions in power technology have made mini-grids a realistic option for supplying off-grid rural areas and small islands [22].

B. Project Reference: Nigeria Electrification Project

The objective of this current World Bank programme is to provide an additional 100 MW capacity to over 40 universities and teaching hospitals as well as to increase access to electricity services for households, public institutions, and underserved micro, small and medium enterprises across the Federal Republic of Nigeria.

A key component of this initiative refers to solar-hybrid mini-grids for rural economic development to be implemented under a market-based and private-sector-led approach. This aims to construct, operate, and maintain the systems in economically viable fashion. Stand-alone solar systems shall provide access to electricity to more than one million Nigerian households at lower cost than currently used small diesel gensets.

Most of the project's funds will be used to establish an enabling environment for private sector involvement by providing financial incentives and technical support as well as strengthening of key institutions and the development of enabling policies and regulations.

V. Leveraging Synergies: Steering the Intermeshing of Antithetical Development Trajectories

In a co-publication of the Agence Française de Développement and the World Bank [20], it was highlighted that Africa is facing major challenges – such as urbanisation, technological change, regional integration and climate change – that need to be factored into electrification efforts.

When creating a substantiated vision on completing the electrification of African countries, the following megatrends and recent breakthroughs in power generation as well as in power transmission and distribution technology need to be considered as main drivers:

- Climate change (preference for renewables);
- Population growth (massive increase of demand);
- Ever cheaper solar PV generation (massive cost drop);
- Ultra-high-voltage power transmission (Chinese grid);
- Smart grid development (improved grid performance);
- Battery boom (US$1bn World Bank initiative ESP).

The natural basis for a future-proof power infrastructure is clean electricity production. As renewable resources are constrained both in time and space and the best wind and solar sites are often located far from demand centres, transmission system expansion is often unavoidable. Considering that the surface area of the African continent is bigger than the one of China, Europe and the US together, linking the winter and summer peak demand regions over different time zones is of interest. Nevertheless, extending the main grid to serve remote communities with low consumption is prohibitively costly in most cases. These facets cover the top-down characteristic of the outlined strategy. As a contrary approach, mini-grids are a viable solution for rural areas. Mini-grid can be classified under a bottom-up approach that enables individual income-generation and can be the basis for regional economic growth [23]. Furthermore, they allow for electric cooking which in many cases is cheaper and carries lower health risks than cooking by traditional wood- or charcoal-fired stoves. Furthermore, electric cooking presents a valuable opportunity for load factor increase and can boost revenues [24].

Condensing the above findings, two main development trajectories can be identified:

- Top-down: High voltage interconnection of national power systems enables effective regional balancing of electricity demands, helps to increase the reliably of renewable supply and reduces the cost of electricity.
- Bottom-up: Mini-grids are a viable option for areas that are too expensive for the main grid to reach but have high enough demand.

As for sustainably achieving the "energy for all" target, the application of a variety of technologies is required, leading to phased implementations with parallel and overlapping work streams. The final stage will be to stepwise integrate the mini-grids into the transcontinental high voltage transmission infrastructure.

VI. Conclusion

The significant technological advancements in recent years in renewable electricity generation and power grid technology form the basis for game-changing and cost-effective solutions to accelerate the completion of Africa's electrification efforts. To reach the United Nations Sustainable Development Goals (SDG), investment in long-term coordinated electrification planning is necessary. Apart from international cooperation on government level to pave the way for transcontinental power transmission, regulations need to be put in place to enable private sector investment on smaller scale in mini-grids.

From today's perspective, individual mini-grids will grow and finally be interconnected with each other on a local or regional basis. Subsequently, the respective load nodes will form the electrical link to the main grid. When the national grid is available at or near the site of a mini-grid, interconnecting them allows any excess power produced on the mini-grid system to be fed into the main grid. Scaling up mini-grids does not mean scaling back the main grid because mini-grids enhance the economic viability of expanding the main grid as significant demand for electricity already exists when the main grid arrives.

While third-generation mini-grids are not necessarily built to main grid standards, most future mini-grids are typically designed to interconnect with the main grid. As such they fit into integrated national electrification planning and align with country-level utility expansion priorities [24].

VII. Recommendation

The centrepiece of a successful electrification rollout is seen in the implementation of government-led national electrification strategies addressing in a systematic manner the institutional, technical and financial aspects of high voltage transmission systems and mini-grids [20]. Based on an empirical study on implementation experience in Africa, Tjäder, Ackeby and Bastholm [25] underline that the best results in increasing the electrification rate were achieved when governments provide clear regulation for grid extension and at the same time support mini-grid development. National electrification planning can leverage the efficient combination of main grid and mini-grid. As there is an increasing number of cases where mini-grids and centralized grids will interconnect, this area of technology receives increasing attention.

A crucial role in the integration of electricity networks on a transnational basis will be played by digital information and communications technology with real-time functionality. Due to the increasing complexity in system operation and data exchange on technical level as well as between market players, latest IT and communication technology is required.

World Bank reports that countries that pursue a comprehensive approach to electrification through main grid extension and mini-grids achieved the fastest gains [22]. This is of major importance as Africa is the only continent in the world where on average the population is growing faster than the rate of electrification. A further challenging development is that according to information from the UN, the total population will have doubled to about 2.5 billion by 2050.

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