Renewable energy sources integration for off-grid electrification using battery energy storage systems

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Diesel generators (DGs) are the most common option for electrification of rural communities. However, the commercial maturation of renewable energy-based technologies like photovoltaic (PV) systems and small wind generators (WGs), as well as the constant rise in fuel prices makes renewable energy (RE) a viable alternative to DGs for off-grid electrification. The variability of PV and WG production makes battery energy storage systems (BESS) of paramount importance for allowing an off-grid load to be supplied, completely or in part, by renewable energy sources (RES).

BESS can be an interesting solution both in developed countries and for rural electrification in developing countries. The average electrification rate in sub-Saharan Africa was about 21% in 2004. Rural electrification rates slowly increased from 3% (1970) to 8% (2004). This means that despite a significant energy potential of the African continent, especially from RES, there are still more than 200-million Africans living in rural areas without access to electricity.

Several off-grid solutions using RES and BESS have been proposed for rural electrification. However, off-grid projects often require much more technical assistance if compared to grid-connected solutions. Sodium-nickel chloride (Na-Ni) batteries offer several advantages under this regard:

- No ancillary equipment (e.g. air conditioning) is needed.
- Battery modules are designed to be maintenance free.
- Battery modules operate comfortably in temperatures between -40°C and +60°C.
- Long calendar and cycle life: 4500 cycles at 80% DOD.

This article focuses on two case studies dealing with off-grid electrification using PV and BESS in two different scenarios:

- Rural community electrification.
- A small island with existing diesel generators.

Assessment of the performances of the proposed solution, both from the technical and economical point of view, showed that PV and BESS can support diesel generators in rural electrification, decoupling the generation sources from the load and thus enhancing full and planned use of renewable energy sources.

Na-Ni cell chemistry and design

BESS can allow renewables integration and time/energy shifting. Furthermore, due to their high efficiency, reliability and long-term performance, those systems can also be used as an effective backup solution. BESS allow reduction of the redundancy and oversizing of production systems that is typically necessary in the presence of only diesel generation, to cover large variations in demand or in special cases, such as black start or emergencies.

Na-Ni technology can be an alternative solution to conventional batteries thanks to their long life, reduced maintenance and ancillary equipment (HVAC) needs, high energy density and constant performance regardless of temperature. The battery utilises common table salt as a raw material and the cells are assembled in the discharged state by mixing NaCl, Ni and Fe powders together with a minor amount of some additives that improve performances and cycle life.

The overall cell reaction is:

\[ 2NaCl + Ni \leftrightarrow 2Na + NICl_2 \]

\[ OCV = 2.58 \text{ V @ 270°C} \]

and

\[ 2NaCl + Fe \leftrightarrow 2Na + FeCl_2 \]

\[ OCV = 2.32 \text{ V @ 270°C} \]

During charge NaCl and metal (Ni or Fe) are transformed into metal-chlorides (NICl_2 or FeCl_2) and Sodium (Na). The discharge process involves the opposite reactions. Electrodes are separated by a ceramic wall that acts as a conductive medium for Na ions but as an insulation layer for electrons.

The cell reaction can only occur when the external current circuit is closed and the external current is equal to the internal sodium-ion flow. Absence of side reactions allows for a unitary coulombic efficiency. No gaseous elements are produced, so that the cell can be hermetically sealed without the need of any venting valve. The cathode is impregnated by a molten salt (NaAlCl_4) that enables the migration of ions from the reaction site (in the cathodic mass) to the ceramic electrolyte.

Battery module design

The ST523 is a 620 V 38 Ah high specific energy [100 Wh/kg or 120 Wh/l] complete battery system based on Na-Ni cells and designed for stationary applications. Series-connected cells are assembled to achieve the desired battery terminal voltage. Na-Ni battery cells are housed within a controlled temperature, stainless steel double-walled case. A high performance thermal insulation material is used to insulate the cell pack.

![Fig. 1: Operating profile of an existing hybrid system during a typical sunny day. Upper graph: Active power profile of generators, load and BESS versus time. Lower graph: ESS state of charge, versus time.](image-url)
The battery is equipped with internal electric heaters to achieve and maintain the internal working temperature required. The operating temperature range is 265 to 350°C, which allows high performances and durability regardless of the ambient temperature, without the need of cooling equipment, even in the harshest environments from -5°C to +65°C. This is of importance in sub-Saharan Africa, where HVAC equipment would result in high capital and maintenance costs and reduced reliability and efficiency.

Battery modules can be assembled in parallel, as represented in Fig. 2, to form large energy storage systems up to several MWh. Each battery module is provided with an electronic controller (battery management system) which allows a reliable and safe operation and performs control and diagnostic functions.

**Application case 1: Off-grid rural electrification**

Hybrid solar/wind/diesel energy systems with battery storage are some of the most interesting and environmentally friendly means of providing electricity in rural areas. Hybrid systems can provide a reliable community-level electricity service, such as village electrification, also offering the possibility of integration into an interconnected distribution network in the future.

Case 1 describes an installed hybrid solar/wind/diesel/battery system for off-grid load connection. The system is composed of:

- A wind generator (rated power 30 kW).
- Three PV generators (rated power 3 x 66.7 kW).
- Two diesel generators (rated power 410 kW).
- BESS with Na-Ni technology: 32 batteries ST5223, 200 kW for three hours.

AC-connected load consumption typically ranges from 40 to 75 kW (approximately corresponding to 150 rural households). The registered values of a typical daily profile are shown in Fig. 1.

As seen from Fig. 1 most of the energy is produced by PV panels, which output exceeds the local load during the sunniest hours of the day. The BESS system stores the excess solar energy and compensates PV power fluctuation. The stored energy is also used during the night. The diesel generators are only activated when the state of charge of the battery falls below the minimum set point. This also allows the diesel generators to run at a constant power (i.e. at optimal regime).

Another installed example of a smaller hybrid (PV/wind/diesel/BESS) off-grid electrification system consists of the following elements:

- Two PV generators: installed capacity 5 kWp.
- One wind generator of 10 kW capacity.
- Two BESS: batteries with a 2 x 30 kW/3 hours rating.
- One diesel generator, rated power 30 kW with a 1000 l tank.

Electrical loads vary between 2.5 kW and 5.5 kW at peak power at 400 V AC and 2 kW at 24 V DC. The bus connection to distribution line is in DC at 690 V. The converters are managed by a control apparatus with a dedicated communication protocol, powered by an auxiliary circuit at 24 V DC. Loads can be supplied in AC 50 Hz, at 230 V (single phase) or 400 V (three phase), by means of DC/AC converter and isolating transformers. The basic approach of the control mode is to use renewables (solar and wind) as primary energy sources and to use a BESS unit to integrate the production of renewable resources if not sufficient to fulfill the load or to absorb the surplus generated energy.

The diesel generator is only used to charge the storage system if the state of charge falls below a predetermined level (20% of its total capacity) or in special cases, such as black start, maintenance activities or emergencies. The control logic will balance energy flows according to the availability of renewables generation, storage systems and to the load request; therefore the algorithm input data are:

- The power absorbed by the load.
- The power produced by renewable unit (two PV systems, one wind turbine).
- The state of charge of the storage (SOC%).
- The availability of different units.

**PV modules**

The PV modules are installed on two different structures with different orientations and inclinations. The normal operating condition of photovoltaic systems is maximum power point tracking (MPPT). In case of excess energy, it will be possible to operate in request power point tracking (RPPT), reducing the power produced by photovoltaic systems to the desired value.

**Wind generator**

The wind generator control logic will ensure start-up of the wind generator above the cut-in speed, and the subsequent power increase up to the nominal power. If necessary, it will be possible to reduce the wind turbine output by performing electric braking, charging the batteries or in case of full charge by using braking resistors.

**Diesel generator**

In nominal conditions, the diesel generator will receive the start/stop order from the control logic and it will be completely decoupled from the load.

**Battery energy storage system**

Two groups of batteries are present in the system. The energy content of each group of batteries is 90 kWh and maximum available power is about 30 kW. The minimum working battery voltage is 480 V DC, and the maximum is 670 V DC. In normal operating conditions the discharge voltage will be between 530 and 590 V DC. The maximum discharge power for the single group of batteries is 10 kW. In case of a single battery malfunction, the remaining group can feed the load. During charge the current absorbed by a single group of batteries would be 40 A.

**Application Case 1 results**

Application Case 1 shows that BESS can be effectively used for integrating a substantial amount of renewable energy sources into small- and medium-scale off-grid systems, enabling their use in rural electrification. In both the above described examples, which
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Fig. 4: Load profile of Pantelleria Island, 20 MW PV scenario.

The load profile in Fig. 3 is evenly supplied by diesel generators (74 MWh, i.e. 57% of the load) and PV systems (64 MWh, i.e. 49% of the load). The losses in the BESS account for about 7.5 MWh (i.e. 6% of the load), with an 80% round trip BESS efficiency. The BESS system must be able to deliver 7 MW and its total daily discharge energy is 30 MWh. The resulting energy/power ratio is about 4 h, which is typical of Na-Ni batteries. The estimated cost of the selected 30 MWh BESS system is conservatively estimated at 1 k€/kWh.

Although the total daily energy production is increased from 130.5 MWh to 138 MWh, the total daily production cost is significantly reduced from 663.864 to 644.081 due to BESS losses. Most of this cost is still represented by fuel cost, while the BESS and PV system depreciation represent less than 25% of the total energy cost.

In order to minimise the use of existing diesel generators the installed PV power should be increased up to 20 MW, as shown in Fig. 4. In this case the load is almost only supplied by PV (128 MWh, i.e. 98% of the load) and diesel generators only account for 18 MWh, i.e. 14% of the load. The BESS losses account for about 16 MWh, with an 80% round trip BESS efficiency.

In this latter case the total energy generation is increased to from 130 to 146 MWh, but the total generation cost is reduced from €63.864 to €28.344. Most of this cost is due to the BESS depreciation, whereas PV systems, although generating most of the energy, only account for 20% of total expenses. The high BESS cost is caused by its large size (62 MWh – 1.4 MW). Significantly, also in this case the resulting 4 h energy/power ratio is suitable for Na-Ni. The case study focused on Pantelleria Island shows that the power generation by using diesel engines in isolated systems has a very high economic and environmental cost. The integration of renewable energy sources such as PV systems would allow for a reduction in diesel fuel consumption. BESS systems are necessary to increase the renewable sources capacity of this small islanded network and can be used for stabilising diesel operation.

Results show that by increasing both the PV and BESS capacity, the total daily generating cost is reduced, even if BESS losses increase the total energy demand. The required energy/power ratio for such BESS is around 4 h, which is the typical value of Na-Ni batteries, which represents a promising technology for the integration of renewable power sources in small islands.

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References

[4] Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas.

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Fig. 3: Load profile of Pantelleria Island, 10 MW PV scenario.

Fig. 4: Load profile of Pantelleria Island, 20 MW PV scenario.

refer to installed (PV/wind/diesel/BESS) systems, Na-Ni batteries have been used.

Application case 2: Integration of renewables

Application case 2 refers to the integration of renewable energy sources in existing medium-scale isolated systems, such as the Pantelleria Island, located about 100 km away from Sicily and not connected to the Italian transmission grid. At the present time the load in Pantelleria is fed by several diesel generators, with rated powers ranging from 950 to 4400 kW, with high operating costs.

Twenty-two PV power plants, with a total installed power of 141 kW, have been connected to the LV distribution networks, accounting only for about 0.6% of the total energy production (about 4.4 GWh [2]). A typical load profile is shown in Fig. 2.

The daily energy load is 130.5 MWh, i.e. about 1/365 of the yearly load. The load is supplied mainly by diesel generators and marginally by PV plants. The load variations are met by turning on and off some of the diesel generators, and varying their power output. The part load fuel consumption can be estimated as 0.25 ild/kWh [3], whereas the full load fuel consumption can be estimated as 0.27 ild/kWh.

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