1. Introduction
One of the main differences between developed and developing countries is the quality of electrical supply in rural areas. There are close to 1.2 billion people with no access to electricity. More than half are situated in Africa and about 40% in developing Asia [1]. When available, the quality of supply in rural areas is very low (voltage stability, reliability) [2], [3]. This is one of the causes for low economic activity and unemployment in rural areas and has led to the migration of rural population towards cities [4]. As the population migrates away from villages, the economic activity concentrates more and more in cities, giving less incentive for utilities to invest in rural distribution grids. In the context, if rural areas are provided with basic necessities, the economic growth of the developing country can be healthier and more balanced.

Local and distributed generation is expected to be well suited for powering rural areas. However, in many cases, renewable energy generation require government incentive to be economically viable. There are several ways to improve the economics of renewable energy projects. Besides the optimal location of the project, two complimentary strategies can be used: 1) optimising the design of power equipment by accepting a small percentage of the electricity curtailment, and 2) adding local storage. These combined methodologies lead to better utilisation of assets and a better integration of renewable energy project on the grid (See figure 1).
Figure 1. Optimisation of renewable energy integration

The optimal project design and grid integration solution depends on the renewable energy pattern, the cost of storage, the cost of power equipments, the feed-in tariff structure, and the grid reinforcement cost. The present methodology is valid in all situations but is especially beneficial when the grid extension is either costly or time consuming, which is the case in many developing countries where rural grids are often already used near their rated capacity and the grid reinforcement procedure slow.

2. Optimal renewable energy integration

2.1. Literature review

Existing methodologies focus on grid reinforcement and the optimal positioning of the new generation. In the scenario described in figure 2a, the wind turbine provides electricity to local loads, reducing the power flow and thus the losses in the main grid. Considering the base load at the end of the line, minor grid reinforcement (for 30 kW to 50 kW) towards the nearest transformer (or nearest greater capacity node) is sufficient to install a 65 kW wind turbine.
The low capacity grid and the long delays in grid reinforcement may be a limiting factor for the fast development of renewable energy projects in rural areas (famous cases are in Tamil Nadu, India). However, wind and solar farms produce at their nominal value a small portion of the time. Indeed, solar panels produce power above 90% of their nominal value less than 4 hours per day at best. A wind turbine with an average power curve (nominal power at 12.5 m/s and 75% of nominal power at 10 m/s) generates above 75% of its nominal output around 15% of the time only (see table 1). In consequence, a static grid limiting factor may be too restrictive in many configurations. When allowing a small percentage of electricity curtailment (~0.75%), a wind farm of 100 kW can be connected to a grid of 85 kW capacity. 0.75% corresponds to a maximum instantaneous loss of 15% due to 15kW in excess at nominal generation, which is happening less than 15% of the time (see test scenario Section IV for more precise calculations). Thus, increasing grid export capacity above 85 kW may not be financially profitable.

Table 1. Frequency of occurrence of wind generation above 75% of the nominal power

| Type of Wind distribution | Weibull K=2.08, Avrg. speed 7.4 m/s | Weibull K=1.74, Avrg. speed 7.7 m/s |
|---------------------------|-----------------------------------|-----------------------------------|
| Percentage of the time where wind generation is above 75% of the nominal power | 16.6% | 12.1% |

In addition to allowing electricity curtailment, local storage can be added to store the peak production and restore it during peak consumption. Storage can thus allow higher renewable energy generation to be connected to low capacity grids while at the same time reducing the nominal sizing of the main inverter. This type of utilisation of storage can be combined with other utilisations such as improving the grid stability or making profit from selling electricity during peak time, through multi-objective control algorithms.

A storage capacity of few hours at 20 kW can enable a wind turbine of 100kW to be connected to a grid of 50kW capacity as illustrated in figure 2b. In this configuration a small percentage of electricity may be curtailed (see Section IV for test case calculations). The storage size can be designed to ensure maximal cost efficiency; the saving in grid reinforcement, in inverter sizing and in energy sells are compared to the capital and maintenance cost of storage and the energy losses (see table 2). In addition storage can be used to improve the reliability of a microgrid in case of failure from the main grid. Most of storage can be made flexible and reused at other locations once the grid is reinforced [12].

Table 2. Benefits Vs cost of storage

| Benefits of storage | Cost of storage |
|---------------------|-----------------|
| Decreases the grid connection requirement | Decreases the required size for the inverter |
| Revenue from Peak time energy sells | Improved microgrid reliability |
| Improved capital and maintenance cost | Round trip efficient: Losses |

Solar parks and wind farm require an inverter to be connected to the grid, inverter may cost up to 20% of the total project cost. When reducing the required size of the grid connection with the method mentioned, the size of inverter can be decreased as well in the same proportions.
2.3. Calculations

The percentage of electricity curtailment for different cases of grid (and inverter) power limitations can be established based on the frequency distribution of the solar radiation (resp. wind speed), the power curve of the solar panel (resp. of the wind turbine) and the internal losses of the solar park (resp. wind farm). Two tests cases are presented in the following section, one with solar PV and one with wind turbines. In each case the frequency distribution of the renewable energy resource is taken for one location. The power curve of solar panel and wind turbine are then used to calculate the frequency distribution of the renewable electricity generation power. Two curves are drawn for each case, one for an ideal one, and one that considers different derating factors. The derating factors for solar PV are shown in Table 3 and for wind turbines in Table 4. The losses are integrated into the calculations using two types: 1) the losses of availability which impact the frequency of occurrence of any generation power by a uniform percentage, and 2) the other losses, which reduce the output power by the specified percentage.

| Table 3. Derating of solar installation | Table 4. Derating of Wind Turbine Output |
|----------------------------------------|-----------------------------------------|
| Derating factors | Losses | Cause of derating | Derating |
| Temperature derating | -0.5%/°C, above 25°C | Environment effect (dirt, insects) | 0.5% |
| Aging losses | 1% to 2%/yr | Wind turbulences | 1% |
| DC wiring losses | 2% | Components misalignments | 1% |
| Dusting losses | 5% | Drive train degradation | 1%/yr |
| MPPT errors | 1% | Internal Cabling | 1% |
| System availability | 2% | System availability | 3% |

A new frequency distribution of power output including the derating factors is then calculated. In this study, the calculations are performed for the first year only. From the frequency distribution of the generated power, it is possible to calculate the amount of electricity produced when the power output at the point of connection and the main inverter is limited (see equations (1) and (2)).

\[
E_p = \int_0^{P_M} p_i f_i
\]  

(1)

\[
E_{\text{limit}} = \int_0^{P_{\text{limit}}} p_i f_i + \int_{P_{\text{limit}}}^{P_M} P_{\text{limit}} f_i
\]  

(2)

Where \( E_p \) is the total electricity produced, \( P_M \) is the nominal power of the generation equipment, \( P_{\text{limit}} \) is the maximal power that can be exported through the grid (and the inverter) and \( f_i \) the frequency of occurrence of each \( P_i \).

The calculation for the amount of electricity curtailed is straight forward (see equation (3)).

\[
L_{\%} = \frac{E_p - E_{\text{limit}}}{E_p}
\]  

(3)

Where \( L_{\%} \) is the loss due to curtailment in percentage of electricity produced. The amount of electricity curtailment for different grid limitations and inverter power provides represent a valuable input for investors. They are thus able to conduct a financial analysis that compares the cost of grid reinforcement and of the inverter, with the decreased profit due to electricity curtailment. The following test cases demonstrate that significant gains can be achieved when following this approach.

3. Case study: Solar output frequency distribution

3.1. Solar PV in Tunis

The frequency distribution of the solar radiation of Tunis is taken for example [13]. Figure 3 illustrates the frequency distribution of the solar irradiance. The power output from a solar panel is almost
proportional to the solar radiation. Assuming that PV panel produce at their nominal power for sun radiations at 1000W/m² and that an MPPT ensures the optimal output throughout the day, the frequency distribution of an ideal solar PV output is represented in figure 4.

![Figure 3. Frequency distribution of solar radiation in Tunis](image)

A more realistic curve is also shown (see figure 4) when considering the derating factors mentioned in table 3. In sub tropical countries the temperature factor plays a significant role. In this study the cell temperature is taken to increase linearly from 25°C in absence of sun, up to 60°C when the sun reaches its peak at 1000 W/m².

![Figure 4. Frequency distribution of solar PV output above X% of its rated capacity](image)

For the first year, the results show that the output of the solar installation almost never reaches above 70% of the rated power capacity of the solar panels. It reaches above 62% for only 2.7% of the time. After a few years, with a yearly derating of 1 to 2%, the output will rarely reach 60%. Thus, in this test case, the grid connection agreement as well as the main inverter can be designed at a rated power between 60% and 70% of the rated power of the solar panels, even without any storage. It is to be noted that the load factor of this project is 0.125, which is within the norm. Considering that the cost of inverter and grid connection represent above 20% of the total cost the project; these results validate that such approach to solar design can lead to significant gain for the developers and thus for the final customer.

3.2. Wind turbine in Tiruchirapalli
The Wind distribution at 10m height of Tiruchirapalli, India is taken for this second test case. It is very close to a Weibull distribution k=1.83 with an average wind speed of 4.97 m/s [14]. The power curve of the 100 kW Nothern Power NPS100C-21 wind turbine is taken for this study (see figure 5). This wind turbine is installed at a standard hub height of 29 m. As wind speed increases non-linearly with height, the wind data are extrapolated. The wind distribution at 29 m height is calculated using the logarithmic rule with a roughness index of 0.01 corresponding to rough pasture (see figure 6). Figure 7
illustrates the frequency distribution of the power output above certain percentage of the rated power, in the ideal case and considering the derating factors as well.

![Figure 5. Power Curve of the 100 kW Nothern Power wind turbine](image1)

![Figure 6. Wind Speed Distribution at Tiruchirapalli at 29 m height](image2)

![Figure 7. Frequency distribution of the wind turbine output power above X% of its rated power](image3)

The results show that the output power reaches beyond 90% only 1.2% of the time. It reaches beyond 80%, 2.7% of the time, and beyond 70%, 4.7% of the time. There is less potential gain when compared to solar due to the smaller derating factors. The following section provides an analysis of this data to quantifying the possible reduction in grid connection and inverter sizing for both the configurations.

3.3. Results and analysis

In both test scenarios it appears clearly that dimensioning the main inverter and the grid connection agreement with the utility, at the rated power of the generation equipment (either solar panels or wind turbines) may not lead to the financial optimal design. Indeed, even the first year of the solar operation, the solar output at the point of connection with utility rarely reaches above 70% of their rated capacity. This is mainly due to the temperature derating in a hot climate. The output is between 60% and 70% only 5% of the time. It is between 50 and 60%, 10% of the time. For the wind turbine test scenario, the derating has much less impact on the output power. The wind distribution is the main parameter to consider. In the case of Tiruchirapalli, the wind generation reaches beyond 90%, only 0.9% of the time; it is between 80% and 90%, 1.3% of the time, and between 70% and 80% 2.7% of the time.

The percentage of electricity curtailed (relative to the electricity produced) is calculated in both scenarios for various rated power of the inverter and the grid in table 5. In the solar (resp. wind) test case, dimensioning the grid connection agreement and inverter for 60% (resp. 80%) of the rated power
of the panel (resp. wind turbine), will only lead to an average loss of 1.2% (resp. 1%) due to curtailment for the first year.

Table 5. Percentage of electricity curtailment for various grid and inverter power limitations

| Solar Tunis | P_{limit} 90% | P_{limit} 80% | P_{limit} 70% | P_{limit} 60% | P_{limit} 50% | P_{limit} 40% |
|-------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Wind Tiruchirapalli | 0.2% | 1% | 2.5% | 4.4% | 6.3% | 8.1% |

To go one step further, a local storage with a maximal charge current at 10% of the rated capacity of the panels can be installed to absorb the peak production and lower further the inverter sizing requirement and grid connection sizing at 50% in the case of solar (resp. 70% in the wind energy case). This storage will be used only 5% (resp. 2% for wind) of the time (the power output is between 50% and 60% of the rated capacity only 5% of the time for solar). Such solution is cost effective in case the storage is considered as a shared resource to achieve other objectives such as supporting the grid during peak time, or provide back up for the microgrid and improve the reliability. In this case a multi-objective algorithm can be designed. As the derating increases with years, storage may not be needed anymore for this optimisation, making it available to achieve other objectives or for being used at other locations.

4. Conclusion
The development of many developing countries has been focused on urban areas. However the current weaknesses of the power system can be worked around. This article has illustrated that wind and solar energy generation can be dimensioned beyond the limiting grid capacity with minimal amount of electricity curtailment. The concept of using the available storage to limit the peak production has also been presented to improve further the grid integration of wind and solar projects. In hot climate such as in India, the benefits of this approach are magnified in case of PV technology due to the important derating of the solar generation related to the negative temperature coefficient. A test scenario has shown that solar PV projects rarely produce at their rated capacity and thus do not require a grid connection at their rated capacity. When the maximum power is limited to 60% of the rated power of the solar panels, the losses represent only 1.2% of the generated electricity for the first year of operation. Considering a derating of at least 1%/yr (recent studies show an average degradation of 2%/yr in India), the required grid capacity agreement is thus close to 60% of the rated capacity of the solar panels. The test case with wind energy generation, shows that when the maximum power is limited to 90% of the rated power of the turbine, the curtailed electricity represents only 0.2% of the electricity produced. When storage is added and controlled by an intelligent algorithm, more solar or wind turbine can be installed for the same maximum output limitation. Both these methodologies render the solar and wind energy projects more appropriate and cost effective in rural areas. In the course of this study it appeared very clearly that such methodology can be applied to any solar or wind project in order to optimise the cost effectiveness of its design. Considering that grid connection can account for 10% of the project cost and that inverter can account for 20% of the project cost, there is much possibility for optimisation of the design using this method. This article also presented the concept of using storage as a shared resource to achieve multi-objectives. More research is necessary to assess the potential benefits such approach. Overall, this work provides a valuable input for researchers and renewable energy developers to optimize their design and the integration of renewable energy generation on the grid.

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