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A set of study cases for the massive integration of solar renewables in non-interconnected areas

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Abstract

The massive integration of solar renewable energies is challenging in non-interconnected areas such as remote islands or isolated regions. Indeed, their power grid, which cannot rely on the support of larger electricity networks, is more vulnerable to the inherent variability of the solar resource and grid failures, such as sudden breakdown of production units or transmission lines. The TwInSolar project, funded by the European Commission, aims to provide support and solutions to overcome the problems faced by island territories not connected to continental electricity grids. As a part of this project, four study cases are presented to the scientific community, each highlighting specific issues observed at different scales on the island of La Reunion. This article aims to provide a detailed description of the four selected systems, the corresponding challenges, and the data available.

Keywords: Solar energy, non-interconnected area, standalone microgrid, grid-connected microgrid, utility scale PV, insular power grid

1. Introduction

Non-interconnected areas encompass all the power grids that are non-connected to the continental grids, like remote rural communities, entire regions of developing countries or islands. The island of La Reunion, situated in the south-west part of the Indian Ocean, is a good example of a non-interconnected area. Decarbonization and energy self-sufficiency of the non-interconnected energy systems require the use of locally available renewable resources (Erdinc et al., 2015). In many cases, such as island territories in the tropical zone, the sun is the most abundant resource. Moreover, solar systems, like photovoltaic (PV) or domestic solar hot water (DSHW) are mature technologies that produce the cheapest energy in the world (IRENA, 2022). The massive integration of solar energy is, therefore one of the possible ways to achieve the objectives of decarbonization and energy autonomy of these regions.

However, the electricity networks of remote areas are more sensitive than continental grids, and new challenges arise from the massive integration of solar energy. Indeed, due to their small size (thereby impacting power system strength typically represented by system inertia and short circuit power) and limited capacity of power reserves, non-interconnected grids are more vulnerable to unexpected events such as generation ramps, forecast uncertainties commonly observed with variable renewables (i.e., solar and wind) or system failures (e.g., power plant breakdown). Moreover, these isolated grids cannot rely on a larger interconnected grid to balance their lack or excess of generation. On the other hand, solar renewables like PV systems are connected to the grid through power electronics that must comply with the appropriate standards. For instance, in La Reunion, PV inverters must comply with the DIN VDE 0126-1-1 (VDE, 2013), which defines frequency and voltage bands for normal operation. Out of these ranges, the inverter must automatically shut down the power generation. For an isolated electricity network, it is more challenging to maintain the frequency and the voltage within these ranges in case of severe failure. In such conditions, PV systems could likely stop their production and increase the risk of a grid blackout. Consequently, the massive integration of solar energy in these specific grids presents new challenges that are likely to be faced by continental grids in future.

The goal of this paper is to highlight the challenges currently experienced by non-interconnected areas, which already have a high share of solar production, through the description of four study cases selected within the framework of the European project TwInSolar (“Twinsolar,” 2023). The study cases, located in La Reunion and illustrated in Fig. 1, are representatives of issues observed at different scales. In addition, data related to each study-case are made available to the scientific community.

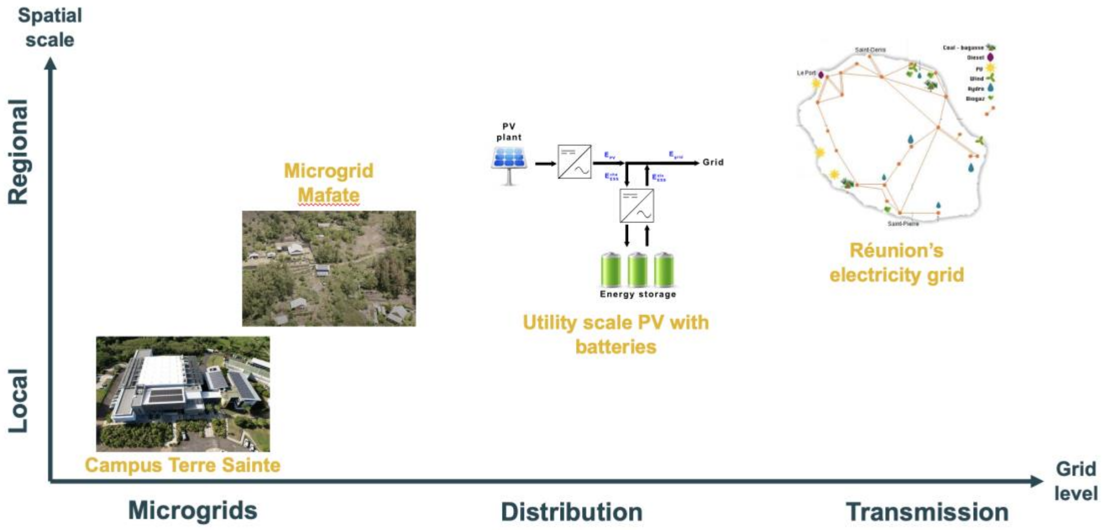

Fig. 1: Positioning of the four study cases selected to highlight the challenges that face non-interconnected island of La Reunion with the massive integration of solar energy.

2. A standalone microgrid

The first case study is a standalone microgrid located in the isolated Mafate cirque, in the heart of a UNESCO World Heritage national park. This micro-region of Reunion has neither roads nor power lines. The small villages in that area are only accessible on foot or by helicopter and must produce their energy locally. Since the 2000s, buildings in Mafate have been mainly powered by standalone PV systems with lead-acid batteries. The first installed photovoltaic systems have recently reached the end of their life. In this context, local authorities have decided to develop isolated microgrids to reduce their replacement costs, facilitate maintenance, and develop a new economic model. These new microgrids connect several houses to a single PV plant equipped with batteries. The proposed study case has three rural accommodations, a single PV plant of 7kWp, and lead-acid batteries with a capacity of 140kWh (Calogine et al., 2019; Francou et al., 2019).

Fig. 2: Aerial view of the remote microgrid located in the Circus of Mafate in La Reunion (Francou 2022)

The current design results from minimizing the risks of electricity shortages and does not consider the possibility of involving users in the operation of the microgrid. Consequently, the battery is strongly oversized, and the resulting Levelized Cost of Energy (LCOE) is exceptionally high. The main challenge is to achieve a cost-effective design and to engage the users in the management of the microgrid. Indeed, optimal sizing of the PV plant and the ESS (Energy Storage Systems) leads to a more reasonable investment cost (Francou et al., 2022). Moreover, efficient demand-side management could be achieved with a better involvement of the users. For this study case, a human interface fed by an Energy Management System (EMS) has been tested to improve the simultaneity between the PV generation and the load (Abbezzot et al., 2022).

The microgrid has been fully instrumented and monitored with a sample time step of 1 minute from 2019 to 2022, the duration of the project "Microréseau Mafate" granted by the European Regional Development Funds and the Région Réunion (Francou et al., 2019). First, a weather station installed on the PV plant shelter recorded the main weather parameters (i.e., global horizontal solar irradiance, temperature, humidity, wind, and rain). Second, a data acquisition system associated with the PV plant measured the PV production, the total power demand, and the battery state (current, voltage, and state of charge). Finally, five energy meters per house monitored the main types of loads (fridge, washing machine, lights, etc.). The anonymized data freely accessible will soon be released.

3. A grid-connected microgrid

The second system is the university Campus of Terre Sainte, which can be considered a grid-connected microgrid. The campus is located in Saint-Pierre, on the southern coastal part of the island. The climate is hot and humid during the wet season (Nov. to Apr.) and cooler with trade winds during the dry season (Apr. to Nov.). The annual solar potential of the site reaches 2000 kWh.m^{-2} on a horizontal surface, making it an ideal location for using solar renewables. The campus hosts approximately 12,500 m^{2} of floor area for the university building, a student residence with 260 rooms, and a restaurant. Fig. 3 gives an overview of the campus and installed PV capacity. Already equipped with 160 kWp of PV (the additional 200 kWp of the faculty of medicine will come soon) and solar Domestic Hot Water (DWH), this microgrid has a self-sufficiency of nearly 15%. The last generation of university buildings built on the campus (Enerpos and ESIROI) are NetZero Energy Buildings (Lenoir and Garde, 2012). Their annual energy demand is balanced by the Building Integrated PV installed on their roofs. With approximately 50% of the area being air-conditioned, cooling is the main load of the microgrid.

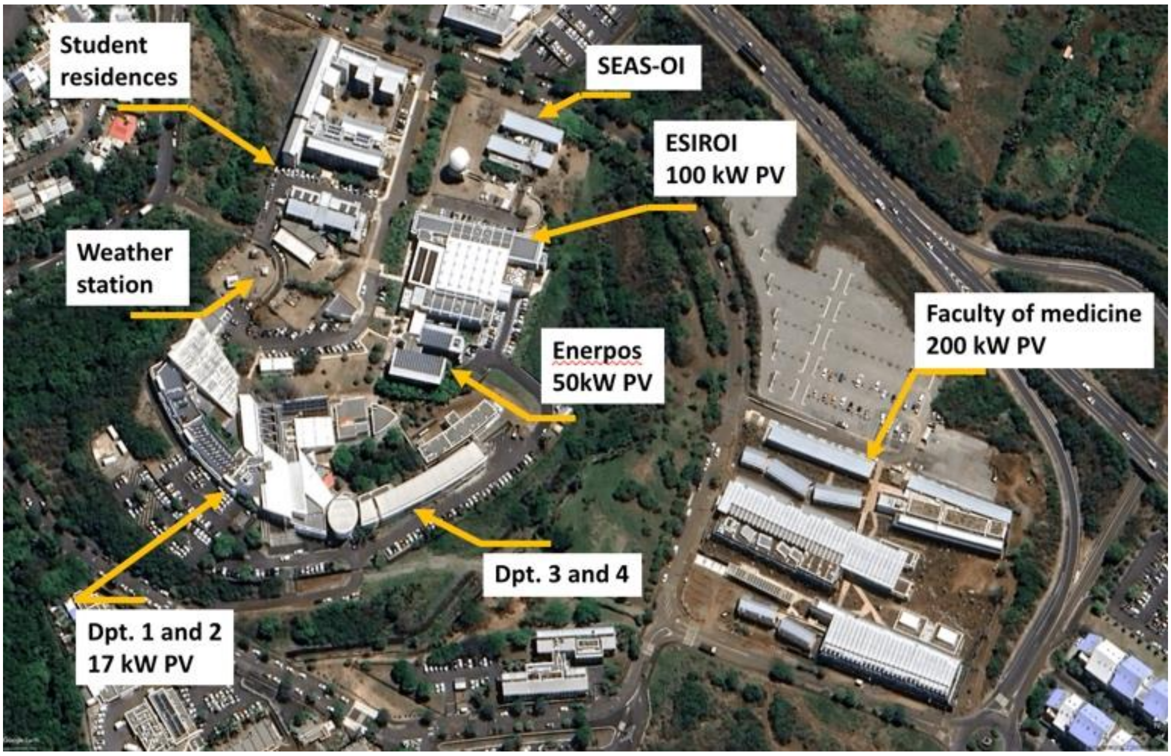

Fig. 3: Overview of the university Campus of Terre Sainte in La Reunion

As shown in Fig. 4, the main load of the buildings, even if they are very well designed like the ESIROI building, is the cooling (purple and dark yellow areas). However, with the increase of electric vehicles (EV), a significant share of the load comes from EV charging (dark green area).

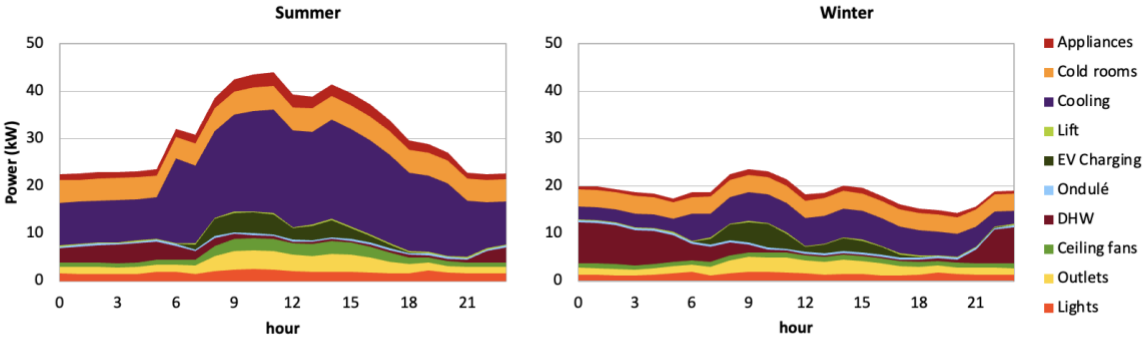

Fig. 4: Average daily profile of electricity demand by type of use of the ESIROI building for summer (Nov. to Apr.) and winter (Apr. to Nov.)

Reducing operation costs and carbon emissions of the whole microgrid requires optimizing the operation and size of the system to enable an increasing share of solar generation. More precisely, the TwInSolar project aims for 80% self-sufficiency from solar. An additional 400 to 500 kWp of PV can be installed on the roofs, and more than 1500 m^2 of parking are also available onsite to create PV shades. The main issue is not to install new PV capacity but to achieve a techno-economic optimum to reduce the operation cost of the microgrid. Complementary approaches have already been tested to reach this goal: a combination of PV with compressed air energy storage (Castaing-Lasvignottes et al., 2016; Simpore et al., 2019) and a predictive Energy Management System (EMS) fed by probabilistic solar forecasts and load forecasts (Ramahatana et al., 2022).

The campus is fully instrumented to monitor weather and electrical parameters with at least a 10-min time step. First, the university maintains its own complete weather station equipped with advanced solar irradiation sensors (global, diffuse, and direct irradiance on a solar tracker) onsite. Second, the electricity demand is recorded for each building separately and for the most recent constructions, the main types of loads (i.e., cooling, lights, ceiling fans, etc.) are also monitored. Finally, the production of the different PV plants is also recorded. A set of consolidated data with a 10-min granularity for two consecutive years, 2021 and 2022, is publicly available on the TwInSolar website in the deliverables section ("Twinsolar," 2023).

4. Utility scale PV systems with energy storage

In order to reduce the uncertainty associated with their production and consequently improve the stability of the main grid, the latest generation of large-scale photovoltaic farms installed in La Reunion must be coupled with an energy storage system (ESS). In 2021, 19 utility-scale PV plants, for a total of 30 MWp, were operated jointly with energy storage (Reunion Island Energy Observatory (OER), 2022). Tab. 1 gives three examples of these atypical systems installed in La Reunion, with their main characteristics. These PV farms comply with the technical specifications required by a series of calls for tenders launched by the government starting from 2011 for the non-interconnected French areas. The operators of these solar power plants must provide a production schedule one day in advance and risk penalties if they do not respect it. Two different ways of planning the production have been proposed:

- the generation of a trapezium-shaped power profile during the daytime (Ministère de l'Ecologie, de l'Energie, du Développement Durable et de la Mer, 2011),
- a free power profile during the daytime and the possibility of producing a constant power during peak hours (i.e., 7:00 p.m. to 9:00 p.m.) with a better selling price (Ministère de l'Ecologie, de l'Energie, du Développement Durable et de la Mer, 2015).

Tab. 1: Examples of utility scale PV systems with energy storage installed in La Reunion

Name (commissioning year)	Operator	PV capacity	ESS capacity	Operation type	Source
Stade de l'Est (2020)	Albioma	1.25 MWp	1,33 MWh	Free daily profile and evening peak	(Albioma, 2023)
Aéroport Saint-Pierre Pierrefonds (2023)	TotalEnergies	7,7 MWp	10 MWh	Free daily profile and evening peak	(TotalEnergies, 2023)
Les Cèdres (2015)	Akuo	9 MWp	9 MWh	Trapezium-shape daily profile	(Akuo, 2023)

We will focus in this work only on the second type of injection profile, which favors the injection of power at peak hours. The left side of Fig. 5 illustrates the profile shape the operator must deliver to the Distribution System Operator (DSO) one day in advance. This profile and delivery times must respect a series of complex rules. Here, we will give a brief overview of the main requirements. The reader can access the detailed technical specifications here (Ministère de l'Ecologie, de l'Energie, du Développement Durable et de la Mer, 2015). The plant operator must transmit the generation profile of the next day to the DSO at 4:00 PM the day before. 4 redeclarations are possible at 4:00 AM, 10:00AM and 2:00 PM on the day of production. To avoid severe ramps during the daytime, the slope of the announced profile must be less than 0.6% per minute of peak power. Deviations ($Deviation{=}Actual\ injeted\ power - Announced\ power\ profile$ (eq. 1) from the announced profile, which exceed a power tolerance of ±5% of the installed peak power, lead to penalties calculated as follows: a positive deviation (i.e., overproduction) is not purchased and a negative deviation (i.e., underproduction) results in a penalty given by $Penalty{=}Feed\ in\ tariff \times \left[\frac{Deviation^2}{Peak\ power} - 0.1 \times Deviation - 0.0075 \times Peak\ power\right]$ (eq. 2. The right side of Fig. 5 illustrates the value of the penalties for deviations ranging from -500 kW to 500 kW for a PV farm of 1 MWp and a feed-in tariff of 215 €/MWh, which corresponds to the average feed-in tariff of the installations awarded by the call of tender launched in 2015 (CRE, 2015). To encourage production during the peak hours, the feed-in tariff was raised by 200 €/MWh.

$$Deviation = Actual\ injeted\ power - Announced\ power\ profile \qquad \text{(eq. 1)}$$

$$Penalty = Feed\ in\ tariff \times \left[\frac{Deviation^2}{Peak\ power} - 0.1 \times Deviation - 0.0075 \times Peak\ power\right] \qquad \text{(eq. 2)}$$

The rules for the penalties are surprising. Indeed, for a simular absolute value of the deviation, you lose more money when you overproduce (positive deviation) than when you underproduce (negative deviation). No penatly jump appears when leaving the 5% tolerance band for negative deviations, as defined by equation 2. For positive deviation, the penalty corresponds to a shortfall because the DSO will not buy your excess of production. The slope is the feed-in tariff and a jump appears because you are not penalized within the 5% tolerance band.

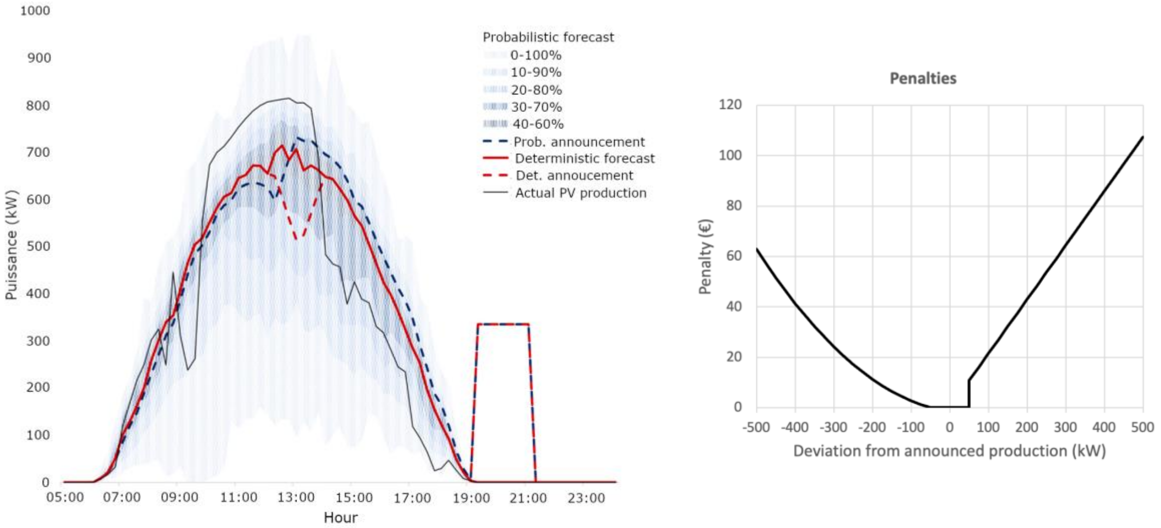

Fig. 5: At the left, one day of deterministic (red line) and probabilistic (grey intervals) forecast, the corresponding announced injection profiles (dashed lines) and the actual PV output power (black line) of 1 MWp PV plant situated in the coastal part of La Reunion. At the right, the penalties resulting from deviation from the announced production profile for a feed-in tariff of 215 €/MWh.

Therefore, the predictive schedule of these plants should reduce penalties while increasing the amount of energy injected into the grid. For instance, to maximize the revenue, a possible strategy is to charge the ESS at 100% during the daytime and to discharge it during peak hours. The main challenge for these specific PV farms and their operators is to select sound solar forecasts and integrate them into the system's EMS (David et al., 2021). Indeed, the quality of a forecast can be evaluated by a large set of indicators, such as the Mean Bias Error (MBE), the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE) for the deterministic forecast (Yang et al., 2020) and the Continuous Rank Probability Score (CRPS), or the Ingnorance Score for probabilistic forecast (Lauret et al., 2019). However, improving these evaluation metrics does not mandatorily correspond to better revenue for the user.

For this study case, the operation data, such as the PV production and the ESS state of charge, are not publicly available because they belong to private operators. However, it is easy to find the main technical characteristics of the PV plants and the ESS on the Internet (see Tab. 1: Examples of utility scale PV systems with energy storage installed in La Reunion. Finally, the technical specifications cited above fully describe the technical and financial rules used to run these PV plants and simulate the EMS. Time series of PV production and forecasts can be simulated through CorRES tool (Koivisto et al., 2019).

5. The power grid of the island of La Reunion

With approximately 400,000 electricity consumers and a wide variety of means of production, the electricity network of La Reunion Island is not a small isolated power grid. Moreover, the distance between La Reunion and the nearest continental grids is so long that interconnection is not possible. This intermediate-size grid, often called non-interconnected, faces different problems from standalone micro-grids. Therefore, it will prefigure the challenges of continental grids with a high share of intermittent renewable energies such as PV and wind power. In 2021, as illustrated in Fig. 6 andFig. 7, the total installed capacity was 931.8 MW and the annual electricity production was close to 3,000 GWh. The same year, with an installed capacity of 223.6 MW (24% of the total installed capacity), the PV produced 8.7% of the electricity mix (Reunion Island Energy Observatory (OER), 2022). With such a high penetration rate of intermittent renewables and to guarantee the grid stability, the French government fixed a regulatory limit of a maximum of 35% of the total produced power coming from PV and wind. Beyond this limit, the local DSO considers that the high penetration rate of renewable energy systems connected via power electronics such as inverters results in an unacceptable risk. Indeed, the inverters must operate within the frequency and voltage bands defined by the DIN VDE 0126-1-1 (VDE, 2013) and, in case of severe failure on the grid, they could stop their production if the frequency or the voltage drop suddenly. With the current conversion to biomass of coal and diesel power plants, the electricity generation will be 100% renewable by 2024 (Ministère de la transition écologique, 2022). However, most of the required biomass (i.e., wood pellets and bio-fuel) will be imported and this conversion will unfortunately perpetuate the high energy dependency of the island.

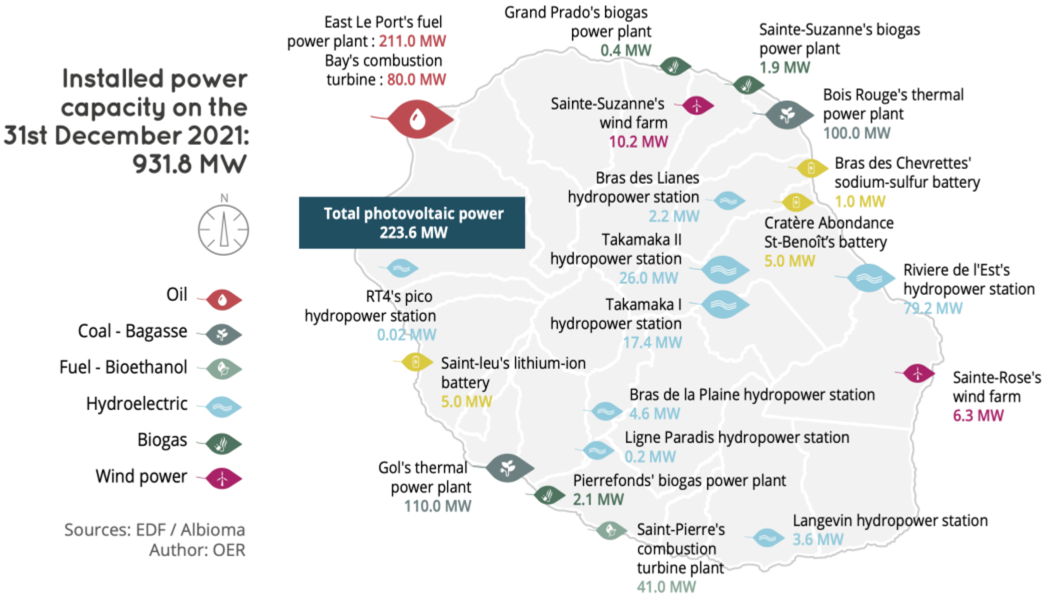

Fig. 6: Schematic diagram of La Reunion's electricity grid in 2021 (Reunion Island Energy Observatory (OER), 2022)

As the sun is the first local renewable resource, the self-sufficiency goal for La Reunion requires a massive integration of solar renewable energies. To reach a 100% renewable with local resource, a prospective study done by the French energy agency ADEME highlights that the future energy mix of La Reunion will be higly dominated by solar technologies (BISCAGLIA et al., 2018). Moreover, the French government, in agreement with the local authorities, plans a strong increase of the PV with a doubling of the installed capacity by 2028 (Ministère de la transition écologique, 2022). If 100% PV electric production with a affordable Levelized Cost of Energy (LCOE) is achievable (Perez et al., 2023), a important capacity of ESS is needed. Therefore, the main challenge is to achieve a massive integration of solar renewable energies into the electricity network through PV generation and demand forecasting, ESS and smart management of the production means.

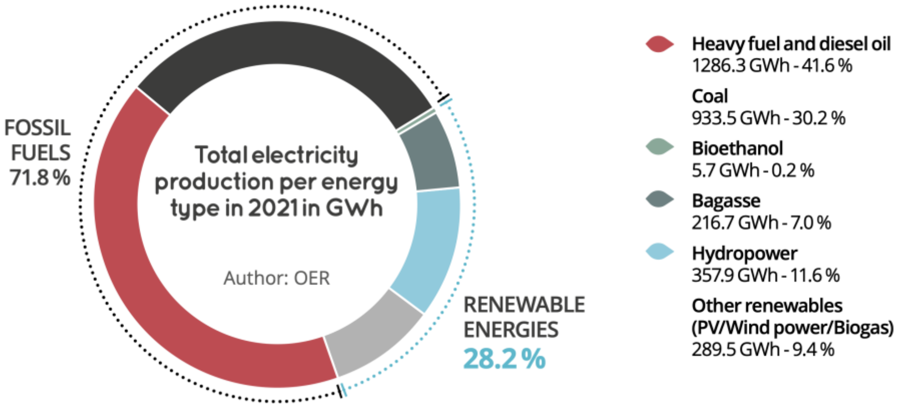

Fig. 7: Electricity production mix of La Reunion in 2021 (Reunion Island Energy Observatory (OER), 2022)

The local DSO, EDF Réunion, recently created a website bringing together a lot of data concerning the island's electricity network (EDF, 2023). These freely accessible data provide a detailed description of the means of production, transport lines and main transformers. Additionally, the web portal also provides hourly records of electricity production by type of generation means and costs from 2016. This dataset provides a useful tool for studying the massive integration of solar energy into a medium-sized non-interconnected power grid.

6. Conclusion

The decarbonization of electricity production and more broadly the energy autonomy of non-interconnected territories like Reunion Island require the massive integration of solar energy in the near future. While solar technologies, such as PV and solar DHW, are mature, the variable nature of the solar resource and their connection to the electrical grid with power electronics raise new scientific challenges to achieve this goal. This work details 4 case studies that highlight these challenges at different scales: an isolated microgrid, a grid-connected microgrid, utility-scale photovoltaic plants equipped with ESS and the electricity network of the island of La Reunion. All these case studies come with freely accessible data allowing the scientific community to study possible alternative solutions to significantly increase the share of solar power in the production mix.

7. Acknowledgements

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