Infinity, a small-scale prototype for firm-PV generation

Federico Andreozzi[1], Gianluigi Bovesecchi[1], Richard Perez[2], Marco Pierro[3], Cristina Cornaro[1]
[1] University of Rome Tor Vergata, Department of Enterprise Engineering, 00133, Rome (Italy)
[2] Atmospheric Sciences Research Center, University at Albany, 12222, Albany, NY (United States)
[3] Institute for Renewable Energy – EURAC, 39100, Bolzano (Italy)
e-mail addresses: federico.andreozzi@uniroma2.it, gianluigi.bovesecchi@uniroma2.it, rperez@albany.edu, marco.pierro@eurac.edu, cornaro@uniroma2.it

SUMMARY OF THE ABSTRACT

The "Infinity" prototype is a small-scale flexible photovoltaic system (f-PV) designed to experimentally validate the concept of firm PV generation, ensuring a stable and dispatchable power output from solar energy.

The system is built around two key principles: PV overbuilding and curtailment of excess energy. By oversizing the PV generation capacity relative to the load, the system reduces the need for large battery storage, instead curtailing surplus energy when the battery is fully charged. This approach enhances grid integration and improves the economic feasibility of firm PV generation.

Technically, the Infinity prototype consists of a 1.815 kWp PV system (three 605 Wp bifacial modules), a 5 kWh lithium battery with BMS, a smart inverter, and a programmable DC load emulator. The power flows are dynamically managed through MatLab, updating the requested load value every minute. When PV production exceeds the energy demand and the battery reaches full charge, excess energy is fed into the grid to simulate curtailment.

The system's flexibility allows for testing different load profiles and storage configurations, making it a versatile platform to investigate storage/PV capacity ratios and their impact on firm PV generation.

Infinity represents an important step forward from previous numerical studies on the feasibility of firm PV generation, previously conducted for the Lazio Region and the Engineering Macro-Area of the University of Rome Tor Vergata. The prototype provides a real-world testbed to validate theoretical findings and assess the effectiveness of different control strategies under actual operating conditions.

Initial results from its first days of operation confirm that the system effectively meets power demands under varying weather conditions. The battery exhibits satisfactory charge times, and curtailment dynamics mostly align with expectations. Further testing will explore the system's resilience and optimization strategies for broader applications in sustainable energy integration.

APPLICABLE TOPIC AND SUB-TOPIC NUMBER

Topic 5: Photovoltaics in the Energy Transition

Subtopic 5.1: Grid Integration and Flexibility Enablers

This research seeks to develop the firm PV generation concept with the aim of transforming solar power into a fully dispatchable energy source through optimal sizing of PV capacity and battery storage and providing an adequate operation strategy. Therefore, this work aligns with the objectives of this subtopic.

EXPLANATORY PAGES

AIM AND APPROACH

The idea behind the “Infinity” (**IN**novative **FI**rm ge**N**erat**I**on proto**TY**pe) prototype is to use a small-scale flexible photovoltaic system (f-PV) to test the firm PV generation concept, which means maintaining a reliable power output from PV systems. [1]. The activity is conducted within the framework of the Rome Technopole project, funded by the Italian National Plan of Recovery and Resilience (PNRR).

The prototype is based on the concepts of PV system overbuilding (also known as implicit storage) and curtailment of the excess energy production. The photovoltaic power generated must meet the electrical load and recharge the batteries even during the winter period and/or prolonged cloudy conditions, so that the capacity/costs of the storage would be minimized since it would be used only to redistribute the photovoltaic production over 24 hours.

The PV system was built at the EsterLab facility [2, 3] on the rooftop of the Industrial Engineering building at the University of Rome Tor Vergata. Its peak PV power is 1.815 kWp resulting from three JA Solar bifacial modules, each providing 605 Wp, and a Huawei lithium battery storage system with a capacity of 5 kWh. The modules are mounted on a fixed stand oriented towards the South, with a 30° tilt angle. Power flows are managed by a Huawei smart inverter and battery management system (BMS). The system is completed by an ITech IT-M3323 programmable DC load emulator, which provides the system with a controllable power load, updated every minute via a MatLab program. A connection to the power grid is used to simulate curtailment of the excess energy produced when the batteries are already fully charged.

Analyzing the power flows (*Figure 1*), the inverter distributes the energy produced by the modules between the load and to the battery and communicates with the BMS, ensuring that once the batteries state of charge reaches the upper limit, the excess energy is fed into the grid. This is done to keep the curtailed energy measurable and, incidentally, enables comparative analyses between flexible PV systems, which curtail all the excess production, and system that sell it to the electricity network. When no energy is produced by the PV (e.g. at night), the inverter requests the battery to satisfy the power load.

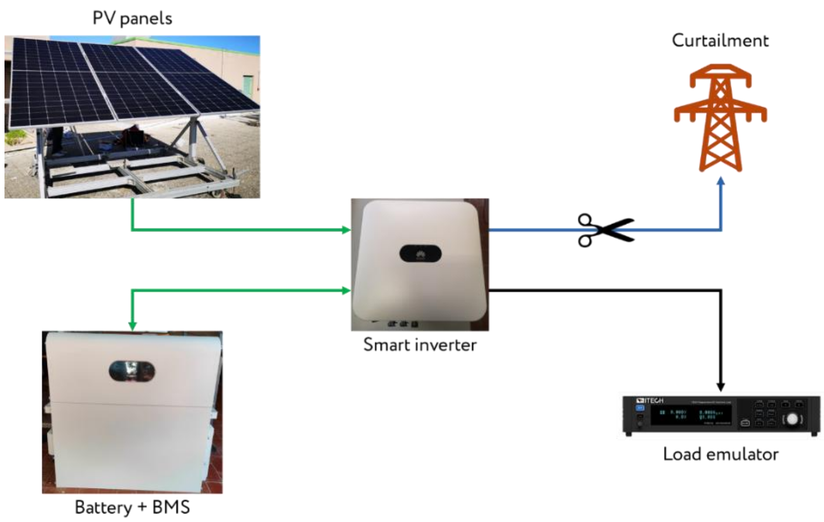

Figure 1 *– Representation of Infinity’s power flows.*

Infinity serves as a testing ground for evaluating the capability of flexible PV systems to transform PV into a fully dispatchable energy source. This has already been proven by previous numerical studies on the feasibility of firm PV generation in the Lazio Region [4] and at the Engineering Macro-Area of the University of Rome Tor Vergata [5]. The prototype is designed to experimentally replicate such studies on a small scale. The power load is therefore modeled based upon the corresponding full-scale one and appropriately scaled down to fit the system size.

The system is designed with an adjustable effective battery capacity, meaning that an upper and lower limit can be set for the batteries state of charge. This allows for modifications to the storage/PV capacity ratio (i.e. storage hours in kWh/kWp) and enables testing on different load profiles (e.g., office or residential buildings or areas) with appropriate scaling.

SCIENTIFIC INNOVATION AND RELEVANCE

Finding a way to transform PV into a dispatchable energy source is one of the challenges the research community is most active on.

Firm PV, overbuilding and curtailment are widely discussed topics in the literature, with contributions from several parts of the world: from the United States [6, 7] to Italy [8, 9], Australia [10], China [11], Portugal [12], Switzerland [13] and more. Additionally, the experts of IEA PVPS Task 16 focus in these subjects through Activity 3.5 – Firm PV generation. However, most of the currently available research on themes is either theoretical or simulation-based.

Infinity takes a different, more experimental approach by feeding an appropriate power load to an actual flexible PV plant, albeit a small-scale one, to compare the results of previous simulations [5, 6] to a real-life application and thus validate the simulation models.

Flexibility is also a relevant feature of this prototype. By means of properly scaling the load and adjusting the storage/PV capacity ratio, the system can be reconfigured to test a variety of load profiles and combinations of overbuilding and battery capacity.

PRELIMINARY RESULTS AND CONCLUSIONS

Infinity has been active and fully functional since the 28th of January 2025 and is currently in its testing phase.

Figure 2 shows the results obtained in the first two days of operation. The power load currently set for the system is the electrical demand of the Engineering Macro-Area of Tor Vergata from 2019, scaled down by a factor of 8500.

The plots show that PV production peaked at about 1.5 kW. Negative values for battery power indicate charging, while positive ones indicate that energy from the storage system is being used to meet the power load. This is particularly evident at night, when the battery power and load plots are overlapped. Curtailment is conventionally represented by negative values.

Moreover, the PV to Load plot represents the portion of power produced by the modules directly used by the load. During daylight hours, this variable mostly overlaps with the load, showing that the PV can generally provide the power requested.

During the first part of the day, the energy produced by the PV is mostly used to recharge the battery, which was drained during the night. Once the full charge is reached, the excess production is curtailed.

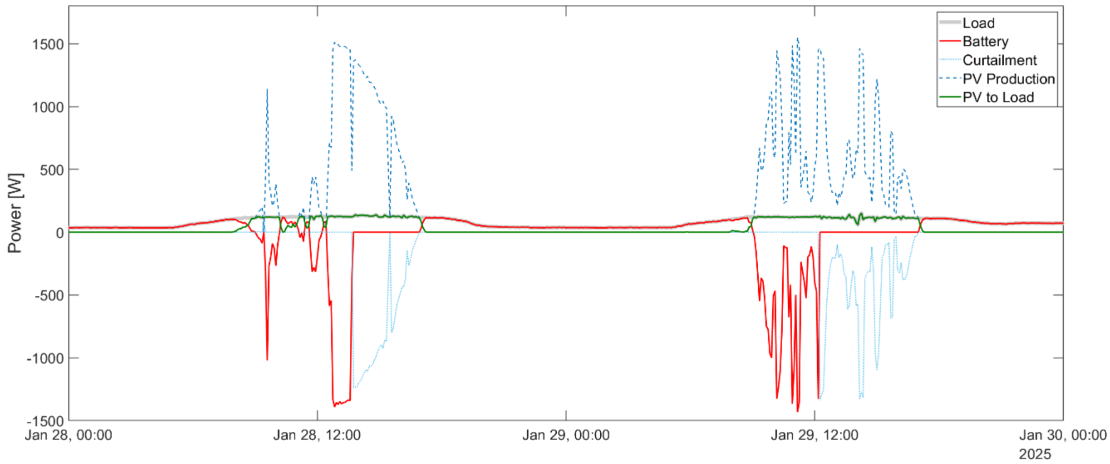

Figure 2 *– Report of Infinity's first two days of operation.*

It is interesting to note that, even in mostly overcast days, the battery rarely intervenes during daylight hours, and that it is able to return to a full charge in about 4 – 6 hours. This suggests that even under the worst weather conditions, the system could still meet the electric demand without grid support, as predicted by simulations. Confirmation of this will only come with further testing in a wider variety of weather conditions.

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