PVInGrid: A Distributed Infrastructure for Evaluating the Integration of Photovoltaic Systems in Smart Grid

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Abstract. Planning and developing the future Smart City is becoming mandatory due to the need of moving forward to a more sustainable society. To foster this transition an accurate simulation of energy production from renewable sources, such as Photovoltaic Panels (PV), is necessary to evaluate the impact on the grid. In this paper, we present a distributed infrastructure that simulates the PV production and evaluates the integration of such systems in the grid considering data provided by smart-meters. The proposed solution is able to model the behaviour of PV systems solution exploiting GIS representation of rooftops and real meteorological data. Finally, such information is used to feed a real-time distribution network simulator.

Keywords: Photovoltaic, GIS, Distributed Infrastructure, Smart-grid, Real-time, Simulation.

1 Introduction and Motivation

Thanks to the commitment of the participating countries to Kyoto Protocol and to Paris Agreement, the presence of distributed Renewable Energy Sources (RES) is increasing in our electricity systems. In this transition from a centralized to a distributed system, converting passive buildings rooftops of our cities into active Photovoltaic rooftops becomes crucial. However, the deployment of PV system cannot be left to chance but needs to be planned with specific tools able to i) estimate PV production in time and ii) to assess the capabilities and requirements of the networks [11]. This research aims at creating PVinGRID, a distributed infrastructure composed by software and hardware components. PVinGRID integrates: i) Geographic Information Systems (GIS) data and algorithms; ii) sensor, such as weather station and smart meter; iii) real-time hardware electricity grid simulator. Exploiting GIS tools and weather station data, PVinGRID estimates the availability of deployable area for PV system on rooftops and simulates sub-hourly PV generation loads in real-sky conditions. By merging data coming from smart meters [1] with simulated PV generation loads, PVinGRID evaluates the integration of PV system in the distribution network exploiting a real-time grid simulator. The rest of the paper is organized as follows. In Section 2, the relationship of this research with smart system is highlighted. Section 3 presents literature methodologies and services for PV energy simulation and integration into the grid. Section 4 presents the specifications and

methodology to develop our solution. In Section 5, the results obtained with PVinGRID are presented. Finally, Section 6 provides the concluding remarks.

2 Relationship to Smart Systems

Information and Communication Technologies (ICTs) are a key factor in the development of smart systems for Smart Energy management. They can provide useful tools for planning and monitoring the deployment of RES systems. Furthermore, the spread diffusion of heterogeneous and pervasive sensors in our houses, district and cities, is increasing the smartness of our distribution grid. With such sensors, it is possible to monitor the electricity behaviours of the users. Information on electricity consumption are needed in both planning and monitoring phases for evaluating: *i)* energy management actions; *ii)* management of electricity distribution networks; *iii)* integration of renewable sources in the city. PVinGRID is a tool useful for both planning and monitoring phases of PV systems, spanning all scales starting from single building up to block, district and city. Our solution can be used for different purposes depending on the needs of different stakeholders. For instance, a ***Single citizen*** uses PVinGRID for estimating the economic benefits that he/she can achieve by installing a new PV system. End-users want to be aware on the avoided CO_2 emission and virtuous actions to perform. ***Energy aggregators and Energy Communities*** can use our solution for scheduling the consumption pattern of their clients for maximizing self-consumption and minimizing energy bills. In particular ***Energy Communities*** can exploit such infrastructure to perform feasibility studies as proposed by [3]. ***Distribution system operators*** (DSO) can use PVinGRID for analysing the reliability of their grids after the deployment of PV system and plan, if needed, retrofits actions and/or extensions of existing distribution grids. They can exploit our solution to avoid network congestions exploiting load balancing. Lastly, ***Energy and City planners*** can use PVinGRID for evaluating the benefits of large PV systems installations in cities or monitoring the performance of already deployed PV systems. Furthermore, if accurate weather forecasts are available, PVinGRID provides also information on generation profilse of existing PV systems to: *i)* ***DSO*** for estimate possible unbalances on the grid and to evaluate load balancing actions (e.g. Demand Response and Energy Storage); *ii)* ***Market Operators*** for creating local or dynamic prices; *iii)* ***Smart Energy management systems*** for evaluating next actions in smart energy management (e.g. usage of storage and load scheduling).

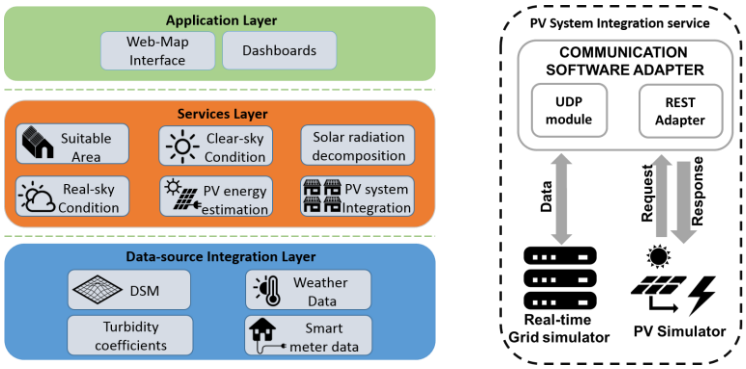
3 State of the Art

Geographic Information Systems (GIS) tools have been widely applied in the estimation of renewable potential as reported in [5] in particular in urban contexts for solar applications [9].

New methodologies exploiting GIS for simulation with spatial and temporal domains of PV system energy production are recently emerging [4,10,12]. A spatio-temporal simulation of PV production integrated with network topology and users

consumption load profiles allows to estimate the real PV potential by evaluating the effects of the penetration of PV systems into the grid [4]. Available web solutions such as [13,18] are limited in the analysis of the time domain and do not integrate electricity consumption and network topology data. Hence, there is the need to develop frameworks that integrate consumption, production and network topology in order to evaluate the integration of PV system, or more in general RES. Real-time simulator, such as Opal-RT®, are applied in the prototyping phase of the development of system or manufacture. This because real-time simulations allow testing solutions that are still not physical prototypes [2,6,19]. With respect to RES, real-time simulations have been applied for PV generation [15] and for wind-farms [14,20]. In this work we propose a simulation framework called PVinGRID that couples PV simulator with a real-time grid simulator, such as Opal-RT®. PVinGRID considers the electric behaviour of the distribution system taking into account both information on electricity consumption and network topology.

4 Contributions and Innovative Aspects



(a) Scheme of the software architecture for PV systems integration into Smart Grids

(b) Integration of PV and Real-Time grid simulators

Fig.1. PVinGRID infrastructure

In this Section, we describe PVinGRID our distributed infrastructure for evaluating the integration of PV systems in a Smart Grid environments. PVinGRID is composed by both hardware and software components. The hardware components are: *i)* real-time grid simulator, *ii)* weather station and *iii)* smart meters. The software component is a distributed infrastructure for estimating PV systems energy production (see Fig. 1(a)).

4.1 Real-Time Grid Simulator

Real time simulation (RTS) is a highly reliable method based on electromagnetic transient simulation which serves a platform to test new control strategies or

technologies on a virtual environment emulating the real world system. It provides very reliable real-like information on impacts and benefits of new strategies or devices. RTS could support decision makings from real-time operation and control phase to long-term planning. Regarding electricity systems, RTS is being widely used in protection and control system development and testing. In particular, for distributed generation modelling of RES integration (e.g. PV generation penetration), and intelligent grids development.

The purpose of using RTS in our work is to model a realistic distribution network to support investigations in terms of PV power penetration impacts in real-world situations. The objective is to simulate the behaviour of prosumers, and the set-up of a Software-In-the-Loop (SIL) platform for laboratory validations of new controls, operations, and planning algorithms for smart grids management [7].

4.2 Photovoltaic System Simulator

In this section we present the distributed software infrastructure for simulating PV generation profiles (see Fig. 1(a)). The development of this solution is needed to model and estimate PV system behaviours in both spatial and temporal domain. Thus, evaluations of their impact in the grid can be assessed. Our solution has been designed following both microservice[1] and REST [8] approaches. This due to the intention of developing a simulation tool with an easy maintenance and to allow integration of third-party software. Our solution is composed by three layers described in the following:

The **Data-source Integration Layer**, the lower layer, is in charge of integrating the following data-sources: *i)* the *Digital Surface Model* (DSM) of the area in study, which is a raster image that represents terrain elevation considering the presence of manufactures; *ii)* the *Linke Turbidity coefficients* that express the attenuation of solar radiation related to air pollution; *iii)* the *Weather Data* coming from the nearest weather station provided by third-party services; *iv)* electricity consumption data provided by external software platforms(eg. [16,17]).

The **Services Layer** is the core of the simulation infrastructure and is composed by independent services that communicates trough REST-API. *Suitable Area* service is in charge of identifying suitable real rooftop surfaces for deploying PV system. *Clear-Sky condition* service, exploiting the *r.sun* tool of *GRASS-GIS*[2], produces a set of maps with the incident solar radiation every 15 minutes in the area of interest. *Solar radiation decomposition* service is used if the nearest weather station provides only global horizontal radiation (GHI). In its core, it has a set of solar decomposition models present in the literature used to estimate direct normal radiation (DNI) and diffuse horizontal radiation (DHI). *Real-sky condition* service produces real-sky maps for each time interval of the simulation. *PV energy estimation* service, using the maps of real-sky condition and suitable area service, estimates the size of the deployable PV system and its production. It considers the cell temperature that affects the PV efficiency. *PV system Integration* service is in charge of correlating the simulation of

[1] Fowler, M.: Microservices (2014), http://martinfowler.com/articles/microservices. html

[2] GRASS GIS, Open Source Geospatial Foundation, http://grass.osgeo.org

PV energy production with data coming from the Smart Grid (e.g. energy consumption). This service provides information on the level of self-sufficiency (i.e. the share local demand fulfilled by PV energy production) and the level of self-consumption of the produced energy (i.e. the share of produced energy that is instantaneously consumed) for the area of interest. Furthermore, it enables the communication with the real-time grid simulator (see Section 4.1) as described in the following Section 4.3.

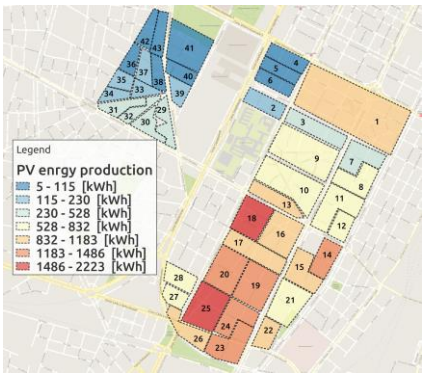
The **Application Layer** provides applications that allows end-users to interact with the simulation results exploiting *Web-Map interface* and *Dashboards*.

4.3 Smart-Grid Simulation Tool

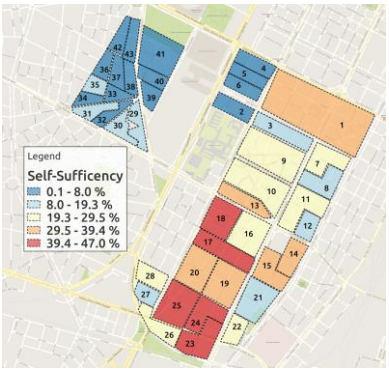
As mentioned in Section 4.2, the *PV system Integration* service in Fig. 1(a) correlates the output of the PV system energy simulation with information coming from the Smart Grid with the same geographic area. In addition, it enables the communication with the real-time grid simulator through the *Communication Software Adapter* (see Fig. 1(b)). The adapter integrates two sub-modules: i) *REST adapter* and ii) *UDP module*. The *REST adapter* parses the simulation request from the RTS to the PV system simulator by translating them into REST calls to remote web-services. The UDP module pushes the simulated PV energy production data in to the RTS. Furthermore, it receives and processes the information coming from the RTS.

5 Results and Critical View

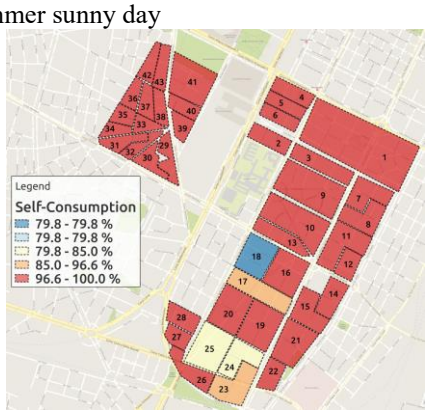
To demonstrate an application of the proposed integrated simulation platform in PV penetration assessment, we present some results of simulating the distribution grid behaviour in a real case-study considering a high PV penetration. The area under analysis is a city district with nearly 2200 residential buildings and 43 MV/LV substations. For this purpose, a summer sunny day where there is the maximum production from PV system has been selected to show the maximum level of both self-sufficiency and self-consumption and highlighting possible violation of MV/LV transformers. The simulation process identified 944 suitable areas in the building rooftops for deploying PV systems with a maximum nominal power equal to 14.21 *MW*. Fig. 2(a) shows the distribution of energy production for each substation in a summer sunny day, which for the whole area is equal to 28.41 *MWh*. In Fig. 2(b) and Fig. 2(c) the levels of self-sufficiency and self-consumption are reported. Fig. 2(b) shows that the sub-station with less production has less than 10% of self-sufficiency.



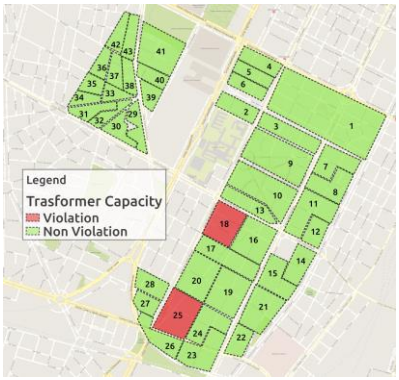
(a) Total PV energy generation in the summer sunny day



b) Maximum Percentage of self-sufficiency of each sub-station



(c) Maximum Percentage of self - consumption of each sub-station



(d) Sub-station violating transformer capacity

Fig.2. Mapped simulation results

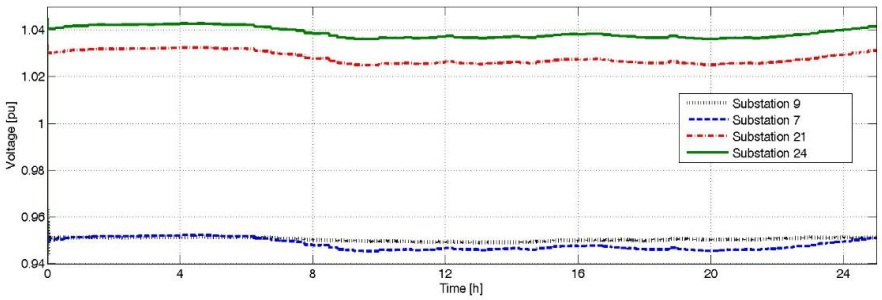


Fig.3. Voltage profile for substations 7-9-22-24

However, sub-stations 17,18, 23, 24 and 25 have a level of self-sufficiency over 39%. Fig. 2(c) revels that almost every sub-station absorbs all the produced energy from PV systems. Only sub-station 17,18, 23, 24 and 25 feed the MV distribution grid and are the one with the highest level of self-sufficiency. Looking at the transformer

capacity map (Fig. 2(d)), integrating PV generation would cause violations in sub-station 17 and 25. The maximum net consumption in these two sub-stations exceeds the transformers capacity due to an high amount of PV generation and low consumption. This highlights that in cases where PV generation is higher than local demand the installation of PV systems should be reduced or grid infrastructures, in terms of transformers (and also cables/lines), should be enhanced to tolerate reverse power injection from substations to the grid.

One of the other challenges due to high penetration of PV generation relates the voltage control: in our case study, we observed that in two feeders which are derived from the same transformer, local generations with respect to local consumptions are not equally/closely distributed. Substations 22 and 24 with high self-sufficiency are connected to one feeder, and substations 7 and 9 with lower self-sufficiency are connected to the other feeder. According to the voltage profiles of these sub-stations (Fig. 3), any changes in the level of transformer voltage to correct over/under voltage in one feeder would result in more deviation in the other feeder.

6 Conclusions and Future Work

In this work PVinGRID a simulation infrastructure for evaluating PV integration into smart grid has been presented. In addition, motivations and relationships of the research with smart system has been highlighted. The results show how PVinGRID can be used for planning the deployment of PV systems and to evaluate the impact of such deployment in distribution grids. As future work a service for economic evaluation will be developed and included in the proposed solution. In particular, the simulation infrastructure will be integrated with a market simulator for evaluating dynamic prices and Demand Side Management policies. Furthermore the overall infrastructure will be used for evaluating Smart Energy actions as storage management, Demand Response events, Automatic Voltage Regulation, Network Reconfiguration and Load Balancing.

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