Planning and real-time management of smart grids with high PV penetration in Italy

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Planning and real-time management of smart grids with high PV penetration in low voltage

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For planning and development and in real-time operation of smart grids, it is important to evaluate the impacts of photovoltaic (PV) distributed generation. In this paper, we present an integrated platform, constituted by two main components: a PV simulator and a real-time distribution network simulator. The first, designed and developed following the microservice approach and providing REST web services, simulates real-sky solar radiation on rooftops and estimates the PV energy production; the second, based on a digital real-time power systems simulator, simulates the behaviour of the electric network under the simulated generation scenarios. The platform is tested on a case study based on real data for a district of the city of Turin, Italy. In the results, we show possible applications of the platform for power flow forecasting during real-time operation and to detect possible voltage and transformers capacity problems during planning due to high penetration of Renewable Energy Sources. In particular, the results show that the case study distribution network, in the actual configuration, is not ready to accommodate all the generation capacity that can be installed as, in certain hours of the day and in certain days of the year, the capacity of some transformers is exceeded.

1. Introduction

In recent years, governments have provided incentives for the connection to electricity networks of low-carbon and sustainable generation technologies, in particular photovoltaic (PV) systems. The conversion of passive buildings rooftops into active PV rooftops is becoming more popular in all cities because in this way it is possible to exploit the available surfaces without subtracting additional portions of land from other uses. Recent works (Brito *et al.*, 2017; Yu *et al.*, 2017) have demonstrated the importance and availability of buildings facades for the deployment of PV systems in addition to classic rooftops installations. This possibility could provide a significant additional area for PV deployment, but should be carefully evaluated as in old cities with narrow streets PVs on facades would produce a small amount of energy and many old buildings with historical importance cannot accommodate PVs on their facades. The importance of integrating PV systems in buildings is highlighted Varney and Vahdati (2014), where authors studied possible integration of PV systems with heating and cooling systems in buildings proving an increase of energy efficiency.

Currently there is no regulation for Distributed Generation (DG) placement and there is no optimized planning strategy. For these reasons specific tools for the analysis of possible scenarios are really important for different stakeholders, such as Distribution System Operators (DSOs), Energy and city planners, policy makers, etc. One of the critical issues relates to the power balance at the power transformers, which might not have sufficient spare capacity to accommodate the solar electricity feed in (Freitas *et al.*, 2018b).

Keane *et al.* (2013) and Spertino *et al.* (2014) state that robust tools that help assess the capabilities and requirements of the networks are required for PV system deployment; in this assessment it is not sufficient to consider the maximum installed peak power for PV production, but it is necessary to perform more sophisticated calculations, taking into account solar irradiance and demand hourly variation (Freitas *et al.*, 2018b).

Geographic Information Systems (GIS) tools have been largely used and are recognized as useful tools for renewable energy planningand estimation as reported by Domínguez and Amador (2007). In their work Gagliano *et al.* (2017) propose a GIS methodology for managing energy use at the urban scale. Freitas *et al.* (2015) reports how GIS tools have been applied for solar energy applications in urban contexts. Camargo *et al.* (2015) highlights that available GIS tools for PV planning are limited because are neglecting time domain. Classic web-based platforms for photovoltaic potential analysis, such as Suri *et al.* (2008); Mapdwell Solar System (accessed July 2018); de Sousa *et al.* (2012); De Amicis *et al.* (2012), do not perform time-dependent simulations but only yearly or monthly estimations. Furthermore, such services do not take into account electricity consumption and network topology, which is relevant to estimate realistic integration of PV systems into the grid.

Camargo *et al.* (2015); Jakubiec and Reinhart (2013); Luka *et al.* (2014) and Bottaccioli *et al.* (2017c) are proposing new methodologies and solutions that integrate spatial and temporal domains in PV energy estimation. These works have paved the way to new possibilities of spatio-temporal analysis in the assessment of PV potential. Spatio-temporal simulations enable the assesment of PV potential by integrating consumption and generation profiles with grid topology. In particular, Camargo *et al.* (2015) integrates simulated PV production with electricity consumption data for a correct PV integration to avoid network congestions. Furthermore, Bottaccioli *et al.* (2017b) co-simulates in real-time the integration of PV systems with storage systems to study battery management strategies, considering metered consumption data and GIS simulation of PV production.

In the methodology the authors propose, a PV simulator is coupled with a real-time grid simulator, in order to be able not only to consider consumption data and network topology, but also to take into account the electric behaviour of the distribution system.

There are a lot of examples on the applications of real-time simulation to electrical systems including grids, power electronics and control systems. There are two main types of simulations: electromagnetic transient and phasor simulations; however, there are some examples on the combination of them. The most common commercial application of real-time simulation is in the prototyping stage of manufacturing a device or developing a system. This capability of real-time simulation provides the possibility of testing even when there are no physical prototypes (Vamsidhar and Fernandes, 2004; Dufour *et al.*, 2008; Bompard *et al.*, 2016). Real-time simulation is also widely used before and after prototyping as design and test phases respectively. For example in photovoltaic generation (Park and Yu, 2004) and wind conversion systems (Wang and Gao, 2008; Pak and Dinavahi, 2009).

The solution presented in this paper is devoted to satisfy the needs of different stakeholders: *i)* ***Energy Communities*** can use it to plan large PV system deployments and perform feasibility studies as proposed in our previous research (Bottaccioli *et al.*, 2015); *ii)* ***Distribution system operators*** can simulate new control strategies for network balancing and plan retrofits and/or extensions of the existing distribution grid in planning phase, and also better estimate network power flow during real-time operation; *iii)* ***Energy and City planners*** can evaluate the impacts of large PV systems installations or monitor the performance of existing ones.

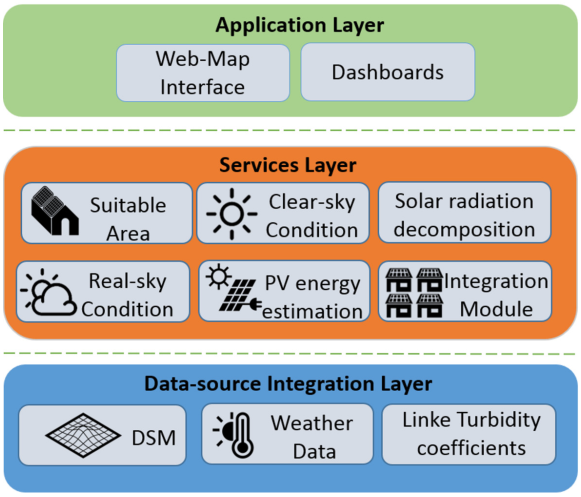


Figure 1. Scheme of the software architecture for PV systems integration into Smart Grids

In the following sections the software architecture is presented, with a brief description of the different modules. The proposed methodology and software architecture, which was previously presented in Bottaccioli *et al.* (2017a), is then applied to a district of the city of Turin, Italy, as a case study.

2. Software architecture for planning PV systems integration into Smart Grids

In this Section, we describe our proposed solution for planning PV systems deployment in a Smart Grid environment and evaluating its impact in the distribution network. As shown in Fig. 1, the distributed software infrastructure consists of three layers: i) *Data-source Integration layer*, ii) *Services Layer* and iii) *Application Layer*. Each layer is described in detail in the following. It is worth noting that we simulate the behaviour of a smart grid through a real-time grid simulator integrated in our architecture.

2.1. Photovoltaic system simulator

In this work, we exploit the PV simulator presented in our previous work (Bottaccioli *et al.*, 2017c, 2016) to estimate the energy generation profiles of PV systems in real-sky conditions. As shown in Fig. 1, the PV simulator has been designed and developed following the microservice approach (Fowler and Lewis, 2014; Newman, 2015) and providing REST (Representational state transfer) Web Services (Fielding and Taylor, 2002). The main inputs of this simulator (see *Data-source Integration Layer* in Fig. 1) are i) a *Digital Surface Model* (DSM) and ii) weather data, i.e. trends of Air Temperature and Global Horizontal Solar radiation (GHI). DSM is a high-resolution raster image. It represents terrain elevation of buildings of interest. A DSM allows recognizing encumbrances on rooftops (e.g. chimneys and dormer) that prevent the deployment of PV panels. In this work, we used a DSM resulting from some LiDAR flights.

The *Services Layer* consists of different software modules and estimates the PV energy production for a given urban area. *Clear-sky condition* module exploits the DSM to estimate the evolution of shadows in rooftops over the year, with 15 minutes intervals. As result, this process produces a shadow model of the city and, together with *Suitable area* module, identifies the available areas on the roof where PV panels can be deployed. The evolution of irradiance on rooftops in real-sky conditions is computed starting from GHI trends retrieved from personal or third-party weather stations such as Weather Underground (accessed October 2017). First, the *Solar radiation decomposition* module decomposes GHI to estimate both Direct Normal Incident radiation (DNI) and Diffuse Horizontal Incident radiation (DHI) (Hofierka and Kaňuk, 2009) exploiting decomposition models in literature, such as Karatasou *et al.* (2003); Engerer (2015) and Ruiz-Arias *et al.* (2010). In decomposing GHI into DNI and DHI, the PV simulator takes into account also the attenuation caused by air pollution by applying the *Linke turbidity coefficient* (Linke, 1922). Then, the *Real-sky condition* module combines DNI and DHI with the shadow model to estimate the irradiance on the available areas obtained in the previous step. The *PV energy estimation* module provides an estimation of the energy production by exploiting all the information computed in the previous steps and by applying the methodology presented in Brihmat and Mekhtoub (2014). The accuracy on estimating the energy production has been already demonstrated in (Bottaccioli *et al.*, 2017c). Finally, we extended the PV simulator with the *Integration Module* that integrates and correlates information coming from the Smart Grid (e.g. energy consumption) with the estimated PV energy production data for the same geographic area. The *Integration Module* also enables the communication with the real-time grid simulator (see Section 2.2). It is worth noting that this module has been designed to integrate also other software platforms for collecting real-time data from the Smart Grid, such as the platforms reported in (Patti *et al.*, 2015, 2016; Pau *et al.*, 2017).

Finally, the *Application Layer* is devoted to user applications, such as *Web-Map interface* and *Dashboards*, to provide information about performed simulations across the city.

2.2. Real-time grid simulator

Real time simulation is a highly reliable method based on electromagnetic transient simulation which can emulate the real world system. It provides very trustable real-like information on impacts and benefits of new strategies or devices, which could support decision makings from real time operation and control phase to long-term planning. The possibility of ex-ante tests reduces costs, and enables more complete and continuous testing of the entire system without interruption. Many possible configurations without physical modification can be also tested safely under possibly dangerous conditions.

Real time simulation is actually reproducing the behaviour of a physical system (e.g. electrical distribution grid) through running its computer-based model at the same rate as actual clock time. In other words, in real time simulation, when the simulation clock reaches a certain time (e.g. 1 s), the same amount of time (1 s) has passed in the real world. It is typically used for high-speed simulations, closed-loop testing of protection and control equipment, and generally all *what-if* analyses. Real time simulation is actually simulating a system, which could realistically respond to its environment, when the inputs/outputs of the simulation are synchronous with the real world.

Considering the advantages of real time simulation, there is a variety of applications to different domains as electricity systems, mechatronics, robotics and industrial automation, automotive application, aerospace, all-electric ships and electric train networks, operator and technician training, electric drive and motor development and testing, and power systems. Among all mentioned fields, power system is the main application domain of real time simulation, using standard hardware-software configuration given by simulator providers. There are two main RTS system providers: RTDS®and Opal-RT®: RTDS products are mainly for power system simulations, and about 80 % of Opal-RT simulators are used for power system applications.

Regarding electricity systems, real time simulation is being widely used in protection and control system development and testing, distributed generation modeling especially renewable energy source (RES) integration (e.g. PV generation penetration), and intelligent grids development.

The purpose of using real time simulator in our work is to model a realistic distribution network to support investigations in terms of PV penetration impacts in real-world situations. The objective is the simulation of the behaviour of prosumers, and the set-up of a Software In-the-Loop (SIL) platform for the laboratory validation of new control, operation, and planning algorithms for smart grids management (Estebsari *et al.*, 2016).

As stated, the distribution grid needs to be first modelled for the specific application. The tool to implement the modelled grid depends on the real time simulation firmware configuration. We use Opal RT with eMEGAsim® configuration which requires MATLAB Simulink® as development environment. Therefore, the grid model is implemented in MATLAB Simulink using Matlab toolbox blocks, our developed blocks, and some external special blocks provided by Opal RT in an additional library. The interface between the development environment and simulator control is called RT LAB®.

2.3. Smart-grid simulation tool

As mentioned in Section 2.1, the *Integration Module* of the PV simulator is in charge of correlating information coming from the

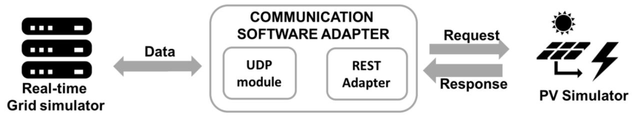


Figure 2. Integration of PV and Real-Time grid simulators

Smart Grid with the estimated PV energy production for the same geographic area. This module also enables the communication with the real-time grid simulator through the *Communication Software Adapter* (see Fig. 2).

The *Communication Software Adapter* has been developed following a methodology presented in Bottaccioli *et al.* (2017b). In its core, the *Communication Software Adapter* consists of two sub-modules: i) *UDP module* and ii) *REST adapter*. The UDP module interacts with the real-time simulation engine through a UDP server-client system: the UDP server receives and processes the information coming from the simulator, while the UDP client feeds the input data into the simulator. The *REST adapter* parses the requests from the simulation engine and translates them into REST calls to remote Web Services provided by the PV simulator. Finally, the Web Services response is retrieved by the *Communication Software Adapter* and its data are pushed into the real-time grid simulator again through the *UDP module*.

Considering the integrated simulation tool as a realized Software In-the-Loop (SIL), the environment which is the smart grid in our case, is executed on the real time simulator. Grid real time simulation module is responsible to emulate real grid behaviour facing different load or generation profile values, and provides the status of the electrical system in terms of power flows, voltage profile, etc. The signals coming from outside of the real time simulator are controlling or defining modelled prosumers behaviour by updating PV generation output. During the simulation the grid model requests the necessary values (active and reactive powers) to update modelled PV generation output, and receives the required data from the PV simulator through appropriate UDP blocks inside the real time model (Fig. 3). The grid model can be run for an electromagnetic transient simulation with 50 μs to 250 μs (or phasor simulation with a few milliseconds) time steps, while the new values of PV generation can be updated every 15 min.

The model is built with the SimPowerSystem (SPS) toolbox of MatLab Simulink. The ARTEMiS software from OPAL-RT is used to provide fixed-step solver dedicated to complex power systems. It is an add-in toolbox to SPS enabling hard real-time simulation of power systems. The main modelled components of the distribution grid are a three-phase voltage source in series with an RL branch as an equivalent model for the upstream high voltage (HV) grid connected to a slack bus, three-phase two-winding transformers, three-phase π section lines to model medium voltage (MV) lines

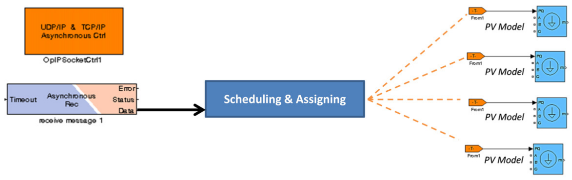


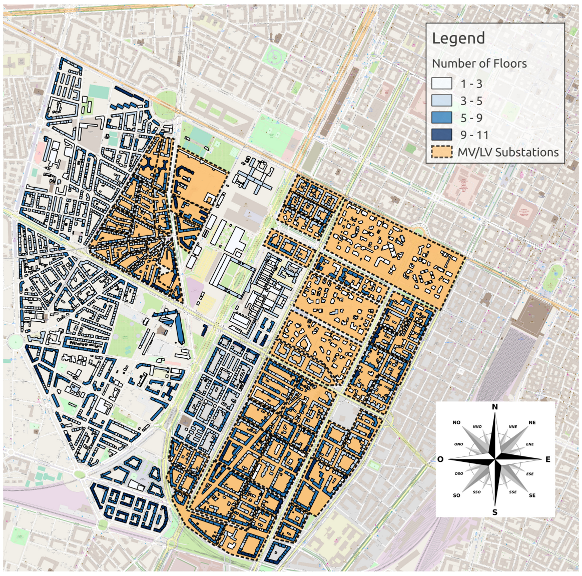
Figure 3. Real time simulator receiving data links to the distributed PV models over the grid

and three-phase three-wire dynamic load models with external control of active and reactive powers to model the prosumers. The prosumers in our case study are (mainly) residential household as customers with their PV arrays on top of the building roofs as distributed producers. The net active and reactive powers of the prosumers are considered positive when the prosumer generation is lower than consumption.

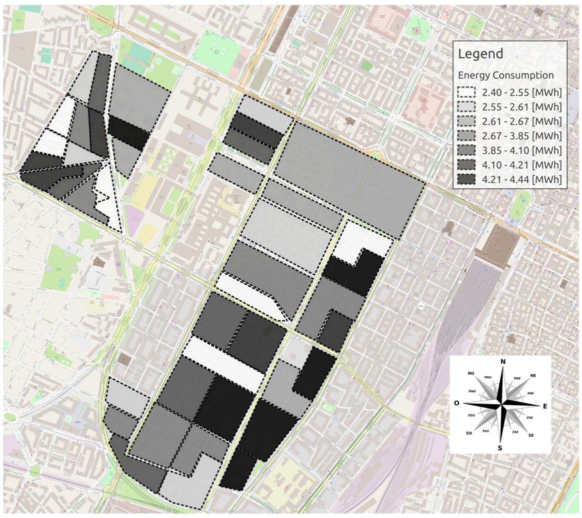
3. Case Study and Results

The proposed methodology has been tested using information about Turin, which is a city in the North-West of Italy. The case study area involves a district where the DSM, with a resolution of 0.5 m^2, and the MV grid topology are available. This area counts 2198 residential buildings connected to 43 MV/LV substations. Each substation serves an area whose extension depends on the number of connected households, as reported in Fig. 4(a). To evaluate the integration of PV systems in the district, a summer sunny and a summer cloudy day have been simulated. During summer days, in Italy, the energy consumption of residential users is lower than in winter days (Maggiore, 2012) because residential households do not usually have air conditioning systems. On the other hand, during winter season, heating systems circulation pumps run almost all day long. In addition, sunny days in summer produce more electricity from PV systems and this can be a critical situation for distribution grids. Fig. 4(b) shows the daily energy consumption for each substation (consumption data were obtained through measurements in MV/LV substations). Energy consumption is not proportional to the area served by the sub-station, but rather to the number of households. Unfortunately, information about DNI and DHI are not available. Hence, the *Solar radiation decomposition* module (see Fig. 1) is used and the values of GHI radiation are retrieved, via web-services, from a weather station located in the center of the district. Finally, high quality mono-crystalline Si PV modules with efficiency $\eta_{pv} = 20.4\%$ in standard test conditions (STC) and thermal coefficient of maximum power $\gamma_{pv} = -0.38\%/^{\circ}C$ have been considered.

The electricity grid is a medium voltage (MV) network with five feeders derived from three 22kV busbars of a 220/22 kV primary substation. Each of the busbars is energized by a 220/22 kV transformer. The total length of MV lines, mostly constituted by underground cables, is around 39 km (Fig. 5). There are 49 MV/LV



(a) Substation areas with buildings



(b) Substation daily energy consumption

Figure 4. Case Study Area

substations out of which 43 are supplying loads (mainly 2200 residential buildings). The MV/LV transformers are characterized by voltage ratio of 22 kV/400 V and a nominal power of 400 kVA, 250 kVA or 160 kVA.

We use the integrated co-simulation platform to assess and discuss the impacts of rooftop PV penetration in this urban district on grid operation status from different perspectives. The advantages of this tool can be seen both in planning and operation.

In phase of planning and network reinforcement, the tool can be used to assess the impacts of different levels of PV penetration on the existing grid. For example, we will show that problems can involve tranformers capacity in case of high penetration of PV in low voltage grids. As another example of planning, homogeneous distribution of PV generation with respect to the level of demand should be taken into account. In our simulation, we will also show how neglecting this point can introduce challenges in the network voltage control. Based on these studies, existing network can be reinforced through investment, or new regulation can be adjusted to meet the requirement of the system (e.g. when new regulations are being made to provide incentives to install PV arrays on the rooftop, different areas may get different incentives). Furthermore, impacts on network could be mitigated by exploiting different tilt angles and orientations of PV systems, as reported by Freitas *et al.* (2018a). However, objective of this work consists on maximizing the energy production and evaluating the effect on the grid.

In the operation phase, the co-simulation tool proves how the PV simulator can provide in time and quite sufficient information about generation to support low voltage system state estimation (Pau *et al.*, 2016). Since there are too many low voltage connected PV panels in the grid, there are a lot of challenges in the estimation of generation data due to the need to install new suitable smart meters, acquiring a huge number of measurements, retrieving so much data so frequently (e.g. every 15 minutes), and fast data processing. In our simulation, we will show how system operator can forecast and monitor substation power flow by using the data generated by the PV simulator.

In the district under analysis (see Section 3), among all the building rooftops the *Suitable Area* module (see Fig. 1) identified 944 areas, equivalent to $71595.53\ m^2$, suitable for deploying PV systems with a nominal power potential equal to $14.21\ MW$. The distribution of power and energy production for each MV substation area during a sunny day in summer is shown in Fig. 6(a) and Fig. 6(b) respectively. As the simulation process considers also the shadows of surrounding buildings and vegetations, rooftops areas with high power production potential can have an energy production impact lower than areas with low power production potential (see Fig. 6(a) and Fig. 6(b)). During the sunny day, the peak power production is around $3.77\ MW$ and the energy production is equal to $28.41\ MWh$. On the other hand, during the cloudy day, it is around $3.94\ MW$ with an energy production of $16.95\ MWh$. The peak power production does not reach the nominal peak power in either of the two cases. The higher peak power reached in the cloudy day can be explained through the phenomenon of irradiance spikes caused by broken clouds (ISBC) (Chicco *et al.*, 2015) or by a lower temperature of the PV arrays.

We discuss in the next paragraphs the results in the two above-mentioned phases (i.e. planning and operation) for voltage control, transformers capacity and substation power flow.

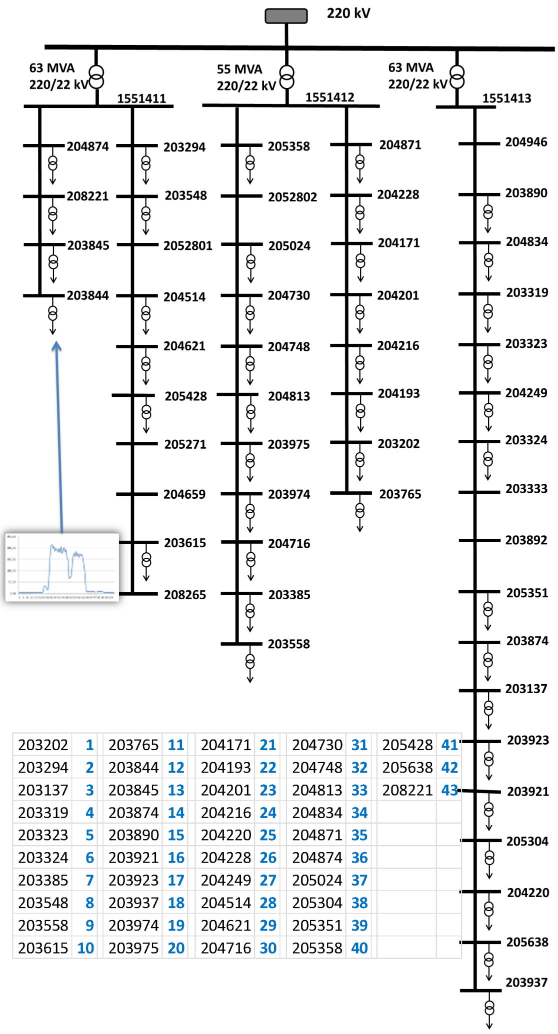
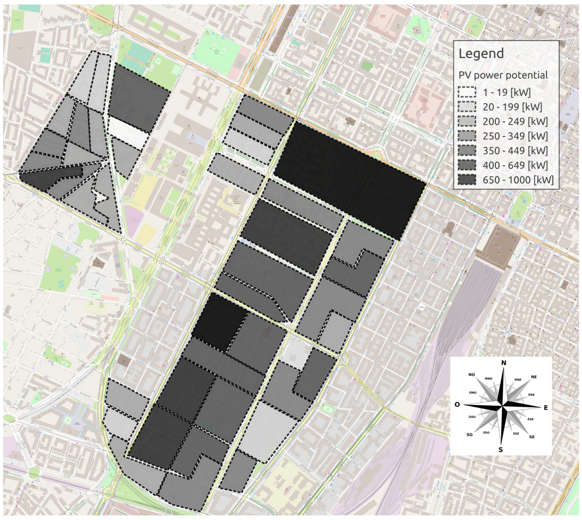
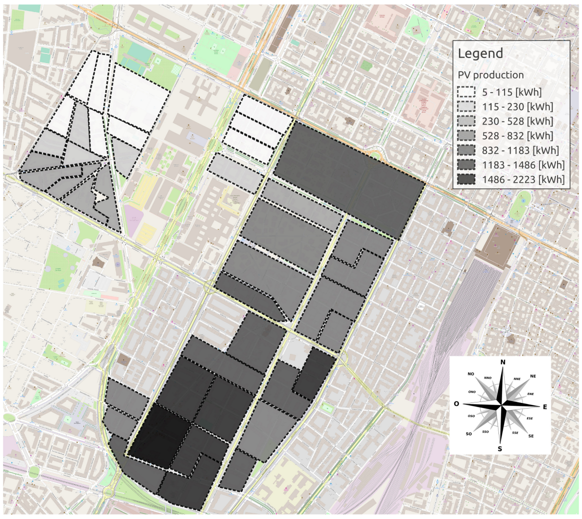


Figure 5. Case Study electricity grid



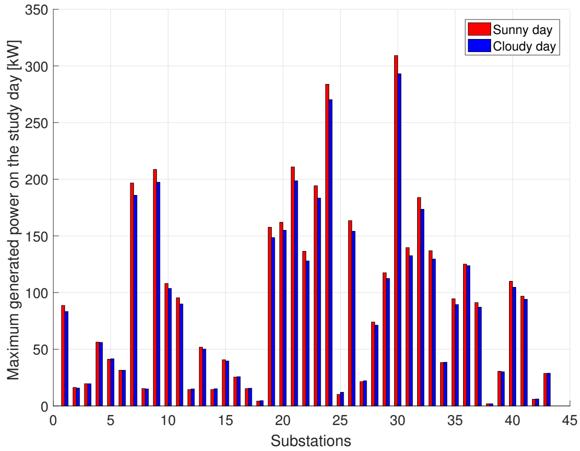
(a) PV power potential (sunny day)



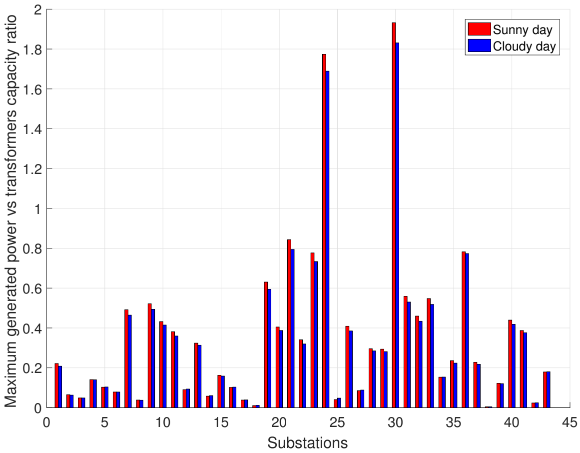
(b) Total PV generation (sunny day)

Figure 6. PV potential and energy production

Voltage Profile. In distribution systems, tap changers of the HV/MV transformers at the primary substations would try to keep the voltage at the MV busbars at a certain level, by measuring and monitoring transformer current. When a transformer feeds several feeders, characterized by different PV penetrations with respect to peak loads, the voltage profiles at the secondary substations on the different feeders follow different profiles. This means that monitoring and regulating the voltage at the beginning of feeders is not necessarily sufficient for keeping voltages of all the substations of all the lines in the desired range. For example, in feeders where generation is higher, in some substations voltages may be above the admissible limit. In our case, the first feeder from the left is characterized by low demand, while its PV generated power is more or less the same as the others. In the second feeder, MV/LV transformers have greater sizes (400 kVA and 250 kVA), and consumption is higher than in the left one in which smaller transformers (160 kVA) are installed. We run the co-simulation for a summer scenario of a sunny day. Fig. 8 and Fig. 9 shows aggregated generation and consumption at substaions 7, 9, 21, and 24, and Fig. 10 shows the net active power injected into the downstream LV grids connected to these subsations. Substations 21 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. 11), 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.



(a) Maximum generated power in a Sunny or Cloudy day



(b) Ratio between maximum generated power and transformer capacity in a Sunny or Cloudy day

Figure 7. Maximum PV generation of each MV/LV substation and transformers capacity

Transformers capacity. The MV/LV transformers at the secondary substations are modelled based on the existing transformers in the real network, which were installed without considering the new PV generation capacity. Maximum aggregated generated power of each substation on the study day is shown in Fig. 7(a).

Transformer capacity is based on maximum apparent power in [kVA] and can be considered for both power absorption and injection (the red continuous lines in Fig. 12). All values of power generation and consumption are calculated for every 15 min of the study day, therefore there would be 96 snapshots of the systems status. To reach the worst scenario, we consider the maximum net consumption (subtracting local generation from local consumption) of each substation during the study day, indicated with large green bars in Fig. 12. As shown with narrow dark bars, the maximum load consumption of all substations is within the transformer capacity

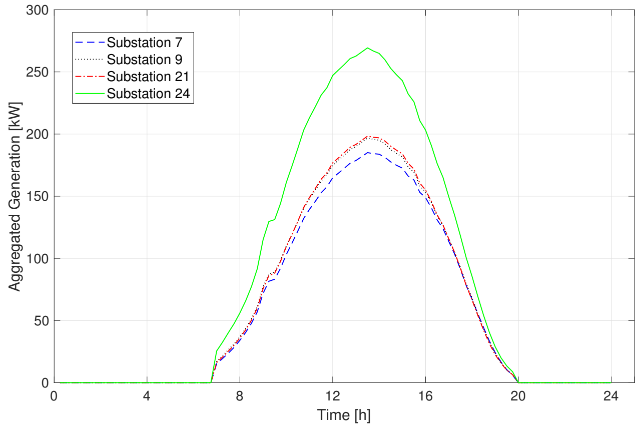


Figure 8. Aggregated PV generation in some substations

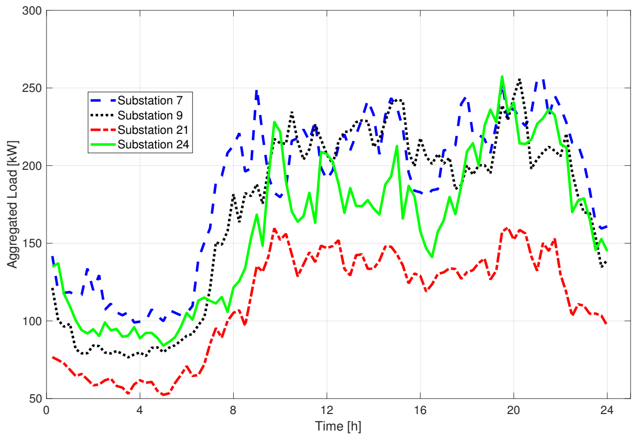


Figure 9. Aggregated load in some substations

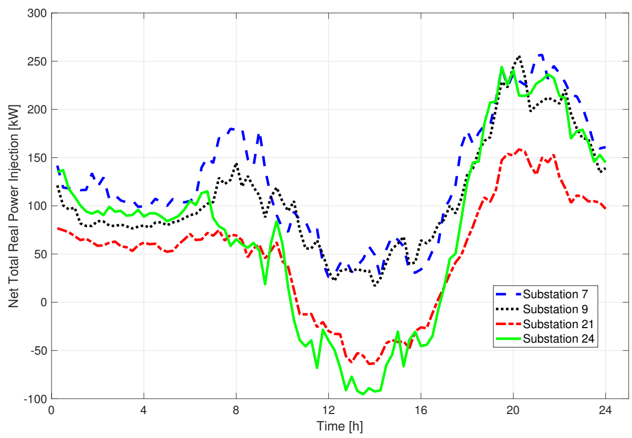


Figure 10. Net total real power injection

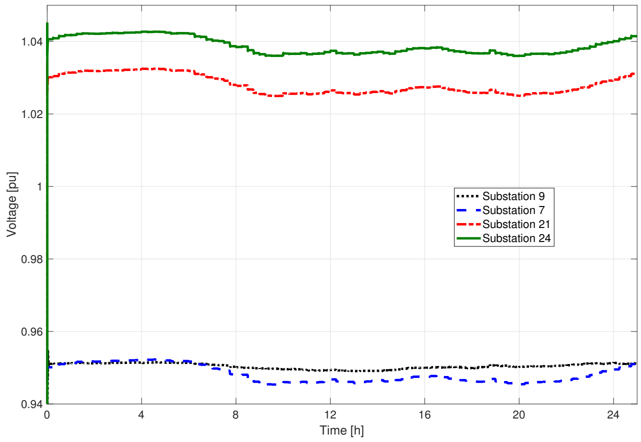


Figure 11. Voltage profile of some substations

range, while integrating PV generation would cause violations in 2 substations (24 and 30 in Fig. 12). The maximum net consumption in these 2 substations exceeds the transformers capacity due to high amount of PV generation and low consumption. This highlights the fact that in cases where local generation is much more than local demand, either the installation of PV arrays 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. Another possible approach consists on installing PV system with different tilt angles and orientations to match power production of PV systems with power consumption. This reduces the power injected in the grid but also reduces the maximum power that can be potentially produced by PV systems. Hence, an accurate multi-criteria cost-benefit analysis should be performed to evaluate the best option.

Power Flow. In this case study, we analyze a scenario in which almost all residential buildings install PV arrays on their rooftops, which reach their peak power on a sunny day of July. The PV generation module does not consider grid constraints and introduces PV generation with the highest possible penetration, considering the available surface areas on the rooftops. In our case, penetration level is 51%, where PV penetration level is defined as total peak PV generation divided by total peak load apparent power. Total PV generation profile in this area in a cloudy day during July is shown in Fig. 13 with a green solid curve. An effect of high PV penetration on such a cloudy day can be observed when generation profiles change dramatically within a few seconds. If a huge generation drop occurs exactly in the ascending period of consumption profile, in high PV penetration scenarios, a large power deficit will be experienced. The blue dashed curve shows the result of power flow at the primary substation in terms of total active power injected to the distribution system; the steep descents means a rapid demand reduction in the distribution system (1.7 MW), and the steep rises imply a fast demand increase in the distribution system. Thanks to the PV simulator, Distribution Management System (DMS) can perform some analysis in advance (e.g. 15 minutes earlier) to prevent these steeps, for example by demand side management through flexible loads, or PV curtailment.

The added-value of this integrated framework is the possibility of concurrently taking into accounts both real-like PV generation behavior from one side, and grid behavior and constraints on the other side, highlighting the fact that it can support DMS during operation mode.

4. Conclusion

In this paper the authors presented an integrated real-time platform for the assessment of the impacts of PV distributed generation in smart grids. The platform is constituted by two main components, a PV simulator and a real-time distribution network simulator. The two components are interconnected over the Internet through a communication software adapter. The proposed tool allows for the simulation of the power produced by PV generators on buildings rooftops under real sky conditions, and for the analysis of the distribution grid behaviour in this distributed generation scenario. The tests carried out on a case study based on a district of Turin, Italy, show that the distribution network, in the actual configuration, may not be ready to accommodate all the generation capacity that can be installed if all the available rooftop surface is exploited as, for example, in certain hours of the day and in certain days of the year the capacity of some transformers is exceeded. The presented platform can be useful, in the future, to analyse different penetration scenarios, to test new operational procedures for the distribution network, to verify the impact of new connection rules and new regulations. Furthermore, the presented platform could be coupled and integrated with energy consumption estimation tools such as those described in Gruber *et al.* (2016) if measured load profiles are missing. In the case study presented in this paper, the behaviour of the LV grid is neglected and all the prosumers fed by a substation are studied in an aggregated way. This is due to two main problems: usually it is not easy to obtain detailed and precise information on the LV distribution system and considering also LV feeders would make the simulation complexity too high. In this case study, to estimate energy production of PV systems, real sky conditions have been simulated by applying some models in literature to decompose Global Horizontal Irradiation into Direct and Diffuse Irradiation. This can be considered a limitation of the PV simulator because the final error rate increases. However, the PV simulator is ready to exploit also real measurements sampled by sensors for Direct and Diffuse Irradiation. This bypasses the decomposition models and decreases the error rate. However, these sensors are not widespread installed in common weather stations because of their high cost.

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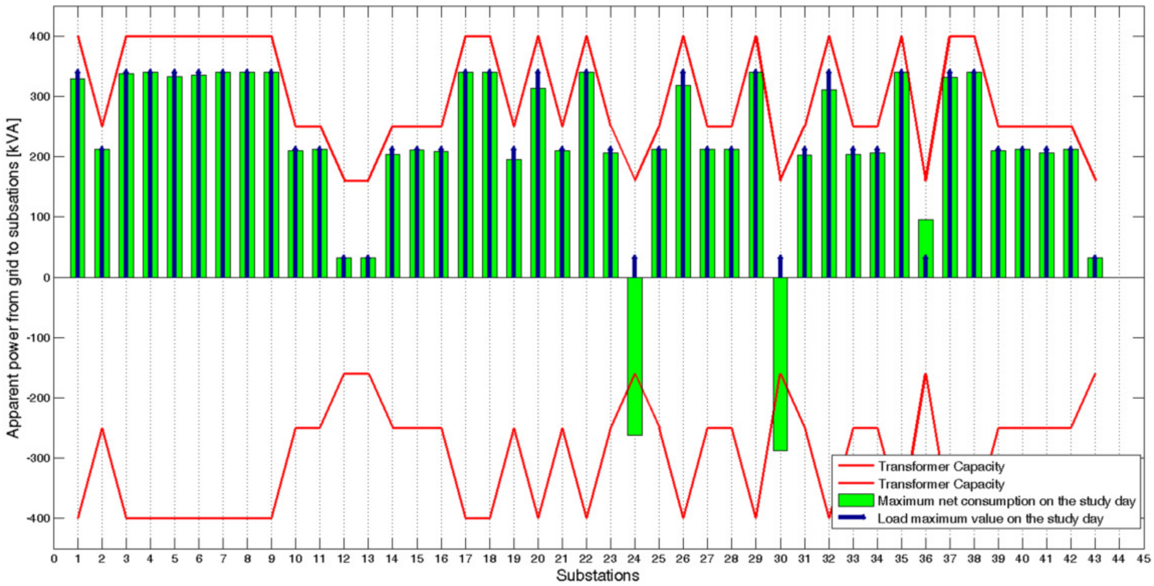

Figure 12. Transformers capacity results

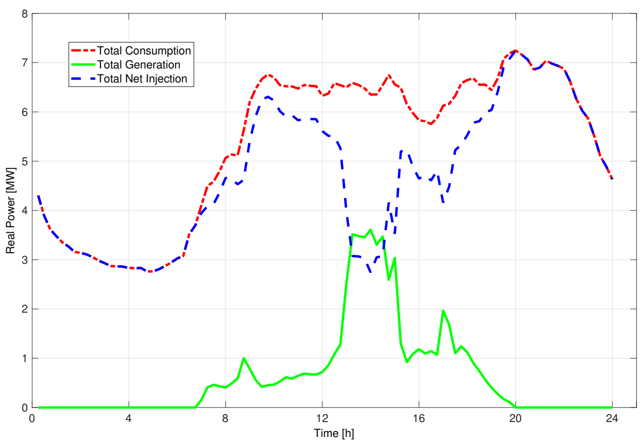

Figure 13. Total load, generation, and net real power

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