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Impacts of Non-Programmable Renewable Sources Penetration on the Italian Energy System: A Tool for Scenario Analyses

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Abstract

The penetration of renewable sources in the national energy mix is necessary for most of the industrialised countries in order to comply with the ever-challenging constraints imposed by environmental impact reduction policies.
However, a big family of renewable sources have the peculiarity of being non-programmable, that is very variable throughout hours and seasons. While the traditional electrical grid management philosophy has always been oriented towards the timely fulfilment of the demand via a set of conventional uninterruptible (or hardly so) large power plants complemented with a set of quickly adjustable smaller power plants, the integration of non-programmable renewable (NPR) power plants may represent a challenge.
The planning of this kind of plants has to be accurately assessed as an over-installation may result in an overproduction of electricity that the existing electrical network cannot be able to transmit and the system to absorb.
The paper presents a tool, inspired by previous NREL studies, to evaluate the effects of the penetration of NPR sources in the Italian energy mix. The study starts from the definition of the load profile of the country and it assesses the percentage of load that can be fulfilled by NPR sources until possible, taking into account the un-flexibilities of the electrical system, mainly due to the base load power plants that can hardly be adjusted. If more NPR electricity is instantly produced, this represents a waste (of energy and money).
Thanks to the developed tool, a set of possible scenarios for the different geographical areas of Italy are presented and discussed, focusing in particular on the increase in the flexibility of the electrical system and in the penetration rate of NPRS.

Keywords:	Non-programmable renewable sources; Electrical grid; Energy mix; Capacity; Storage

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1. Introduction

The penetration of renewable sources in the energy mix of a country is more and more necessary to comply with the constraints and targets set by environmental impact reduction policies. However, renewable sources (in particular wind and photovoltaic) have the peculiarity of being variable throughout hours and seasons and, as a consequence, they can be considered non-programmable (Non-Programmable Renewable Sources, NPRS). This fact originates several issues related to their integration, that can be clearly understood by analysing the structure of the traditional power systems and their management, mostly focused on conventional (and almost uninterruptable) large plants for covering the base load and adjustable smaller plants for the peak coverage.

Considering the studies already available in the scientific literature, it can be noticed that a large number of authors highlight the need for quantitatively evaluating the impacts on the power system of an increasing penetration of NPRS. This is due to the inflexibility of the system itself and to the necessity of additional solutions in order to allow large penetration rates avoiding relevant excess of NPRS production.

Among these studies, the one carried out by Denholm et at. [1] can be mentioned. In particular, it focuses on the assessment of the effects of solar photovoltaic (PV) on the ERCOT (Electric Reliability Council of Texas) power system, performed by simulating scenarios in which up to 50% of the system energy is produced by PV. Several options in order to avoid the limitations related to the integration of significant amount of PV have been considered. The authors highlighted that an increase in system flexibility is crucial to ensure a relevant integration; however, additional actions are needed to manage the excess of PV production, especially during non-summer seasons. For this purpose, the potential contribution given by load shifting and energy storages has been explored.

Denholm et al. [2] also performed further simulations on the ERCOT grid to analyse the system variations corresponding to scenarios in which different mixes of solar PV, concentrating solar power (CSP) and wind are able to satisfy up to 80% of the electricity demand, under the hypothesis that the ERCOT system cannot exchange power with other grids. The results show that an increase in flexibility allows NPRS penetration rates up to 50% with curtailments lower than 10%; if a penetration rate of 80% is requested, the increase in flexibility is not sufficient by itself but a combination of storage systems (both electrical and thermal) and load shifting is needed.

Denholm et al. [3] in a technical report of the National Renewable Energy Laboratory (NREL) also stress the economic issues related to the increase in NPRS penetration, including the integration costs of NPRS and the evaluation of the maximum NPRS penetration before storages become the most economic alternative for further increase. This study also underlined the opportunity of performing optimisation analyses (i.e. of finding the system configuration that corresponds to the minimum cost) and cost/benefits analyses related to the storage systems.

Referring to works carried out by other authors, the one of Kirby et al. [4] still focused on the US power system, and in particular on the modification of the operating reserve policies caused by the increase in the penetration of NPRS. It highlights the need for these operating reserve requirements to become dynamic, particularly considering the possible relevant level of penetration that NPRS could reach in the future.

As the NPRS issue arises in selected geographical areas where the potential is high, it is interesting to mention the work of Solomon et al. [5], who analysed and quantified the effects on the Israeli power system of the integration of very large-scale photovoltaic plants (VLS-PV). They underlined that this quantification is important to help planners in finding the optimal siting of VLS-PV plants and the best technological option to adopt and in defining future grid expansion strategies able to take into account the need for increasing flexibility (in anticipation of a possible increase in NPRS penetration).

Focusing again on the Israeli power system, Fakhouri et al. [6] based their analysis on the Government's target of a NPRS penetration equal to 10% by 2020, evaluating the need for backup in the system, also considering that Israel – from an electrical point of view – is a closed market, i.e. an electricity island. Like many of the previously mentioned studies, this work shows that an increase in NPRS penetration rate has to be coupled with an increase in flexibility of the system and with the implementation of options like storages in a framework of a smart management of the network in order to ensure quality and reliability of the electricity supply.

Erdinc et al. [7] underlined the additional critical issues that a high penetration of NPRS in power generation could cause in insular electric systems, which usually suffer from a structural fragility in comparison with the continental ones. This weakness is mostly due to the low number of interconnections with the main grid and the small size of the local networks (with a low number of generators causing a low inertia of the systems and relevant sensibility to possible outages).

Oree et al. [8] show the need for considering the variability and intermittency of the NPRS in planning techniques (commonly based on least-cost optimisation or, more recently, on multi-criteria methodologies), critically analysing the models and methodological approaches currently available in the scientific literature.

Ulbig et al. [9] proposed modelling techniques to describe and evaluate the operational flexibility of individual power system units and of clustering of several power system units.

Franco et al. [10] focused on some possible scenarios able to ensure an optimal NPRS penetration in the Italian energy system. The authors underlined that an increase in renewable penetration could be effective in reducing the consumption of fossil fuels (in particular natural gas for power generation), thus enhancing the energy security level of the Country (contributing to decrease the relevant dependency on import of fossil commodities). They also suggested that the increase in CHP plants and electric vehicles could promote the integration of wind and photovoltaic power. They further highlighted the possible issues deriving from the distance between large hydropower plants (mainly located in the North) and wind farm (mainly located in the South), which could impede the implementation of a wind and water model helpful in controlling the power intermittency.

Still referring to an Italian case study, the study performed by Barelli et al. [11] can be mentioned. In this work, the authors focused on a peculiar issue of the Italian power system, i.e. the effect of the renewables penetration on the thermoelectric production. In fact, policy strategies aiming at promoting renewable sources penetration (especially photovoltaic) implemented in the period 2007-2013, the concurrent absence of additional actions to optimise their integration in the power system and the higher cost of natural gas, with respect to coal, led to the use of gas combined cycle (CC) plants as backup for renewable plants and no more as base-load plants, thus causing a decrease in the thermal generation efficiency, mechanical stresses on the CC plants and an increase in the related maintenance costs. In order to overcome this problem – as alternative solution to the retrofitting of the existing power plants – the authors suggested the integration between energy storage systems and large CC plants, allowing them to operate again close to the nominal conditions (with relevant benefits from the efficiency point of view), by storing the produced energy surplus.

Eventually Gullì et al. [12] and Bigerna et al. [13] analysed the economical and market aspects related to the enhancement of renewables penetration in Italy. Gullì et al. evaluated the impact of photovoltaic power generation on the wholesale electricity prices: they showed that an increase in production from PV could lead to non-univocal effects on the price. Bigerna et al. studied the influence of RES penetration on the possible contagion effect among the six regional electricity markets in which Italy is divided (North, Center-North, Center-South, South, Sicily and Sardinia) as a consequence of a shock in a certain market: they demonstrated that evidences of an increase in such effects caused by renewables penetration cannot be found.

Starting from these studies and findings, the goal of this work is to analyse the Italian power system, which can be considered an interesting case study due to its peculiarities. The analysis of the NPRS effects on the Italian electrical transmission grid under different penetration rates and flexibility levels is performed by developing a tool based on the NREL approach methodology [3]. The penetration rates proposed are assumed in order to verify the sensitivity of the present system.

2. Methodology

The adopted approach aims to calculate the percentage of energy produced by NPRS that cannot be immediately consumed because it exceeds the instantaneous flexibility of the system, i.e. the difference between the instantaneous load and the minimum output power of the other plants belonging to the analysed system. This minimum power is defined inflexibility (Figure 1) and corresponds to the threshold below which the production of the base load plants has to be modified, often causing the shutdown of certain units in order to avoid damages.

Starting from the load profile and the NPRS production profile, the net load is evaluated as the difference between the hourly load of the considered system and the hourly production from NPRS. As a consequence, the obtained profile corresponds to the load that has to be covered by base-load units, load-following units and peak shaving units. If the net load is lower than the inflexibility value, the surplus of energy produced by NPRS plants cannot be instantaneously consumed: if storage systems are available, it could be stored and used later, otherwise some NPRS plants have to be disconnected from the grid.

2.1. Data

To proceed with the analysis, input data were collected from the Italian grid operator, Terna, which, in a dedicated section of its website [14], provides access to data related to load, generation and transmission profiles. Figure 2 shows values of hourly load and NPRS generation retrieved on Terna database for a representative day in 2013 (January 3rd). To prepare this figure, data were summed up for the different Italian areas and the NPRS production has been assumed equal to the sum of wind and photovoltaic electricity production. Later in the analysis, the different geographical areas were kept separated to allow a more structured analysis.

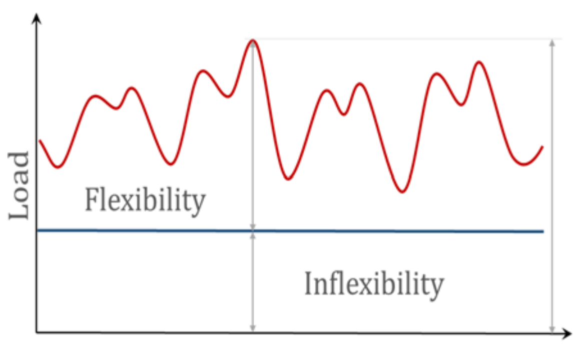

Figure 1. Definition of Flexibility / Inflexibility in an electric system

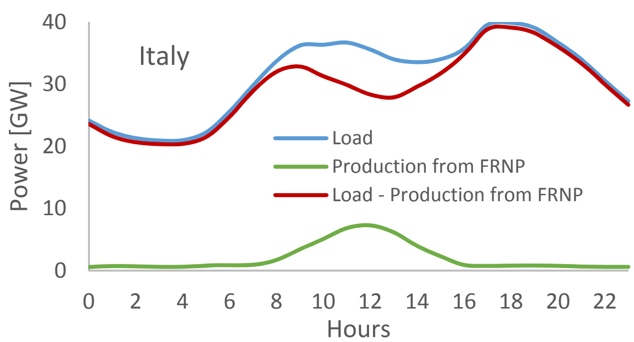

Figure 2. Typical load and NPRS generation profile for a sample day (January 3rd, 2013) [14]

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2.2. Procedure

A MATLAB-based simulation tool has been developed; the general approach adopted for the implementation can be summarized as follows.

Input Data

Starting from an Excel template including data on the hourly load, the hourly wind and photovoltaic production (expressed in GW) in 2013 for several Italian areas (corresponding to the regional market zones mentioned in Section 1), the algorithm firstly calculates the following parameters:

- Electricity production from NPRS for each hour in all the considered areas:

$$\mathrm{NPRS\ production\ (h,z)} = \mathrm{PV\ production(h,z)} + \mathrm{Wind\ production\ (h,z)} \quad [\mathrm{GW}] \tag{1}$$

where:

h = hour (ranging over the year)

z = ID of the geographical area

$\mathrm{h} \in \mathbb{N}\,[0\,;8760]\,;\quad \mathrm{z} \in \mathbb{N}\,[1\,;7]$

$\mathrm{z} = 1 \rightarrow \mathrm{NORTH}$

$\mathrm{z} = 2 \rightarrow \mathrm{CENTER-NORTH}$

$\mathrm{z} = 3 \rightarrow \mathrm{CENTER-SOUTH}$

$\mathrm{z} = 4 \rightarrow \mathrm{SOUTH}$

$\mathrm{z} = 5 \rightarrow \mathrm{SICILY}$

$\mathrm{z} = 6 \rightarrow \mathrm{SARDINIA}$

$\mathrm{z} = 7 \rightarrow \mathrm{ITALY}$

- Net load for each hour in each geographical area:

$$\mathrm{Net\ load\ (h,z)} = \mathrm{Load\ (h,z)} - \mathrm{NPRS\ production\ (h,z)} \quad [\mathrm{GW}] \tag{2}$$

- Annual load and NPRS production in each area:

$$\mathrm{Total\ load\ (z)} = \frac{1}{1000} * \sum_{\mathrm{h}=1}^{8760} \mathrm{Load\ (h,z)} \quad [\mathrm{TWh}] \tag{3}$$

$$\mathrm{Total\ NPRS\ production\ (z)} = \frac{1}{1000} * \sum_{\mathrm{h}=1}^{8760} \mathrm{NPRS\ production\ (h,z)} \quad [\mathrm{TWh}] \tag{4}$$

- Percentage contribution given by NPRS to the total load in each area:

$$\mathrm{NPRS\ contribution\ (z)} = \frac{\mathrm{Total\ NPRS\ production\ (z)}}{\mathrm{Total\ load\ (z)}} * 100 \quad [\%] \tag{5}$$

- Peak load and minimum load:

$$\mathrm{Peak\ load\ (z)} = \max\big(\mathrm{Load(h,z)}\big) \quad [\mathrm{GW}] \tag{6}$$

$$\mathrm{Minimum\ load(z)} = \min\big(\mathrm{Load(h,z)}\big) \quad [\mathrm{GW}] \tag{7}$$

- Minimum flexibility factor of the system:

$$\mathrm{FF_{minimum}(z)} = \frac{\mathrm{Peak\ load(z)} - \mathrm{Minimum\ load(z)}}{\mathrm{Peak\ load\ (z)}} * 100 \quad [\%] \tag{8}$$

NPRS penetration and Flexibility Factor

For each geographical area, the annual quantity of energy produced by NPRS that cannot be instantaneously consumed is evaluated as a function of the imposed NPRS penetration and of the Flexibility Factor of the system.

First of all, the factor *K* is defined as the ratio between the imposed NPRS penetration and the corresponding annual production:

$$\mathrm{K(z)} = \frac{\mathrm{NPRS\ penetration}}{\mathrm{NPRS\ contribution\ (z)}}\,;$$

$$\mathrm{NPRS\ penetration} \in \mathbb{R}\,[0\,;100] \tag{9}$$

$$\mathrm{Total\ NPRS\ (z)} = \mathrm{K(z)} * \mathrm{Total\ NPRS\ production\ (z)} \quad [\mathrm{TWh}] \tag{10}$$

For each area the inflexibility corresponding to a certain imposed Flexibility Factor *FF* is then evaluated:

$$\mathrm{Inflexibility(z)} = \mathrm{Peak\ load(z)} * \left(1 - \frac{\mathrm{FF}}{100}\right) \quad [\mathrm{GW}] \tag{11}$$

where:

$$FF \in \mathbb{R}\,[FF_{minimum}(z)\,;100]$$

The net load profile corresponding to the imposed NPRS penetration is:

$$\mathrm{Net\ load\ (h,z) = Load\ (h,z) - K(z)} *$$
$$* \mathrm{\ NPRS\ production\ (h,z)\quad [GW]} \qquad (12)$$

The amount of energy given by NPRS that cannot be instantaneously consumed is then:

$$\mathrm{Excess\ (h,z)} = \begin{cases} \mathrm{Inflexibility\ (z) - Net\ load\ (h,z)} \\ \mathrm{if\ \ Net\ load\ (h,z) < Inflexibility\ (z)} \\ 0 \\ \mathrm{if\ \ Net\ load\ (h,z) \geq Inflexibility\ (z)} \end{cases} \qquad (13)$$

Summing over the total number of hours, the annual quantity of NPRS energy that cannot be immediately consumed is:

$$\mathrm{Excess_{annual}(K, FF, z)} =$$
$$= \textstyle\sum_{h=1}^{8760} \mathrm{Excess(h,z)}\quad \mathrm{[GWh]} \qquad (14)$$

As a consequence, the percentage rate of unconsumed energy from NPRS referred to the total energy yearly produced by NPRS can be expressed as:

$$\mathrm{Excess\ rate\ (K, FF, z)} =$$
$$= \frac{\mathrm{Excess_{annual}(K,FF,z)}}{\mathrm{Total\ NPRS\ (K,z)}} * 100\quad [\%] \qquad (15)$$

By applying the above described procedure to different NPRS penetration and *FF* values, the evolution of the Excess rate for each geographical area can be obtained.

3. Results

The Excess rate as a function of the NPRS penetration is plotted in Figure 3 and 4 a-f (respectively at National and area scale) for different *FF* values (i.e. 70%, 80%, 90% and 100% for all the areas and 60% for the major islands) where *FF* = 100% means that the amount of energy produced by NPRS is sufficient to cover the entire annual load).

In all the simulations, the obtained curves are monotonically increasing: the annual amount of energy produced by NPRS that cannot be instantaneously consumed increases when the NPRS penetration increases or *FF* increases.

Referring to the single areas, in the case of NPRS penetration = 100%, it can be noticed that in the most favorable case about 30% of the NPRS production cannot be instantaneously consumed (SOUTH with *FF*=100%), while in the worst case the amount of inconsumable NPRS energy is higher than 70% (NORTH with *FF*=70%).

In particular, NORTH and SOUTH areas show a behavior slightly different in comparison with the one of the remaining areas, as – for the same *FF* value – the amount of NPRS production that cannot be instantaneously consumed is higher, as it can be noticed comparing the curves represented in Figure 4 for a certain *FF* (for instance, *FF*=70%).

4. Discussion and conclusions

The results obtained in this study highlight the relevant role that the amount of energy from NPRS that cannot be instantaneously consumed plays when the issue related to the integration of the NPRS in the power generation system is taken into account. As previously shown in the analysed case study, in fact, this parameter can reach high values (in particular, it can be equal to 70% of the production). As a consequence, if alternative solutions (like storage systems or ad hoc interconnections) are not available, this limitation can have a significant impact on the increase in NPRS penetration, especially for power systems characterized by an already high amount of NPRS installed capacity: this is due to the fact that further new wind or photovoltaic plants could be affected by longer payback time and the whole management of the system could be more complex.

In order to reduce the amount of energy that is not instantaneously consumed, different alternative options can be explored.

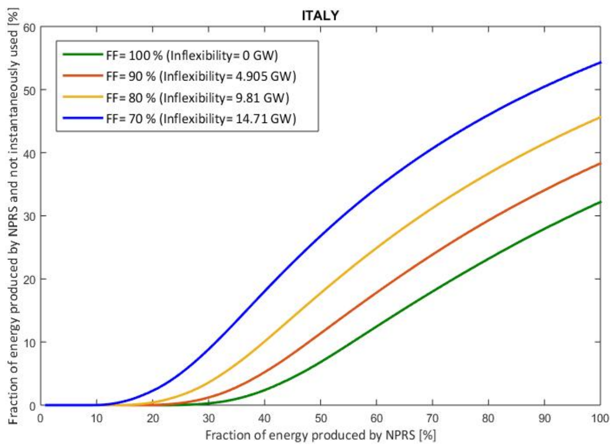

Figure 3. Energy yearly produced by NPRS that cannot be instantaneously consumed (Excess rate), expressed as a function of the fraction of energy produced by NPRS (NPRS penetration) for different *FF* values at National scale

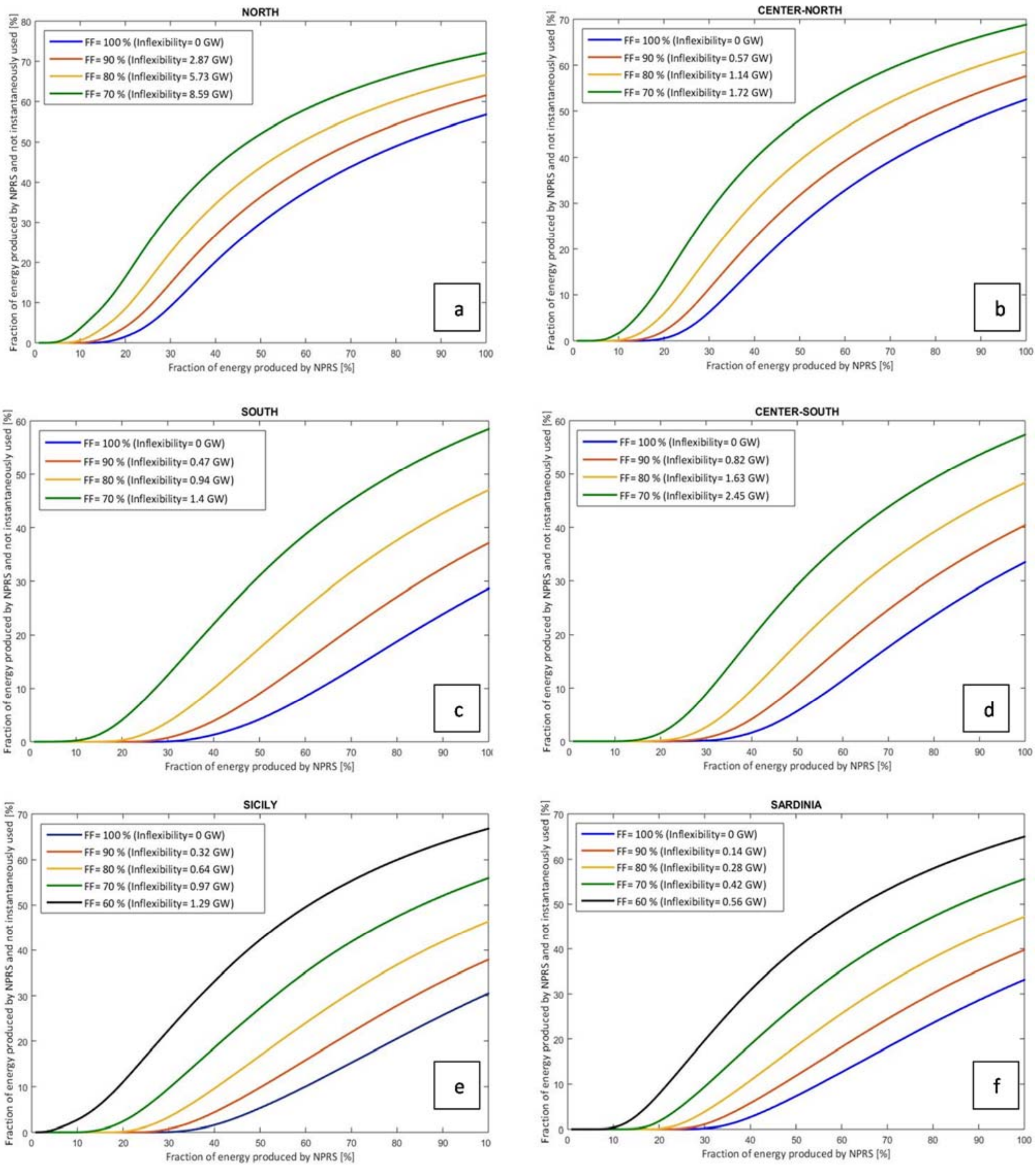

Figure 4. Energy yearly produced by NPRS that cannot be instantaneously consumed (Excess rate), expressed as a function of the fraction of energy produced by NPRS (NPRS penetration) for different *FF* values at area scale

The first one is the increase in the flexibility of the power system. This goal could be reached by substituting the base load plants with more flexible ones (like load-following units). These interventions, however, are characterized by relevant investment costs and the obtainable benefits could be not so relevant, because – as previously seen – even in the case of a Flexibility Factor equal to 100% a significant amount of NPRS energy still cannot be consumed, especially in some areas. It can be noticed that this solution could be more effective if applied to Southern Italy and to the islands (Sicily and Sardinia).

The second alternative is to increase the transmission capacity among the different areas. This solution gives only limited benefits in terms of reduction of the Excess rate and requires relevant investments; however it can be useful not only for the purpose of allowing a better management of the NPRS but mainly to obtain a more reliable service and an easier dispatching.

The last option is the introduction of storage systems that can be particularly valuable for electrical systems characterised by an NPRS penetration of about 60% and an NPRS production mostly based on photovoltaic.

Each of these possible actions has to be considered and explored for each area independently, in order to find an equilibrium among reduction of the NPRS Excess rate, economical aspects, technical feasibility, possible future developments, climatic conditions, etc. However, generally speaking, it has to be underlined that the best solution for each area could be represented by a mix of the three actions above described, according to more detailed studies and analyses.

It can be further demonstrated that the kind of NPRS plants installed, be they photovoltaic plants or wind plants, matters. The power generation mix has to be suitably defined: by well-balancing the contribution given by wind and photovoltaic, a significant reduction in the Excess rate can be obtained, up to 25%. The main advantage of this solution is represented by the fact that no further investments in new plants are required.

Furthermore, the presented case study shows that the obtained results remain similar even if the load profiles are quite different among the considered areas; this means that the NPRS Excess rate seems to be independent from the load profile. However, this outcome should be confirmed by taking into account other typologies of load profiles and by applying the methodology to different countries.

Referring to other possible future improvements, it has to be underlined that the available data used for the analysis are hourly based and so they do not allow to extend the study to the sudden load variations (usually characterised by an order of magnitude of minutes, seconds or fractions of a second) that can happen in a power system. Some of the storage technologies (like flywheels and supercapacitors) are used to face these rapid load changes, and thus a finer timescale should be adopted when these systems are implemented into the algorithm.

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