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ASSESSING FREQUENCY SUPPORT AND VOLTAGE REGULATION BY WIND TURBINES: SCALABILITY AND REPLICABILITY ANALYSIS OF THE OSMOSE PROJECT

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CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

TSO Transmission System Operator	Transmission System Operator
RES	Renewable Energy Sources
POD – Point Of Delivery	Point Of Delivery
SG	Synchronous Generator
OLTC	On Load Tap Changer
UC -Use Case	Use Case
WP- Work Package	Work Package
WT	Wind Turbine
PV	Photovoltaic
BESS	Battery Energy Storage System
BMS	Battery Management System
SSC	System Supervisory Control
DC	Direct Current
PCS	Power Conversion System
SCADA	Supervisory Control And Data Acquisition
AVC	Automatic Voltage Control
SCID	Synthetic Inertia Control Device
SRA	Scalability And Replicability Analysis
S&R	Scalability And Replicability

SOMMARIO

Questa tesi di laurea ha avuto come obiettivo quello di condurre una analisi di scalabilità e replicabilità all'interno di un progetto Europeo relativo alle smart grid. Nel dettaglio, ci si è concentrati sui risultati raggiunti da due impianti eolici pilota che hanno implementato la fornitura di inerzia sintetica e la regolazione automatica della tensione. Da una analisi di scalabilità e replicabilità, ci si aspetta di ottenere sia indicazioni assolute sulle performance delle soluzioni implementate sia, soprattutto, indicazioni su quelle che potrebbero essere le principali barriere e difficoltà nell'implementare le medesime funzioni su differente scala o con differenti condizioni al contorno. Perciò, si sono impostate due diverse tipologie di analisi: una di tipo qualitativo, che ha direttamente coinvolto i partner del progetto con lo scopo di investigare sulla tecnologia utilizzata, e una seconda analisi quantitativa, che si è svincolata dagli aspetti tecnologici dei singoli impianti e quindi ha analizzato la disponibilità e gli impatti che i nuovi servizi di regolazione avrebbero sull'intera penisola italiana. La prima analisi ha permesso di comprendere potenzialità e barriere delle singole implementazioni. La seconda invece, si è resa necessaria per stimare i risultati che potrebbero essere ottenuti estendendo le funzioni innovative a tutti gli impianti esistenti sul territorio, tenendo conto che nella fornitura di servizi basata su fonte eolica è fondamentale considerare la variabilità e arbitrarietà caratteristica del vento.

ABSTRACT

This thesis aimed to conduct a scalability and replicability analysis within a European smart grid project. In detail, the focus was on the results achieved by two pilot wind farms that implemented the provision of synthetic inertia and automatic voltage control. From a scalability and replicability analysis, it is expected to obtain both absolute information on the performance of the implemented solutions and information on what might be the main barriers and difficulties in implementing the same functions on a different scale or with different boundary conditions. Therefore, two different types of analysis were set up: a qualitative one, which directly involved the project partners with the aim of investigating the technology used, and a second quantitative analysis, which analysed the functional aspects of the implemented solutions by assessing the availability and impacts that the new regulatory services would have on the entire national perimeter. The first analysis allowed to understand the strengths and barriers of each implementation. The second analysis, on the other hand, was necessary to estimate the results that could be obtained by extending the innovative functions to all existing plants in the area, bearing in mind that in the provision of services based on wind power it is essential to consider the variability and arbitrariness characteristic of wind.

INTRODUCTION

The increase of renewable energy sources in the electricity sector is and will be one of the crucial steps toward the full decarbonisation. The challenges that arise are not only limited to the massive installation of power plants that are totally independent of fossil fuels but, they are also linked to the externalities that new generation technologies bring with them. Starting from the arbitrariness and uncertainty of source availability to the need for new mechanisms to provide the power system the required ancillary services needed for a safe operation. So, it will be necessary to extend also to the renewable power plant the services provision that usually are provided by traditional fossil-fuel power plants. However, this does not seem sufficient. In fact, the most promising generation technologies are linked with the exploitation of the wind and solar resources, which have very different characteristics compared to traditional generation by means of synchronous generation. That is, it is essential to increase the hosting capacity of the electricity system to be able to interconnect more and more generators in order to follow the energy transition. The hosting capacity is defined as the amount of new installed production and consumption players that could be interconnected to the power system without compromising or jeopardising the stability of the whole system. In this context, this master thesis was conducted within the OSMOSE project whit the intent to improve the understanding and consideration of flexibility needs and resources in future power systems through collaborations with partners and pilot plants. The main purpose of this thesis is to conduct a scalability and replicability analysis of the implementation of two innovative services tested in two demo wind farms within the European Project. In detail, the thesis contains two introductory chapters, the first of which deals with issues relating to the stability and control of the power system, while the second looks at the condition of things in the use case subject to scalability and replicability assessment. The document then goes on to analyse the current state of the art of guidelines and techniques to carry out a scalability and replicability analysis on a smart grid demonstrator. So, in Chapter 4 is presented the methodology developed to analyse the specificity of the two demo plants. Therefore, Section 5 presents the qualitative analysis in which, thanks to the involvement of the project's partners, a detailed evaluation is carried out to understand strengths and weaknesses with respect to the new implementations tested. Finally, Chapter 6 presents the quantitative assessment which analyses benefits and barriers that can be achieved or arise if the services provision is extended outside the pilot plants perimeter. This section presents how the wind source impacts on the availability of wind farms to provide ancillary services.

1 POWER SYSTEM STABILITY AND CONTROL

1.1 Power System Stability

The definition of power system stability is the ability of an electric power system, starting from a given initial condition, to recover a state of operating equilibrium after the action of a physical disturbance, with the entire system intact as before [1]. During the operation, a power system has to operate under different conditions. In fact, loads change continuously over time and in case of faults or outages more severe perturbations may occur. This in turn, after the intervention of the protective relays could change also the topology of the system. It is important to say that stability is related by two parameters: the initial condition of the entire system and the entity of the disturbance. Therefore, system instability could arise from a small disturbance on a stressed system or vice versa, from a severe perturbation on a non-stressed system. In any case, a power system in equilibrium may be stable for certain disturbances but unstable for others. This because is unfavourable, from an economic point of view, to develop a system that is able to overcome disturbances over a certain threshold. Anyway, the magnitude of the perturbation has to be weighted with the size of the interconnected area. Indeed, the larger the area, the more robust the system will be at the same disturbance. Generally, it can be said that following a perturbation, a system is stable if a new equilibrium condition is reached at the end of the transient evolution set by the disturbance and all loads and generators are still connected to the grid. On the contrary, if the system is not able to overcome a severe disturbance, the transient evolution leads to a run-away or run-down situation, which will probably establish a snowball effect that will gradually cause the disconnection of all the generators until a blackout is reached.

Before continuing, it is important to define what it is meant by power system working at equilibrium. In an equilibrium point, all the various opposing forces acting on the entire system are equal in any time instant i.e., the resultant force after the overall summation is equal to zero. It is also important to underline, that the equilibrium point reached at the end of the transient evolution caused by a general physical perturbation is not necessarily identical to the previous one. Following a disturbance, many devices connected to the grid are involved, so variation in network power flow, network bus voltages and speed generators may occur.

1.1.1 Classification of Power System Stability

Even if the stability of the power system can be assumed as a single problem, it can be very useful try to classify the different forms of instability that it can arise. As mentioned in the previous paragraph, equilibrium in the power system is identified as the physical equilibrium between opposite forces. Various network topologies, system operation conditions, various magnitudes and types of perturbations could lead to different forms of instability caused by different set of opposing forces. So, power system stability can be classified by three macro categories and each one contains several sub-categories as it can be seen in the Figure 1.

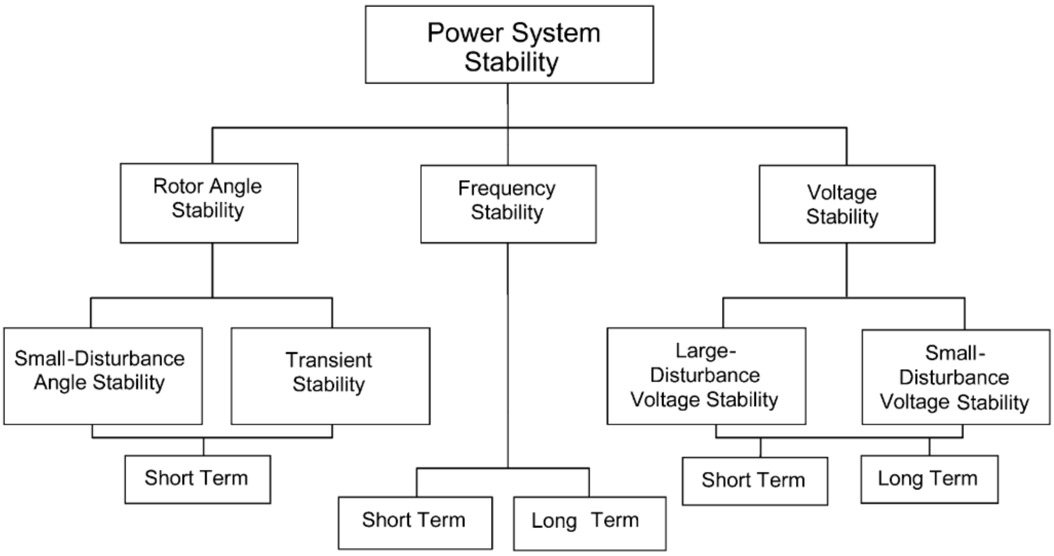


Figure 1: Classification of Stability [1]

1.1.1.1 Rotor Angle Stability

Rotor angle stability refers to the ability of the system to remain in synchronism. That is, the ability to maintain or recover the equilibrium between the electromagnetic torque and mechanical torque in each generator. The risk associated with such instability is connected to the loss of synchronism by some generators due to an excessive increase of the angular swings. To better understand the fact, it can be observed that in the case of steady-state condition, in any generator connected to the grid, mechanical torque (provided by the prime movers) equals the electromagnetic torque related to electric loads connected. The Figure 2 shows a generic synchronous generation unit, in particular, it's possible to notice the torques acting on the shaft mentioned above.

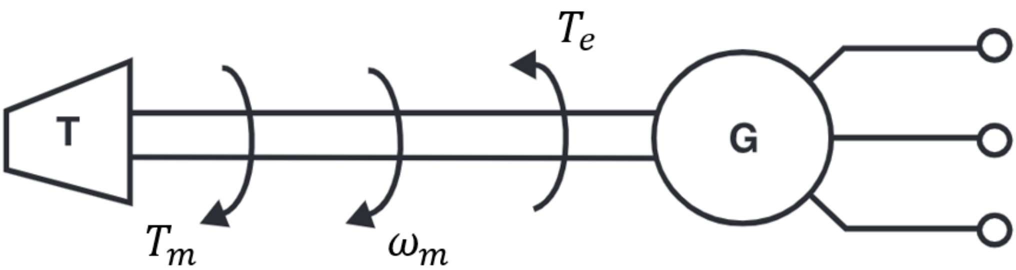


Figure 2: Generic prime mower and Synchronous generator[2]

When mechanical and electrical torque are equal in absolute value, the machine experiences no variation in the rotating speed and by the (2.1), this also is true for the electric frequency.

$$f = \frac{n \cdot p}{60} \tag{2.1}$$

n stands for the speed in *rpm/min* and *p* are the pole pairs of the generator. Since the rotating speed is constant, the angular acceleration is null, this is valid also for the angular position δ_m that remains constant as in the (2.2).

$$J\frac{d^2\delta_m}{dt^2} = T_{acc} = T_m - T_e \tag{2.2}$$

J is the total moment of inertia of the rotating mass, T_{acc} is the accelerating torque defined as the difference between mechanical and electromagnetic torque T_m and T_e respectively. δ_m is the angular rotor position, computed respect to the rotor field axis as it can be appreciated in the Figure 3.

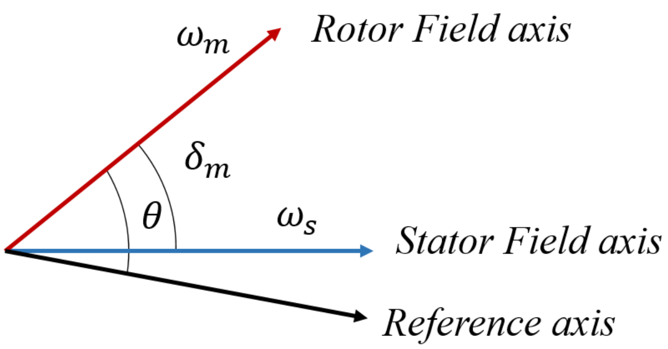


Figure 3: Swing angle of a generic Synchronous generator

So, when an imbalance between forces acting on the shaft occurs, the result is an acceleration or deceleration of the rotating element. This leads to an increase or decrease in the angular position of the rotor i.e., it changes the position of the rotor field axis respect to the stator ones. If for example a generator runs temporally faster than others, its angular position increases so it increases its output power. This phenomenon relocates part of power generation from the slowest to the fastest machine, thus it helps to re-establish the equilibrium. In fact, each generator has a specific relation between the angular position and the power generated. Generally, the output power increases (non-linearly) as the angular separation increases until a certain limit is reached: after that, an increase of δ_m results in a decreases of output power causing further increase of δ_m. When it happens, the machine is no longer able to remain connected to the network, so the synchronism is lost and the generator is disconnected.

1.1.1.2 Frequency Stability

Frequency Stability refers to the ability of the power system to maintain constant frequency when large imbalance between loads and generation occurs. Instability rises when a deviation in frequency causes the intervention of the protective relays. Subsequently, generators are disconnected when the frequency deviates from an admitted band imposed by the TSO. In addition, load shedding can be done in the case of severe under frequency perturbation, cutting part of the loads in attempt to restore the equilibrium. The frequency stability depends on the ability of the system to put in place all the regulation strategies to restore the equilibrium between generation and load and later to restore the nominal frequency value. Detailed information about the frequency regulation will be provided in the following paragraph.

1.1.1.3 Voltage Stability

Voltage stability refers to the ability of the power system to keep voltage at all buses at a constant value after a perturbation. Instability rises when the voltage in some busses tends to increase or decrease triggering protective relays. Also for this case, voltage stability is related to the ability of the system to keep in equilibrium the generated power and the requested power from the loads. Various events could establish a voltage instability, such as loss of load or loss of synchronism. However, the main parameter affecting voltage instability along lines is the flow of reactive power [1]. Since in high voltage transmission lines, the reactance is more relevant with respect to resistance. So, it is reasonable to say that reactive power has a crucial role in the voltage drop along the lines.

1.2 Inertial Response

In general, inertia is the resistance an object has to a change on its state of motion i.e., its velocity: speed and directions. Applying this definition to the power system, the physical object that are in motion are the rotating generators/motors connected to the power system and the resistance to the change in speed is expressed by the moment of inertia of the rotating masses [3]. Traditional synchronous generators are connected in parallel to the grid, so they are synchronous with the entire grid. Their rotating elements (rotor and prime mower) have stored a certain amount of kinetic energy and this energy tends to oppose to speed variation of the rotating masses.

The kinetic energy stored in a general generator can be written as follows:

$$E_{k,n} = \frac{1}{2} \cdot J \cdot \omega_{m,n}^2 = \frac{1}{2} \cdot J \cdot \frac{2\pi \cdot f_n}{p}^2 \qquad (2.3)$$

J is the total moment of inertia, $\omega_{m,n}$ is the shaft angular velocity and f_n is the nominal electric frequency. It is immediate to note that the energy depends on the square of the speed of the machine. Furthermore, dividing the total kinetic energy [MJ] by the electrical rated power S_n [MW] the inertia time constant of the *n-th* synchronous machine H_n [s] can be derived:

$$H_{gen,n} = \frac{E_{k,n}}{S_n} \qquad (2.4)$$

H_n helps to quantify the kinetic energy stored because it expresses the number of second that are necessary to inject an equivalent electric energy at the rated power. Furthermore, if we multiply the previous equation by 2 a parameter named as Starting Time T_a can be obtained which will be useful in the next steps. The inertia constant depends on the size, speed and type of machine. Usually, its value is in the range of 2-9 seconds. In addition, it tends to reduce as the nominal power increases (comparing production unit by the same technology) as it can be seen in the Figure 4 [3].

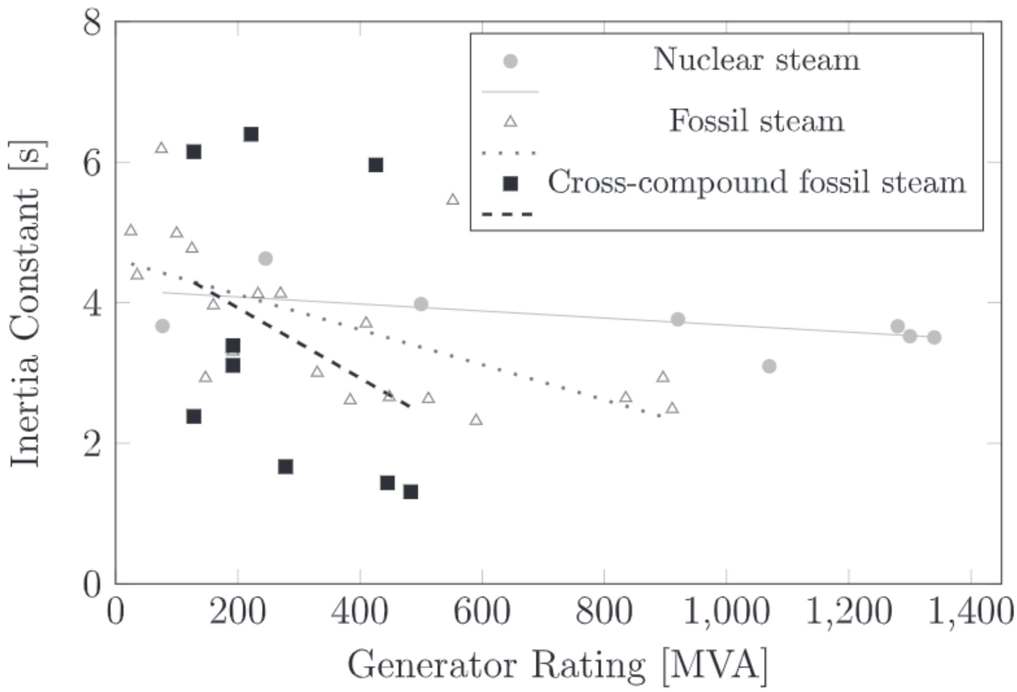


Figure 4: Inertia constant as function of rating power and technology [3]

Let us now analyse the behaviour of single synchronous machine during a disturbance. Starting from the (2.2) and referring to Figure 3, it can be stated that an imbalance in the torque (i.e., $T_a \neq 0$) results in acceleration or deceleration of the machine since:

$$\theta = \omega_r \cdot t + \delta_m \tag{2.5}$$

$$\frac{d\omega_m}{dt} = \frac{d^2\theta}{dt^2} = \frac{d^2\delta_m}{dt^2} = T_{acc} \tag{2.6}$$

θ and δ_m are previously defined in Figure 3, ω_r is the reference axis angular speed. Since the derivative of the angular velocity can be written as follows:

$$\frac{d\omega_m}{dt} = \frac{1}{2 \cdot \omega_m} \frac{d\omega_m^2}{dt} \tag{2.7}$$

And so, substituting into (2.6) it can be obtained:

$$\frac{d\left(\frac{1}{2} \cdot J \cdot \omega_m^2\right)}{dt} = T_{acc} \cdot \omega_m \tag{2.8}$$

Where on the left-hand side it is immediate to recognize the first derivative of the kinetic energy and on the right-hand side the accelerating power. Thus, the (2.8) can be written as:

$$\frac{d}{dt} E_k = P_{acc} = P_m - P_e \tag{2.9}$$

Now, considering the relation between the electric frequency and the kinetic energy from the (2.9) can be obtained the final relation that links the derivative of the frequency with the accelerating power.

$$\frac{T_a \cdot P_n}{f_n} \cdot \frac{df}{dt} = \frac{T_a \cdot P_n}{f_n} \cdot ROCOF = P_{acc} \tag{2.10}$$

Where f_n is the nominal frequency, T_a is the starting time as defined previously and $ROCOF$ (Rate of Change of Frequency) is the derivative of the frequency over the time. The (2.10) can eventually written as a function of the inertia constant H dividing by 2. It is relevant to observe that in case of a negative $ROCOF$ i.e., a reduction of the frequency value, it's followed by a reduction of the kinetic energy stored in the machine. The opposite for positive $ROCOF$. Thus, inertia response plays a positive role because the machine releases or stores energy to contrast the perturbation as of the first instant that it happens.

So far, a system composed by only one SG has been considered. Anyway, since the frequency is considered as a global system parameter, the (2.10) can be extended for the whole power system and the (2.11) can be obtained.

$$\frac{\sum_{i=1}^{N}(T_{a,i} \cdot P_{n,i})}{f_n} \cdot ROCOF = \sum P_{gen} - \sum P_{load} \tag{2.11}$$

On the left hand side the starting time is replaced by the total starting time of the overall N synchronous generators, while the right hand side is the summation of the overall power generated and the overall demand. As the $\sum P_{load}$ can include also rotating elements also them contribute in the total starting time. In terms of inertia constant, the overall inertia constant of a generic system composed by N generators and M rotating loads can be written as:

$$H_T = H_{gen} + H_{loads} = \sum_{n=1}^{N} H_{gen,n} + \sum_{m=1}^{M} H_{loads,m} \tag{2.12}$$

Obviously, can be derived the total starting time of the grid multiplying the (2.12) by 2. As it can be observed from the (2.11), the inertial response plays a crucial role to contain the ROCOF in the initial instant (the inertia response is exerted generally within 1s) when a disturbance occurs. In fact, a grid with higher starting time shows lower frequency deviation in the first time instant (i.e., a smaller ROCOF) for the same disturbance and power installed.

1.2.1 Impact of Renewable Energy Sources on Inertia

Due to the intrinsic characteristics of the most of Renewable Energy Sources (RES), production plants based on them are connected to the grid via inverters. Wind turbines, even if are composed by rotating elements, usually need power converter to ensure speed variation to follow the variability of the wind speed. So, power converters decouple the turbines inertia from the grid [4]. Photovoltaic plants do not provide inertia because inverters are needed since generators are not composed by rotating elements. Connecting rotating generators by power electronic converters results in a decoupling between the generators and the grid. Consequently, they do not provide rotational inertia to the system. Thus, with an increasing of penetration of inverter-connected power unit i.e., traditional power generation is substituted by inertia-free generators, the total rotational inertia of the power system is reduced. Moreover, the overall inertia can vary significantly due to the non-programmability of the renewable energy sources [5]. Indeed, there may be situations (typically when the demand is low) where the renewable generation could cover large part of the demand reducing dramatically the overall system inertia and exposing it to less stability. System with low inertia shows higher initial ROCOF i.e., the value of the derivative of the frequency just after the perturbation before that any controls become active. Traditionally this value has minor relevance as the system were composed mainly by synchronous generators, but it becomes more relevant since the penetration of renewable energy sources increases [6]. The higher initial ROCOF caused by the disconnection of a generic generator/load can be estimated as:

$$\frac{d\Delta f}{dt} = \frac{f_n \, P_k}{2 \sum_{i=1, i\neq k}^{N} H_i \, \cdot S_i} \tag{2.13}$$

$\frac{d\Delta f}{dt}$ is computed in $t = 0^+$ i.e., just after the disconnection of either a generator or load (P_k) from the power system. On the denominator appears the summation of the overall inertia constant of the rotating elements with exception of the one just disconnected. Obviously, the presence in the power system of inertia free generators reduces the overall summation with respect of the same system composed only by traditional generators. This results in a reduction of the ability of the system to damp frequency oscillation exposing the system to less ability to provide transient stability [7].

1.3 Frequency Regulation

Few seconds after an imbalance of generated and absorbed power a deviation in the system frequency is observed. The ability of the system to restore the nominal frequency value depends, as it was stated in the 1.1.1.2, on the ability of the system to put in place all the regulation strategies to counteract over the disturbance. Italian's grid code defines specific frequency admitted value as function of the operating condition of the system [8]:

- The nominal frequency value is equal to $f_n = 50Hz$
- Under normal or in alarm condition the frequency is maintained in the range of $49.9 - 50.1\ Hz$, except for Sardinia and Sicily where condition the frequency is maintained in the range of $49.5 - 50.5\ Hz$.
- Under emergency or restoring condition frequency may varies in the range of $47.5 - 51.5\ Hz$.

It is easy to note that during normal operation such narrow range of admitted values of frequency implies a complex and precise regulation mechanism that must correct the input power of each generator to follow both the fluctuation of load and generation that happens during the operation.

Mainly two processes compose the frequency regulation scheme:

1. Primary Frequency Regulation (*response in 5s to 30s*)
2. Secondary Frequency Regulation (*response in 30s to 15min*)

Each one differs from the other for functioning, timing and purposes. A detailed review is proposed following. For completeness, there is a further mechanism that is activated on request by the TSO. it is called tertiary regulation and its task is to provide an additional regulating power in addition to the secondary one.

1.3.1 Primary Frequency Regulation

The primary speed regulation is defined as the set of operations aimed at maintaining a balance between generation and demand. Therefore, the primary regulation restores the equilibrium acting on speed governors of generators increasing or decreasing the output power in accordance with the disturbance. As a consequence, each production unit that participate to the regulation needs a certain margin to be able both increase or decrease their output power respect to its working condition. This power is known as *primary reserve* and the summation of each regulation band compose the *primary reserve of the entire national power system* [9]. In Italy, primary frequency regulation is a mandatory service for production units with installed power above *10 MW* except for power plants based on non-programmable renewable energy sources (except for conventional hydroelectric based on dams). In the [9], TSO reported all the requirement for the provision of the services to the production units.

1.3.2 Secondary Frequency Regulation

However, once the transient related to the action of the primary regulation ends, the system works in a new equilibrium condition that is characterized by a different value of frequency. In addition, also the power flow across each control zone of the power system differs from those defined ex-ante. For these reasons it is necessary another regulation mechanism that re-establish the nominal value of frequency and the proper value of the power exchanged between zones. So, after about ten seconds the secondary frequency regulation intervenes. As for the case of the primary regulation, the secondary regulation can rely on the *secondary reserve* provided by the production unit that participate to the services. A device in Italy called *"Regolatore di rete"* centrally controls the secondary frequency regulation. The controller processes both the errors in frequency and power to generate the control signal to be sent to the production units to correct their output power [9].

1.4 Voltage Regulation

Voltage regulation means al activities necessary to keep the voltage at all grid nodes within certain predefined limits [10]. TSO defines nominal and operating voltage value for any POD in normal, alarm and emergency situation. As stated in 1.1.1.3, voltage along the lines is regulated by controlling the reactive power flow. To understand the link between the two quantities, it is useful to observe the approximate form of the voltage drop (2.14) and the reactive power formula (2.15).

$$\Delta V = \sqrt{3} \cdot \left(r \cdot l \cdot I \cdot cos(\phi) + x \cdot l \cdot I \cdot sen(\phi)\right) \tag{2.14}$$

$$Q = \sqrt{3} V I sen(\phi) \tag{2.15}$$

ΔV is the voltage drop between two points which are l kilometres distant from each other. It is immediate to notice the contribution of the reactive power in the voltage drop equation i.e., the reactive component of the current defined as $I\ sen(\phi)$. Such contribution is more relevant respect to the active power since in high voltage lines the ratio between *r* and *x* is very small. As it happens for the frequency regulation, the TSO manage and coordinate all the procedures related to the voltage regulation. The devices involved by the voltage regulation are:

- Production units
- Transformers and autotransformers
- Power factor capacitors and reactance

In addition, loads are involved indirectly since end users must correct their power factors if the values go out from defined thresholds. Production units usually are interested in injecting active power into the grid, since it is remunerated, but if the plant is classified eligible to provide voltage regulation, the provision of primary and secondary voltage regulation is mandatory [8]. Generator specifications must ensure that the required active power is fed in within the declared limits and at the same time guarantee that the required reactive power is fed in within the defined capability curves. A generic synchronous generator connected to the grid

1.4.1 Primary Voltage Regulation

The primary voltage regulation consists in maintain to a specific voltage value at the POD of each production unit. Each group of generators is provided by RAT (*Regolatore Automatico di Tensione – Automatic Voltage Regulator*) that receiving as input a reference voltage V_{rif} and acting on the excitation current correct the output voltage. The plant operator in accordance with the TSO sets the V_{rif} value manually in the RAT. Usually, two different reference voltage are set: one for the hours when the demand is high and one for low demand hours since with low demand the voltage drop is smaller respect to higher loads scenario. Sometimes, RAT can correct the V_{rif} keeping in consideration different corrective signals such as the output reactive power to compensate the voltage drop on the elevator transformer and the angular velocity in order to dampen transient oscillations in the rotor [10].

1.4.2 Secondary Voltage Regulation

Secondary voltage regulation differs from the primary regulation because it is centrally organized. In fact, a regional controller monitors the voltage in specific nodes within the area of responsibility. Then, the regional regulator controls some production units and stations that are located in the competence area. In the case of stations, the regulator controls devices as power factor capacitors, reactance, OLTC and static var compensator. Instead, it can also control the production units of the area sending to each one the proper value of reactive power that has to be injected. The signal is calculated starting from the total reactive power necessary to correct the voltage in the node and subdivided by the available production units. Subsequently the operator computes the V_{rif} that has to be set on each RAT in order to satisfy the requested value of reactive power injection.

1.5 Italian Technical Prescription for Wind Farms

Since now, it has been explained the stability and the regulation scheme needed in a power system based on conventional synchronous generator, but it is also important to deal with the increasing of penetration of renewable power sources. Before analysing innovative solutions for managing wind turbine, we will now look in depth at what is required of wind farm by the grid code. In "*Allegato A.17*" of the Italian grid code are contained all the requirements that wind based power plant must meet [11]. The scope of application is all the wind farms connected on the national grid at a voltage level of $110\ kV$ or more without storage except for plant composed by wind turbines ordered before the 15th of May 2018.

As it was said before, loosing generators means a disturbance for the power system. For this reason, the wind turbines must be able to remains connected in parallel to the grid also in emergency condition and during the system recovery operation. In detail are proposed following frequency and voltage working zones.

$$47.5\ Hz \leq f \leq 51.5\ Hz \tag{2.16}$$

$$85\%\ V_n \leq V \leq 115\%\ V_n \tag{2.17}$$

In addition is also required that the wind farm remains connected to the grid while external fault occurs, except for those that the failure extinction cause the disconnection of the production unit.

1.5.1 Wind Farms Frequency Regulation

As it happens for traditional power plants, also wind farms are called to participate to the frequency regulation. To do so, automatic controller act measuring the grid frequency ad modify the output active power in accordance with the pre-defined behaviour of the wind turbine. In Figure 5 it is reported a generic power curve as function of the frequency.

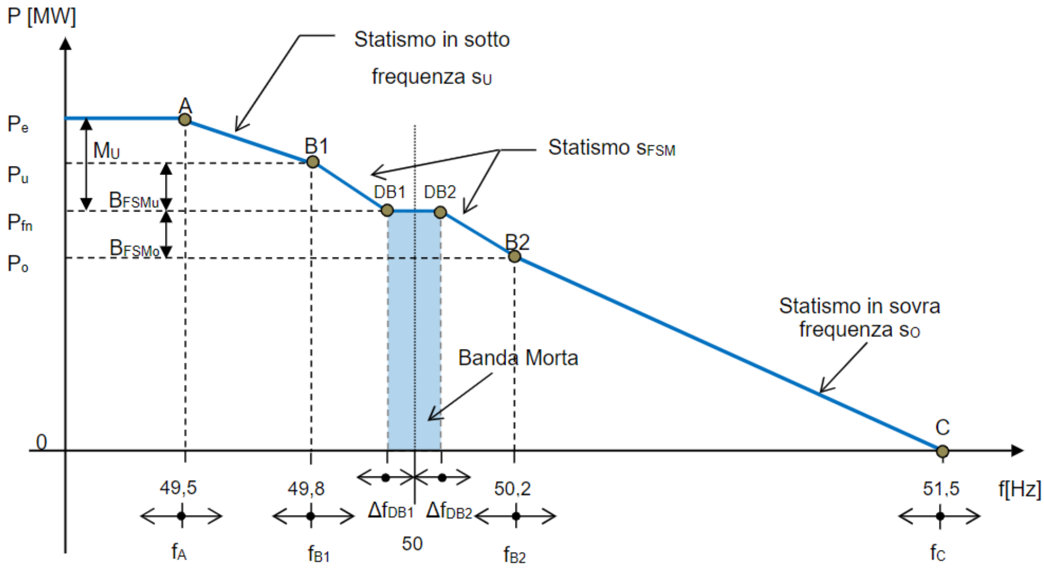


Figure 5:Wind farm P(f) generic curve [11]

The control scheme is different according to the frequency value and three different zones could be identified:

1. Frequency Sensitive Mode: this is essentially the primary frequency regulation required of traditional power plants. A specific droop is required between f_{B1} and f_{B2} and a dead band of *10 mHz* is set around the nominal frequency value.
2. Limited Frequency Sensitive Mode-Over Frequency: during temporary over frequency over f_{B2} wind farms are called to reduce the output active power following a droop s_o. The output is reduced until the zero value when frequency reach f_c value set at *51.5 Hz*.
3. Limited Frequency Sensitive Mode-Under Frequency: during temporary under frequency under f_{B1} wind farms are called to inject up to the maximum active power available with a defined droop s_u.

1.5.2 Wind Farms Frequency Support

In addition to the frequency regulation, the "*Allegato A.17*" requests the participation of wind farms in the frequency support. In fact, in according with the grid code, plants must be designed to provide an active power response during transient under-frequency disturbance. It is required that the plant controller triggers the WTs to inject the extra power when the frequency value falls below a certain configurable value. The threshold has to be set between 49.5 Hz and 50 Hz with a step of 0.05 Hz. However, without request by the TSO the standard value is set at 49.8 Hz. The required power step must be adjustable between 0% and 10% of the machine's rated power, with a default value of 6%. Due to electrical and mechanical constraints, the frequency support has to be active if the power output of the WT at the time the disturbance occurs is greater than the minimum value set by the WT manufacturer, which in any case must not exceed 30% of the generator power. Following the intervention, depending on the pre disturbance WT working condition, it may be necessary to restore the optimal maximum power condition. In fact, the extraction of the extra power contribution can be achieved decreasing the speed of the generator or increasing the pitch angle of the WT. Then, if at the end of the intervention the speed is lower than the optimum, a recovery phase is activated to restore the rotor speed to the nominal value. This procedure blocks the service provision and can last 60s.

1.5.3 Wind Farms Voltage Regulation

TSO requires wind farms to participate in voltage regulation trough two different logics:

1. *Local Control:* the TSO sends the voltage reference value to a wind farm that has 15 minutes to set it into the regulator. Then the difference between the reference voltage and the measured one is assessed so, according to the reactive power as function of voltage curve of the plant (Figure 6) is computed the proper value of Q that has to be injected. TSO also prescribes that the plant must be able to inject the 90% of the available reactive power within 2 seconds and then reach the 100% within 5 seconds.

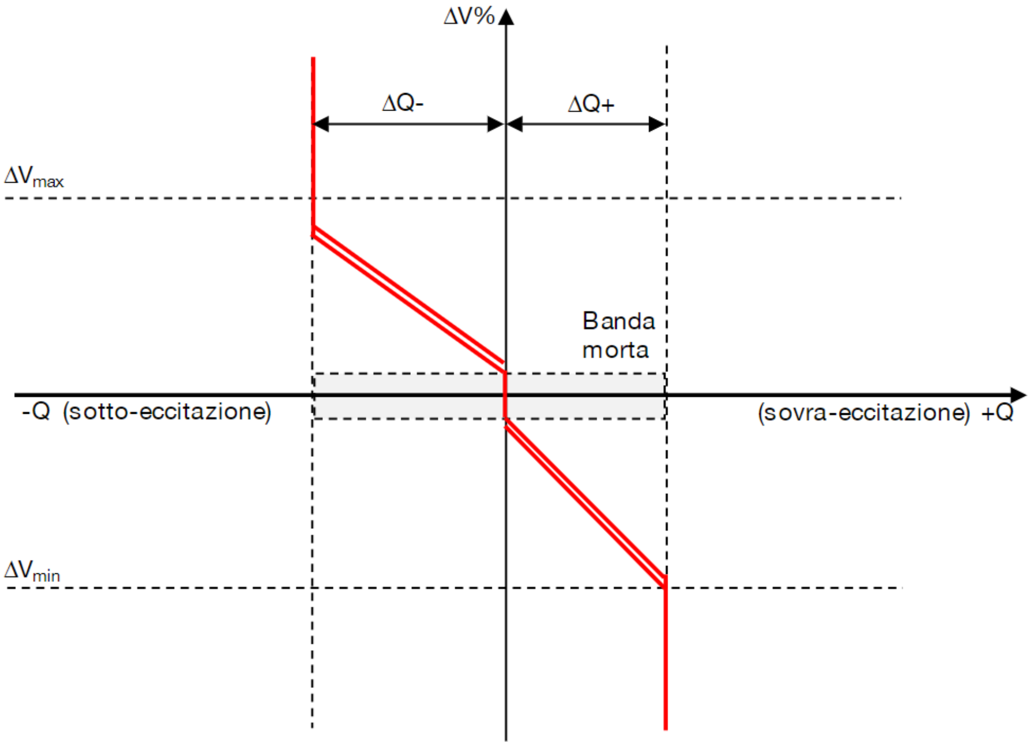


Figure 6:Generic curve Q=f(V) [11]

2. *Remote Control:* TSO continuously computes the reactive power that has to be injected by the plant and it sends the value (or eventually the reference voltage value) to each production unit in real time. On the other hand, the operator receives the signal and must send to the TSO their own reactive power limits of injection computed from both the operating condition of the plant and the plant capability curve. This bidirectional communication between wind farm and TSO must be carried out at least every 4 seconds.

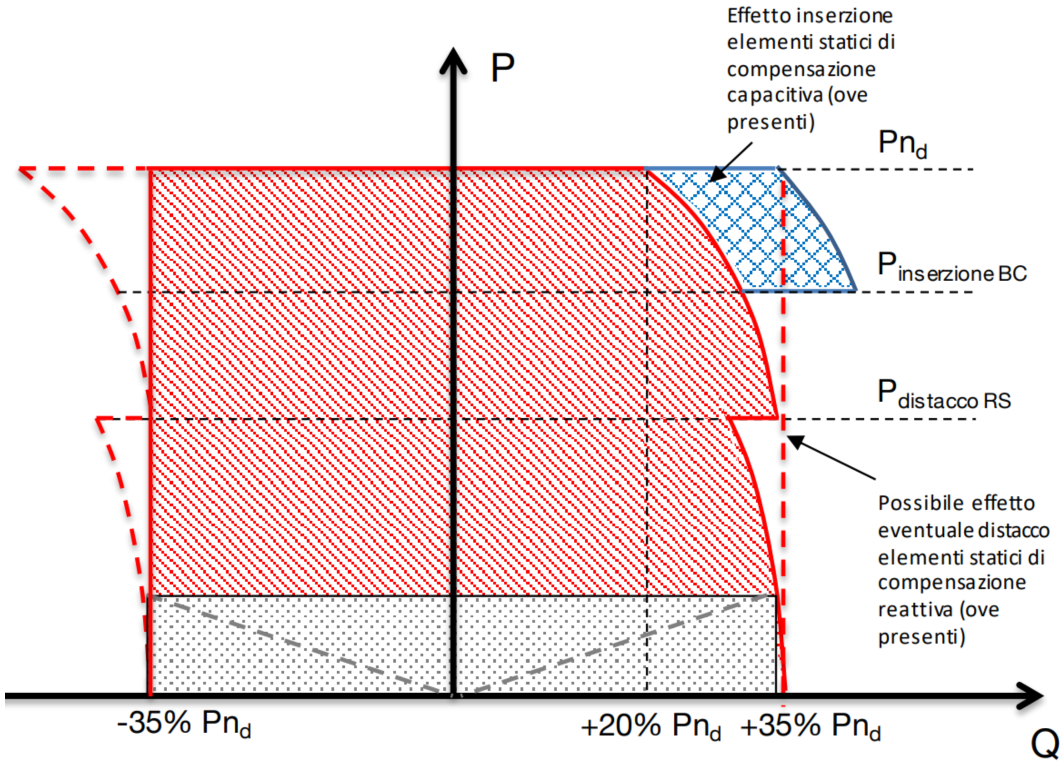


Figure 7 P-Q Capability Curve at POD [11]

TSO also prescribes the shape of the equivalent capability curve at the POD. The grid code requires the overall plant to provide continuous voltage regulation in the red area shown in the Figure 7. The proposed capability curve has a curve shape due to the capacitive reactive power put in place by the MV cables during low power operation and the reactive power consumption of the BT/MT and MT/AT transformer during high active power operation. When the active power falls in the grey area, the voltage regulation is disabled i.e., the regulation is activated when the injected active power is above the 10% or the 20% of the plant rated power. In the case the plant operates above the activation threshold, two zones are identified. On the left side of the y-axis, it is the under excited zone and it is requested to inject up to the 35% of the nominal power. Instead, on the right side of the y-axis is the over excited zone, which can be different for each plant, but in any case, must be guarantee at least the 20 % of the nominal power up to 35% as in the previous case (in terms of reactive power injections.

2 OSMOSE Project: WP5-UC2

The OSMOSE (Optimal System-Mix Of flexibilities Solutions for European Electricity) project aims to identify and develop the optimal mix of flexibilities for the European power system to enable the Energy Transition. It started in 2018 and it lasts four years, it was founded inside Horizon 2020 programme which is the financial instrument instituted by the European Commission to promote research and innovation. The project involves 33 partners including European TSOs, RES electricity producers, research centres, universities, and companies. In detail the overall project is subdivided in seven Work Package (WP) which in turn are subdivided in Use Case (UC). This master thesis is developed within the UC2 of the WP5. In particular, the WP5 deals with multiple ancillary services provided by grid devices and RES power plant, innovative dynamic thermal rating and innovative energy management system.

2.1 Solution Proposed in the UC2

Going into detail of the Use Case 2, its main objective is to assess the provision of innovative grid services provided by wind farms, in particular Synthetic Inertia (SI) and Automatic Voltage Regulation (AVC). The Italian TSO leads the UC2, and two wind farms located in the south of Italy are the demo sites where the innovative solutions are developed and then on field tested [12].

2.1.1 Synthetic Inertia

The first innovative solution assessed is the provision of synthetic inertia by wind turbines. The goal of this innovative service is emulating the inertial response of traditional power plants by wind farms. Since the power converters required to connect variable speed generators hide the inertial response of the rotating masses, the developing of algorithm and innovative control logics of the plant components are required. As it is stated in [13], the provision of synthetic inertia means the contribution of additional electric power by sources that inherently do not provide a power response proportional to the ROCOF. The actual Italian grid codes prescribes, as reported in 1.5.2, that WTs support the frequency injecting an extra power as the frequency deviates from the nominal value exciding a defined threshold. This request may at first appear to look like an inertial response of the WTs. Nevertheless, to correctly emulate the inertial response of a synchronous generator the increase or decrease in power injection must be proportional to the ROCOF as it is stated in 1.2. That is, to correctly develop the SI on RES power plant it is necessary to develop a plant control strategy that implements the (3.1) on the power converter i.e., the generator must change the output power in accordance with the (3.1) as it happens on a synchronous generator:

$$\Delta P_{SI} = -k_{SI} \cdot ROCOF \tag{3.1}$$

The (3.1) put in relation the ΔP_{SI} i.e., the output power increase/decrease, and the computed ROCOF, trough the synthetic inertia constant k_{SI}. The minus sign on the left-hand side is required since a positive value of ROCOF it's related to an increasing of frequency value. This must be followed by a decrease in the output power to counteract to the disturbance. Conversely in the case of a negative ROCOF. Besides, the (3.1) needs additional parameters to be correctly implemented in a power converter. In Figure 8, it can be noted that on the x-axis is reported the ROCOF and on the y-axis the additional power injected/withdrawal. The contribution is not triggered if the ROCOF is within a defined dead band. Nevertheless, as the ROCOF exceeds the dead band, the contribution is activated and the response is then proportional to the ROCOF by the inertia constant k_{SI} till a maximum/minimum value of admittible power of the system is reached (i.e., the A parameter). Then also if the ROCOF moves away from the B parameter the ΔP_{SI} saturated at the A value. Finally, when the ROCOF returns within the dead band, the SI contribution is deactivated when the derivative of the frequency reaches a Threshold as shown in Figure 8.

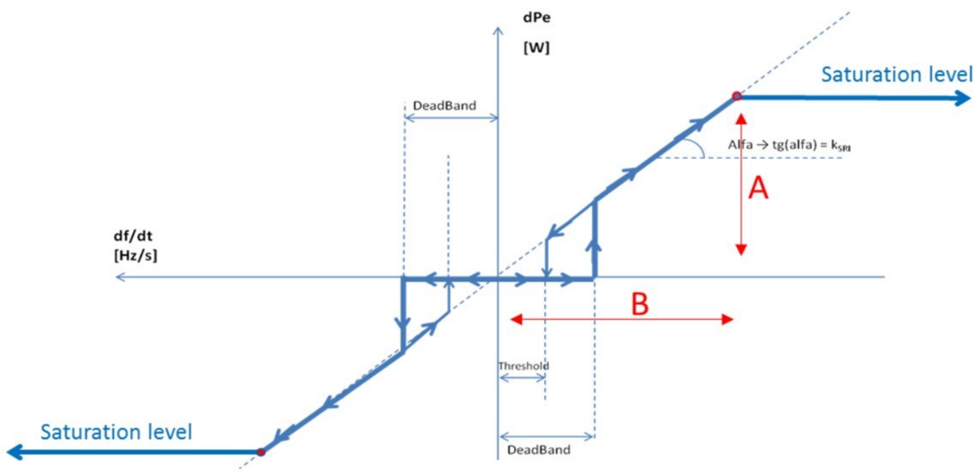


Figure 8: Synthetic Inertia Control Logic [14]

The (3.1) and the Figure 8 put in evidence an important aspect: to deliver upward SI (i.e., to increase the output power), the presence of energy stored behind the power converter is compulsory [13]. Normally, as mentioned in 1.2, this energy is stored in form of kinetic energy in the rotating masses that composes a generator directly connected in parallel to the grid. However, in the case of RES it is not necessarily the case that such energy is available.

Thinking on PV power plant, no energy is stored in the system and the logic of the power converters adapts the plant working conditions to extract the maximum power that is available in the field. So, this aspect precludes the availability of the upward generation margin required to support the frequency [15]. However, one of the scopes of this thesis is the provision of SI by WTs. As mentioned in 1.2.1 WTs have a certain amount of kinetic energy stored in the rotating elements, but the power converters hide the inertial response. Along the OSMOSE project two different method to provide SI are assessed. The first solution exploits the kinetic energy stored in the WT instead the second uses a Battery Energy Storage System (BESS) to supplies the generation margin.

2.1.1.1 BESS Based SI Provision

The second method assessed to supply SI is unlinked from the WTs technology installed in the plant. In fact, it is based on a battery energy storage system. So, the ΔP_{SI} is made available from the energy stored in the batteries and not from the kinetic energy stored in the WT. Hence, during the frequency support the wind plant can operate without changing the logic that extracts the maximum available power from the wind. So this approach seems, at first glance, to be applicable regardless of the technology used in the generators thanks to such a disconnection between the grid service (provided by the BESS) and the generator. The architecture of a general grid storage system is now analysed, and in the following paragraphs it will be explained how the implementation of services is done. In general a BESS is composed by multiple independent subsystem each one made by a specific set of components. Batteries require a battery management system (BMS) and a system supervisory control (SSC). The BMS's role is to manage all the operations that involves the battery. In fact, to ensure the safe operation of the batteries it measures and computes parameters like the state of charge, the state of health, temperature, voltage and current limits (e.g., the maximum discharge current as function of the overall working parameters). In addition, since stacks are composed by multiple cells connected both in series and parallel the BMS needs to balance the charge over the single modules. Multiple stacks, each one equipped with a dedicated BMS, are in turn connected to others in parallel to reach the requested capacity. Each BMS is then linked with the SSC that interface the battery stacks to the grid. So, the SSC is aware of the status of each stack. Consequently, when the grid requires the intervention of the BESS the SSC choses the best setting to inject/absorb the requested power. The SSC communicates to each of the chosen stacks the reference power to be injected to fulfil the overall demand. [19]

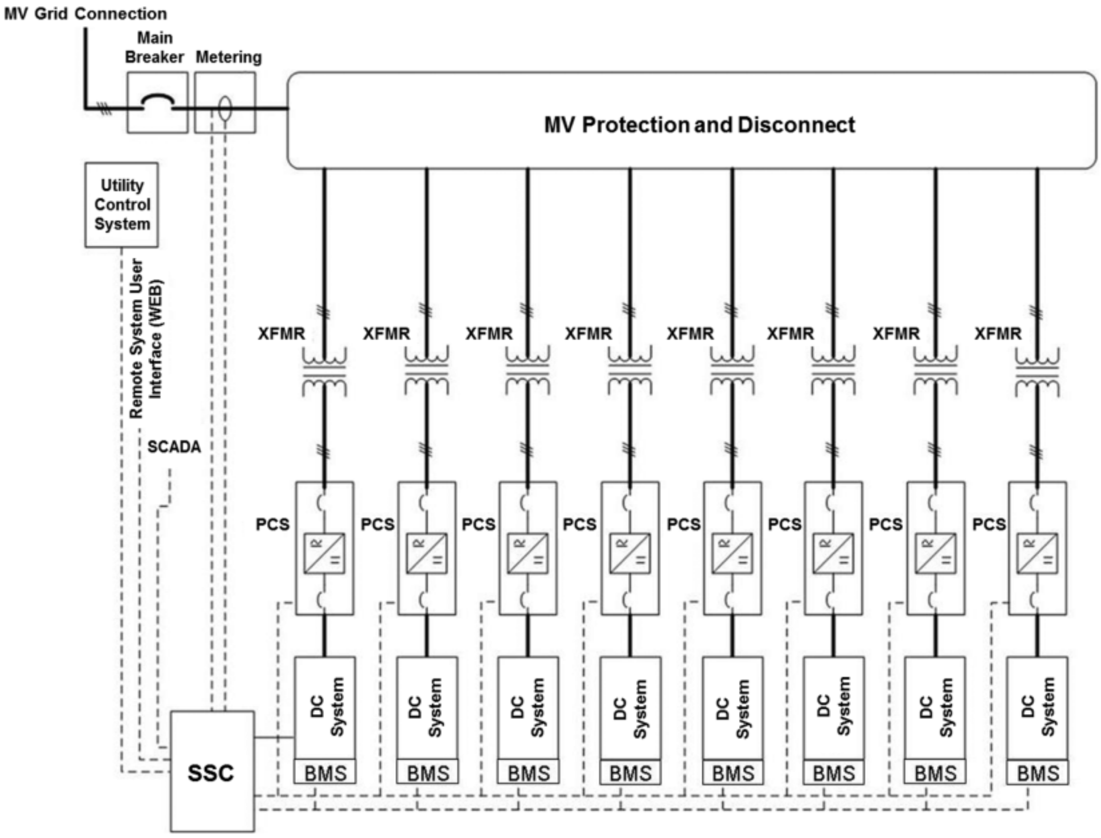


Figure 9: General grid storage architecture [19]

In Figure 9 is proposed a general grid storage system architecture composed by multiple battery stacks. The DC Systems are the multiple cells, connected both in series and parallel, that composes the battery. Each DC source is therefore equipped with a PCS i.e., the power conversion system. The PCS is a 4-quadrant DC/AC power converter and it manage the charge/discharge process of the battery. Finally, a transformer connects the PCS to the grid. Note that the Figure 9 is a simplified scheme and the configuration may be different in each case.

The provision of SI is managed from the plant master SCADA that controls the BESS at on site level. The amount of power to be inject or withdrawal is evaluated starting from the measure of the frequency value to compute the time derivative of the frequency. Then the algorithm, using the (3.1) and the P over df/dt curve showed in Figure 8, emulates the inertial response of a synchronous machine. The new reference power signal enters in the SSC and triggers the proper BMSs that in turn changes PCSs reference power values. In addition, the master SCADA also controls the RES power plant and manage other grid services.

2.1.1.2 Provision of SI by DFIG

Asynchronous Doubly Fed Induction Generators (DFIG) are quite common technology in the wind turbines generators. In fact, DFIG differently from traditional asynchronous machine admits speed variation from the nominal one, ensuring an optimal exploitation of the wind source. The generator is composed by a wounded rotor asynchronous machine where the stator is directly connected to the grid and the rotor is connected by a power converter. Respect to solution that uses permanent magnet synchronous generators that require inverters sized at the rated power of the generator, DFIGs require inverter sized at a fraction of the machine rated power [16]. Resulting in an overall reduction of the total cost of the machine. Usually, a traditional asynchronous machine works as a generator only if the rotational speed is higher than the synchronism speed imposed by the grid frequency. Despite that, controlling the electrical rotor parameters by the inverter, a DFIG can generate power also under the synchronous speed. Moreover, the electrical rotor parameters controlled by the inverter can vary the electrical breaking torque generated to the main shaft resulting in a control of the mechanical breaking torque of the WT. So, a possible strategy to extract the ΔP_{SI} could be increasing the breaking torque acting on the rotor electrical parameters. However, more power can be extract from the wind also increasing the pitch angle of the blades. So, with these two different strategies it is possible to make available the generation margin needed to provide upward SI. To well understand how a possible emulation of the inertial response by WTs DFIG based works it is relevant to distinguish three common operation condition that WT are subjected.

1. $P_e < P_{limit}$ i.e., the generated electric power of the WT is below a defined threshold that does not allow the delivery of inertia due to mechanical and electrical constraints.
2. $P_e = P_{wind} < P_{nom}$ i.e., the generated electric power is below the nominal rated power of the WT. In this case, the power surplus ΔP_{SI} is achieved increasing the torque applied by the generator to the shaft. In other words, the electric power extracted by the WT equals the maximum power available by the wind so, extracting more power results in a reduction of the rotational speed. During this process, the kinetic energy stored in the WT is reduced. As a result, at the end of the contribution, the WT starts a recovery process to re-accelerate the turbine.
3. $P_e = P_{nom} < P_{wind}$ i.e., the wind power is higher than the nominal power. In this condition, the electric output power is usually limited to the nominal power decreasing the aerodynamic performance of the WT. In this condition, the ΔP_{SI} can be obtained increasing the pitch angle of the blades extracting part of the excess wind power available. As the turbine is working at the electrical rated power before the

contribution, increasing the output power by ΔP_{SI} results in output power higher than the nominal one. Even if the excess power is maintained for a relatively short time, electrical and mechanical evaluations may be required by the WT manufacturer.

According with [17], WT based on DFIG could be suitable to provide frequency support during frequency deviation. Critical aspect should be relevant when the WT is operating near the P_{limit}. In fact, in this condition the rotational speed is well below the nominal one and so the kinetic energy stored is limited. This obviously results in a limited and not precisely estimation of the contribution. In general, it can be notice that extracting too much power from the WT by acting on both the inverter control and to the pitch angle exposes the WT to the stalling of the rotor or excessive speed reduction [18]. As a result, providing frequency support far away from the nominal speed might expose the grid to a secondary disturbance. In fact, the speed reduction under the minimum admitted speed triggers the under-speed protective relay resulting in the disconnection of the WT that enlarge the disturbance. Moreover, the WT is subjected by additional mechanical stress due to the power surplus requested during the frequency support.

2.1.2 Automatic Voltage Control

The second services implemented in OSMOSE WP5 is the automatic voltage control (AVC) compliant with the Italian grid code discussed in 1.5.3. Also, in this case the two demo plants differently implemented the provision of automatic voltage control. The first one chose to deliver the reactive power requested by the TSO exploiting both the inverter of the BESS and the WTs converter. Instead, the second one uses only the converter on board on the DFIG based WTs to inject the reactive power developing a control strategy described in the following paragraph.

2.2 UC2 Demo Plants

This sub-section aims in outline the main characteristic of the plants involved in the tests. The methods used to implement the services will also be outlined in the following paragraph.

2.2.1 Plant V

The first of the two demo plants involved in testing the innovative solution proposed in the UC2 is locate in Basilicata. The industrial scale plant is composed by 14 WTs of 2.5 MW of rated power each. Therefore, the plant has an overall installed power of 15 MW. The installed generators are equipped by a DFIG and have 80 m hub height and 114 m of rotor diameter. WTs are interconnected by an internal medium voltage grid (30 kV). Then the plant is interconnected to the 150 kV electrical station via a step-up transformer and by a high voltage underground cable. The plant does not have a BESS installed, so the innovative functions are completely provided by the WT. Testing of the provision of synthetic inertia began with the development of a new firmware for the inverter located in the WT nacelle. In addition, also an update in the PLC that controls the WT was necessary. These activities involved the WT manufacturer who carried out simulations and laboratory tests to identify a suitable set of parameters that could enable SI without affecting the useful life of the WT. Unfortunately, due to unforeseen difficulties encountered in the laboratory test, the final firmware and software were not sufficiently developed to allow the service to be implemented on a WT in the plant. However, laboratory tests showed that a maximum 10% of the nominal power of the WT can be injected without overcoming electrical and mechanical constraints. Instead, in the case of over-frequency events the reduction of the injected power could exceeds the 10 % without overcoming WT's constraints. From an AVC supply point of view, the implementation of this second innovative service required the installation of a first level SCADA and the creation of appropriate communication channels between the data centre and the local component on site. The TSO communicates to the operator the appropriate signal for voltage regulation (V_{rif} or Q) and through the data centre, owned by the operator, the signal reaches the local embedded installed on site. This component then, in collaboration with the new first level SCADA, processes the signals to be sent to the plant controller, which in turn processes the reactive power setpoint to be sent to each WT according to their operation condition.

2.2.2 Plant P

The second demo plant is also located in Basilicata it is composed by 9 WTs of 2 MW each i.e., 18 MW in total. Then the wind farm is connected to a 150 kV electrical station. The internal grid that connects all the WT is at a 20 kV, so a 20/150kV step-up transformer interfaces the plant. Like the Plant V, the WTs are DFIG based. However, the Plant P plant has been integrated with a BESS. So, the provision of services could be done both by the BESS and the WTs. The 2MW/2MWh storage is composed by 2 Modules of 1MW/1MWh each, the PCS, the LV/MV transformer and the MV Panel to interface the BESS to the WTs and to the gird. Following is reported the overall layout of the power plant.

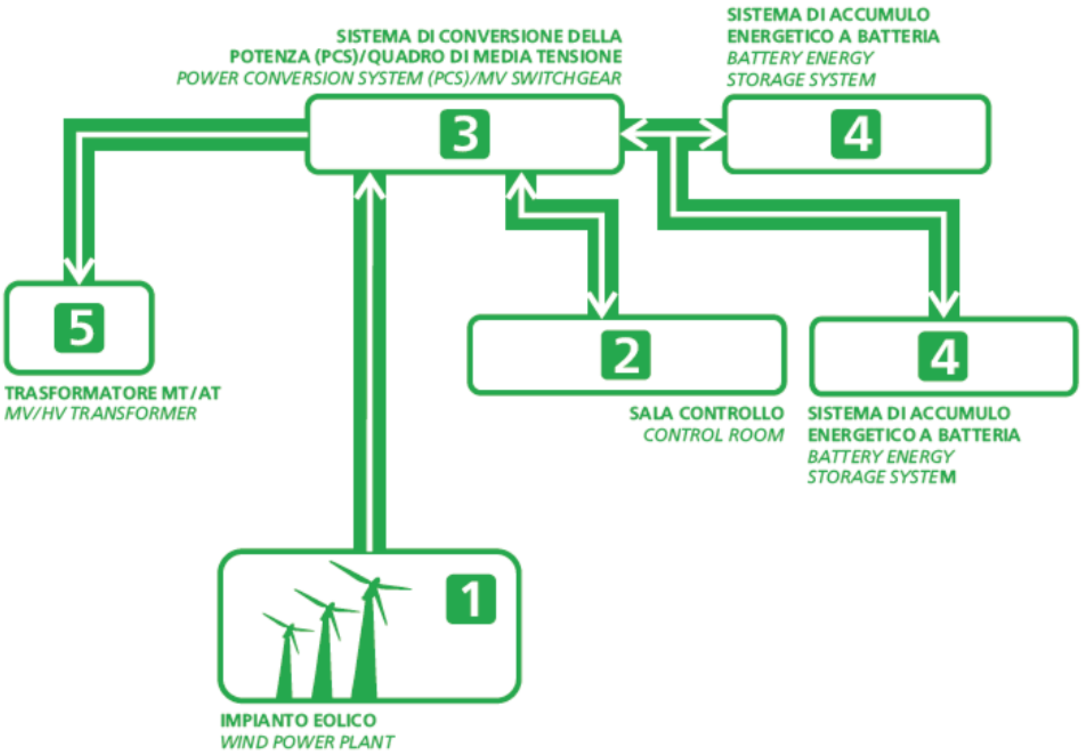


Figure 10 Plant P Layout [14]

The control of the system is subdivided in two different areas:

1. *On-site services:* locally, the RES plant and the BESS are managed by the Master SCADA. The controls manage both the production and the provision of services. Indeed, the master SCADA controls the energy flows exchanged by the RES acting on each WT. Then, the power flows coming from the WTs are managed between the grid and the BESS. Furthermore, the BESS fully provides the SI, so WTs do not participate. Instead, the on-site control also manages the AVC based on the voltage reference (as explained in 1.5.3 in *Local Control*). In this case, both the BESS and the RES participate in providing the reactive power. In this respect, the BESS is preferred in the injection of reactive power; if it saturates its capability then the WTs are called to participate in the AVC. Furthermore, the Master SCADA controls other ancillary services that are under testing even if they are outside of the scope of the project such: scheduling and energy shifting, frequency regulations.
2. *Centralized services:* they allow the remote control and the monitoring of the entire plant. In particular, the operator can set the requests coming from the TSO. The operator can modulate the plant output power, both the active and reactive, modifying remotely the setting points. So, the Remote Control voltage regulation

be provided. In addition, if TSO request a curtailment of the active power injected, the operator can optimally manage the situation taking advantage of the BESS.

The next step is to analyse what changes have been made to implement the innovative services proposed in UC2. Starting from the SI provision, the plant was equipped with a specific device named as Synthetic Inertia Control Device (SICD). The device is realised with a PLC with appropriate computational performance because its main task is to detect the ROCOF event in order to trigger the active power response according to the set parameters. In fact, the power response following a frequency perturbation can be tuned by setting different parameter. The first set of parameters are the minimum and maximum state of charge (SOC) of the BESS that define the band where the service is active. The second parameter is also related to the SOC of the BESS; indeed, it is called Objective SOC and represents the SOC that results after the active power contribution. The last set of parameters refer to the shape of the active power response after a trigger event. They are: ROCOF, dead bands, droop coefficient, hysteresis and a holding time. ROCOF and frequency dead bands define the grid event that triggers the BESS. Thus, after the triggering of the BESS the output power increase linearly following the droop coefficient. Finally, when the grid event is detected, the SICD blocks the measurement of the ROCOF and wait the holding time before to trigger again the BESS. During the holding time the SICD sends to the PCS the signal to inject the requested active power. After the holding time is set a ramp down period that progressively reduces the output power to zero. In addition, during the on-field test it was observed that the BESS triggers only monitor the ROCOF value and can lead to errors in the determination of grid disturbance. For this reason, the SICD triggers the PCS whether both ROCOF and frequency thresholds are exceeded. This means that a frequency deviation must also be detected in addition to the detection of a ROCOF event in order to activate the SI contribution. Instead, from the AVC provision point of view, the implemented logic control uses primarily the reactive power available from the BESS and secondarily from the WTs, when the capability curve of the BESS's inverter is saturated. In normal operation therefore i.e., when the BESS’s inverter is available to provide the requested active power, the WTs compensate the reactive losses of the plant MV voltage cables regardless to the setpoint required by the TSO.

3 SCALABILITY AND REPLICABILITY ANALYSIS: DEFINITIONS AND GUIDELINES

"*... SRA (Scalability and Replicability Analysis) can bridge the gap between pilot demonstration projects and large-scale deployment of new technical solutions...*" [20].

This section outlines definition, general notions and approaches or guidelines followed in previous smart grid project. Firstly, it may be useful to give general definitions of scalability and replicability. Scalability means the ability of a system, network or process to increase its size/scope/range to adequately meet growth in demand. It is important to notice that this first definition does not imply that the scaled-up system works with the same performances as the starting one. For this reason, an additional more restrictive definition of scalability can be provided: scalability is the ability of a system to maintain its performance and functionality, and be able to keep all its properties, without increase the system complexity, when its scale is increased. Instead, replicability refers to the ability of a system, network, or process to be duplicated in another location or time [21] [22]. In this context, a SRA of a smart grid demo or innovative solution means to evaluate effects, outcomes or barriers that may be expected from the implementation on innovative solution on larger scale or in different time and location [23]. Pilot projects can show relevant results and asses new innovative solution to manage problems. However, demonstrate in a demo plant the validity of the solution in terms performance is not enough if it is requested to develop the innovative proposal in large scale and in different environments. That is, it might be useful perform an SRA to compare the performance and the effectiveness of the tested solutions working under different boundary condition, scale and under different stress conditions reducing the risk of projects to remaining bounded on the demo plants [24].

3.1 Areas and Factors Classifications

For a general simple system, it might be easy to define the scalability and replicability rules. I.e., the laws that determines the change in physical dimension as consequence of a change in an input parameter. Unfortunately, power systems cannot be considered as simple systems because of the large number of components involved and the complexity of the laws governing all the variables. So, it is not trivial to clearly identify what can make a project scalable or replicable. For this purpose, it can be useful try to identify factors that may influence the scale-up or the replication of innovative smart grid projects. In scientific literature these factors refer to a general innovative power system project so, they are sufficient general to cover the wide areas of sectors covered in smart grids project. Scalability and replicability factors are grouped in areas i.e., areas are groups of factors covering the same aspects. Four common relevant areas can be identified in smart grid projects: Technical, Economic, Regulatory and Stakeholder Acceptance.

Figure 11: Relevant Areas

1. **Technical Area:** it regroups all the factors concerning the compatibility of the technical environment where the demo is tested and the interaction between components. Technical aspects are evaluated both from the component and the software point of view.
2. **Economic Area:** it represents a group of factors that evaluates the profitability and the economic issues related to the project implementation.
3. **Regulatory Area:** factors within this area concern the regulatory framework where the demo solution is tested.
4. **Stakeholder Acceptance Area:** the last area proposed regroups factor that consider the support of the involved stakeholders as they usually play a crucial role in supporting the development of the solution.

In literature, areas could be also three as the regulator can be considered as a stakeholder for the plant operator so, the Regulatory area can be considered within the Stakeholder Acceptance.

3.1.1 Scalability Factors

Within the areas defined previous, the factors influencing the scalability are following proposed. Please note that factors can be also called dimensions.

1. **Technical:**
    1.1. *Modularity:* it is an important factor that affects the scalability of the solution. It refers to the use of modular components that can integrate the current system increasing size and functionality. It might be useful know whether components are fully interchangeable with others, in fact, this could help the scaling-up of the solution. E.g., usually electrical substations are composed by modular component and modular architecture to help the scale-up process if it is necessary.
    1.2. *Technology Evolution:* this factor evaluates if the scale-up of the tested solution is affected by technology evolution. E.g., it might be relevant to assess whether the computational resources of a centralized control system can control a larger size solution without compromising the overall performance.
    1.3. *Interface Design:* it refers to the ability to develop interfaces that could foster the process of adding new component to increase the size of the solution. E.g., develop of a standard communication protocol could facilitate the connection of new element in the system.
    1.4. *Software Tools Integration:* it is related to the software tools needed to control/manage the solution. In fact, it may be important to assess the software performances (or the computational cost) as the size of the solution and the number of component increase.
    1.5. *Compatibility Analysis:* this factor refers to two different types of compatibility: outside the boundary of the demo plant and inside the demo area. In fact, the site where de demo plant is located is a limited area with proper characteristics. Therefore, it is important to understand whether the solution's boundary area affects the scalability of the solution itself. Secondly, the factor investigates on the component's compatibility as the dimension of the solution increases.
2. **Economic:**
    2.1. *Economy of Scale:* This factor is related to the relationship between costs and revenues as the size of the project varies. An economy of scale is set when beyond a certain size, the cost increases less than the revenue since unitary costs are divided for a larger size of the demo. So, a scalable project is likely to have the cost function that increase less than the revenue as the size is increased.

2.2. *Profitability:* it refers to the ability of the solution to increase the relative profits at least equals to percentage of increase the size of the project. In fact, a solution can be scaled up if it is viable from an economic point of view.

3. **Regulatory:**
   3.1. *Regulation:* regulation might set potential barriers in scaling the solution. So, this factor investigates on the influence of the regulatory framework in the development of the solution.
4. **Stakeholder Acceptance**
   4.1. *Consent:* a project involves several stakeholders (e.g., partners, end users, TSOs, DSOs, component manufacturers) so this factor keep under consideration their willingness to support and to participate to the developing of the solution.

Table 1 briefly summarizes the scalability factors.

Table 1: Scalability Factors

Area	Factor/Dimension
Technical	*Modularity*
	Technology evolution
	Interface design
	Software tools integration
	Compatibility analysis
Economics	*Economies of scale*
	Profitability
Regulatory	*Regulatory issues*
Acceptance	*Consent*

3.1.2 Replicability Factors

Like scalability, factors/dimensions that affect replicability are now defined.

1. **Technical**
   1.1. *Standardization:* it refers to the development of standardized, possibly licensed products that could facilitate installation process in different environments. In fact, using standardized product may facilitate the replication also in different country.

1.2. *Interoperability:* it evaluates the ability of the solution to works with different products and systems. In fact, the replicated solution is not necessarily composed by the same components present in the solution tested in the demo plant. So, evaluating the interoperability guarantees that different products work properly in the replicated plant.

1.3. *Network Configuration:* the replicated solution needs to be able to work in different environment and under different external condition. So, this factor studies the impact of the external network configuration on the performance of the solution. In fact, results obtained in the testing process could be influenced by external grid condition like e.g., the short circuit power at the POD.

2. Economic

2.1. *Macro-economic*: the first economic factor, studies the impact of macroeconomic factors in the replication of the solution. Macroeconomics factor usually considered: inflation rate, discount rate, carbon costs etc.

2.2. *Market Design:* it refers to the structure of the market used to sell services associated to the tested solution (if the solution involves services). More in general, the factor investigates on how the remuneration is obtained.

2.3. *Business Model:* like the Market Design but more focused on the characteristics that make the solution viable e.g., remuneration scheme, positive and negative externalities generated by the solution.

3. Regulatory

3.1. *Regulation*: regulatory aspects can play a crucial role in the replication of the solution. Firstly, it might be useful evaluate the perimeter (regional, national, European) of the replication since different areas can have different rules. Secondly, also if the solution is developed in a homogeneous perimeter the regulatory may raise some barriers that limit the diffusion of the solution.

4. Stakeholder Acceptance

4.1. *Acceptance*: this factor basically impacts as the same manner of the scalability one.

Following, the table summarizes the replicability Factors/Dimensions considered in this thesis.

Table 2: Replicability Factors

Area	Factor/Dimension
Technical	*Standardization*
	Interoperability
	Network configuration
Economics	*Macro-economic factors*
	Market and business model
Regulatory	*Macro-economic factors*
Acceptance	*Market and business model*

3.2 Qualitative and Quantitative Assessment

After identifying the areas and factors influencing the scalability and replicability of a project, it is important to define the methodology by which the factors will be evaluated. In general, analyses are usually divided in two macro-types: qualitative and quantitative analyses. Starting from the qualitative approaches, they analyse the physical architecture of the system and the specific characteristic of the components that compose the solution implemented on the demo plant. So, these analyses do not require the setting up of simulation models as they are focused on the specific characteristics of the demo plant. I.e., qualitative methods assess the specific technology behind the solution developed. Usually, expected results are potential technical, economic and regulatory barriers that might limit the scalability or the replicability of the solution analysed. So, they can be useful to evaluate the extent of barriers to scalability and replicability. Differently from the qualitative approaches that are technology-oriented, quantitative approaches are functionality-oriented i.e., they analyse the scalability and replicability of the concepts related to the proposed solution and not the specific devices and component involved. These analyses require the developing of a simulation model that, starting from input parameters, evaluates the impact and the requirements of the functionalities implemented in the demo solution as the boundary condition changes (e.g., size, location, grid constraints). From the quantitative analyses are expected trends, graphs and maps that estimate the change in effectiveness or availability of the functionalities when developed on larger scale or in different environment. [21]

3.3 BRIDGE Guidelines to Perform an SRA

In scientific literature it is hard to find a common approach to fully perform an SRA of general smart grid project. In fact, solutions and functionalities implemented in smart grid demos can be very different and cover different application areas making it difficult to develop a strict common method to perform SRA. However, with the aim of providing a common guideline to perform SRA within Horizon 2020 smart grid projects, in the 2019, the BRIDGE task force on scalability and replicability was created. In particular, the main goal of the proposed guidelines is to create a general path that any smart grid project can follow to deliver a high-quality SRA regardless of the solution developed in the demo. To do so, BRIDGE separates the SRA into stages and then in step, each step can be seen as a checklist to verify that any elements that could influence the scalability and the replicability has been considered.

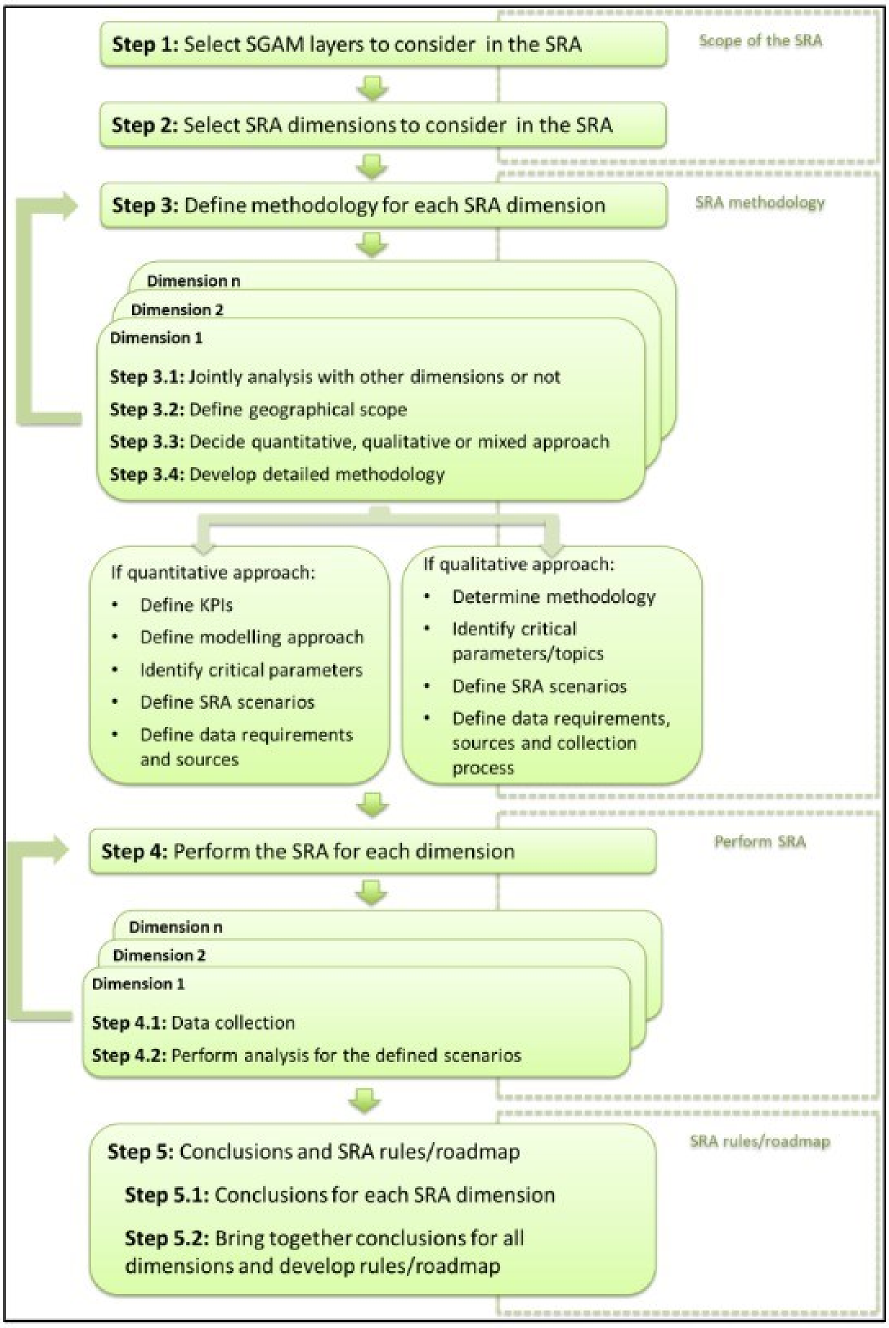


Figure 12: BRIDGE SRA Approach [25]

The suggested steps to perform an SRA are resumed in Figure 12. Four general stages of the SRA can be identified which include the five steps that are suggested to follow to perform a high-quality analysis. Following are explained the stages and steps reported in Figure 12.

Stage 1. **Scope of the SRA:** in this first stage is defined the scope of the SRA. To do this, it is recommended to locate the solution into the SGAM (Smart Grid Architecture Model) which is a reference model for smart grid project developed by the CENELEC.

In detail, BRIDGE guidelines suggest to refers to the following model to map all the characteristic of the tested solution:

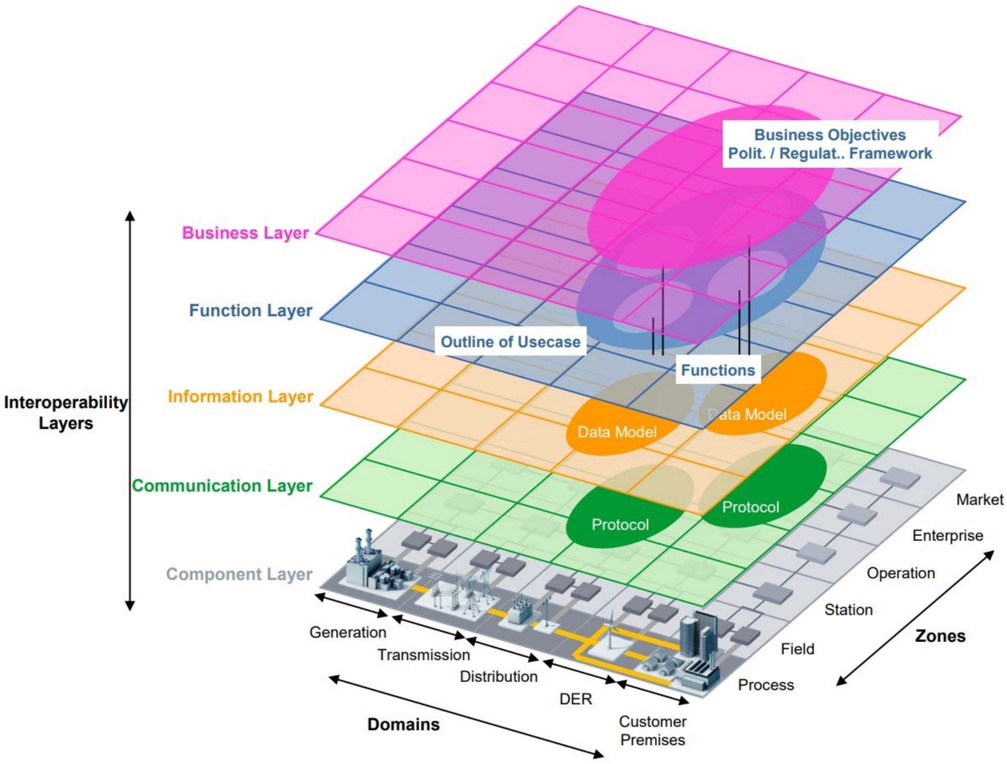


Figure 13: Smart Grid Architecture Model [26]

The SGAM model is composed by five layers that represent business objectives and processes, functions, information exchange and models, communication protocols and components. Layers are developed over the smart grid plane i.e., the grey area. This surface is composed by the electrical domains that the solution involves and the zones that represent the levels of the power system. This model allows the presentation of the current state of implementations in the electrical grid. [26]. In this context, this first stage includes the Step one and two.

Step 1. *Select SGAM layers to consider in the SRA***:** This first step aims to identify which of the five layers proposed in the SGAM will be evaluated during the SRA.

Step 2. *Select SGAM dimension to consider in the SRA:* In this step is then introduced the concept of dimension. Dimensions can be: Regulatory analysis, Economic analysis (CBA), Business models, Stakeholder's perspectives, Software scalability, Software replicability, ICT scalability, ICT replicability and Hardware. Dimension that will be assessed in the SRA are selected for each layer chosen in the Step 1.

Stage 2. **SRA methodology:** the second stage requires to define the methodology that will be used to assess each dimension assessed in the previous stage. This stage contains the Step 3.

Step 3. *Define the methodology for each SRA dimension:* this step requires an accurate definition of the analysis that will be carried out for each of the dimension selected. Indeed, the *step 3* starts with the identification of the boundary conditions that affects each dimension. It then goes on to specifically define the type of analysis that will be conducted, which can be qualitative or quantitative. The choice of methodology therefore influences the data needed to carry out the SRA. Conversely, if there are expected to be difficulties in obtaining data, this may influence the type of analysis chosen

Stage 3. **Perform SRA:** the third stage refers to the performing of the SRA for each dimension mapped in the first stage using the methodology defined in the previous stage. The performing of the SRA starts from the data collection from the stakeholders involved in the innovative solution and it ends when results are obtained. During this process, could be necessary to go back in the **stage 2** to correct the pre-defined approach.

Step 4. *Perform the SRA for each dimension:* In *step 4* the analysis starts. the operational analysis is simplified by the complete definition in the previous steps of both scopes and methodology. *Step 4* also includes the collection of the data needed to perform the evaluations.

Stage 4. **SRA rules/roadmap:** the aims of the last stage are defining a set of SRA rules and a roadmap that could foresee the replication path of the solution. SRA rules could consist in scaling and replication factors or in putting in evidence the main barriers that could affects the scalability and the replicability of the solution.

Step 5. *Conclusions and SRA rules/roadmap:* The final step consists in the evaluation of the outcomes deriving from the *Step 4*. This process starts from the analysis of the results obtained by the SRA of each dimension. Then the results of the analyses, carried out on each dimension, are compared in order to obtain a general and joint view of the scalability and replicability of the whole project under examination.

The proposed Bridge approach has to be intended as a flexible mechanism that could help in guiding a SRA. Indeed, the SRA developer may need to fine-tune the process based on available data and resources from all project stakeholders. In conclusion, the methodology proposed by Bridge can be seen as the backbone of the SRA activity.

3.4 GRID+ SRA Approach

GRID+ project, which started in 2011 and ended in 2013, aimed at supporting the European Electricity Grids Initiative to achieve the European energy market targets to the 2020. In particular, the GRID+ objective was to ensure the implementation of all necessary actions to demonstrate smart grids technologies. Among the results proposed by GRID+ project, a scalability and replicability tool has been proposed which will now be analysed.

The GRID+ SRA approach started with the identification of general factors which affect the scalability and replicability of smart grid project. Although they have slightly different variation in nomenclature, they can be traced back to the ones presented in Section 3.1. In any case, they are briefly resumed in Table 3 where Group refers to the Areas presented in Figure 11.

Table 3: GRID+ Scalability & Replicability Factors

Group	Scalability Factors	Replicability Factors
Technical	Modularity	Technology Standardization
	Technology evolution	Technology Interoperability
	Interface design	Network configuration
	Integration	
	Infrastructure Compatibility	
Economics	Economies of scale	Macro-Economic Factors
	Profitability	Market and Business Model
Acceptance/Societal	Regulatory issues	Regulatory issues
	Acceptance	Acceptance

The detected factors were then used to create two questionnaire (one for medium voltage smart grid projects and the other for transmission smart grid project) that aimed in assessing the ex-ante scalability and replicability analysis of the related project. Questions developed in the survey aimed in evaluating how the detected factors impact on the scalability and the replicability of the demo project. Then, was developed a methodology to assess the scalability and replicability potential of the solution investigated with the questionnaire. The developed approach is presented in the diagram depicted in Figure 14.

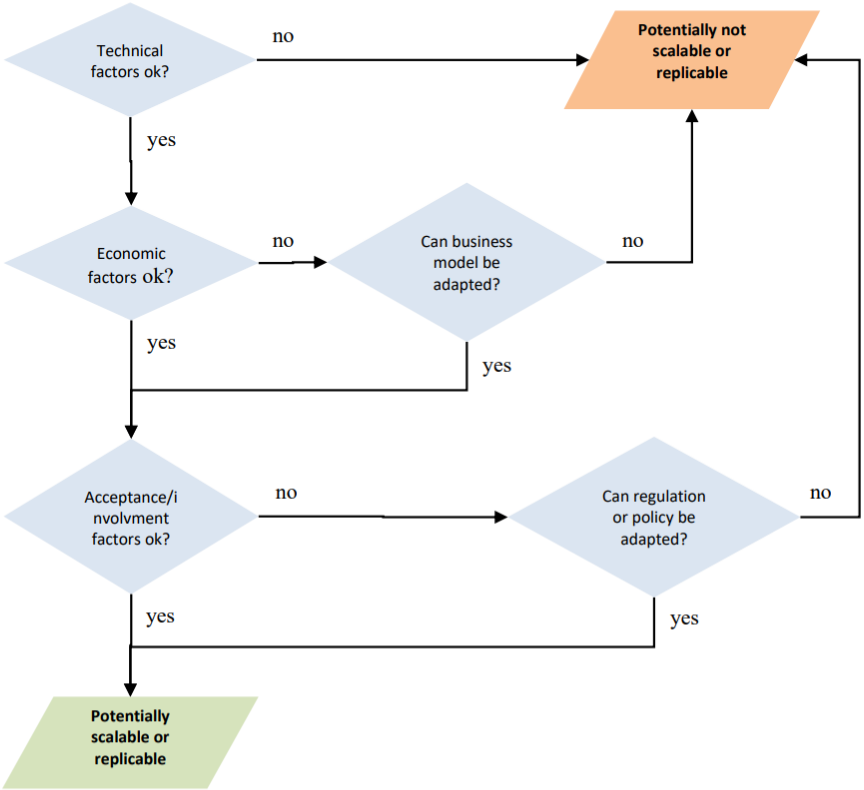


Figure 14:GRID+ Methodology to Assess Scalability & Replicability Potential

Figure 14 shows the flow chart developed to assess the potential scalability or replicability of the demo project. The approach starts ordering the areas/groups according to a certain hierarchy. Firstly, the readiness of technical factors is assessed, as they are at the basis for the functioning of the innovative solution and so at the basis of the SRA. Then, if technical factors allow the replicability or the scalability, economic factors and consequently acceptance/involvement factors are evaluated. If one of these two areas is not scalable with respect to technical factors, the question arises as to whether a modification of e.g., the business model or grid code could make the solution scalable or replicable. So, analysis of the questionnaire could result in potentially scalable or replicable or not. In addition, the questionnaire was then updated in an online tool that could be directly used by project leader to self-assess the scalability and replicability potential of the developed solution. From the surveys analysed within GRID+ were then evaluate the technical, economic, regulatory and stakeholder limitations. From what emerged it was seen that one of the most common difficulties reported from the partner was related to the overcoming of barriers that depends by player outside the project perimeter. However, the highest and common barriers detected by the analyses of the questionnaires provided to both distribution and transmission system operator regarded the regulatory and acceptance factors. In fact, the scalability resulted particularly affected by the lack of rules to provide the innovative services and by the opposition of the involved stakeholders. Moreover, the geographical variation of the rules resulted in an obstacle the replication process of the demo plant in others site. For sure, also the uncertainty of the remuneration resulted in a high barrier for both the scale up and the replication of the demo plant.

4 UC2 SRA METHODOLOGIES DEFINITION

This section outlines the framework that was followed in the scalability and replicability activity carried out in the UC2 of the OSMOSE Project. SRA involved all the UCs within the WP5. So, it was centrally manged by a coordinator who set a general common approach to make it possible to compare the results achieved from each UC within the same WP. However, the approach developed and subsequently followed is the result of adapting and extending the methodology proposed by the coordinator to the specific case of the solutions proposed in the UC2. The overall structure of the SRA was composed of two different types of analyses investigating different aspects of the developed solution. Firstly, a qualitative analysis was set up with the aim of finding potential barriers to the scale up or to the replication of the tested solutions in the demo plants. Secondly, a quantitative analysis was carried out to well understand the national framework in which the innovative grid services could be developed in the future. So, starting from the definition, notions and methodologies addressed in the previous chapter, the approach used in the two analyses is now proposed.

4.1 UC2-WP5 SRA Approach for Qualitative Assessment

The qualitative assessment was based on the developing and analysis of a survey. Indeed, it was created to evaluate how the scalability and replicability factors proposed in the previous chapter impact on the two demo plants. In this activity, partners were directly involved in the information and data collection process as they were asked to fill in the survey. The purpose of the questionnaire was to carry out a wide-ranging study of the physical architecture of the solutions developed by the partners. In particular, the analysis aimed to well understand the solutions' strengths and weakness that could drive or affect both the scalability and the replicability. The use of a questionnaire to collect information about demo project it is a quite common approach to develop a SRA. Indeed, European smart grid projects such GRID+, EvolvDSO or GRID4EU have used surveys among partners and stakeholder to understand whether the result of the tested solutions are compatible with the scale-up or with the replication process [23].

The steps used to carry out the analysis are now proposed, which were developed on the basis of the considerations made in the previous chapter.

- Step 1. Identification of the subjects of the SRA
- Step 2. Identification of affecting factors (in the BRIDGE Guidelines factors are defined as dimensions)
- Step 3. SRA methodology definition and identification of benefits.

Step 4. Data and information collection.

Step 5. Qualitative assessment of the factors analysed

Step 6. Results in form of recommendation, rules, barriers etc.

4.1.1 Step 1 - Survey Content

In this first step was defined which aspects of the developed projects the questionnaire should analyse. Firstly, open ended questions were used to investigate the scalability and replicability aspects. Although the main questions of the surveys delivered to the two partners were the same, the different approaches used to implement the solutions led to the creation of two different questionnaire to assess the performance of the two solutions. However, in order to directly compare the results of the two solutions, most of the questions are intentionally the same for both partners, or if different, they still covered the same aspect. Furthermore, for each question of the survey both the partners were asked to answer with two answers: one referred to the provision of SI and one for the provision of AVC. The choice of asking a dedicated answer for each service was made because of the significant technical differences between the implementation of SI and AVC.

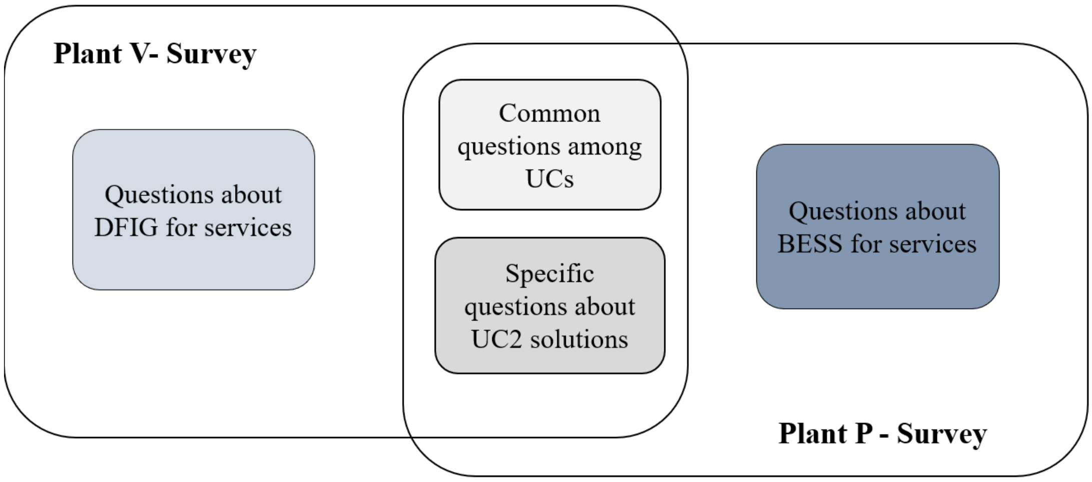


Figure 15: UC2 Surveys Content

Questions developed for the questionnaire can be grouped according to the topics they refer to. Figure 15 summarises all the categories of question that can be recognized in the 2 questionnaires delivered to WP5 UC2 partners. *"Common questions among the UCs"* were the same for each survey delivered to WP5 partners. I.e., they were sufficiently general to be answered by all the partners involved in the WP5 participants. In the analysis, these questions will allow to direct put in comparison the result carried out from the different UC. *"Common questions among the UCs"* composed the raw questionnaire initially provided by the SRA coordinator to the UCs. Starting from this, additional questions were developed which led to the realisation of the questionnaire delivered to the two partners within the UC2. The developed additional questions were tailored both to the typology of services provided (SI and AVC) and to the technical characteristics of the solutions implemented (BESS or DFIG). In fact, as can be noticed in the Chapter 2, the way the SI provision and AVC were implemented by the two demo plants was completely different. This has led to the creation three additional categories of questions:

1. *Specific questions about UC2 solutions*: this category of questions investigated the impact of scalability and replicability factors in the provision of SI and AVC regardless on the technology. E.g., the impact of the size of the plant in the contribution or the reliability of the solution. Both the partners were asked to reply to this category of questions.
2. *Specific questions about the use of DFIG based WTs for the provision of services*: The purpose of these questions was to analyse some features that only concerned the implementation of the solution using DFIGs (e.g., the possible issue regarding the coordination of the intervention of the WT). For this reason, this set of questions was developed to be included only in the questionnaire dedicated to the Plant V.
3. *Specific questions about the use of BESS for the provision of services*: On the contrary respect to the just mentioned set of questions, these were addressed to the operator of the Plant P who implemented the solution using a BESS. For example, this category investigates the optimal size of the BESS in relation to the size of the system, which is obviously a matter for the Plant P.

4.1.2 Step 2 - Survey Structure

As it can be seen from the previous section, the questions developed can be regrouped in four categories depending on the subject to which they relate to. However, a second classification of the question created can be recognized. In fact, questions can be regrouped according to the scalability or replicability factor and then area to which they refer. This classification allowed the differentiation of questions related to scalability and those related to replicability allowing the question to be presented sorted according to areas and factors defined in 3.1.

Table 4:Surveys Areas and Factors

Area	Scalability Factor/Dimension	Replicability Factor/Dimension
Technical	Modularity	Standardization
	Technology evolution	Interoperability
	Interface design	Network configuration
	Software tools integration	
	Compatibility analysis	
Economics	Economies of scale	Macro-economic factors
	Profitability	Market and business model
Acceptance	Regulatory issues	Regulatory issues
	Consent	Acceptance

Table 4:Surveys Areas and Factors summarises the factors taken into account in Step 2. Thus, applying this categorization, two different questionnaires one for each demo plants cited in chapter 2 were developed. The content of the two questionnaires were then organized in two spreadsheets. This paragraph describes the main common structure of both surveys. In detail, each questionnaire was composed by five sheets:

1. *ReadMe Section*: this is an introduction section which provides general information and instructions on how to complete each of the following sheets.
2. *Hardware and Software Solution Details*: This was the first part that the partner has to fill in. It was organized in two table: one related to the SI and one related the AVC. Each table, investigated in the hardware and software needed to implement the solution at the demo scale. Consequently, this sheet allowed to understand and compare the complexity of the solution. In addition, the partners were also invited to state the costs related to the implementation of the innovative solution in their demo plants. Cost information could help to make a simply economic evaluations about the two different solutions.
3. *Scalability Q&A:* this sheet, regrouped all the questions related to the scalability factors. The questions were organized and grouped by Area and factors as in Table 4.
4. *Replicability Q&A:* as for the previous, this part regarded the impact of replicability factors on the replication of the project's solutions. Also the categorization of the question was made as the same way of the Scalability Sheet whit the difference of using the replicability factors proposed in Table 4.

5. *Cost-Benefit Q&A*: this last sheet contained questions about the benefits and the costs of the tested solution. This sheet has not been modified with respect to the one provided by SRA coordinator.

4.1.3 Step 3 - Survey Analysis Approach

The next step was to define ex ante the methodology used to analyse the surveys compiled by partners. In particular, it was defined how to evaluate each of the analysed area and then defined how they impact on the overall scalability and replicability of the tested solution. The proposed approach assesses each factor with a score from 0 to 5. The score indicates the attitude of the solution to be scaled up or be replicated. Obviously, the score is derived from the answers that partner provided during the step of data collection and information process i.e., during the Step 4. In addition, scores were also followed by a comment that resumes the answers provided within the factor analysed as more than one questions is proposed for each factor. Table 5 and Table 6 explain scores and their meaning. For both the table a score of zero (i.e., the minimum score) does not correlate with the identification of barrier in the factor analysed but refers to a lack of information that does not allow the factor to be assessed.

Table 5: Scalability Factor Scores

Score	5	4	3	2	1	0
Meaning	**Scalable with benefits - No Barriers detected** (i.e., Scalable with benefits means that the scaled-up solution, from the point of view of the analysed factor, is more competitive than the solution to be scaled-up)	**Scalable, no Barriers detected**	**Scalable, but possible barriers detected** Furthermore analyses and verification needed	**Potentially scalable - Barriers detected** The solution needs to be further developed to overcome the identified barriers	**No scalable** Due to lack of compliance with specifications or presence of large barriers	**No scalable/Not assigned** Due to lack of information

In the scalability analysis it is important to note that the maximum score of 5 is reached when the solution shows a high grade of scalability that allows benefits to be derived from the solution if scaled up. E.g., if the costs of implementing the solution are not correlated with the size of the solution itself so, scaling up the demo might decrease the unitary costs resulting in a benefit.

Table 6: Replicability Factor Scores

Score	5	4	3	2	1	0
Meaning	**Replicable with benefits - No Barriers detected** (i.e., Replicable with benefits means that the replication process of the demo, from the point of view of the analysed factor, could increase the competitivity of the solution itself (e.g. replicate the solution could decrease the unitary cost of the solution))	**Replicable, no Barriers detected**	**Replicable, but possible barriers detected** Furthermore analyses and verification needed	**Potentially Replicable - Barriers detected** The solution needs to be further developed to overcome the identified barriers	**No Replicable** Due to lack of compliance with specifications or presence of large barriers	**No Replicable/Not assigned** Due to lack of information

As for the replicability, the maximum score of five is reached if the factor shows benefit in the case the solution is replicated. In this case, if for example, the replication of the solution foster the standardization of the components it results in benefit from the standardization point of view.

Next, the approach to jointly evaluate all the scores given to the individual factors was define. For this purpose, a numerical weight was associated to each factor evaluated. This value represents the importance of the dimension in the analysis in a similar way as seen in the Figure 14 in the case of the GRID+ project. The score goes from 0 to 1 and the closer the score is to one, the more important is the zone in the analysis. During the developing phase of the SRA methodology was decided that technical factors and economic factors weight more than acceptance. However, in the following tables are reported al the numeric weights associated to each area.

Table 7: Scalability Weighted Scores

Area	Scalability Factor	Numeric Weight
Technical	Modularity	1,0
	Technology evolution	0,6
	Interface design	0,8
	Software tools integration	0,9
	Compatibility analysis	0,7
Economics	Economies of scale	0,9
	Profitability	0,7
Acceptance	Regulatory issues	0,6
	Consent	0,5

Table 8: Replicability Weighted Scores

Area	Replicability Factor	Numeric Weight
Technical	Standardization	1,00
	Interoperability	0,90
	Network configuration	0,80
Economics	Macro-economic factors	0,75
	Market and business model	0,90
Acceptance	Regulatory issues	0,90
	Acceptance	0,60

Then, a scalability and replicability indicator were defined in relative term dividing the sum of the factor's weighted scores (i.e., the numeric weight of the factor times the factor score) of each area by the sum of the maximum weighted score of the area. In absolute value, the score two was considered the minimum value to consider the solution scalable or replicable i.e., reaching a factor of two makes the area scalable or replicable within the flow chart of the Figure 14. In Chapter 5 the entire analysis and so Step 4, Step 5 and Step 6 will be proposed.

4.2 Approach for Quantitative Assessment – Wind Provincial Power Profile

This sub-section outlines the methodology followed in the qualitative assessment of the SRA. In particular, the focus was on the possible territorial extension of the provision of the innovative services tested in the UC2. The analysis was necessary because the service provision depends on the punctual operating condition of the wind farm i.e., the plant has to work above a certain percentage of the nominal power to be able to provide services. This condition is obviously linked to the availability of the wind source and therefore it introduces a certain variability and arbitrariness in the services provision. Consequently, to evaluate the availability of wind farms in providing both SI and AVC it was necessary to have a punctual set of data containing information about the specific operation condition of the studied plants over the time. To correctly estimate the provincial availability of services the provincial annual energy produced or provincial installed power is not sufficient as no information about how individual plants have performed during the year are contained in the data. Indeed, the same amount of annual energy value can be obtained by an infinite combination of hourly generation condition. E.g., the province in object could be characterised by a low but constant wind speed that makes the plants work most of the time at power below the activation threshold, being unsuitable for the supply of SI or AVC. Conversely, the power profile could be characterized by a low number of hours but at a high power making the service provision available for a low number of hours. In addition, the variability of the wind source on a geographical scale makes the assessment of aggregated data on a national basis very inaccurate. For these reasons, the quantitative analysis required the setting up of a mathematical model to reconstruct the provincial power profile over several years. The following paragraphs outline the steps and approximations that led to the realisation of the model.

4.2.1 Input Data

The data needed to build the model obtained taken from the ENTSO-E Transparency Platform and from the GSE Statistical Publications [27], [28]. ENTSO-E makes available the annual hourly generation data by production technology for each Italian bidding zone. So, the first step consisted in download the annual data associated to the wind energy from the 2015 to the 2019. The downloaded files consisted of annual .csv files containing the average power generated in MW for each hour divided between onshore and offshore plants. Then each hourly data was accompanied by temporal information such as the date and time of reference. As each average power value refers to one hour, the value can be seen also as the energy injected in MWh. Then merging the files, the generation profiles for each of the six geographical bidding zones that were active in those years were reconstructed. In this step, the off-shore generated power have been aggregated to the predominant on-shore generated power obtaining the total average hourly power generated power by the wind plants. The profiles obtained in this way contain punctual information, but they are still too general. This because Italian bidding zones refer to wide areas as they may contain many regions as it can be noticed in Table 9. So, to make possible analysis at plant level it would be necessary to assume that plants within a bidding zone operate at the same condition resulting in a too coarse assumption considering the variability of the wind source.

Table 9: Italian Bidding Zones

Bidding zone	**Region**
NORD	Valle d'Aosta Piemonte Lombardia Trentino P.A. Trento Bolzano Veneto Friuli Venezia Giulia Liguria Emilia Romagna
CNOR	Toscana Marche
CSUD	Lazio Abruzzo Campania Umbria
SUD	Molise Puglia Basilicata Calabria
SICI	Sicilia
SARD	Sardegna

Therefore, to increase the accuracy in geographical terms a second set of data has been integrated to the previous. From the GSE (Gestore Servizi Energetici) website was downloaded the statistical annual report about the renewable energy sources in Italy. These reports contain the annual summary of the total installed wind power and the produced energy on different geographical scale. In fact, they provide, in a specific section, both the percentage of the installed power and the percentage of the energy produced by each region and province respect to the national frame. Therefore, from the data contained in the annual reports corresponding to the years 2015 to 2019 have been extracted the percentage of the provincial installed power, the percentage of the provincial energy produced and obviously the overall values of installed power and energy produced. This dataset was then organised in a worksheet adding to each information the reference year and the corresponding bidding zone.

In summary, the wind generation profile subdivided by bidding zone from 2015 to 2019 and the provincial percentages of energy $\%E_{y,i}$ and installed power $\%P_{inst,y,i}$ for the same years have been the input data for the model. The index i refers to the province and the index y to the year.

4.2.2 Data Elaboration and Assumption

The first assumption that was made in the processing of the data was necessary due to approximation errors in the GSE annual statistics. In fact, the summation over the year of the provincial percentage of the installed power over the total, in certain years slightly differs from 1 and the same happens for the percentage of the provincial energy summation. For this reason, both $\%E_{y,i}$ and $\%P_{inst,y,i}$ were corrected as following:

$$\%E_{y,i}^{corr} = \frac{\%E_{y,i}}{\sum_{i=1}^{\#prov} \%E_{y,i}} \tag{5.1}$$

$$\%P_{inst,y,i}^{corr} = \frac{\%P_{inst,y,i}}{\sum_{i=1}^{\#prov} \%P_{inst,y,i}} \tag{5.2}$$

I.e., for each year, the percentage of energy and power was divided by the sum of the overall contributions of provinces over the year. The second step that has been made to obtain the provincial annual power profile, was to calculate the energy share that each province contributes to the total energy produced in the bidding zone to which it belongs. So, all the quotas coming from provinces off the same bidding zone were aggregated obtaining the following table:

Table 10: Bidding zones energy share

		NORD	**CNOR**	**CSUD**	**SUD**	**SICI**	**SARD**
	Index	1	2	3	4	5	6
Year	**2015**	1,36%	1,45%	16,00%	51,12%	17,07%	13,00%
	2016	1,20%	1,50%	17,15%	52,34%	17,25%	10,57%
	2017	1,10%	1,50%	17,22%	51,05%	18,62%	10,51%
	2018	1,10%	1,31%	16,57%	53,51%	18,17%	9,34%
	2019	1,00%	1,50%	17,74%	53,31%	16,43%	10,02%

Each cell of the table was named as $\%E_{y,j}$ where the index y refers to the year and the index j refers the bidding zone. Then, $\%E_{y,j,i}$ was computed for each province using the (5.3). $\%E_{y,j,i}$ is the quota of the energy produced by the province i to the bidding zone j in the year y.

$$\%E_{y,j,i} = \frac{\%E_{y,i}^{corr}}{\%E_{y,j}} \tag{5.3}$$

It can be seen that the way the model has been constructed, the sum of the energy percentages of the provinces forming a bidding zone in a given year is equal to1. Subsequently, the installed power for each province for each year was calculated by simply multiplying the $\%P_{inst,y,i}^{corr}$ with the total installed power in the reference year. The new dataset obtained from the above calculations was then correlated with the hourly data from ENTSO-E's Transparency Platform. In fact, the $\%E_{y,j,i}$ allowed the subdivision of the hourly data aggregated by bidding zone simply multiplying the hourly data with the respective $\%E_{y,j,i}$. Values were organized in a matrix where the columns were the provinces and the rows corresponded to the time instant to which the calculated value referred. In order to make results easily comparable was defined an hourly production coefficient matrix where each cell was the ratio of the hourly province average power and the provincial installed power. Here, it was assumed that all plants within a province were working under the same condition. Consequently, under this strong assumption the hourly production coefficient can be seen as the percentage of power injected by any plant in the province respect to its rated power. Finally, as the availability of the provision of some services by WTs requires that the produced power is above a certain activation threshold, to make consideration about the availability of services was implemented another set of data. Therefore, starting from the hourly production coefficient matrix, was created another matrix which evaluates when the plants of each province are eligible to providing grid services. The availability matrix was constructed by comparing the hourly production coefficient with a characteristic threshold of the service to be provided. This resulted in a matrix composed by 1 when the plant power injected is above the threshold in the reference hour and vice versa 0 when the power is below the limit set. Different availability matrices were computed varying the activation threshold related to the service provision.

4.2.3 Output Data

To recap, the output data from the model implemented were a five-years provincial hourly generation profile, a five-years provincial hourly production coefficient and finally a five-year availability matrix. As each row of the above-mentioned results refers to a specific time instant, information has been organized according to the scheme shown in Table 11. On the right side of the table were reported all the provinces with the respective hourly information (e.g., the hourly production coefficient).

Table 11: Example of the spreadsheet used to catalogue the results

MONTH	YEAR	DATE	DAY PHASE	SEASON	STARTING TIME	ENDING TIME	…
…	…	…	…	…	…	…	…
3	2018	05/03/2018	Evening [18-0]	Spring	18:00:00	19:00:00	…
3	2018	05/03/2018	Evening [18-0]	Spring	19:00:00	20:00:00	…
3	2018	05/03/2018	Evening [18-0]	Spring	20:00:00	21:00:00	…
3	2018	05/03/2018	Evening [18-0]	Spring	21:00:00	22:00:00	…
…	…	…	…	…	…	…	…

The provincial availability matrix and the provincial power profile were at the basis of the quantitative assessment presented in Chapter 6. Finally, Figure 16 resumes the overall process that has led to the creation of the above-mentioned model starting from the input data to the output data.

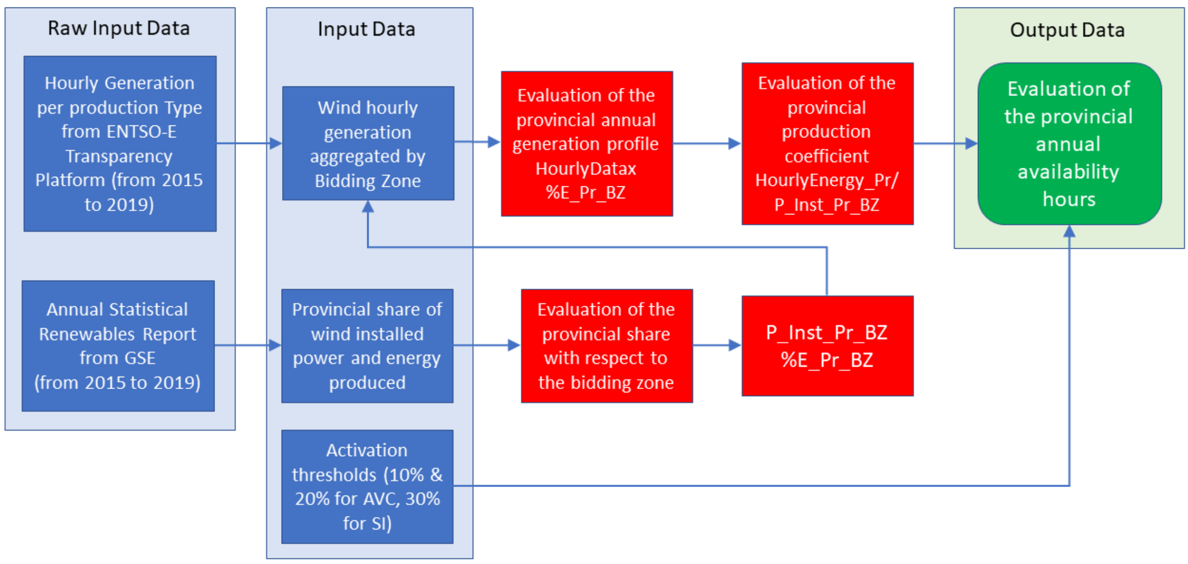


Figure 16: Flowchart of the Process

5 QUALITATIVE SRA – SURVEY ANALYSIS

This section proposes the Step 5 and Step 6 i.e., the qualitative SRA and results based on the surveys analysis. In fact, after the Step 4 that directly involved the partners in the data and information collection, surveys were analysed following the guidelines provided in 4.1.3. The analysis proposed is composed by three parts. Firstly, it is showed a statistical preliminary analysis that evaluates the completeness of the answers provided by partners. Secondly, it is proposed the discourse analysis that presents the answers of the partners re-elaborated and in an aggregate form. Finally, the score associated to each factor and the results of the qualitative SRA are proposed.

5.1 Statistical Preliminary Analysis

This first sub-section presents a statistical preliminary analysis which assesses the completeness of the answers provided by both the partners involved. The analysis below presents the average compilation data of the two partners aggregated against the technology investigated in the survey.

Table 12: SI Aggregated Statistical Analysis

SI				
Type of questions/area	Total number of questions asked	% Uncompleted questions	Number of added questions	% Involved partner that filled the questionnaire
	Scalability SI			
Technical questions	33	9%	19	100%
Economical questions	14	21%	10	100%
Regulation questions	14	79%	4	100%
	Replicability SI			
Technical questions	30	23%	15	100%
Economical questions	12	17%	9	100%
Regulation questions	14	14%	5	100%
	CBA SI			
Cost benefit questions	22	50%	0	100%

From Table 12 and Table 13 can be noticed that scalability regulation and economical questions about SI showed a high percentage of incompleteness respect to the technical ones. This may have been caused by difficulties in providing complete information on aspects that are not yet standardised both at grid code and remuneration level, more considerations will be made in the discursive analysis. Instead, the replicability sheet of SI showed a good level of completeness except for the technical questions. In essence, a low degree of technical standards can be expected to have influenced this category of questions.

Table 13: AVC Aggregated Statistical Analysis

AVC				
Type of questions/area	Total number of questions asked	% Uncompleted questions	Number of added questions	% Involved partner that filled the questionnaire
	Scalability AVC			
Technical questions	32	9%	19	100%
Economical questions	14	0%	10	100%
Regulation questions	14	71%	4	100%
	Replicability AVC			
Technical questions	27	4%	13	100%
Economical questions	12	17%	6	100%
Regulation questions	12	17%	4	100%
	CBA AVC			
Cost benefit questions	22	59%	0	100%

Analysing Table 13 can be notice that scalability Regulation question about AVC showed a high value of incompleteness respect to the others. Instead, good results are achieved both on technical and economic issues. Finally, comparing the two tables it can be seen that in general the questions concerning AVC were more completed.

5.2 Discourse Analysis

Is now proposed the discourse analysis of the questionnaire. The discursive analysis is based on the answers given by the partners to each question related to each factor (ANNEX). The analysis is proposed by first proposing scalability analyses by function and technology and then replicability analyses in the same order.

5.2.1 RES +BESS for SI Scalability

5.2.1.1 Technical

Modularity

In this case, SI to support network stability is supplied only by the BESS, whereas WTs are not equipped to provide the service. BESS could be easily scaled up, depending on technical-economic analysis, by adding additional components (batteries/BMSs/inverters) connected in parallel downstream the plant POD. It should be noted that this solution assures the maximum flexibility in setting the SI contribution since main characteristics of the BESS response (e.g., maximum power contribution, gain, activation thresholds, etc.) are not directly related to the wind plant rated power, then they could be sized independently in accordance with grid requirements. Field tests demonstrated a contribution up to 800 kW (4.44% of the rated power), according to BESS capability constraints. Since the SI is provided by the BESS, the availability of the plant in supplying the service is independent from the primary source availability. An additional HW device called Synthetic Inertia Control Device (SICD) was developed by the partner to allow the BESS to provide SI. The SICD consists in a PLC. Its size, main specs and implemented functionalities do not depend by BESS size and type. Then, nothing has to be added on the SICD to scale-up the solution's size.

Technology evolution

The present TRL ensures the scalability of the solution without significative barriers. To achieve the commercial stage of the developed equipment, industrialization and certification of the product will be required. Improvements of inverter performances (e.g., smart inverter with grid-forming functionalities, reduced response time, increased accuracy, and reliability) could help to increase size, effectiveness and competitivity of the solution in providing SI. An improvement in the measurement chain and in applied logics is required to correctly identify network events that require the provision of SI by the BESS.

Interface design

SI is provided only by the BESS, then the solution does not require strong coordination with WTs. SICD is programmed to limit the SI contribution in the case the plant production is very high and providing SI could results in exceeding the maximum power injection agreed with the TSO in the connection contract. A similar logic is imposed to avoid excessive power absorption from the network in the case of over frequency and absence of wind. Scaling-up the solution in terms of absolute value (i.e., increasing the maximum SI power contribution during frequency perturbations) can lead to install additional BESS units in parallel. In this case, it is highly recommended that only one measurement device evaluates the ROCOF for the entire BESS system and controls all the BESS units. This allows to avoid anomalous behaviours of single BESS units caused by inconsistent measurements independently performed by each BESS unit (e.g., due to unexpected delays or errors in the ROCOF measurement). In general, considering that BESS units are installed closely, this does not involve significant limitations in terms of required communication devices.

Software tools integration

The software installed in the SICD to control the BESS in providing SI is fully in-house developed. Software performances are not affected by the size of the plant, consequently they do not represent a barrier in scaling-up the solution. In fact, independently from the overall BESS size, the software measures frequency and ROCOF in a single network point close to BESS terminals. Then, it elaborates the SI contribution and sends the reference power to the inverters of operative BESS units. SI contribution is locally controlled according to a set of configuration parameters agreed with the TSO (e.g., SI gain, activation thresholds in terms of both frequency and ROCOF, hysteresis values, etc.).

Compatibility analysis

At present, the SI contribution is limited by the maximum power injectable at the POD (parameter agreed with the TSO) in the case of under-frequency and high wind availability. Similarly, the SI contribution is constrained by the maximum power absorption at the POD in the case of over-frequency perturbation during wind absence. Considering the aging of BESS components, providing SI implies an increased stress due to rapid charge/discharge cycles imposed by the service, which falls in the range of power-intensive uses of storage devices. This additional stress is directly influenced by the set of configuration parameters and modalities to be agreed with the TSO, such as for example the SI gain and the activation thresholds (both in terms of frequency variation and ROCOF). Reducing activation thresholds involves a more frequent use of the device, even in the case of normal frequency perturbations. On the other side, increasing the activation thresholds limits the SI provision only to serious network events.

5.2.1.2 Economics

Economies of Scale

The installation of a BESS in a wind farm is not a consolidated practice to date, then providing the SI by making use of the BESS requires that this device is already installed in the site. In this case, the cost to implement the solution is related only to the SICD. Since only one SICD is required independently from the size of the BESS, the relative cost of the SICD (i.e., cost per MW of the BESS) decreases as the size of the BESS increases. So, scaling-up the solution can be advantageous to reduce relative cost of the SICD (even if the SICD cost remains very limited in comparison with the entire BESS investment). it is necessary to consider that the optimal size of the BESS needs to be assessed by the plant owner taking into account both technical constraints (e.g., required SI contribution according to wind farm rated power) and economic issues, considering that convenience and competitiveness of the BESS are related to a set of ancillary services that it can provide to the main network and to the wind farm itself.

Profitability

The solution profitability is clearly correlated with the BESS capital cost. It is difficult to evaluate the profitability of the scaled-up solution since no remuneration schemes for the provision of SI presently exist. It seems reasonable that in future the service will be remunerated if the plant will be able to provide SI according to defined criteria in terms of performance and availability.

5.2.1.3 Acceptance

Regulatory Issues

SI is not presently regulated from both the technical and the economical point of view. The Italian grid code currently prescribes a fast frequency regulation i.e., wind power plants connected to the HV main grid have to be able to supply a surplus of active power (0-10% of the plant rated power, standard value 6%) for a time interval (0-30 s, standard value 10 s) in the case of network under-frequency exceeding an activation threshold (range 49.5-50 Hz, standard value 49.8 Hz). The contribution is required to WTs if they are producing more than a minimum power according to primary source availability (30% of the rated power is the standard value). ROCOF is not considered in the present grid code.

Consent

TSO consent is very important since it is considered the most important stakeholder for SI provision. In general terms, the scale-up of the new functionality can improve the company's position (social, environment...) since making renewables more flexible and capable to provide services till now offered only by traditional power plants will remarkably foster energy transition to sustainability.

5.2.2 DFIG for SI Scalability

5.2.2.1 Technical

Modularity

In this solution, SI provision is achieved directly from the WT by suitably controlling both the mechanical and the electric/electronic sides of the machine. This allows to intentionally reduce the rotor speed to extract a part of the kinetic energy of rotating parts and transfer it to the electrical network in form of frequency stabilizing contribution. This consists in a temporarily increase of the injected power during under-frequency events i.e., during the SI provision the generated electrical power exceeds the primary source availability, considering conversion losses. The time trend of the stabilizing contribution is defined according to a regulation law (in particular, it is proportional to ROCOF once activation thresholds are overpassed, and maximum power contribution is not reached) applied by acting on power converters and relative controllers. Then, SI is supplied by WTs depending on their specs, operating conditions, and settings. The overall contribution of the entire plant is influenced by its rated characteristics (number of WTs, etc.) and operating conditions of each WTs, particularly depending on primary source availability. However, since the stabilizing contribution is individually supplied by each WT, scalability analysis will generally refer to the single WT instead of the entire wind farm (wind farm overall rated power is not univocally correlated with the WT size). If all the installed WTs are compliant with SI requirements, then the overall plant can be considered compliant as well. A specific analysis is required to define if the ROCOF measurement has to be centralized or individually performed by each WT, even if the centralized solution could avoid possible instabilities caused by errors in local measurement devices. Even if considering the developed solution applied to larger WTs, it seems difficult to obtain the SI contribution if the WT power production is lower than a minimum threshold (reasonably 30% of the WT rated power), since an excessive reduction of rotor speed could impact on the stability of the machine. This suggests to characterize the SI contribution made available by this solution also considering a statistical approach and near time monitoring. Scaling-up the solution means implementing the logic for obtaining the extra active power contribution on larger WTs. The solution modularity is clear, since a part of the controller providing the SI contribution could be the same independently from the WT size. However, make a WT compliant with SI specs means working on the onboard PLC, that it is usually a proprietary part of WT manufacturers. In addition, each WT adopts specific converters and PLCs. This necessarily requires a hard involvement of WT manufacturers, as done during this research project. Particularly, interest of manufacturers could only focus on new or current WT models, whereas the application of the developed logics to older models seems hard to be achieved. Currently, no standards for SI provision exist. This, as well as the required WT manufacturers' involvement, could result in a possible barrier for scaling-up the solution, especially if the service will not be mandatory in future applications.

Technology evolution

A TRL 5 has been reached. The new function was tested in laboratory on a standard WT, not specifically designed to provide SI. More analyses and tests on an actual WT scale are required to validate both modelling results and laboratory tests before implementing the developed solution on a real plant connected to the main grid. This phase requires the direct involvement of WT manufacturer to preserve both certifications and warranties of the WT.

Interface design

In the developed solution, SI is provided individually by each WT which locally measures the ROCOF, then no coordination among WTs have been tested. In a real wind farm, WTs are installed remotely, with distances of several hundreds of meters between towers. If the ROCOF measure will remain independently performed by each WT, severe specs must be considered to avoid measurement errors and delays, which potentially impact on the overall plant behaviour in response to the network frequency perturbation. Oppositely, if a single ROCOF measurement device will be installed for the overall power plant (e.g., at the plant POD or close to the control room), a suitable communication infrastructure has to be considered (primarily in terms of latency). No other issues about interface design have been faced.

Software tools integration

Software and firmware integration could result in a barrier for scaling-up the solution since they have to be developed, tested, and installed (in the converter in the nacelle and in the PLC controller) by the WT manufacturer to preserve certifications and warranties of the entire WT. At present, the developed software needs further validation and tests before the implementation on a grid connected WT/plant (this phase could not be carried out in this research project due to lack of time). Advanced versions of software and firmware able to provide SI seem hard to be installed on old WT models due to different technological standard and limited performances of installed equipment.

Compatibility analysis

No evident issues are detected associated with the area where the demo is implemented. The case in which an under-frequency perturbation occurs while the plant is operating at its maximum power requires to be defined in terms of connection rules, since providing SI could lead the overall injected power to overpass the rated power of the plant during the reduced time interval in which the SI is provided (few tens of seconds). About the additional aging of WTs caused by the service, it has not yet been assessed whether the SI supply could limit the lifetime of WTs due to the additional stress associated to the provision of extra power, both in terms of mechanical aspects and electrical/electronic issues. Obviously, it will also depend on the set of parameters imposed to WTs in terms of gain, activation thresholds, maximum required power surplus, etc.

5.2.2.2 Economics

Economies of Scale

Costs for developing the solution on larger size WT are difficult to be computed from the partner point of view, since this evaluation should be done by the WT manufacturer. In general terms, on modern WT with similar internal architectures, the cost could be limited in relative terms in comparison to other ways to obtain SI, since implementing SI on larger WTs results in a simple adaptation of existing components and technologies (hardware/software), with no expensive equipment to be added. Differently, applying the solution to different WT product families or old WT models could require specific software and firmware that have to be developed and tested. For this reason, it is difficult to identify a general relationship between cost and size of the WT.

Profitability

The cost to adapt modern WTs to SI provision seems limited in comparison with other technical solutions to provide SI, even if the on-field validation process is not completed. It is difficult to evaluate the profitability of the scaled-up solution since no remuneration schemes for the provision of SI presently exist. It seems reasonable that in future the service will be remunerated if the plant will be able to provide SI according to defined criteria in terms of performance and availability.

5.2.2.3 Acceptance

Regulatory Issues

SI is not presently regulated from both the technical and the economical point of view. The Italian grid code currently prescribes a fast frequency regulation i.e., wind power plants connected to the HV main grid have to be able to supply a surplus of active power (0-10% of the plant rated power, standard value 6%) for a time interval (0-30 s, standard value 10 s) in the case of network under-frequency exceeding an activation threshold (range 49.5-50 Hz, standard value 49.8 Hz). The contribution is required to WTs if they are producing more than a minimum power according to primary source availability (30% of the rated power is the standard value). ROCOF is not considered in the present grid code. It is important to note that laboratory tests confirmed the ability of the analysed WT in providing a power surplus up to 10% the WT rated power, with a time duration from some seconds (if the wind speed is low) up to tens of seconds if the actual power overpass a minimum threshold.

Consent

TSO consent is very important since it is considered the most important stakeholder for SI provision. In general terms, the scale-up of the new functionality can improve the company's position (social, environment...) since making renewables more flexible and capable to provide services till now offered only by traditional power plants will remarkably foster energy transition to sustainability.

5.2.3 RES +BESS AVC Scalability

5.2.3.1 Technical

Modularity

In this case, reactive power to support network voltage regulation is primarily supplied by the BESS and secondly by WTs. WTs are priorly required to compensate internal reactive "losses", caused by the reactive power absorption of plant MV cables, which can vary from inductive (during high power production resulting in high currents flowing on cables) and capacitive (caused by no-load reactive absorption of MV cables). Then, the amount of reactive power that the plant can exchange with the grid depends on both the BESS inverter's size and the capability curve of the WTs. The KPI was evaluated considering the AVC provided by the sole BESS, which supplied the required reactive power according to the BESS inverter capability (1 Mvar, both inductive and capacitive). The test did not consider the entire plant capability (about 7 Mvar in terms of reactive power). BESS characteristics could be easily scaled-up depending on technical-economic analysis. It could be done by adding batteries/BMSs/inverters connected in parallel downstream the network POD. Physical dimensions of BESS generally remain very limited in comparison with the wind power plant and required equipment for grid connection. Reactive power demands exceeding the BESS inverters' capability could be supplied by WTs in accordance with WTs' specs, both in terms of capability area and dynamic performance (e.g., the regulating time). From the Master SCADA point of view, no improvements or additional components are required to scale-up the solution size i.e., the developed device is easily appliable to larger inverters and WTs. In fact, the Master SCADA hardware and the implemented functionalities are independent from both the BESS size and the wind farm characteristics (number and size of WTs, plant topology, distance among WTs in the power plant, etc.). Then, the solution implemented on the Master SCADA level shows a very high level of modularity.

Technology evolution

The solution consists in an innovative additional functionality implemented in plant Master SCADA. It can be a feature of a future standard Master SCADA, then it can be considered at maximum TRL.

Interface design

AVC is provided by the overall plant basing on the BESS characteristics and, secondly, on WTs' specs and plant data. A centralized controller drives the BESS inverter to provide the required reactive power. In the case the required reactive power exceeds the BESS inverter capability area (or if the BESS is unavailable), it evaluates the set points to be sent to each WT, according to the voltage measured at the plant POD and the voltage reference signal (or the reactive power setpoint) received by the TSO. The function is hard to be decentralized to single WTs, since this could lead to instabilities also considering that the internal distribution system may cause differences in voltage levels at each WT. Even in the case WTs are involved in providing the regulation service, no severe characteristics are required to the local communication infrastructure (e.g., in terms of latency). Finally, the centralized control can encourage the scalability as it simplifies the integration of new or larger components.

Software tools integration

The software needed by the hybrid plant (WTs and BESS) to provide AVC was fully in-house developed. Software performances are not affected by the size of the plant. No significant updates to the control logic of the BESS are required even in the case of larger size. However, in the case of larger WTs, the control logic may need to be slightly tuned according to WTs specs (e.g., in terms of dynamic behaviour) with the aim of optimizing the coordination and involvement of WTs in the provision of the service.

Compatibility analysis

A detailed study to characterize the transmission network is required to tune the AVC service in terms of limits in reactive power exchanges at the POD. In terms of plant components' lifetime, the provision of reactive power by the hybrid plant (BESS and WTs) appears to have no significative impact beyond normal usury (caused by higher currents flowing on cables and other electric components).

5.2.3.2 Economics

Economies of Scale

The installation of a BESS in a wind farm is not a consolidated practice to date, then providing the AVC by making use of the BESS requires that this device is already installed in the site.

Present BESS unit costs are hard to be justified by the sole AVC function, even in the case this regulating service will be remunerated in the future and considering larger sizes of plant. This makes difficult to evaluate possible economies of scale for this technology in providing AVC. However, on the other hand, a BESS is able to provide several ancillary services, both to the wind farm itself (capacity firming, generation profile control, etc.) and to the main network. AVC provision does not impact on other ancillary services related to active power (e.g., frequency support, generation time-shift, etc.). Furthermore, AVC capability is mainly related to the size of the inverter of the BESS (and not influenced by its storable energy), then oversizing only this component could make the plant able to provide a larger AVC contribution with limited additional costs. Once the BESS is installed in the plant, few costs are expected for increasing the size of the solution to adapt the specific control to different WT dynamics.

Profitability

It is difficult to evaluate the profitability of the scaled-up solution since no remuneration schemes for the provision of AVC are currently operative. In the case AVC will be remunerated in the future, it could contribute to make the BESS economically profitable (also considering that the regulating contribution is substantially independent from the primary source availability). At present, the Italian grid code imposes to wind farms connected to the HV transmission system an almost rectangular capability curve, then the AVC contribution has no direct impact on current plant profitability, since it does not affect the injection of remunerated active power.

5.2.3.3 Acceptance

Regulatory Issues

Present grid code imposes the wind farms to make available a defined capability curve, but no remuneration schemes are applied. A pilot project on renewable power plants upgrades for voltage regulation, promoted by the Italian TSO and Italian NRA, is following in the next years and will deepen technologies performance in providing voltage regulation on a system level.

Consent

TSO consent is very important since it is considered the most important stakeholder for AVC provision. In general terms, the scale-up of the new functionalities can improve the company's position (social, environment...) since making renewables more flexible and capable to provide services till now offered only by traditional power plants will remarkably foster energy transition to sustainability. A relevant interest of the TSO exists for exploiting the AVC contribution made available by renewable plants.

5.2.4 DFIG for AVC Scalability

5.2.4.1 Technical

Modularity

Reactive power to support AVC is entirely supplied by WTs according to their capability areas. The capability area of the entire power plant, as seen at the POD, is directly influenced by WTs' specs and plant main characteristics (in. particular, length and rated voltage of internal MV distribution network). WT specs are directly influenced by local grid codes. The participation of the plant to AVC has required the installation of additional components (SCADA and communication channels) that can be easily applied to larger plants since their technical characteristics and cost are independent from the plant size (in terms of both WT rated power and overall number of WTs). The entire capability of the wind farm was tested and issues about the maximum reactive power contribution of WTs (caused by a software configuration of the WT) and the regulation time (controllers and installed WTs are compliant with the previous grid code requirements according to their installation date) were observed. Additional reactive contributions could be obtained by adding reactive compensation devices as modulating capacitor banks or inductors (currently not installed). Physical dimensions of these additional systems are generally limited in comparison with wind power plant and other equipment. Moreover, there could be difficulties in controlling discrete equipments integrated with the WTs plant controller.

Technology evolution

The main barrier to scalability with regards to TRL consists in fulfilling the response time required by the TSO in the current grid code (considering that the latest version of the Italian grid code introduced a fast regulation of reactive power). Particularly, difficulties concern the plant controller, since the overall hardware installed in the communication chain (from the TSO control room to the plant controller, and from this to each single WT controller) introduces a delay that reduces the time available to WTs to reach the required reactive power setpoint. The scaling-up of the solution does not impact on this issue. A TLR level 7 could be considered reached.

Interface design

AVC is provided by the overall plant according to WTs' specs and plant characteristics. A local embedded apparatus computes the overall reactive power basing on both local measures and a reference signal sent by the TSO (reference voltage or required reactive power exchange at the connection node). Then, a reactive power set point for each WT is computed and locally transmitted. In future implementations, the field test suggested to improve the remote communication performances and the system architectures to minimize the time required from receiving the signal from the TSO and sending the reactive power set point to each WT. However, this aspect is not directly related with the scalability of the solution.

Software tools integration

The software to provide AVC is installed in the local embedded device that gather data and information to a centralized datacentre where a second level SCADA is operating. The software was developed in-house by the partner. It is scalable to larger size plant (both in terms of WTs with higher rated power and plants with more WTs). Even in terms of monitoring and controlling interface apparatus, the size of the plant has no significant impact.

Compatibility analysis

No significant incompatibilities between the size of the project and the area where it is located have been addressed during field tests. Scaling-up the solution can make available a larger amount of reactive power, but a specific study on network characteristics is required to better configure the required regulating service. Even if WTs' full capability curve has not been deeply tested in past installations, it seems reasonable to estimate that WTs' lifetime should not be impacted by providing AVC, with exception for few electrical components which could experience more severe operating conditions (in particular, higher currents flowing on cables, transformers, and other devices).

5.2.4.2 Economics

Economies of Scale

Costs to implement AVC on larger modern wind plants (both in terms of WTs rated power of plants with a higher number of WTs) can be considered negligible in comparison with the cost of the overall generation plant (especially the WTs' cost). The control system including a local SCADA in communication with a remote centralized second-level SCADA seems to be a common practice, then this does not impact in terms of additional costs. An improved version of the developed software can be easily installed and correctly perform the required service. Instead, in the case of small-scale plants or in sites making use of old models of WT (i.e., not in compliance with recent grid code requirements), the solution seems to be applicable with difficulties to be evaluated case-by-case.

Profitability

It is difficult to evaluate the profitability of the scaled-up solution since no remuneration schemes for the provision of AVC are currently operative. At present, the Italian grid code imposes to wind farms connected to the HV transmission system an almost rectangular capability curve, then the AVC contribution has no direct impact on current plant profitability, since it does not affect the injection of remunerated active power. In the case AVC will be remunerated in the future, the additional cost of the plant to contribute in AVC is quite limited in comparison with other solutions and it directly depends on the dynamic performances required to the plant (including both WTs and the control unit) in making available reactive power at the POD.

5.2.4.3 Acceptance

Regulatory Issues

Present grid code imposes the wind farms to make available a defined capability curve, but no remuneration schemes are applied. Fulfil current grid code requirements in term of time response was the main difficult encountered in the field test. Many causes impacted on this: (i) installed WTs were purchased before the last grid code update, then they are not able to fully meet the requirements in terms of regulation time (2 s for providing 90% of the reactive power set point); (ii) performances of the communication/control chain (local embedded device, based on a Windows embedded operating system, remote communications with a central datacentre for a second level SCADA, local communications with the first level SCADA server through OPC protocol, etc.). A pilot project on renewable power plants upgrades for voltage regulation, promoted by the Italian TSO and the Italian NRA, is following in the next years and will deepen technologies performance in providing voltage regulation on a system level.

Consent

TSO consent is very important since it is considered the most important stakeholder for AVC provision. In general terms, the scale-up of the new functionalities can improve the company's position (social, environment...) since making renewables more flexible and capable to provide services till now offered only by traditional power plants will remarkably foster energy transition to sustainability. A relevant interest of the TSO exists for exploiting the AVC contribution made available by renewable plants.

5.2.5 RES +BESS for SI Replicability

5.2.5.1 Technical

Standardization

The solution is at the prototypal stage and can be standardized once TSOs will regulate the provision of SI by renewable power plants. This impacts on several aspects of the BESS providing the stabilizing function, from sizing hardware components to designing software and firmware to be installed in controllers and converters. Finally, the product has to be industrialized and certificated. In fact, one of the targets of the research project is to foster and suggest a clear and rationale definition of needs and technical requirements for this innovative service. Whereas it appears reasonable to standardize the SICD, including the ROCOF measurement device, it should be noted that BESS sizing is also affected by other design drivers depending on other ancillary services suppliable, since its cost is hard to be justified by the sole SI provision, even if remunerated in the future. For example, the BESS tested in the pilot site has been sized basically to respect the wind farm production profile scheduled the day ahead. Consequently, in a short term, it is difficult to develop a standardized product that could be easily replicated elsewhere, both in national and international contexts. Standardization can include specific requirements in terms of prescribed accuracy, reliability, and availability of the service. It is important to underline that the developed SICD is very flexible in terms of configuration parameters, then the SI contribution can be easily modified according to specific standards that will be locally applied.

Interoperability

SI provision is regulated by the SICD, consisting in a PLC that measures both frequency and ROCOF and consequently controls the BESS. The SCID can be easily implemented with any PLC in the case it has the appropriate specifications in terms of signal sampling and computational processing capabilities. Grid code standards will have to specify the characteristics of SI contribution, both in terms of accuracy and dynamic performances. The developed solution can be replicated regardless the type of BESS installed. Furthermore, this solution to provide SI does not require specifications on WTs installed in the plant, since SI is obtained by ad additional components in parallel to the traditional plant downstream the network POD. These aspects make the solution easily replicable from the interoperability point of view. Even, the SI contribution obtainable by combining a BESS and a SICD could be suppliable in the absence of primary source, in dedicated storage units and in combination with other types of generation plants (e.g., photovoltaic plants).

Network configuration

No relevant barriers in replicability were detected from the network configuration point of view. It is recommended a detailed grid analysis to determine the proper characteristics of the SI contribution and, in case, to identify limits in active power injection and absorption. The availability of the SI contribution is independent from the primary source. This remarkably increases its importance in a future scenario with huge amount of renewables and reduction of traditional inertia in the system. On the other hand, BESS availability is influenced by the way the storage system is managed in accordance with the provision of other, potentially remunerated, ancillary services (e.g., in terms of internal state of charge), then rules to preserve the SI contribution in case of network events have to be defined. The solution can be replicated also at different voltage levels, even if technical and cost/benefit analyses are required to better address the point.

5.2.5.2 Economics

Macro-economic factors

Analyses are currently underway to assess the impact of macro-economic factors on other possible plants where the solution could be replicated. No specific conclusions can be done at the moment since no remuneration schemes for the SI contribution has been developed.

Market and business model

Analyses are currently underway to evaluate the best business and market model under which the solution could be economically viable. Certainly, the lack of a market for the provision of SI, both in Italy and in other counties, is a high barrier to the deployment of the new service. SI provision will difficultly justify the BESS cost, then BESS sizing is expected to be impacted by several other drivers to consider all the possible ancillary services that a storage unit can supply, in particular the ones that will be remunerated according to local standards.

5.2.5.3 Regulatory

Regulatory issues

Lack of remuneration schemes is a relevant barrier in terms of replicability. SI provision through BESSs (power-intensive use of the storage system) implies that components are more stressed respect to other operative modalities in which charging and discharging times are longer (energy-intensive uses). Therefore, a remuneration would be appropriate at least to cover the extra costs both in terms of installation and accelerated aging. Since the stabilizing function is not currently defined by grid codes (in terms of required contribution, activation thresholds, admitted delay and accuracy, etc.) and a certified characterization of frequency perturbation (number of events, perturbation entities in terms of frequency deviations and ROCOF, etc.) does not exist, it is difficult to investigate how much and how many times the service will be required. Considering the entire power system, in the future, inertia support could come also from renewable sources. Particularly, this solution makes the SI contribution continuously available if BESS operating conditions are respected (e.g., in terms of internal state of charge) and independently from the primary source availability. This approach can also be replicated in combination with other types of generators (e.g., photovoltaic plants) or in stand-alone BESS units. Furthermore, SI response is completely configurable through a suitable set of parameters, then it can be adapted according to specific network requirements.

Acceptance

Certification requirements according to local standards could be a problem in terms of acceptance. Since the solution is appliable also to other generation technologies and to stand-alone BESS units, a great interest is expected if a suitable remuneration scheme will be introduced for the service.

5.2.6 DFIG for SI Replicability

5.2.6.1 Technical

Standardization

The solution is currently being tested in the laboratory. Field tests are needed to accurately estimate the requirements in terms of standardization, industrialization, and certification. Furthermore, it may be difficult to standardize the solution as the provision of SI directly by WTs could be implemented differently by each WT/converter manufactures. Standardization can include specific requirements in terms of prescribed accuracy, reliability, and availability of the service. Particularly, a standardized approach for the evaluation of the ROCOF could be suggested in the case this network measurement is independently performed by each WT. This allows to obtain a correct overall dynamic response of the entire plant and to preserve the system from possible instabilities.

Interoperability

The developed solution, independently applied by each WT, does not require to interact with the local centralized plant controller or other remote apparatus. All the devices involved in the SI provision, from the frequency/ROCOF measurement to PLC controllers and converters/drives, are installed in the WT. Field tests are needed to accurately assess the interoperability of the solution and, in detail, to investigate if a centralized measurement of frequency and ROCOF could improve the dynamic response of the entire power plant in the case of severe network perturbations. In this case, a suitable communication system is required to assure required availability and admitted latency. The set of parameters that define the SI contribution (e.g., gain, activation thresholds, hysteresis behaviour, etc.) are configurated in the WT controller (usually property of WT manufacturer and not accessible to the plant manager).

Network configuration

Even if providing SI in different locations may have different levels of effectiveness depending on the grid configuration, no barriers in replicability were detected from the network configuration point of view. Differently, it has to be taken into account that WTs can be able to provide SI only if they operate above a minimum generation level (e.g., 30%) to prevent shutdowns due to excessive rotor speed reduction. Then, since the actual SI contribution availability is strongly related with the primary source, wind speed distribution plays a crucial role when the solution is replicated in different locations. A suitable characterization of primary source availability (in space and time) is then required to address typical trends on daily and seasonal intervals, and to estimate the SI contribution consequently. Real-time measurements from wind plants can also be used to dynamically quantify the stabilizing contribution made available by plants equipped with WTs able to provide SI.

5.2.6.2 Economics

Macro-economic factors

Analyses are currently underway to assess the impact of macro-economic factors on other possible plants where the solution could be implemented. Results strongly depend country by country on wind plant diffusion (which impacts on the level of interest of WT manufactures for the specific market area), local market characteristics, technical normative framework and grid code requirements.

Market and business model

Analyses are currently underway to evaluate the best business and market model under which the solution could be economically viable. Certainly, the lack of a market for the provision of SI, both in Italy and in other counties, is a high barrier to the deployment of the new service. In this case, SI provision could imply a small additional capital cost for WTs according to service specs that will be introduced in each country, even if a sort of standardization could be suggested to limit costs for WT customization and certification. It should be noted that, standing on preliminary laboratory results, sizing of main devices and control logics are quite similar to the ones currently required to support fast frequency regulation as prescribed in some grid codes (e.g., Italy, Canada, etc.).

5.2.6.3 Regulatory

Regulatory issues

Lack of remuneration schemes is a relevant barrier in terms of replicability. Additionally, since the stabilizing function is not currently defined by grid codes (in terms of required contribution, activation thresholds, admitted delay and accuracy, etc.) and a certified characterization of frequency perturbation (number of events, perturbation entities in terms of frequency deviations and ROCOF, etc.) does not exist, it is difficult to investigate how much and how many times the service will be required. Then a concrete estimation of machine aging is not addressable at the moment. In general, a remuneration would be appropriate at least to cover the extra costs both in terms of installation and increased aging. Considering the entire power system, in the future, inertia support could come also from renewable sources. This could solve the issue of system inertia reduction caused by an increase of wind exploitation, since SI could be available when wind farms are producing energy (i.e., WT power injection overpasses a minimum limit to preserve the machine stability, e.g., 30% of the rated power).

Acceptance

The acceptance of WT manufacturers is required to industrialize and certificate technologies able to provide SI. In fact, it seems that the plant owner cannot develop an in-house solution to provide SI without affecting the performance and reliability of the WTs, which means impacting on machine warranties. Further considerations can be made as the solution will conclude field testing.

5.2.7 RES +BESS for AVC Replicability

5.2.7.1 Technical

Standardization

Since at grid code level the provision of the AVC by wind farms has not been standardized yet, it is difficult to predict which standards (reliability, accuracy, and availability) might help the replication of the solution in other plants. Furthermore, it is difficult to indicate a standardized size of the BESS (to provide the AVC service) as a function of the plant rated power, since the overall plant capability curve (prescribed by the grid code) can be fulfilled by both the BESS's and the WTs' contributions. Indeed, the lack of remuneration of the service does not allow direct economic evaluations. At present, the size of the BEES is optimally choose also evaluating the provision of other remunerated services, even if the BESS inverter size is the main characteristic that directly impact on the AVC provision (whereas storable energy has no significant role in this). In any case, the solution implemented on Master SCADA level uses standard communication protocols that can increase the compatibility of the solution with other storage devices.

Interoperability

Thanks to the standard communication protocol adopted in the demo plant, the solution can be implemented on others Master SCADA devices. If the plant has already installed a BESS, implementing the AVC consists in an update of the control logic of the BESS Master SCADA, with no large investments required.

Network configuration

No barriers in replicability were detected from the network configuration point of view. In fact, the ability of the system in exchanging reactive power seems not affected by the area where the plant is located if network voltage at the POD remains inside the admitted tolerance around the rated value. If network voltage exceeds admitted limits, the plant capability curve is reduced. Instead, the effectiveness of controlling reactive power at the plant POD in terms of AVC is directly impacted by network data, in particular the network rated voltage (transmission/sub-transmission system) and grid parameters such as the equivalent impedance. Obviously, since the innovative function is applied to a power plant exploiting a renewable and partially unpredictable energy source, a part of the availability of the plant in providing AVC (i.e., the contribution from the WTs) may be influenced by the availability of the primary source. According to the current Italian grid code, a reduction in reactive power availability is admitted in the case the power plant active power generation drops under 10-20% (i.e. the wind speed is quite close to the cut-in value). However, it is remarkable to note that the AVC contribution made available by the BESS is substantially independent from WTs' operating conditions, then BESS can be continuously available to support network voltage independently from primary source availability. This means that it can be exploited independently from the plant operating condition and, in case, as an individual resource or in combination with other generation plants (e.g., photovoltaic plants, where a storage device could be installed also to provide other ancillary services to the network or to the power plant itself). As a general recommendation, implementing the AVC on a new plant requires a preliminary grid analysis to assess the hosting capacity at the POD, the maximum reactive power contribution, and its effectiveness in terms of AVC. In future application, WT manufacturers could investigate the exploitation of inverters installed in DFIG WTs (inverter rated power about 30% of the WT rated power) and in full-converter WTs (inverter rated power equal to the WT rated power) to support AVC even if wind availability is very low or completely absent.

5.2.7.2 Economics

Macro-economic factors

Analyses are currently underway to assess the impact of macro-economic factors if the solution is replicated in other plants, both at national and international level. Remuneration of AVC service or adaptation of grid code to prescribe this functionality plays a significant role in this analysis.

Market and business model

Market and business model analyses strongly depend on local approaches to the AVC service. Particularly, AVC support could be mandatory or voluntary, remunerated or not. Focusing on the developed solution and referring to current market data, BESS cost could be justified in the case it provides several remunerated ancillary services, both in active power (capacity firming, generation profile control, etc.) and in reactive power (AVC).

5.2.7.3 Regulatory

Regulatory issues

From the economic point of view, solution replicability strongly depends on regulatory aspects defining if AVC will be mandatory or voluntary, remunerated or not. Technical issues involved by local grid codes seem to be resolvable by adapting the developed solution to local specifications (e.g., capability curve to be provided by the plant, dynamic response time, communication infrastructure between TSO and wind farm, etc.).

Acceptance

The innovative solution tested in the demo plant can be easily applied to new plants, both at national or international level, with adaptations according to local technical and economical specifications. It could be developed during revamping/repowering of existing power plant too.

5.2.8 DFIG for AVC Replicability

5.2.8.1 Technical

Standardization

At present, the solution is not fully compliant in terms of AVC with standard requirements included in the current grid code (it is compliant with the previous version of the grid code). Particularly, when reactive power is delivered under remote control, it is difficult to comply with the timescales defined in the grid code due to the delay introduced in the communication chain between the TSO and each single WTs (first level SCADA hardware configuration, local communications through OPC protocol, etc.). Furthermore, installed WTs are compliant with the previous grid code in terms of dynamic response to a variation of the reactive power set point and problems in providing the entire reactive contribution arose during the test due to a software issue identified by the WT manufacturer. This results in a barrier for the direct standardization of the developed solution. In addition, the solution (implemented on the local embedded) needs to be interfaced (trough the Master SCADA) with the WT's regulator. Usually, this is not a standard component as it differs for each WT model/manufacturer (e.g., in term of performance, communication protocol, etc.). The part of the developed solution that could be easily standardized is the software developed in the local embedded. The reliability is medium - high. Nevertheless, some improvements could be added to increase it.

Interoperability

From the interoperability point of view, the main barrier detected is the interface between the local embedded device and the WT plant controller. In the demo plant, this was done via OPC (Open Platform Communication) which introduces a certain time delay that makes the solution potentially not compliant with requirements in terms of dynamic response. Furthermore, the used protocol depends on the model/manufacturer of the WT, making interoperability of the solution a bit complex and suggesting a standardization of this device or, at least, of its interfaces.

Network configuration

No barriers in replicability were detected from the network configuration point of view since the wind farm is able to provide the entire capability area in the case the network voltage differs from the rated value less than admitted thresholds. Otherwise, the reactive power contribution made available by the generation plant is reduced according to the current grid code. From the network configuration point of view, providing AVC in different locations may have different results depending on the grid equivalent characteristics at the POD. When AVC is fully provided by WTs, wind availability plays a crucial role since the service is directly related to the amount of primary source. This aspect has to be investigated to address the availability of the plant in supporting AVC, also considering seasonal/daily typical variations. In the case the wind speed is very low, but higher than the cut-in value (reported in WT datasheet), the availability of reactive power exchange is reduced respect to WTs operating at higher loading in terms of active power production. If the wind speed drops under the cut-in speed, the plant can regulate the reactive power at the POD only acting on compensating devices that can be optionally installed in the site to fulfil the entire capability area required by the grid code (e.g., modulating capacitor banks or inductors). Finally, extending the solution to other wind farms, the overall performances may be different as the capability curve is directly related to the type/model of WTs installed in the plant. In future application, WT manufacturers could investigate the exploitation of inverters installed in DFIG WTs (inverter rated power about 30% of the WT rated power) and in full-converter WTs (inverter rated power equal to the WT rated power) to support AVC even if wind availability is very low or completely absent.

5.2.8.2 Economics

Macro-economic factors

Analyses are currently underway to assess the impact of macro-economic factors if the solution is replicated in other plants, both at national and international level. Remuneration of AVC service or adaptation of grid code to prescribe this functionality plays a significant role in this analysis.

Market and business model

Market and business model analysis strongly depends on local approaches to the AVC service. Particularly, AVC support could me mandatory or voluntary, remunerated or not. If the AVC support is provided by WTs, it is important to note that new WT models can implement the AVC with limited additional costs. Oppositely, in the case of old WT models, it is quite difficult to assess if the solution is feasible from both the economical and the technical point of view. However, analyses are currently underway to assess the best business and market model under which the solution is economically viable.

5.2.8.3 Regulatory

Regulatory issues

From the economic point of view, solution replicability strongly depends on regulatory aspects defining if AVC will be mandatory or voluntary, remunerated or not. Technical issues involved by local grid codes seem to be resolvable by adapting the developed solution to local specifications (e.g., capability curve to be provided by the plant, dynamic response time, communication infrastructure between TSO and wind farm, etc.).

Acceptance

The AVC provision obtained by WTs can be easily applied to new plants, both at national or international level, with adaptations according to local technical and economical specifications. An industrial solution for control and communication devices could be developed starting from results obtained in this project, with the aim to solve some issues regarding the dynamic response of the plant while providing AVC (e.g., latency, computation time and communication delays). The solution could be applied also during revamping/repowering of existing power plants if WTs will be replaced with modern machines able to suitably regulate their reactive power exchange with the plant.

5.3 Scores and Results

This sub section outlines the scores achieved by each factor evaluated in the discursive analysis. Scores are presented in absolute value by tables and radar plots and in relative terms by the scalability and replicability index defined in 4.1.3.

5.3.1 Scalability Results

Table 14 reports the scores reached by each factor during the analysis process. The radar graphs presented in Figure 17 and Figure 18 help to draw some considerations in relation to the table.

Table 14: Scalability Scores

		Scalability			
		SI		AVC	
Area	**Key Factor/Subareas**	**BESS**	**WTs**	**BESS**	**WTs**
Technical	Modularity	4	2	5	4
	Technology evolution	3	2	4	3
	Interface design	4	3	4	4
	Software tools integration	4	2	4	4
	Compatibility analysis	3	3	4	4
Economics	Economies of scale	3	3	2	4
	Profitability	2	3	2	3
Acceptance	Regulatory issues	2	2	2	2
	Consent	2	2	3	3

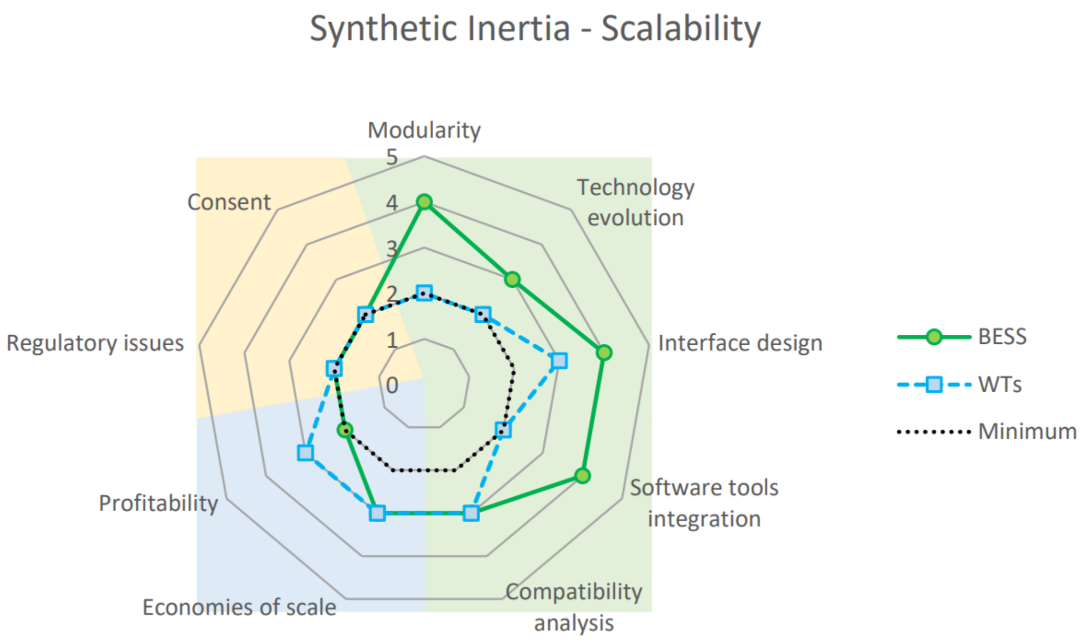


Figure 17 Radar Plot of SI Scalability

The radar graph regarding the scalability of SI shows that all the factors have achieved the minimum score of two i.e., all factor reaches the minimum score to be considered at least potentially replicable. From the Technical point of view the solution that has implemented the SI using the BESS shows higher scores as the solution requires the scale up of the BESS and WTs are not interested in the scaling up process. Instead, from the economic point of view, the solution that has implemented the SI directly using the WTs seems slightly more competitive since no extra cost for new components are needed respect to the solution that uses a BESS and a SICD to provide inertia. Consent, reaches the minimum score in the solution that uses the WTs as the WT manufacturer engagement is strongly require to scale up the solution.

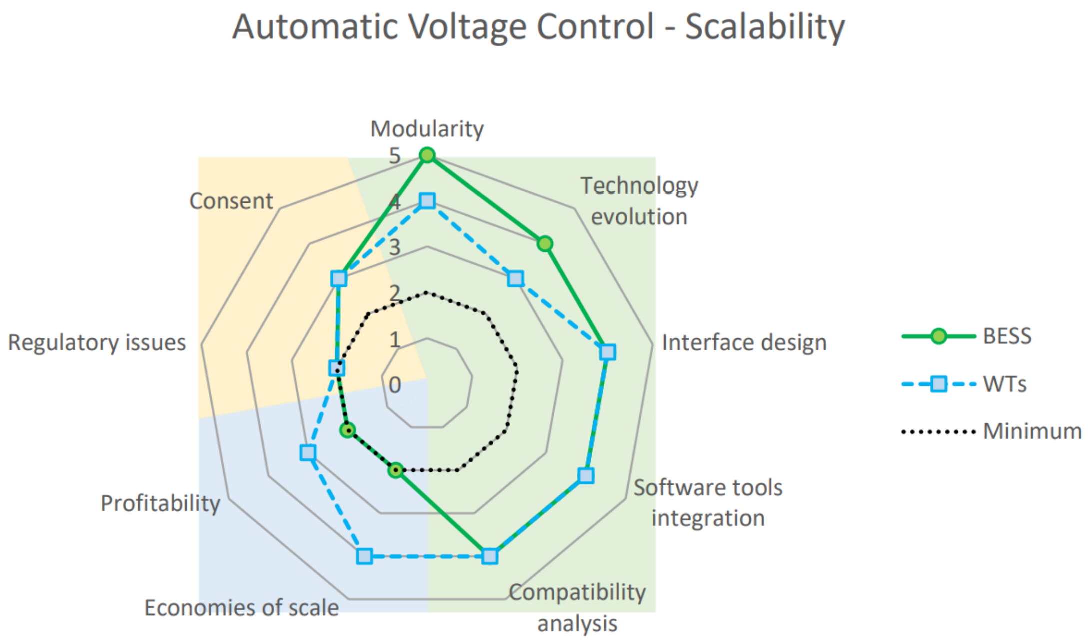


Figure 18 Radar Plot of AVC Scalability

From the AVC scalability point of view, the economic competitiveness of the solution that has implemented the solution using WTs is increased since less expenditure is expected in the scale up of the solution. This can be noticed also in the technical area because even if the BESS solution shows higher scores respect to the WTs, the gap in terms of scores respect to the SI is reduced. Finally, it can be observed that the modularity factor of BESS solution reaches the score 5, i.e., scalable with benefits. This because the implementation of the solution consists in a update on the logic control of the BESS's inverter so the scaling up of the solution can be seen as a benefit from the modularity point of view.

Table 15 Scalability Index

	Scalability			
	SI		**AVC**	
Area	**BESS**	**WTs**	**BESS**	**WTs**
Technical	73,5%	47,5%	85,0%	77,0%
Economics	51,3%	60,0%	40,0%	71,3%
Acceptance	40,0%	40,0%	49,1%	49,1%
TOTAL	62,7%	49,3%	68,4%	71,0%

Table 15 summarises in relative value the scores reported in absolute value. The indexes resume the results reported in the radar plots and in the discursive analysis.

5.3.2 Replicability Results

As for the scalability, this subsection resumes the results of the replicability analysis. Table 16 shows that all factors reached the minimum score of 2 i.e., all factor reaches the minimum score to be considered at least potentially replicable. further considerations on the score trends are made below the SI and AVC replicability radar plots.

Table 16: Replicability Scores

		Replicability			
		SI		AVC	
Area	Key factor/Subareas	BESS	WTs	BESS	WTs
Technical	Standardization	3	2	3	2
	Interoperability	4	3	4	2
	Network configuration	4	3	4	4
Economics	Macro-economic factors	2	2	2	2
	Market and business model	2	2	2	3
Regulatory	Regulatory issues	2	2	3	3
	Acceptance	3	2	4	3

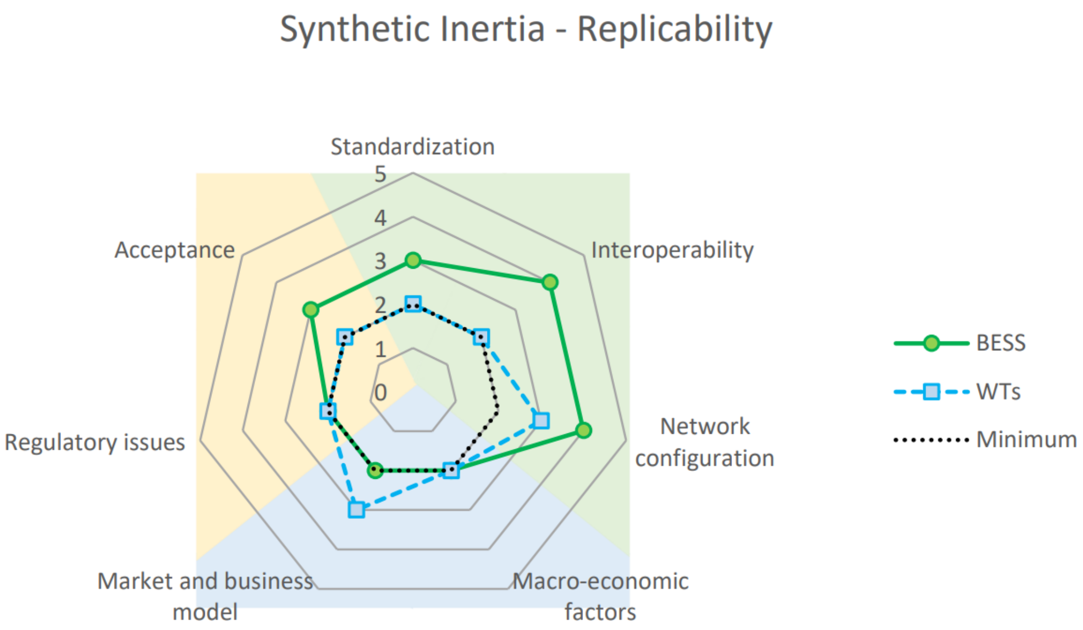


Figure 19 Radar Plot of SI Replicability

In the SI radar plot can be seen that the solution that has implement SI using the BESS has reached higher score in the technical area. This because the solution seems to be easily replicated on other BESS with the installation of few components (seems to be necessary only the SICD). On the contrary, the solution that has directly implemented the SI using the DFIG generators shows difficulties to be replicated since the developed approach involves the WT controller (that usually is owned by the WT manufacturer). But, since the implementation of SI in DFIG based WTs do not require significant installation of new component it reached higher score in the economic area respect to the BESS solution.

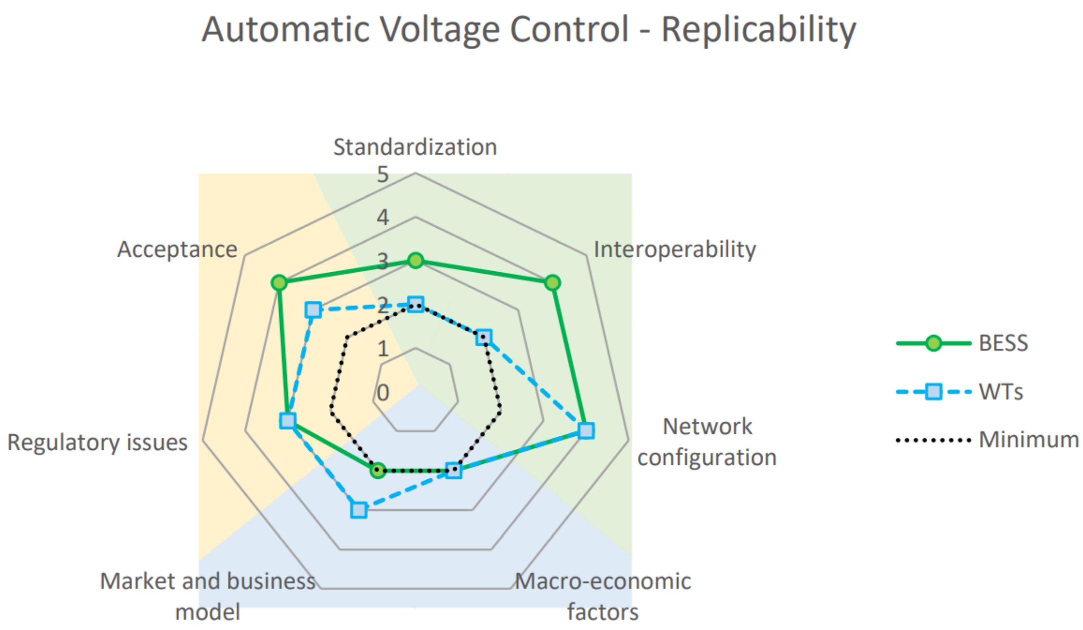


Figure 20 Radar Plot of AVC Replicability

In Figure 20 can be observed the same trends reported previously for the SI. The WTs solution reached better score in the AVC acceptance area respect to the SI (as it can observed also in relative terms in Table 17) since the involvement of the WT manufacturer is less relevant in the reactive power provision. Both in SI and AVC the BESS solution reached a score of 4 in the Interoperability as the solution is replicable also in absence of the primary wind source or in other RES power plant e.g., on photovoltaic power plants.

Table 17 Replicability Index

	Replicability			
	SI		AVC	
Area	BESS	WTs	BESS	WTs
Technical	72,6%	45,9%	72,6%	51,9%
Economics	40,0%	50,9%	40,0%	50,9%
Acceptance	48,0%	40,0%	68,0%	60,0%
TOTAL	57,1%	45,8%	62,2%	53,7%

Finally, by comparing the replicability index can be seen that in general the AVC is more replicable respect to the SI due to the greater technical, economic and acceptance difficulties in implementing the SI provision. However, the solution that has a better replicability index is the one that implemented the innovative services using BESS thanks to the less technical and acceptance difficulties encountered.

6 Quantitative SRA – Provincial Availability of Services

The quantitative analysis focused on the assessment of the availability of the innovative services tested in the two demo plants. As the provision of services by WTs is activated if the output power reaches a certain threshold respect to the rated power, the study was conducted on three activation thresholds. For the provision of SI was considered a minimum value of 30% of the WT nominal power to enable the services provision. Then two thresholds of 10% and 20% of the nominal power were considered for the enabling of the AVC in according to what prescribes the TSO in the grid code [11]. Then, as regulating contribution is proportional to the rated power of the plant, it was estimated the contribution achievable both replicating the innovative solution to the whole Italian wind farms and tacking in to account future scenario. In detail, the analysis regarded the benefits that could be achieved in the 2030 according to the goals reported in the Piano Nazionale Integrato Energia e Clima 2030 (PNIEC2030) [29]. Finally, it was studied how the two major Italian inertia free generation technology (Wind and Photovoltaic) contributes to cover the national and local load to estimate the benefits and barrier that WTs innovative services can make available.

6.1 Unit Production 2015-2019

To begin with, the assessment started with the evaluation of the provincial unit production (i.e., the equivalent number of hours at which the plant works at the rated power in a year) and the installed wind power from 2015 to 2019. The figure below, reports on x-axis the Italian provinces where the wind installed power is different from zero. Moreover, the background of the figure then represents the bidding zone to which the province belongs (ordered as NOR, CNOR, CSUD, SUD, SICI, SARD). Histograms report in MW the provincial amount of installed power from 2015 to 2019 (left y-axis). Finally, lines depict the annual provincial unit production in H/y (right y-axis). The average provincial value evaluated on the basis of the reported years is reported with the bold red line.

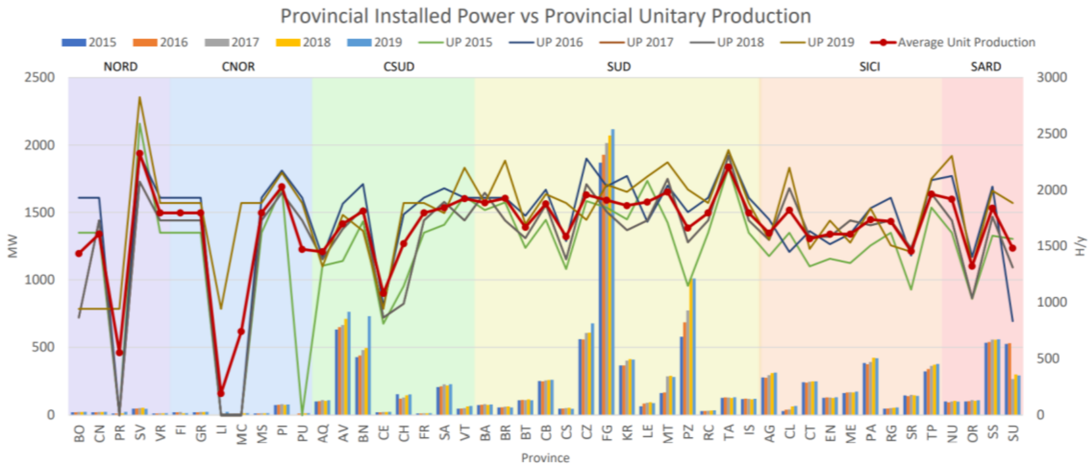


Figure 21 Provincial Installed Power vs Unit Production

It is immediate to notice the different geographical distribution of the wind farms as the southern provinces show higher installed power. This will be useful in the following evaluations as the absolute value of the contribution in terms of active power (required to provide SI) and reactive power (required for the AVC) is proportional to the plant rated power. On the other hand, the annual provincial unit production helps to understand the variability of the wind source both in geographical and annual scale. In fact, it is possible to notice how different could be the unit production different on annual scale. It results that 2015 was the worst year of those considered in terms of equivalent hours at full power (the overall Italian value resulted 1620 h/y). On the contrary, 2016 and 2019 resulted more productive. This can be noticed both on the provincial punctual data in the plot and on the Italian overall unit production (1880 h/y in the 2016 and 1885 h/y in the 2019).

6.2 Local Availability of SI Provision

The first assessment on service availability provision was to analyse how provincial availability hours to provide SI vary over the years. Since the availability of wind is not constant over the years, the number of operating hours above the 30 % threshold was evaluated for each year. So, the annual provincial hours of availability of SI are represented on y-axis by lines. Then the average value computed in the analysed years is represented with a black dotted line. An anomalous behaviour can be observed in the 2017 as the source data presents the same percentage value of provincial installed power and provincial energy produced.

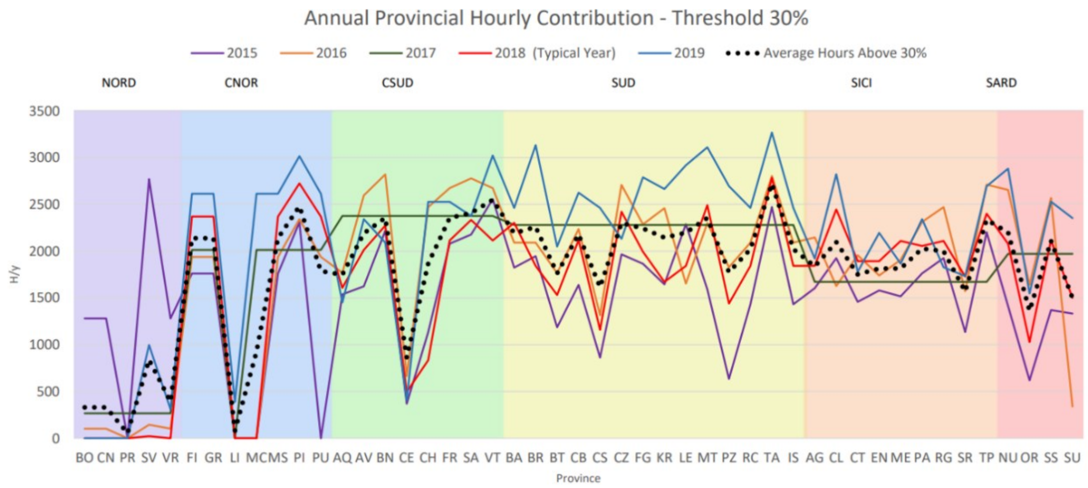


Figure 22 Annual Provincial Hourly SI Contribution

From an analysis of the plot some interesting consideration can be made. Starting from noticing that the availability of the wind source influenced the number of hours available to provide the service. In detail, the 2015 can be recognized as the most unfavourable year of those analysed. In fact, the number of hours resulted almost always lower in all provinces. Conversely, the 2019 results the best year in terms of availability in providing SI. These results are appreciable also in the unit production of the two above mentioned years. 2019 also marked the highest number of hours recorded in terms of hours available to provide SI. The record in fact belongs to the province of Taranto, which reached a maximum value of 3133 hours of availability of SI. The next step was evaluating the average and typical year i.e., the real year that showed values closest to the average year. So, for each province was evaluated the yearly average hours of availability. Then, the deviation of each province for each year respect to the correspondent average value was computed. The 2018 resulted the typical year as the summation of all the provincial deviations was the lowest. Further consideration can be made from the geographical point of view. In fact, in the northern part of the Italy can be recognized lower values and less constant over the provinces respect to the southern one. Additional geographical considerations will be made by analysing other graphs on the following pages.

Following, a second analysis focused on how seasonal variations in wind source can impact the hours of availability of SI. In fact, it cannot be taken for granted that reduced producibility translates into a reduction in the availability of hours during which it is possible to supply SI. This is because, a reduction in the hours equivalent to maximum power does not necessarily reduce the hours of partial operation by much. For these reasons, it has been analysed the seasonal composition of the average year.

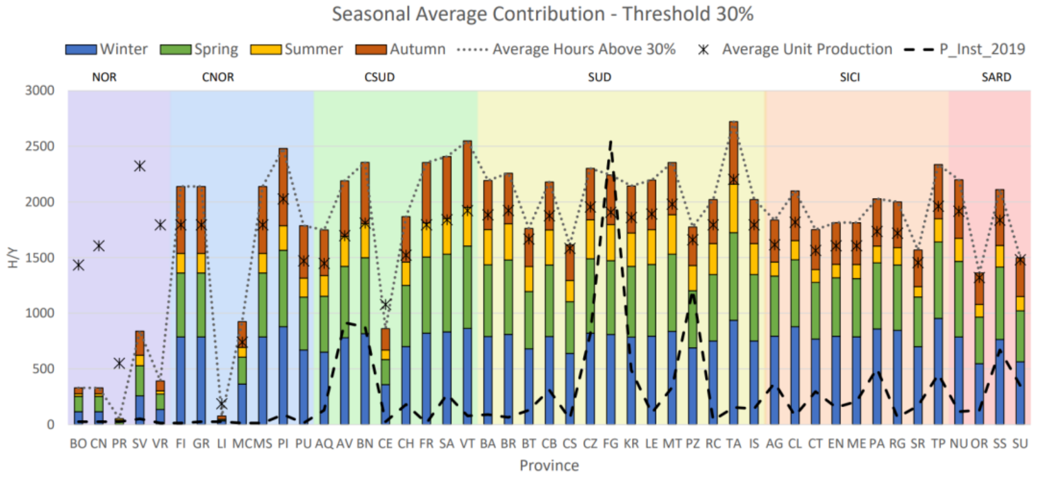


Figure 23 Seasonal Average SI Contribution

Histograms depicted in Figure 23 represent the average seasonal composition of the average value of availability hours in providing SI (grey dotted line). In addition, the black dotted line reports the provincial installed power in MW reached until the 2019 (values refer to right vertical axis). Finally, in form of * is represented the average unit production in H/y.

From Figure 23 can be observed that seasons impact in the number of hours that wind farms are able to provide SI. Indeed, during the winter the number of hours that are achievable is higher than the other seasons, with summer being the most unfavourable season to provide the service. Moreover, the figure shows that there is no correlation between the unit production and the number of hours at which the plant works above the 30% of the rated power. This can be observed in the norther region i.e., province belonging the bidding zone NORD, where the unit production it is very high respect to the number of hours where SI is available. Conversely, the provinces like as example Foggia shows a higher value of hours in availability of SI (around 2800 h/y) respect to the average unit production (around 2000 h/y). Probably, plants located in Foggia operate for a large number of hours at a power well below the nominal one but still more than the 30%. Then, to explain the difference between the unit production and the number of hours of availability in providing SI is proposed the per unit daily curve referring to 2019 of the province of Foggia. The y-axis represents the per-unit power i.e., the ratio between the province instant power and the total provincial installed power and the x-axis represents the hours of the 2019.

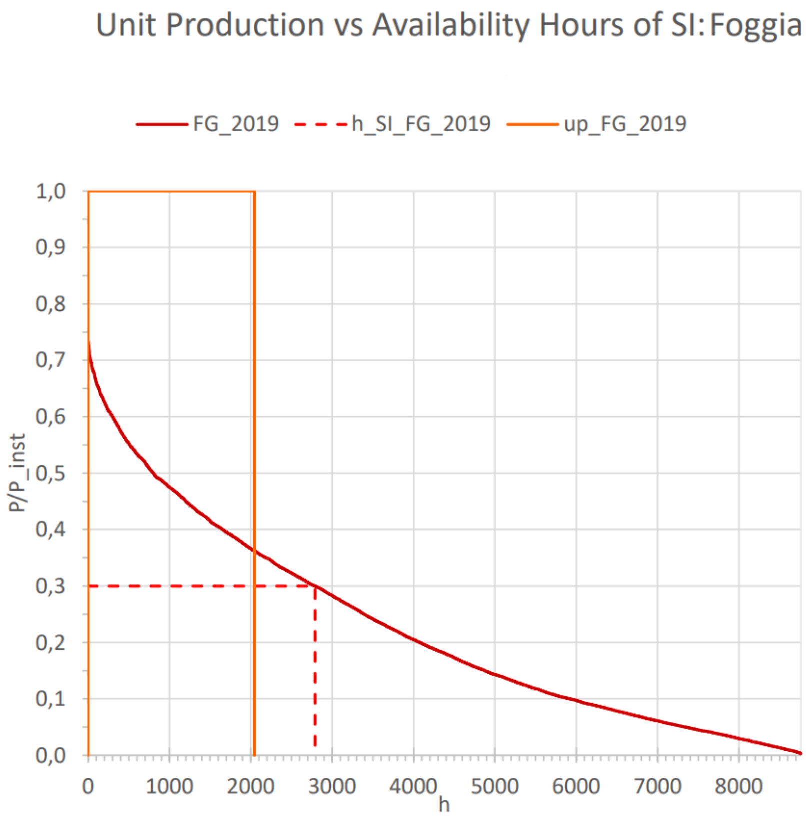


Figure 24 Foggia PU Daily Curve

In Figure 24 it can be noticed that the value of unit production it is equal to the horizontal base of the orange rectangle that is 1 high and has an area equal to the area under the daily curve (dark red line). Instead, the number of hours above the 30% of the rated power corresponds to the value of the abscissa at the intersection of the line of the daily curve and the horizontal line starting from 0.3. So, the availability of SI provision depends on the numbers of hours above the threshold instead, the unit production depends on the integral of the daily curve. Figure 25 reports the comparison between the per unit daily curve of Taranto, which reached the top value, and Cesena which seems an unfavourable location for the SI provision. From the dark blue line, it is immediate to notice that wind turbines installed in Cesena operates for most of the hours at a very partial load resulting in a very flat daily curve, which exceeds 30% of the nominal power for a limited number of hours in a year. Conversely, the trend of the daily curve in Taranto (dark green line) motivates the high number of hours when SI is available reached by the province.

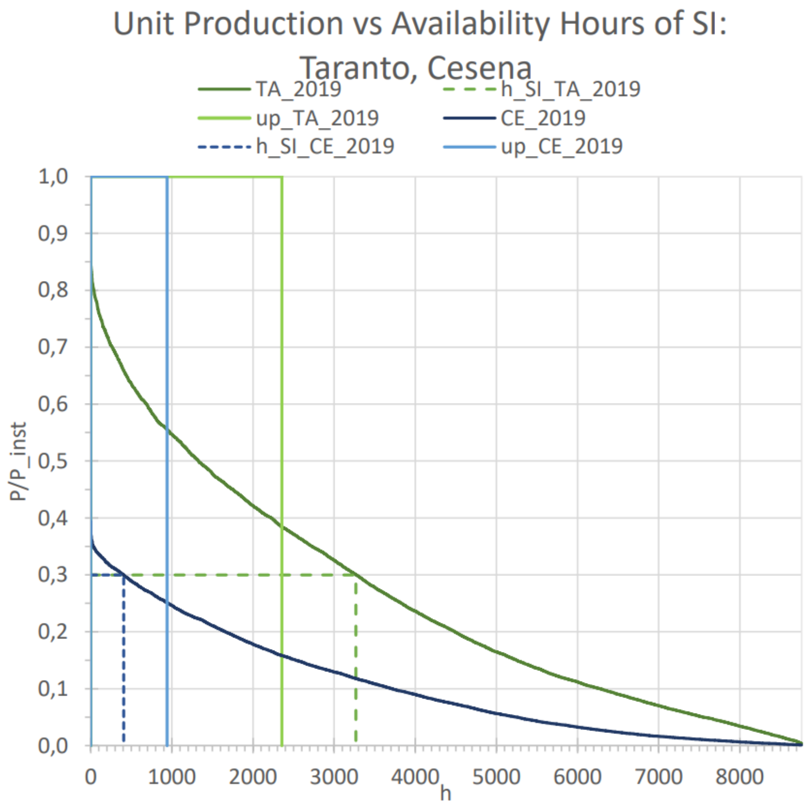


Figure 25 Foggia vs Cesena PU Daily Curve

Moreover, the analysis focused also on the average seasonal day phase contribution to evaluate whether the contribution is homogeneous during the day. From the analysis of the graphics, it can be observed that during the winter months the contribution of the various phases of the day resulted equally distributed. In particular, the southern regions show an almost equal share during the day. During the autumn and spring, the trend is almost the same of the winter except for the areas of south were in spring during the afternoon the contribution shows an increase in Sardinia and in the region within the CSUD. The phenomenon then amplified in the summer. In fact, it can be recognized that in Sardinia, Sicily, CNOR and NOR the afternoon contribution become dominant, particularly at the expense of the night and morning hours.

6.3 Local Availability of AVC Provision

As for the SI provision also the AVC availability is influenced by the plant operation condition. As stated in 1.5.3 the AVC is activated when the plant operates above the 10% or the 20% of the plant rated power. So, this subsection evaluates the availability of AVC analysing two different activation thresholds.

The first two plots (Figure 26,Figure 27) propose the annual provincial hours of availability of AVC provision. Firstly, it can be noticed how the annual contribution increases as the activation threshold decreases. For example, the highest values recorded for each threshold are 3250 h/y for 30%, almost 4500 h/y for 20% up to just over 6000 h/y for 10%. However, also from this set of plots it is appreciable the impact of the wind source on the availability hours in providing services. For sure, by decreasing the threshold even unfavourable locations (in terms of wind availability) could participate more in the service provision. In any case, southern provinces (i.e., within SUD bidding zones) contribute on average, with the highest values.

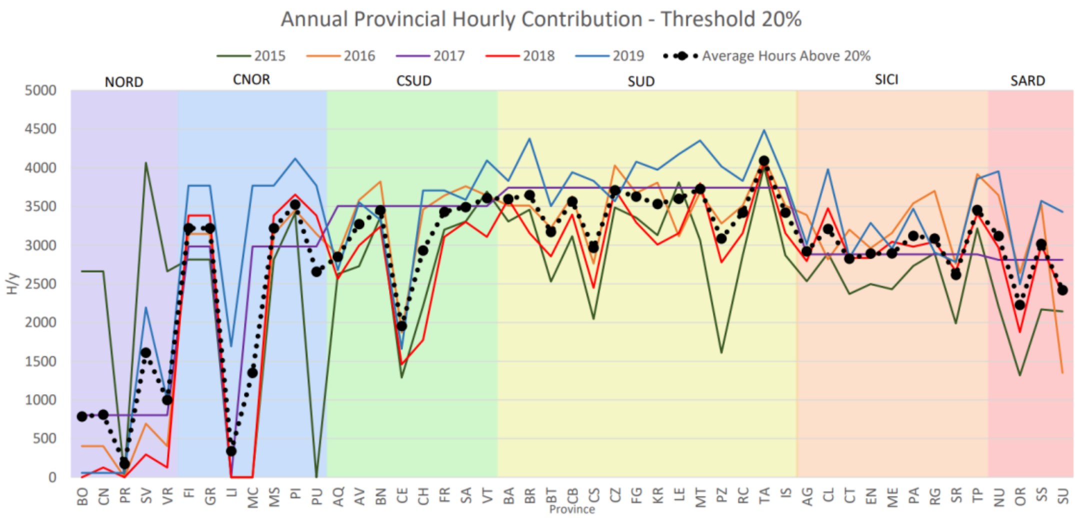


Figure 26 Annual Provincial Hourly AVC (20%) Contribution

From the plot with the lowest threshold (Figure 27) can be observed as the annual variation, in relative terms, tends to decrease respect to the average year.

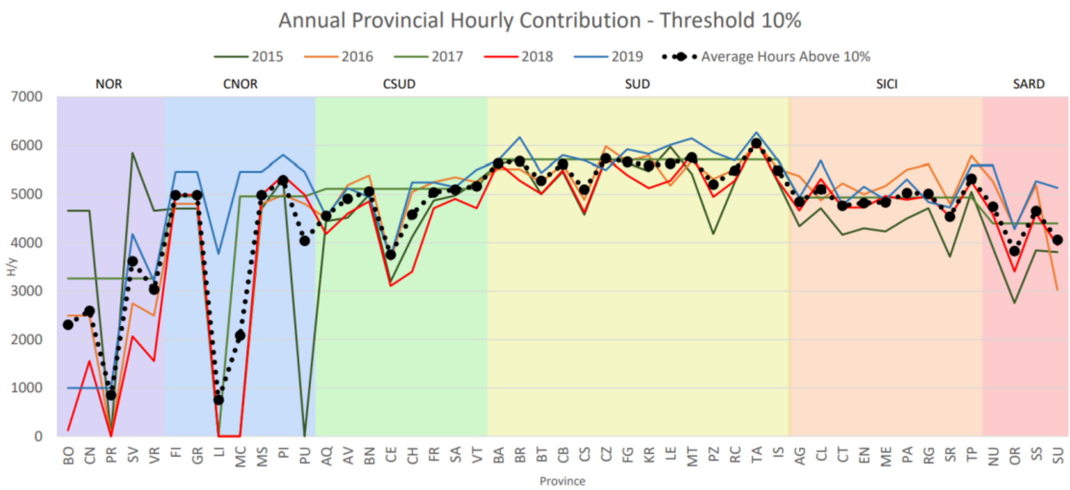


Figure 27 Annual Provincial Hourly AVC (10%) Contribution

From the seasonal average analysis point of view, Figure 28 reports the seasonal share referring to the 20% of activation threshold instead, Figure 29 reports the same information but referring to the 10% as the activation threshold. It can be notice that as it happens for the availability of SI provision (Figure 23) also for AVC summer and autumn months contribute less respect to winter and spring. However, with the threshold set at 10% the reduction during summer months seems in relative terms slightly reduced. Finally, by lowering the threshold the contribution became more constant, in terms of annual hours of availability, in SUD, SICI and SARD bidding zone. This is a very relevant because 78% of Italy's total wind installed power (referring to 2019) is installed in these three bidding zones.

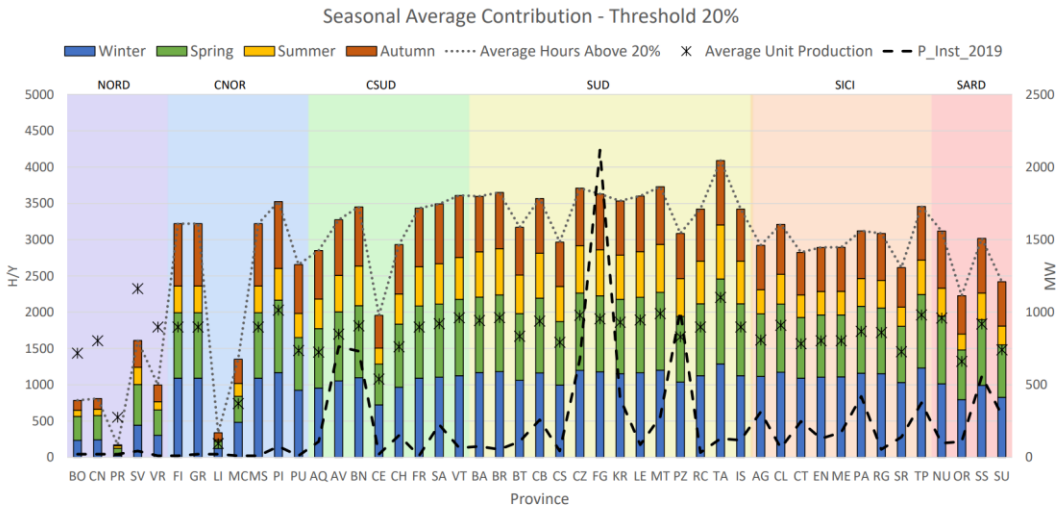


Figure 28 Figure 23 Seasonal Average AVC (20%) Contribution

In the previous paragraph was discussed about the no correlation between the provincial unit production and the hours of availability with the activation limit set at 30%. In the case of AVC can be observed that at the 20% threshold in the provinces within NORD, unit production is significantly higher than the hours when the service is available. Conversely, in the others bidding zones the unit production is always lower than the hours of availability of AVC provision and in addition, the two quantities seem to show some proportionality. By lowering the activation threshold to the 10% of the nominal power all the provinces show the trend mentioned above i.e., the provincial unit production is always below the availability of AVC provision, and it is 1.6 to 4 time smaller than the availability.

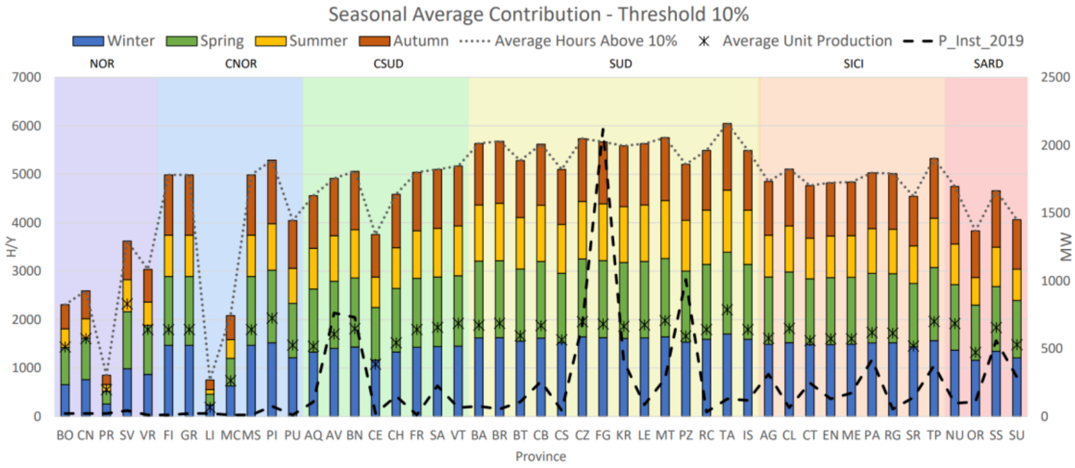


Figure 29 Figure 23 Seasonal Average AVC (10%) Contribution

6.4 Evaluation of The Regulating Contribution

After the evaluation of the local hours of availability in providing services by WT it is important to evaluate the amount of services that could be provided in terms of active power available for SI contribution and in terms of reactive power available for AVC. Results for SI contribution are present aggregated on national scale as the frequency can be considered as a parameter of the whole interconnected area. On the contrary, the evaluation of the reactive power contribution is presented aggregated by bidding zone as the voltage regulation is related on local scale.

6.4.1 SI Annual Contribution

Starting from the results obtained from the plant which tested the DFIG for the SI provision (5.2.2) this assessment aims to evaluate the overall contribution of SI inertia if the solution will be replicated in all the existing Italian wind farms. In fact, the partner suggested to limit the power injection at the 10% of the rated power of the WT to reduce mechanical and electrical stresses. So, it is possible to correlate the plant rated power with the effective contribution that it is possible to inject if the working condition of the plant allow it i.e., if they are working above the 30% of the nominal power. Thus, Figure 30 presents the duration curve of the total Italian wind power (thin grey line) and it is compared with the duration curve of the power above the 30% (thin blue line) and in addition with the cumulated rated power of the overall plants which shows a production coefficient above the 30 % (bold black line). To obtain this plot the provincial data were aggregated i.e., for each hour of the 2019 the hourly provincial power above the 30% were summed to obtain the national power above the 30%. Moreover, to obtain the overall rated power above the 30% the installed power of each province that has the production coefficient equals to 1 were summed together for each hour of the 2019.

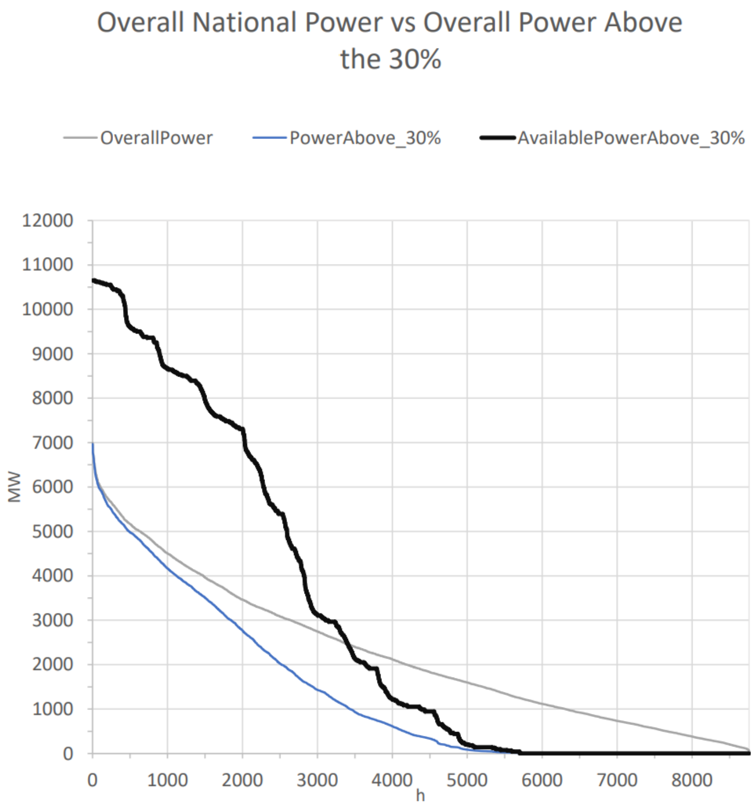


Figure 30 Daily Curve of the Power Above the 30% and The Total Available Power Above 30% (Year 2019)

From the plot analysis it is possible to notice that, looking at the Italian framework, for almost 4000 h the power available for the SI provision is null or almost null. Then from 3000 h and 2000 h it is possible to note a steep increase of the bold line. This results in a value of 7 GW of installed power (that corresponds to the 65% of the total installed power in the 2019) available for 2000 h to provide SI. In general, it is possible to evaluate the effective delta power that could be injected scaling the black bold curve by a factor of 0.1. This analysis remarks, from a different point of view, how directly using RES to provide grid services introduces uncertainty not only from the point of view of the hours when the service is available but also from the point of view of the quantity of the service that can be provided.

6.4.2 AVC Annual Contribution

To evaluate the reactive power contribution, reference is made to the "Allegato 17" of the Italian Grid Code which prescribes the equivalent capability curve at the POD. So, as it is stated in the 1.5.3 in the plant must provide the 35 % of the rated power in terms of capacitive reactive power and the 20 % or 35 % of the rated power in terms of inductive capacitive power. So, extending the tested AVC to all the Italian wind farms it can be evaluated the contribution simply multiplying the available installed power by 0.35 or by 0.20 in the same way as the available active power was assessed for the SI. In this analysis was considered the minimum activation threshold prescribed in the Grid Code i.e., the 10 % of the nominal power. In Figure 31 is presented the Italian duration curve of the Wind source (thin grey line), the duration curve of the Italian available power above the 10% of the rated one (thin blue line) and finally with bold lines are depicted the total installed power above the threshold divided by bidding zone. To make the graph clearer, the nominal installed power of each bidding zone is also depicted by thin dotted lines.

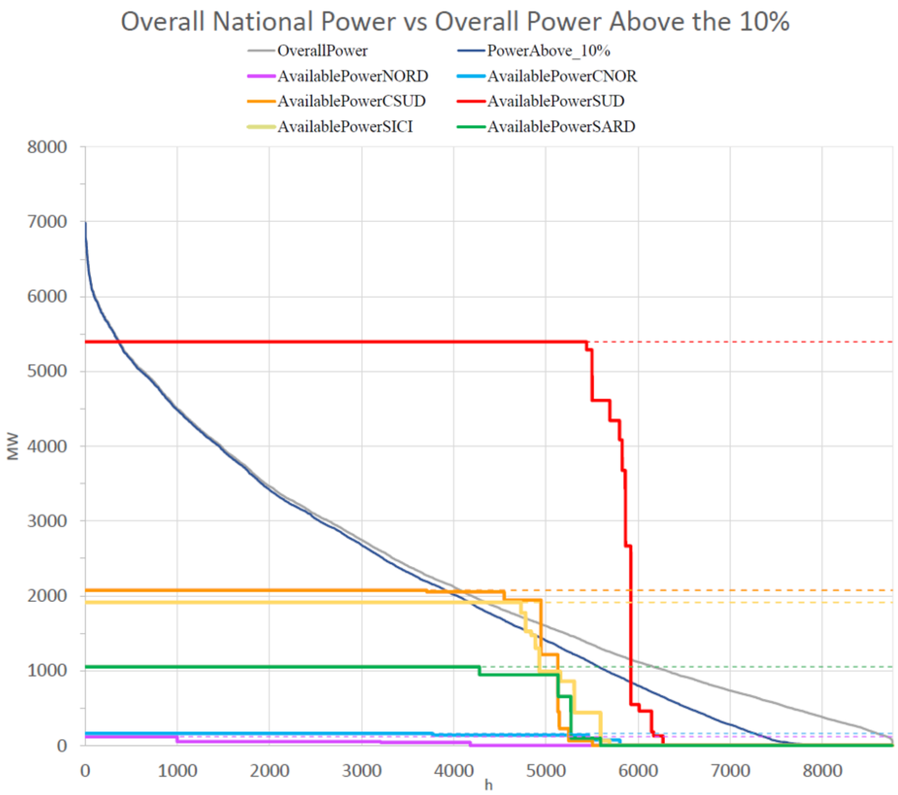


Figure 31 Daily Curve of the Power Above the 10% and The Total Available Power Above 10% divided by Bidding Zone (Year 2019)

From the analysis of the plot, it is immediate to notice how the daily curve of the power above the 10% is close to the overall daily curve. This is very good result because if the daily curve above 10% is close to the overall daily wind curve, it means that the total energy produced in a year has been produced by plants operating at a power higher than 10% for most of the time. This aspect reflects to the available installed power above the activation thresholds. In fact, it is possible to appreciate that the contribution for almost all bidding zones is constant and equal to the 100% of the installed power installed in the bidding zones (dotted lines) over a large number of hours. For instance, all the provinces within the SUD are able to provide AVC for more than 5000 h with an available reactive power of 1889 Mvar both inductive and capacitive considering the 35% value of nominal power reported on the grid code. However, as we move through the northern bidding zones, the value of installed power reduces in absolute value, while still maintaining 100% of available power for a discrete number of hours. E.g., CNOR keep the 100% of the installed power available for the AVC provision for almost 3800 h.

6.5 Trends and Future Scenarios: PNIEC 2030

This analysis takes in account the possible expansion of the RES in the electricity generation according to the PNIEC 2030 (Piano Nazionale Integrato Energia e Clima). Figure 32 depicts the trend expected to RES electricity generation in the next future. It can be immediately noticed that wind (green line) and PV (yellow line) will increase significantly by 2030 (Please note that * sign on Hydro, Wind and Bioenergy refers to continuous lines that represents the normalised figures evaluated according to the rules established by Directive 2009/28/EC).

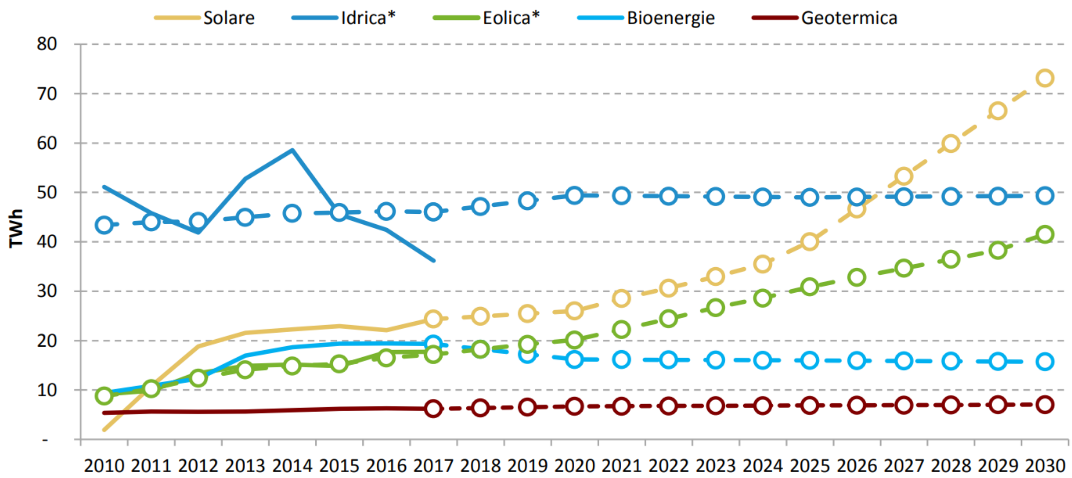


Figure 32 Future RES Electricity Share According to PNIEC [29]

So, in this context it will be interesting to evaluate how the contribution will be in the 2030 considering the increase of the installed power outlined by the PNIEC. In wind energy sector, 19.3 MW of wind farms are expected to generate more than 40 TWh of energy in 2030. So, considering that in the 2019 (year analysed in the previous sub-section) the installed wind power was equal to 10.7 MW, in the 2030 the overall installed power will increase by the 80% respect to 2019. Thus, also the power available in providing both SI and AVC will increase. For this purpose, Figure 33 reports the estimated ΔP available for SI provision in the 2019 (red line) with the expected ΔP that could be obtained in 2030 considering the national targets (red dotted line). It is assumed that all the plants participate to provide SI and AVC as in the 6.4.

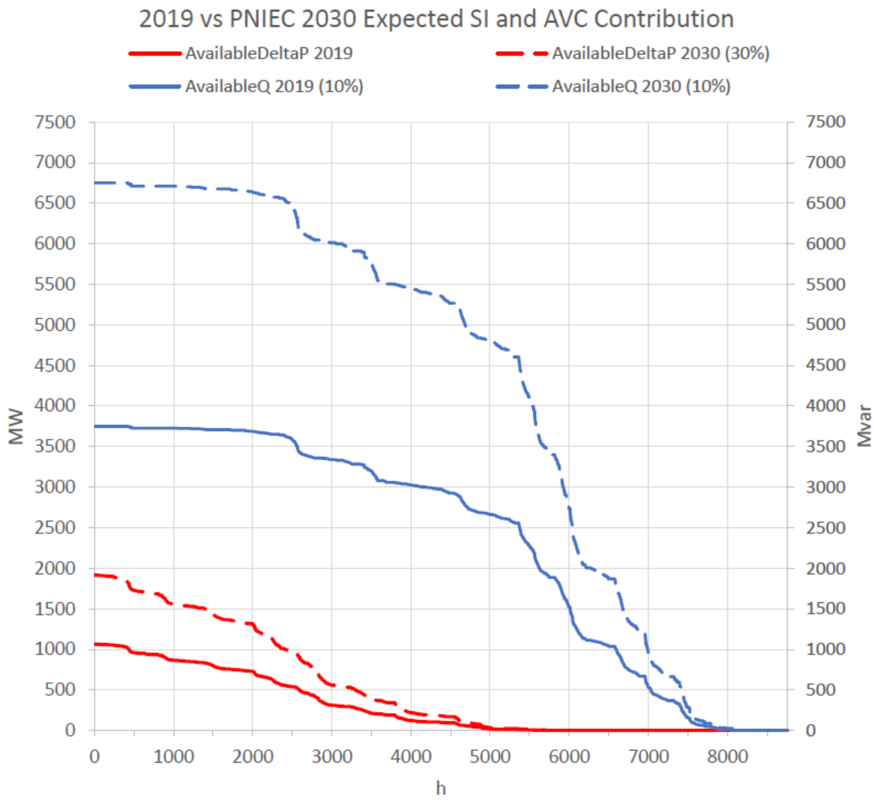
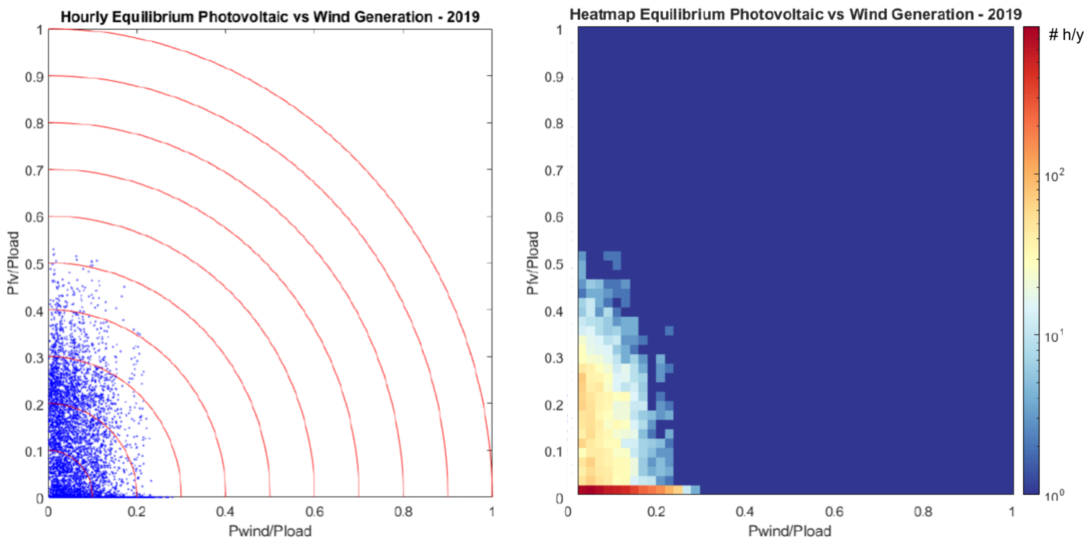


Figure 33 PNIEC 2030 Expected SI and AVC Contribution

It can be seen that the maximum value of almost 1 MW of ΔP in the 2030 could be obtained for around 2500 h compares to the 0 hour of the 2019. In addition, Figure 33 also compares the availability of reactive power in the 2019 (blue line) and in the 2030 (blue dotted line). From the reactive power availability point of view, the increase of 80% of the total wind installed power results in an increase of the total reactive power available of 3000 Mvar both capacitive and inductive considering the value of 35% of rated power and the activation threshold of 10% of the nominal power.

6.6 Comparison Between Wind and Photovoltaic Power Profile

This last section jointly analyses the generation profile of wind power and photovoltaics. In fact, the aim of this analysis is to evaluate how the two generation technologies contribute to the load coverage. Indeed, photovoltaic and wind energy are the most installed renewable energy sources which are inertia free and in addition they usually do not provide AVC. So, the analysis was then carried out to assess how the two energy sources cover the load (national or local) on an hourly scale. Using the ENTSO-E Transparency Platform were downloaded both the photovoltaic and load profiles aggregated by bidding zones as explained in 4.2.1 for the year 2019. However, in this case was not necessary to evaluate the provincial data as results were presented on national scale or eventually aggregated by bidding zone. For each hour of 2019, the two generated powers were evaluated and weighed against the corresponding hourly load (national or bidding zone depending on the type of analysis). That is, a vector containing 8760 points was then created and graphed in the form of points and heatmaps by placing the ratio of wind power to load on the x-axis and the ratio of photovoltaic power to load on the y-axis. The first representation helps to understand the quota of inertia free generation thanks to the equipotency lines reported in red. Instead, the second representation helps to quantify how the dots are distributed i.e., the heatmap represents how many dots (hours) fall in a square with a side equal to 2% of the total represented in the axis. Following are presented the results obtained in this assessment.

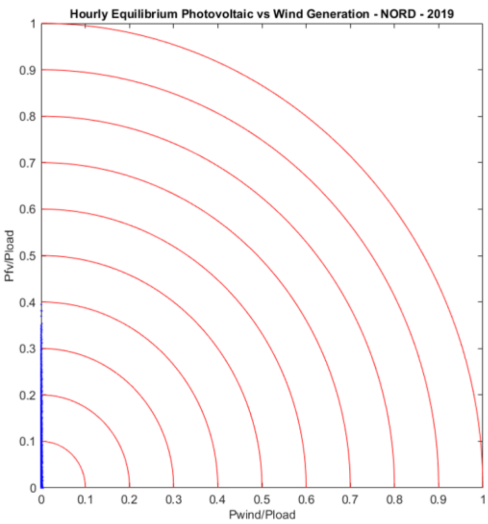


a) b)

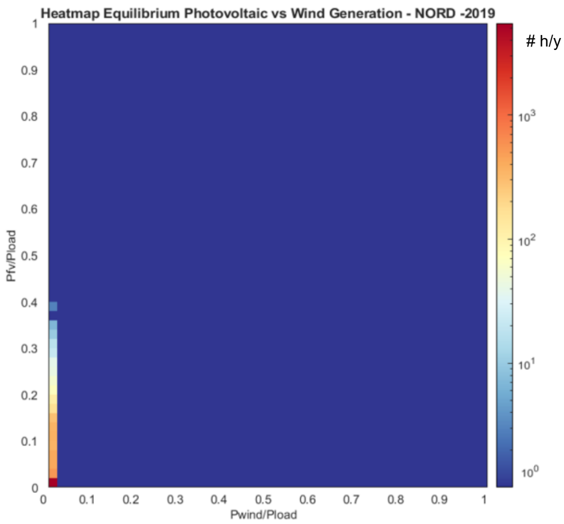
Figure 34 National Equilibrium PV-Wind Power

Figure 34 is a national representation of the PV over Wind power so, it helps to make consideration about the SI provision. Indeed, it is possible to appreciate that PV plants cover a higher quota of the load respect to the wind power. However, thanks to the night hours, there is a higher number of hours where the only wind generation is present (red squares close to the x-axis in Figure b)) respect to the number of hours where the only PV generation is working. This could be interesting in terms of SI because, assuming that WTs will be providing SI, they could mitigate the effect of the reduction in inertia caused by wind generation. Finally, extending the SI on WTs can also mitigate the reduction of inertia caused by the simultaneous production of both photovoltaic and wind power plants. In fact, it is appreciable the area depicted in yellow/orange in Figure 34 b) where the wind turbines generate together with photovoltaic plants. However, a different scenario could be defined in which, as emerged from the qualitative analysis, the solution that implemented the services with the BESS could also be replicated on photovoltaic installations. In this case, the hours in which the service is available from RES would increase as the PV-only hours would also contribute but, also the amount of regulation contribute would increase due to the joint action of both PV and wind when both are in operation.

Then the same analysis is replicated for each Italian bidding zone to evaluate how the share of photovoltaic generation and wind generation impacts on the local load (i.e., the load of the reference bidding zone). This helps to understand how inhomogeneous RES availability can be in relation to load in Italy.



a)



b)

Figure 35 Equilibrium PV-Wind Power – NORD

Figure 35 reports the PV-Wind load coverage balance in the bidding zone NORD. Here, the very low wind installed power results in almost null load coverage and mainly only PV contributes to the NORD load coverage. As results of the previous analyses on local availability of SI and AVC, the low wind installed power and the low unit production of the northern area create a low contribution of WTs in providing innovative services. Also in this case, the regulating contribution could be relevant in the case of replication of the BESS solution also to PV-based power plant.

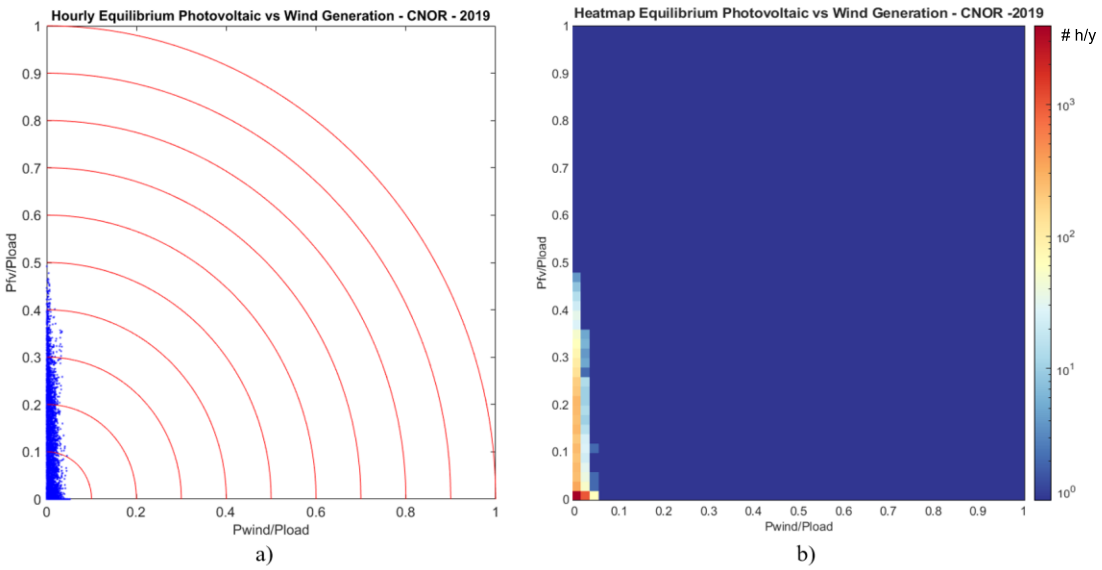


Figure 36 Equilibrium PV-Wind Power – CNOR

As in the NORD, in CNOR, although the contribution of wind power is slightly greater in relative terms than in the previous case, there is a clear imbalance towards photovoltaic production.

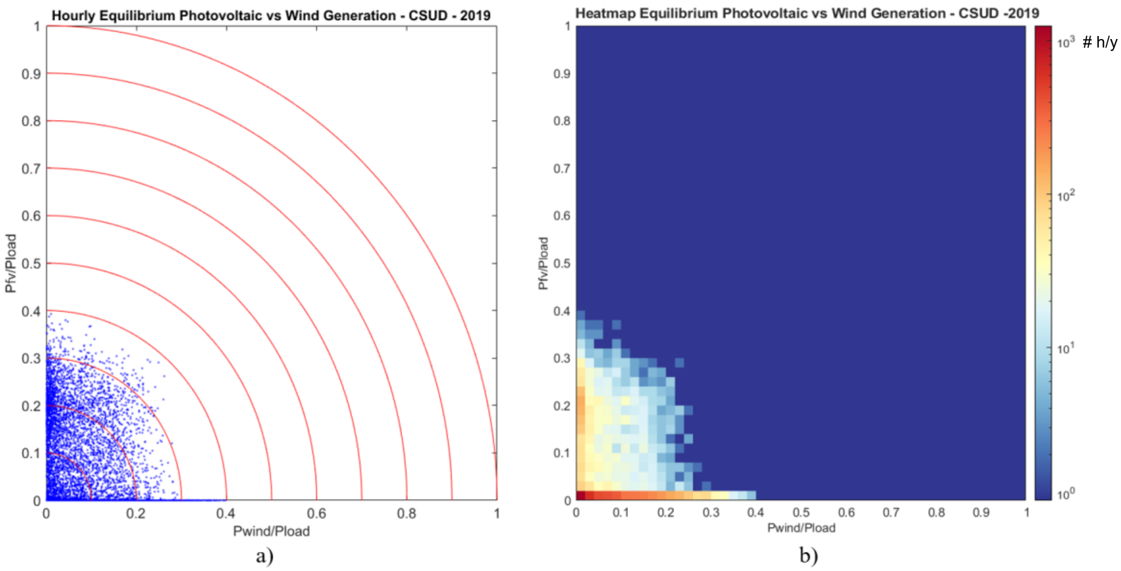


Figure 37 Equilibrium PV-Wind Power – CSUD

Moving through the southern regions, either because the load decreases, the share of installed RES becomes higher and because the sites are more productive, there is a better homogeneity of RES production. In the specific case of CSUD (Figure 37 a) and b)), it can be appreciated that when the two sources operate simultaneously, up to about 30% of the load coverage (red line equipotential 0.3 on Figure 37 a)) the load is often equally distributed (with a slight imbalance towards photovoltaics). However, due to the night hours, there is a marked imbalance in the hours when only the wind source is producing (red squares on the x-axis in Figure 37 b)).

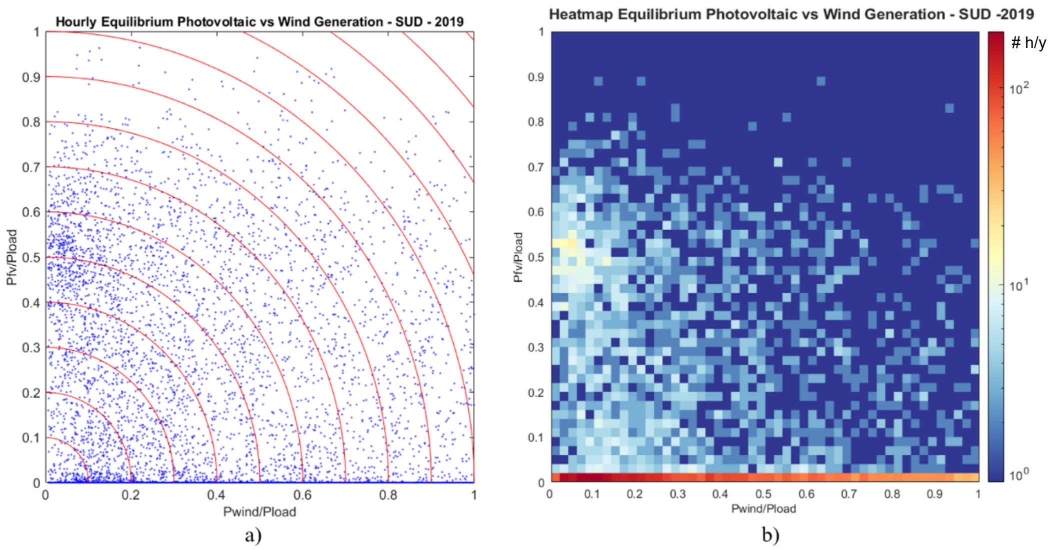


Figure 38 Equilibrium PV-Wind Power – SUD

Figure 38 a) and b) reports the load coverage for the SUD. In this case, it can be appreciated the same trend noticed in CSUD with the difference of an increase in the load coverage (in relative terms) till reaching the full coverage of the load (blue dots around the equipotency line 1 on Figure 38 a)). Moreover, from the heatmap can be noticed how the hours are sparse respect to the axis origin. In this context, it would be desirable for WTs to provide AVC and SI given the large shares of renewable that cover most of all the local demand making exports to other areas necessary. Then, the bidding zone shows a significant number of hours where the PV power it is around the 50% of the total load but the wind power is absent or very low (yellow and light-yellow area near the y-axis on the heatmap). So, during these hours the overall provision of AVC and SI coming from WTs is very limited. As it was observed, wind generation exceeds the local load for some hours (up to the 160% of the SUD load) thus it is reported in the extended version of the Figure a) in Figure 39.

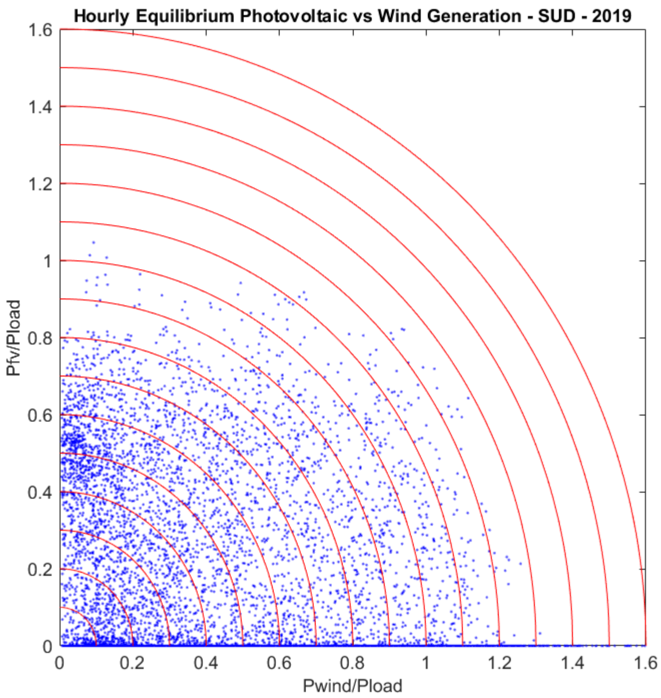
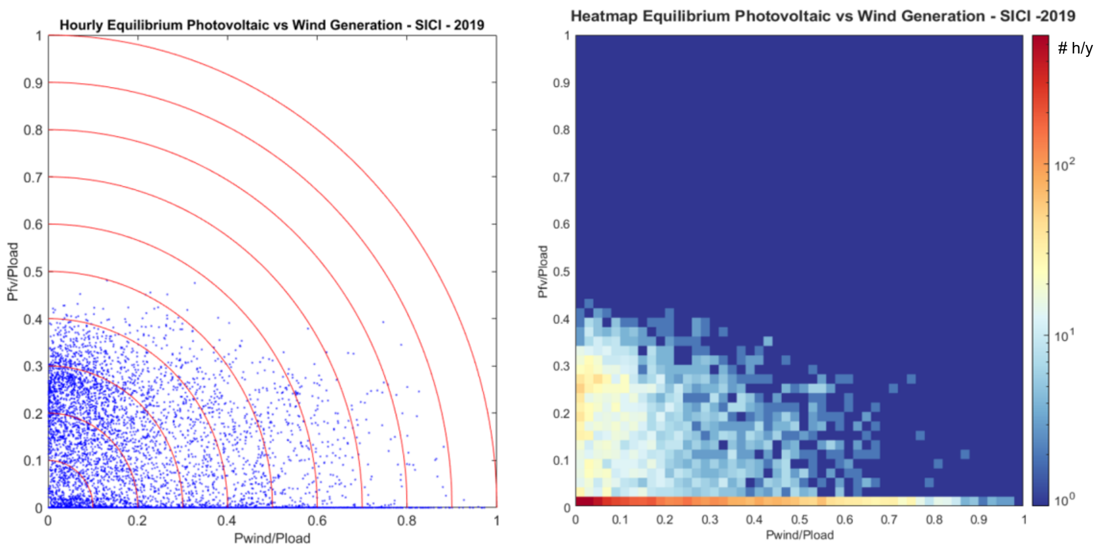


Figure 39 Extended Load Coverage - SUD 2019

The last two bidding zones refer to the two major Italian islands. Indeed, Figure 40 and Figure 41 reports the share of wind power over PV power for Sicily and Sardinia respectively.



a) b)

Figure 40 Equilibrium PV-Wind Power – SICI

In Sicily it can be observed that the wind power contributes more, both in terms of maximum value of load coverage (Figure a)) and in terms of hours at which the wind power is relevant to the PV (figure b), respect to the local PV power. However, there is a densification of points around 30% of the load coverage with photovoltaics where the wind source is very low or almost zero. At such times, therefore, it could not experience the beneficial effects that could be obtained if wind turbines were equipped with AVC at SI. However, a large number of hours where the wind power is greater to the PV are present making it possible to provide by WTs the innovative services tested.

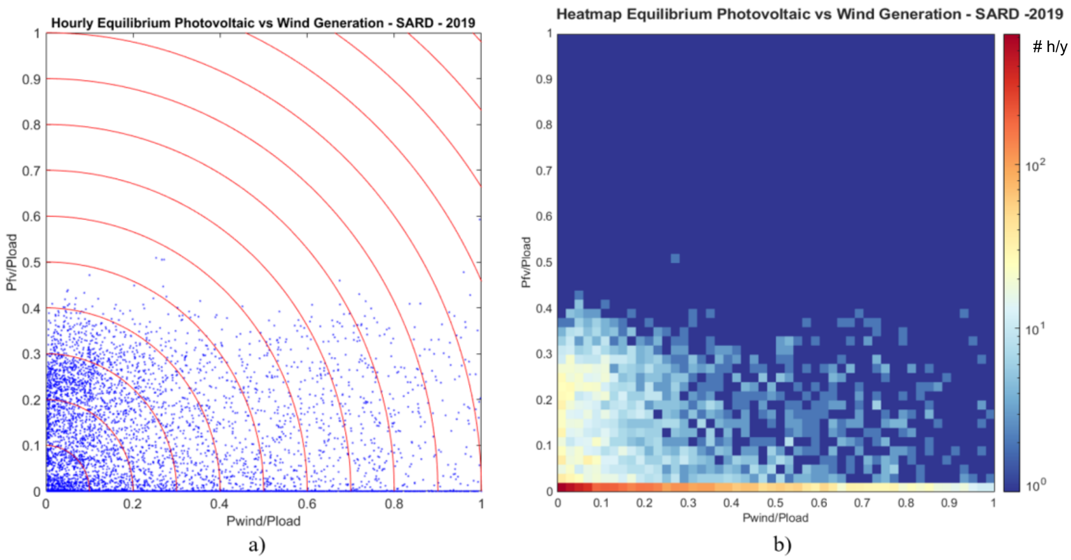


Figure 41 Equilibrium PV-Wind Power – SARD

Finally, it is presented the results referring to the Sardinia. From the analysis of the two figures can be noticed that the wind source covers the local load for a significant number of hours. The only PV power covers up to the 30% of the total load on the contrary conversely, the wind source covers up to the 200% of the total load (Figure 42). Also in this case, the yellow area close to the y-axis indicates a quite high numbers of hours in which the wind power is zero or almost, resulting in potential no contribution in terms of reactive power and SI.

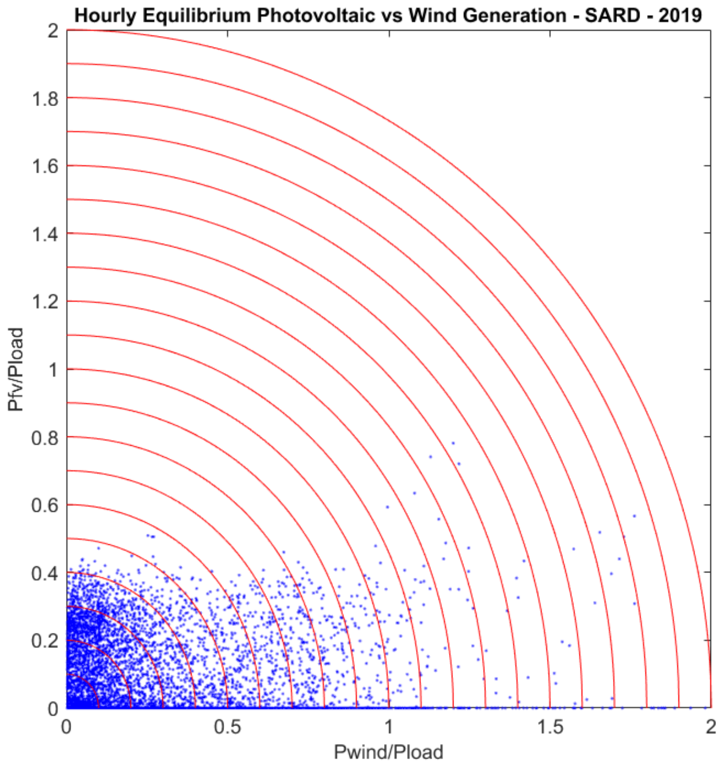


Figure 42 Extended Load Coverage - SARD 2019

7 Conclusion

In conclusion, after the identification of the needs of innovative grid services caused by the increase of the renewable energy sources exploitation, the work carried out with this thesis showed the importance of conducting a SRA on a smart grid project. Indeed, the results obtained by the SRA are of crucial importance to support the overall outcomes of the pilot project. The SRA tend to reduces the risk that the innovative solution would remain bounded within the perimeter in which it has been tested. Anyway, several observations can be made from the results obtained in the thesis. Firstly, to make it easier and truthful the performance comparison of different projects would be desirable a common methodology for evaluating smart grid projects. Then, looking in deeper on the analyses carried out, the first relevant result concerns the weight of technical aspects in deciding the success of the implementation. That is, technical aspects are for sure at the basis of both the scale-up and replication process, but they are not sufficient. In fact, qualitative assessment showed how important are regulatory and economical aspects in a smart grid project. The lack of remuneration for services provision and the lack of a regulatory framework greatly reduces the chances of success of the project. This is because the developing of innovative solution implies costs and sometimes involvement of players that usually are not directly involved in the normal plant operation. So, the presence of a remuneration scheme could support and incentivise the replication and scaling process of the tested solution. Then, a well define regulation framework could help the standardization and certification process, helping the development of standard and easily scalable technical solution. Going on to the assessment of the main results of the SRA, after the first qualitative analysis, the quantitative approach showed the potential performance of the innovative services provision along the national perimeter. It has been revealed that not all the sites are adequate for the provision of the tested services and in particular, the unit production value alone is not enough to estimate the performance of a site. Furthermore, both the spatial location of the wind-based power plants and the variability of the wind source imply different amount of contribution, both along the peninsula and along the time. This reflects the characteristics of RES in terms of produced power also in the services provision. However, since the solution that has implemented the innovative services provision using a BESS seems to be replicable regardless the generation technology of the entire plant, it might be very interesting to conduct additional analyses on the implementation and validation of the BESSs performance in providing services on photovoltaic plants.

ANNEX A

Following is reported the developed questionnaire delivered to the partner. D During the collection of information each partner received a specific survey containing only questions related to its implementation. Here, however, for reasons of space the questionnaire is given in aggregate form i.e., the tables contain both questions concerning Plant V and Plant P.

Scalability Survey

SCALABILITY Q&A				
Area	**Key factor**	**ID**	**Question**	**Partner: Plant P or Plant V or Both**
Technical	**Modularity**	**QS1**	*Can you easily (technically) add components to your solution to increase your solution's size? If yes, which ones and how? If no, why not?*	Both
		QS2	*Are there any limits that affect the proper functioning of the solution or the possible adding extra components within your solution? If yes, explain what the constraints in the technical solution will be.*	Both
		QS3	*Are all components fully interchangeable with others (similar specs but different producers) or specific product are requested? (e.g., BESS, BMS, inverter)*	Both
		QS4	***For Plant V:*** *Which is the obtainable SI contribution in terms of maximum power in relation with the WT size (Plant V)? Does the SI contribution, in relative terms, increase/decrease with the WT size?*	Plant V
	Technology evolution	**QS5**	*Do you foresee technological advances in the short to medium term that will make adding components easier (technologically)? If yes, which ones and why?*	Both
		QS6	*Can you say something about the TRLs (technology-readiness levels) before the start and at the end of OSMOSE? Do you foresee technological advances in the short to medium term that will mitigate a possible performance reduction?*	Both
		QS7	*In which part of the demo, technology evolution is primarily required in order to increase size, performance and competitivity of the solution?*	Both

		QS8	*Is scalability of the solution limited by a lack of TRLs ? In which section/part of the plant (mechanical/aerodynamic, electrical generation and electronic power conversion, system controller, BESS, etc.) ? Is the suppliable contribution, in relative terms, affected by the WT/BESS size (it increases or decreases with the component size?)?*	Both
	Interface design	**QS9**	*How is the interaction between the components controlled? If control is organized centrally, describe how this is done and indicate which level of centralized control is needed/optimal.*	Both
		QS10	***For Plant V:** When the system has to provide services (SI or AVC), according to which criteria the control system manages the single WTG that are available in the plant (Plant V)? Are this logics affected by the WT size or the overall plant size ?*	Plant V
		QS11	***For Plant P:** When the system has to provide services (SI or AVC), according to which criteria the control system manage the BESS and WTs that are available in the plant (Plant P) ? Are these logics affected by the WT size or the overall plant size?*	Plant P
	Software tools integration	**QS12**	*If some components are software products (tools, databases, models, etc.), does the growth of your solution affect their performance (calculation time, etc.)? If yes, how and why? If no, why not? Are there other limits to the software solution (if applicable) ?*	Both
		QS13	*Have the softwares required to manage the solution been fully developed?[Yes, they are fully developed - No, software are partially developed so in-house developed are needed - No, software aren't yet developed]*	Both
		QS14	*Please indicate how the software required to manage the solution has to be updated/improved to be applied to larger sizes*	Both
		QS15	*If some functions are remotely controlled (e.g., the voltage support), does the size of the plant impact on the technology to interface the plant with the TSO?*	Both
	Compatibility analysis	**QS16**	*Does the current infrastructure where the project is deployed (outside of your solution) create any limits on the maximum size that can be reached? If yes, what are these external limits, and can they be easily overcome?*	Both
		QS17	*Is there an upper limit in the size of the solution imposed by the specific characteristics of the demo power plant?*	Both

		QS18	*Can the development of the solution reduce the lifetime of WTs?* ***For Plant P:*** *Can the development of the solution reduce the lifetime of the BESS (Plant P)? Which are the key elements (activation thresholds, network frequency perturbations, etc.) impacting on lifetime reduction of WTs and BESS (Plant P/Plant V)?*	Both
Economics	**Economies of scale**	**QS19**	*If the size of the solution increases, how does the cost of your solution increase?*	Both
		QS20	*Is the business size large enough to appreciate economies of scale while applying the solution to different WT/BESS sizes (considering realistic sizes of WTs and BESS)? Is there a minimum size under which the regulating function is not suppliable or is too much expensive to be applied?*	Both
		QS21	*Is there a specific size of the solution that could minimize the relative cost of the solution?*	Both
	Profitability	**QS22**	*Is the actual project economically viable? If yes, what is the main reason for the benefits being larger than the costs? If no, why not?*	Both
		QS23	*Which is the preferred condition in order to provide the service associated to the solution? Choose from the proposed answer. [MANDATORY | MANDARORY + REMUNERATED | VOLUNTARY + REMUNERATED | NO ONE OF THE OTHER (please provide an alternative in this case)]*	Both
		QS24	*In the case the service is mandatory, which is the minimum size above which the service has to be provided (in terms of WT size, BESS size, overall plant rated power) . In the case the service is remunerated, which is the remuneration scheme preferred: availability of the service / effective supply of the service / mixed remuneration (in which percentage), etc.?*	Both
		QS25	*Can the solution (or part of it) be also used for other purposes (e.g., other remunerated grid services) without compromising the performance?* ***For Plant P****: E.g., in order to provide SI contribution, a minimum SOC is required. How the control system prioritizes the different functions of the BESS (in the case that multiple services are requested simultaneously)*	Both
Acceptanc e	**Regulatory issues**	**QS26**	*Are there any regulations that might drive the uptake of the innovation?*	Both

		QS27	*Are there any regulatory barriers concerning the size and scope of the project? If yes, which ones and how do they affect the project's solution?*	Both
		QS28	*Do you foresee evolutions (in regulatory frameworks) in the short to medium term that will positively influence the cost-benefit ratio of your solution?*	Both
		QS29	*Do you consider opportune that the service is suppliable only by WTs/BESS/plants above a minimum size? In terms of size of the single machine (WT and/or BESS) or of the overall plant?*	Both
	Consent	**QS30**	*Is stakeholder acceptance important for your project? If yes, explain.*	Both
		QS31	*Do you foresee any challenges concerning stakeholder acceptance? If yes, which ones and how could they be overcome?*	Both
		QS32	*May the scaling up of the solution improve your reputation, e.g., increase the Environmental Social and corporate Governance (ESG) value, attract new investors…?*	Both

Replicability Survey

REPLICABILITY Q&A				
Area	**Key factor**	**ID**	**Question**	**Partner: Plant P or Plant V or Both**
Technical	**Standardization**	**QR1**	*Is the solution standards/grid codes compliant? If yes, with which standards (mandatory, voluntary, open, or proprietary)? Could you mention the benefits and/or challenges you expect for being your system/solution compliant with the contemplated standards?*	*Both*
		QR2	*Is the solution easily (economically and technically) made compliant with a defined different set of standards? If yes, describe how? If no, explain why not?*	*Both*
		QR3	*In your opinion, are some characteristics of the components required as a standard in order to facilitate the replication process?*	*Both*

		QR4	*Which is the reliability of the developed solution to provide SI and AVR (excluding the issue related to the primary source availability)?*	*Both*
		QR5	***For Plant V:*** *In a standardized application, which could be an interval of realistic SI gains made available by the WT?* ***For Plant P****: In a standardized application, which could be an interval of realistic SI gains made available by a BESS?*	*Both*
		QR6	***For Plant V:*** *Do you consider that a central coordination of SI contribution made available by each WT by means of a unique controller (which performs the frequency measure at the point of delivery) is an alternative respect to providing SI independently at each WT? Is it possible taking into account limits in terms of communication technologies or others? Which are advantages/disadvantages of this alternative solution?*	*Plant V*
		QR7	***For Plant P****: Which are the drivers that affect the size of the BESS/inverter as regards to the size of the overall wind plant (Plant P)?*	*Plant P*
	Interoperability	**QR8**	*Are all components/functions of your solution plug & play, i.e., able to adapt their working and interactions to a different setting? If no, which ones not? If yes, why and how has the plug & play characteristic been obtained?*	*Both*
		QR9	*Can the solution be easily deployed in different environments without additional investment (time/money)? If no, why not? If yes, describe how*	*Both*
		QR10	***For Plant V:*** *Which specs are required to a WT with DFIG generator in order to provide both SI and AVC? Could existing plants made available SI and AVC or their contributions are suppliable only by new installations/revampings?*	*Plant V*
		QR11	***For Plant P****: If a plant has already installed a BESS, which specs are required in order to provide SI and AVC without installing new components? If a system update is required to supply SI and AVC, which could be the required actions?*	*Plant P*

		QR12	*Could the providing of the solution arise some instability due to the multiple WTs/plants interventions or any other undesired effects? Which specs are required to WTs/BESS in terms of measuring devices and machines to avoid instable behaviours of the grid (e.g., which spec are required to frequency/ROCOF measurement to assure that SI contributions are similar and synchronized?*	*Both*
	Network configuration	**QR13**	*Does the correct functioning of the solution depend on a natural resource that is specific/abundant in the current environment? If yes, which resource?*	*Both*
		QR14	*Is the functioning of the solution influenced by the specific infrastructure of the location of your demo? If yes, by which aspects?*	*Both*
		QR15	*Is this solution applicable elsewhere? Can your solution be extended to other voltage levels, locations?*	*Both*
		QR16	*Do you foresee that in the future (e.g., the Terna CEN scenario) the functions proposed by demos are necessary to ensure a reliable operation of the power system?*	*Both*
		QR17	*For evaluating the demo performances and their impact on network stability in the case the solution is widely replied, which is the set of parameters that you suggest to consider (in addition to ex-ante defined KPIs)?*	*Both*
Economics	**Macro-economic factors**	**QR18**	*The profitability of the solution, when exported to a different country, depends strongly on the different macro-economic factors. The influence of these factors can typically be found via a limited scenario analysis on a few selected target countries. Have you undertaken or do you plan such an analysis?*	*Both*
		QR19	*Can your solution be exported to other countries and still be profitable considering the different macro-economic factors?*	*Both*
	Market and business model	**QR20**	*Is the project still economically viable under a different setting (e.g., other EU member states)? Do you already have plans for exporting your solution abroad? If so, which barriers (economically and regulatory) did you detect?*	*Both*
		QR21	*How important is the development of a remuneration for SI in order to spread out the technology tested in*	*Both*

			the demo? [(Not relevant) 1 - 2 - 3 - 4 - 5 (Very important)]	
		QR22	*How important is the development of a market for the Reactive Power (remunerated for RES) in order to spread out the technology tested in the demo? [(Not relevant) 1 -2 - 3 - 4 - 5 (Very important)]*	*Both*
		QR23	***For Plant V:** Which could be the extra-cost of a WT able to supply SI and AVR as regards to a standard model (Plant V)?* ***For Plant P:** Which are the costs for installing a BESS unit to provide SI and AVR (taking also into account all externalities that a BESS could presents and possible alternative remunerations obtainable by supplying other ancillary services)?*	*Both*
		QR24	*How much overall capacity has to be installed to reach the minimum of the unit cost of the solution? Which are the elements that primarily impact on this aspect?*	*Both*
Regulatory	**Regulatory issues**	**QR25**	*Are there any regulatory barriers concerning the size and scope of the project? If yes, which ones and how do they affect the project's solution?*	*Both*
		QR26	*Does your solution depend on elements of current national or regional regulation necessary for your solution to be feasible and viable? If yes, which ones (describe these elements briefly)?*	*Both*
		QR27	*Are there any barriers arising from the dependency on those elements of current regulation for the feasible deployment of your solution in other environments?*	*Both*
		QR28	*Do you foresee that TSO could force all RES power plant to provide SI at the power system? In the case SI will be mandatory, do you think that the function should be remunerated or not when it will be supplied? Does providing SI impact on plant cost of components aging?*	*Both*
	Acceptance	**QR29**	*Do you foresee acceptance problems when exporting your solution to other countries?*	*Both*
		QR30	*Thanks to the revamping activity, can the solution have more chance to be installed? For existing plants, which are the expected criteria to be used for revamping WTs (e.g., lifetime of WTs) or the overall plant (e.g., installing a BESS)?*	*Both*

		QR31	*Do you think that replying to the demo on several other plants (including other countries) could improve your reputation at a European/worldwide level (e.g. increase the ESG value, attract new investors…)?*	*Both*

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