# ComSos

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# *"Commercial-scale SOFC systems"*

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## The grid balancing role of SOFC-based distributed generation

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# Abstract:

The following deliverable is focused on the analysis of SOFC integration in a Virtual Power Plant for grid balancing. The document includes a first description on the status of grid balancing roles with focus on Italy and Germany, followed by an analysis of two possible optimized case studies where an SOFC is integrated within a supermarket (COMSOS case study) with the aim of performing also grid balancing activities.


# Keyword list:

Grid balancing, virtual power plants, SOFC, cogeneration,

# Summary

# 1. Introduction

## 1.1 A Clean Planet for all

The European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy can be a very interesting opportunity for developing industrial attractiveness for new and efficient technology in the energy landscape.

The enhancement of deployment and market penetration of variable Renewable Energy Sources (vRES) will be the keystone of this clean energy transition, as we can notice from Figure 1. This will lead in the coming decade to a smarter and more flexible system, building on consumers' involvement, increased interconnectivity, improved energy storage deployed on a large scale, better demand side response and management through digitalization [1].

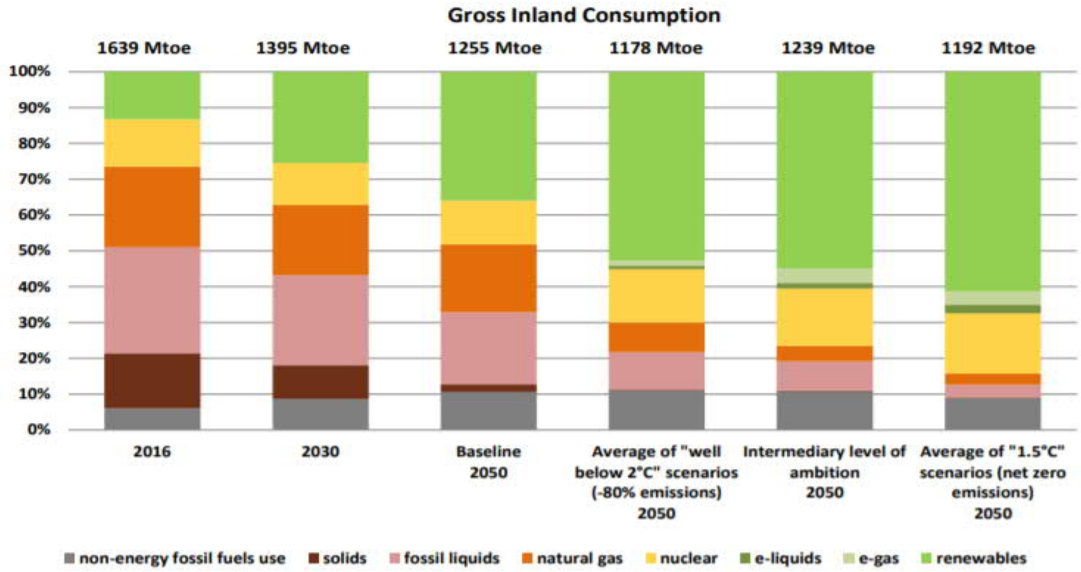



*Figure 1: Gross European Inland Consumption scenarios* [1].

The increasing share of wind and solar photovoltaics (PV) will induce a fundamental transformation of our power systems due to their fluctuating and weather-depend nature. In particular, the expected scenarios show a reduction of thermal power generation because of reduction of residual demand and its increased volatility, within the growth of electrification across all sectors.

At present big power plants are compelled to participate in energy and ancillary service markets, thus acquiring specific duties at their own point of connection to the grid, while a small-scale non-programmable RES, is authorized to inject power to the grid without a specific schedule.

Over time, we will see an essential attention on flexible sources and technologies, that shall provide the essential basis for the vRES integration. The focus will be on assets with high power modulation capacity, high responsiveness and low overall balancing cost. Moreover, they will ensure negligible service condition constraints, which means for example fast black start or minimum service period in the order of magnitude of minutes or few hours.

### 1.2 Distributed energy resources

Distributed Energy Resources (DER) are small-scale power generation units located close to where the electricity is needed. They offer the potential for increased service reliability, higher energy efficiency and lower cost, thanks to their higher degrees of freedom and the reduction of transmission losses.

As a result of technological advancements and EU policy impulse, DER will become a viable alternative to conventional power generation for the provision of balancing services to transmission system operators. They meet the need for better responsiveness in facilities generating dispatchable energy and controllable load [2], [3].

To better integrate small and less controllable DERs, these assets can be aggregated into Virtual Power Plants (VPP). A VPP commonly combines many different DERs to constitute a virtual plant that can communicate as a unique entity with energy markets and grid operators. The aggregation reduces the communication interfaces to external partners and enables more flexible energy production and consumption management in defined areas [4].

### 1.3 Grid balancing opportunity for Solid Oxide Fuel Cells

Fuel cells operate more efficiently than thermomechanical technologies (combustion engines, turbines) in terms of energy production as direct energy conversion eliminates the need for combustion. High temperature stationary fuel cells, such as Solid Oxide Fuel cells (SOFC), have proven to be a highly efficient cogeneration systems (Combined Heat and Power, CHP) with an overall system efficiency up to 85-90%. They can combine the benefit in reduction of primary energy consumption of cogeneration systems with achievable electrical efficiency in the range 50-60%.

Moreover, SOFCs still operate very efficiently at partial loads, differently from other CHP technologies which are affected by a significant performance degradation as they move away from their nominal working conditions. SOFCs indeed tolerate significant degree of modulation, even below 50%.

High temperature fuel cells have an operation temperature beyond 500°C, which provides high exergy potential for the combined heat and power production and high fuel flexibility for different gases, including natural gas and syngas, due to the high carbon tolerance. This leads to a perfect matching between the technology and the existing infrastructure and energy mix. A continuous operation is preferred in order to avoid long start-up and shut-down time, that affects negatively the availability factor and generates degradations phenomena within the cells (due to thermal cycles).

Furthermore, this technology basically eliminates all local pollutants (NOx, SOx, VOC) and particulates emissions. When using natural gas and thereby building on existing infrastructure, stationary fuel cells can substantially reduce $CO_2$ emissions as highly efficient conversion of low-carbon natural gas (lower emitted tons of $CO_2$ per kWh). When the SOFC runs on renewable biogas or hydrogen, emissions are carbon-neutral and zero-carbon, respectively. SOFCs are also perfectly suitable for carbon capture because of streams separation of fuel and oxidant by plant design, thereby facilitating high levels of carbon capture without substantial additional cost.

These characteristics, besides the flexible modulation capacity, show strong potential for a range of applications, including grid-support activities, in the context of a power mix marked by always more intermitted renewables and electric heating solutions like heat pumps. As we will see in Chapter 2, the SOFC features seem to fit very well with the restrictions of the less responsiveness balancing product, the manual frequency restoration reserve. In Chapter 4, we will investigate the SOFC access to the balancing market as an interesting asset in a VPP portfolio, whose concept is presented in Chapter 3. Finally, in Chapter 5, the results of the activity resulting demonstration of the project are submitted and a review on the most suitable solution to grid balancing for a SOFC power plant.

# 2. Electricity Balancing Systems

## 2.1 Main actors

In Europe, four different types of actors mainly interact in the electricity balancing market: balance responsible parties, transmission system operators, balancing service providers and distribution system operators.

- *Balance responsible parties (BRPs)* are market entities that have the responsibility of balancing a portfolio of generators and/or loads. Each physical connection point is associated with one BRP. In the balance planning phase, BRPs submit energy schedules to the transmission system operator on the day before delivery, maintaining planned energy generation and consumption for each Schedule Time Unit (generally 15 minutes) within the day of delivery. In the balance settlement stage, they are economically responsible for the imbalances (schedule deviations) in their portfolio [5], [6].
- *Transmission system operators (TSOs)* are responsible for controlling and operating the transmission network. TSOs need to ensure the equilibrium between energy supply and demand, maintaining stable frequency levels at 50 Hz, in the range of a positive or negative deviation of maximum 0.2 Hz, by managing energy infeed or withdrawal. TSOs activate balancing power to balance demand and supply if the sum of the BRP imbalances is non-zero. They need to procure the energy they use according to transparent, non-discriminatory and market-based procedures [5]-[7].
- *Balancing service providers (BSPs)* supply reserve capacity and deliver energy if dispatched by the TSO. They are obliged to deliver energy under pre-specified terms, such as within a certain ramp rates and for a minimum specific time interval. The TSO can apply two different methods of BSPs remuneration: one based on balancing capacity availability (in €/MW) and one on the energy delivered (€/MWh). The first is recognized for the provision of the offered power in a corresponding time interval, whereas the second compensates for the energy actually delivered [5].
- *Distribution system operators (DSOs)* are responsible for operating, ensuring the maintenance of and developing the distribution system in each area, in order to ensure the long-term ability of the system to meet reasonable demands for the distribution of electricity. They operate local

electricity networks, traditionally distributing electricity from the higher-voltage transmission network and from small generators into houses and businesses [7].

### 2.2 Standard balancing products

Balancing services involve two main arrangements:

- balancing energy, the real-time adjustment of balancing resources in order to maintain the system balance;
- balancing capacity, the contracted possibility to dispatch energy during the contract period in case of imbalance occurrence.

The active power generation must constantly match the demand. Instabilities in this balance are immediately compensated for by the kinetic energy of the rotating generators and motors connected to the grid; resulting in a variation in the system frequency $f$ from its set-point value, 50 Hz. Several levels of control are performed to maintain the system frequency at its set-point value $f_0$. Each of them has its own specifications and relies on a given amount of power reserve that is kept available to cope with power deviations [8].

TSOs must determine, ex ante, and active, in real time, the amount of capacity which needs to be earmarked as power reserve. TSOs fulfil these tasks thanks to three different standard balancing products, that differ from each other in purpose, response time and the procedure they are activated (see Figure 2).

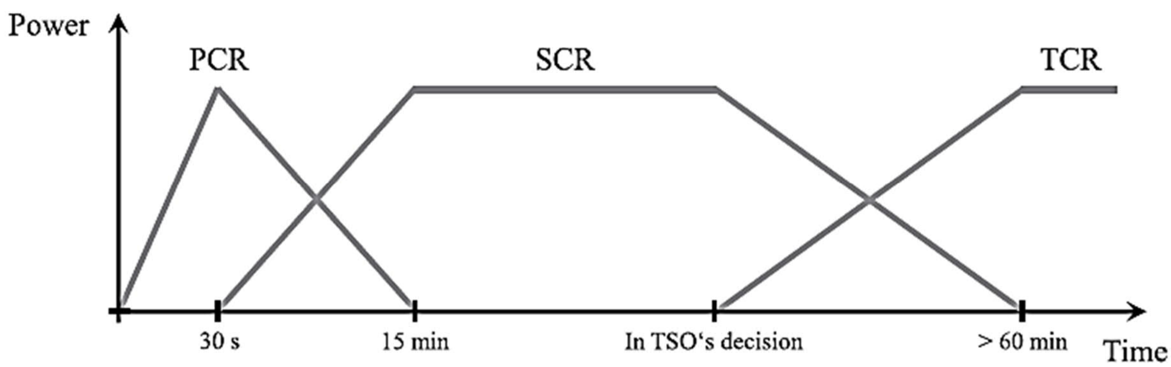



*Figure 2: Starting and deployment times of primary (PCR), secondary (SCR) and tertiary control reserve (TCR)* [9].

The *primary control reserve (PCR)*, which is the frequency containment reserve (FCR), is automatically activated within a few seconds after detecting a frequency deviation on local level. It is not activated by the TSO and it is calibrated such that the frequency fluctuations are contained in acceptable levels, but not restored. It is characterized by the most responsiveness technologies, that are able to reach the full activation within max 30 seconds [2], [5], [9].

The *secondary control reserve (SCR)* is the automatic frequency restoration reserve (aFRR), which is activated successively within a few seconds. It is activated centrally and automatically by the TSOs with an IT signal. aFRR is used to restore the nominal frequency of the system and to release the primary reserve, that has a limited service period [5], [9].

Finally, the *tertiary control reserve (TCR)*, which is also called manual frequency restoration reserve (mFRR), is the less responsiveness reserve characterized by a full activation within 15 minutes. TCR aims to replace the SCR over time and to manage grid congestions. Activation is a decision taken by the TSO according to the evolution of deployment of SCR. TCR can be provided by a larger audience of assets due to its wider market access possibility. It can be an interesting opportunity both for stand-by generators and DER units with an end-user load to be satisfied [5], [9].

## 2.3 Short term market

The electricity market arrangement is generally based on three different short-term market: Day-Ahead Market (DAM), Intra-Day Market (IDM) and Balancing Market (BM).

The *Day-Ahead Market (DAM)* hosts most of the day's volumes of electricity sale. Hourly energy blocks are traded and a dispatch schedule for each of the day's intervals is prepared. The DAM remunerates flexibility when there are high variations in residual demand, since some less-flexible units cannot ramp up and down to follow these variations.

*Intra-Day Market (IDM)* integrate new information, that were not available at the day-ahead stage and adjust the market-based dispatch of supply and demand resources. Only flexible capacity can participate in intraday and balancing markets due to shorter product lengths and planning horizons. Thus, generally there are additional remuneration of flexible capacity from the DAM to the IDM and BM, as we can see from Figure 3.

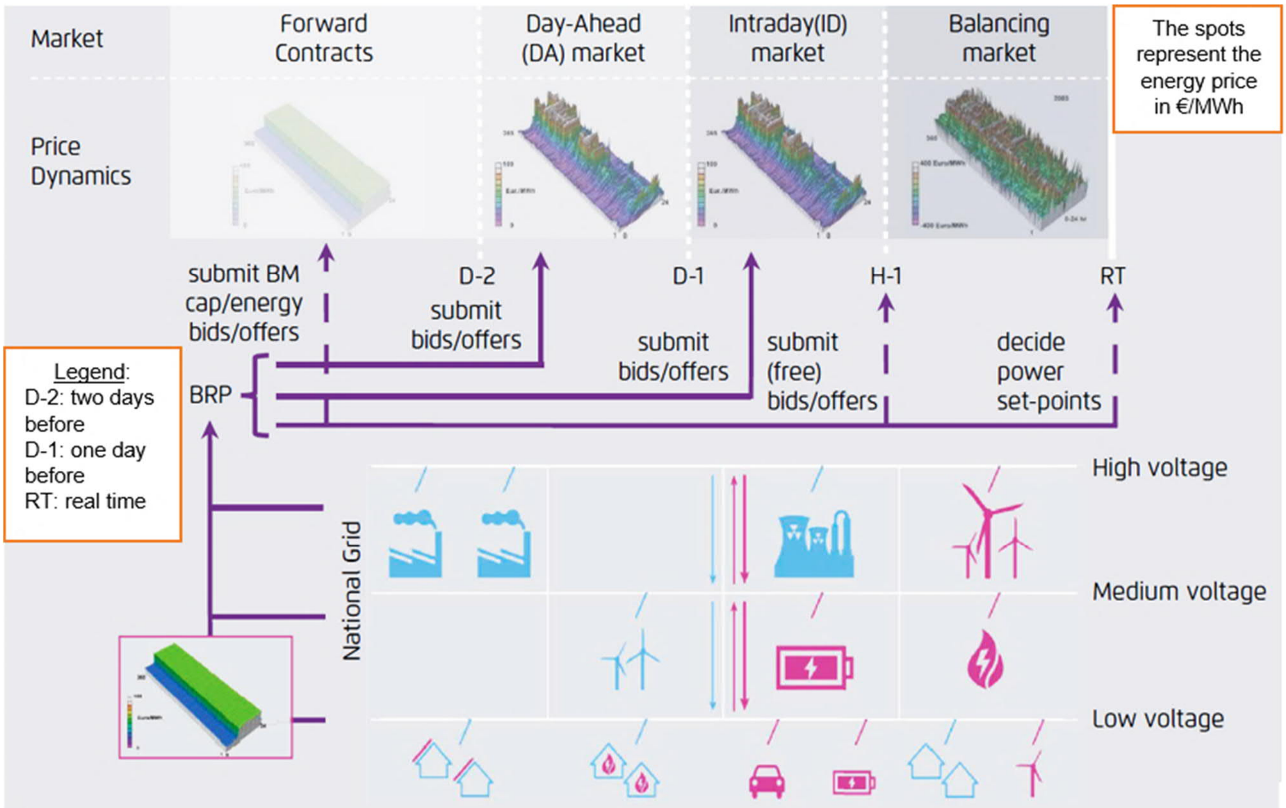



*Figure 3: Typical organisation of electricity markets in Europe. Different generators and loads connected to the national grid and associated with a BRP are shown, ordered by voltage level. At the top, the price volatility evolution is presented moving from the DAM to RT* [3].

The *Balancing Market (BM)* is the final stage for trading electricity energy. Complying with the commitment to accommodate increasing shares of vRES, BM allows the matching of production and consumption levels during the operation of electric power systems in real time, covering frequency regulation and ensuring system reliability. The TSO calls upon submitted bids to provide balancing energy (this can come from generation, demand response, or storage units); selected bids in the balancing capacity market are thus transferred to the balancing energy market [3].

The transmission system operators must arrange cost-effective ways to balance supply and demand in real time. The volatility of real time price in the BM is related to non-accurate forecast of vRES production or unforeseen events that can compromise the grid reliability. These can be sudden weather condition changes, or service interruption that may occur in both transmission and generation equipment. Moreover, prices in real-time energy market are sometimes negative since generators should be turned off, when running at their low operating limit, due to low residual energy demand [10].

The definition of the right short-term market target is therefore crucial for all the assets involved in the grid balancing services. Big power plants without an end-user load to be satisfied, that based their business cases on the interface with the electrical grid, will mainly tend to submit bids on the early market sessions in order to make sure a large volume of electricity sale and to avoid the risk of being excluded from the balancing energy market. On the other hand, small DERs will basically wait for the last session of the market to benefit from the price volatility, accepting the related risk.

### 2.4 Energy auctions

The electricity market is based on auction exchange, where system balancing products are treaded between the market participants, in order to promote the competition in procurement.

The auction remuneration settlement is generally based on a uniform or pay-as-bid pricing rules. Under the uniform pricing rule, all market participants with accepted bids are paid with a uniform (single) price, which is the *market-clearing price (MCP)*, regardless of their bids. The MCP is determined as the offer price of the highest accepted bid in the market. Meanwhile, under *pay-as-bid (PaB)* pricing rule the BSPs with the accepted offers are paid according to their bids and no single MCP is established by the TSO [11].

In this framework, the auction characteristics play an important role for the oncoming transition. For example, low frequency and following extended lead time (period between the moment the auction is performed until start of delivery of the product) can penalize BSPs who manage assets highly dependent on external factors (wind, sun etc.) difficult to forecast. On the other hand, high frequency can lead to business risk, due to the uncertainty over the payment for a long period of time.

The bid features also affect the possibility of market accessibility. Lowering minimum bid size can facilitates the participation of small BSP. Moreover, the permission of joint use of distributed energy resources (DER) can expand the possibility to participate in balancing market to those realities that present relatively small individual capacity. This pooling possibility can allow the BSPs to integrate in their portfolio different type of reserve technology (RES, conventional, storage, demand response system) in order to increase their flexibility and capability. We will describe this opportunity and its local restrictions in detail in Chapter 2.5.

To give an actual example, **Error! Reference source not found.** provides an overview of the design choice in Italy and Germany regarding the three balancing products and the main auction features, FCR, aFRR and mFRR [2], [12].

| | **Italy** | **Germany** |
|---|---|---|
| **vRES access to the balancing market** | No | Yes, for wind turbines that want to provide negative mFRR (pilot phase) |
| **Pooling** | Allowed | Allowed |
| **Activation speed and duration** | • FCR: reaction in few secs, automatic activation 100% within 30 secs;<br>• aFRR: reaction in few secs, full activation within 5 mins;<br>• mFRR: full activation time is 15 mins for balancing (except for slow replacement reserve (RR) “riserva terziaria di sostituzione” which has a full activation time of 120 mins). | • FCR: reaction in a few secs; full activation within 30 secs for minimum 15 mins;<br>• aFRR: reaction in maximum 30 secs; full activation within 5 mins;<br>• mFRR: reaction in maximum 5 mins; full activation within 15 mins. |
| **FCR** | | |
| **Minimum bid size** | FCR products are not open to the market. It is mandatory for generators and conventional power plants with installed capacity of 10 MW to provide it | 1 MW |
| **Frequency of bidding** | | From 01.07.2019 the product period was reduced from one week to one day, with the call for tenders taking place every working day D-2 at 3 p.m. |
| **aFRR** | | |
| **Minimum bid size** | 1 MW | 5 MW (1 MW increments) |
| **Frequency of bidding** | Daily | Daily |
| **mFRR** | | |
| **Minimum bid size** | 1 MW | 5 MW (1 MW increments) |
| **Frequency of bidding** | Daily | Daily |
| **Remuneration** | | |
| **Pricing rule** | • FCR: capacity payment;<br>• aFRR and mFRR: PaB for capacity and energy, including start-up fee (€) for thermal generators | • FCR: uniform price method;<br>• aFRR and mFRR: PaB for capacity and energy |

*Table 1: Design choice and auction features for the procurement of the balancing products in Italy and Germany.*

In Italy, FCR products are currently not open to the market. It is mandatory the relevant generation units to provide it. In particular, if the asset is installed in mainland, it must provide ±1.5% of its effective power to FCR. Plants in Sicily and Sardinia must provide ±10% of their effective power. The aFRR products are currently close to demand response (DR) and DER. Their procurement is through bilateral agreements between the TSO and the generation units, characterized by a 1 MW minimum bid size. Finally, the mFRR products present an open market with few minor existing barriers in requirement structure and a DR and DER participation trough aggregation.

In Germany, all balancing services are open to all market parties and all technologies, as long they fulfil the technical requirement, also in an aggregated form. The three standard balancing products are procured in auctions on daily basis in 6 four-hours blocks. However, the minimum bid size mainly settled at 5 MW (except for FCR participation) is still a significant limitation [12].

## 2.5 Pooling

The pooling allows the grouping of different consumers, producers or prosumers within the power system to engage in the balancing market as a single entity. This opportunity has been developed in the past few years to face the rising share of intermittent renewable electricity generation. This change was driven by the concerns about keeping a high security and reliability of supply. The TSOs show interest in aggregation as a tool to improve the responsiveness of the grid with greater degrees of decentralised flexibility. It also stimulates the market for developing new services.

Regulators may allow or prohibit the joint use of DER. If pooling is allowed, each BSP, that benefits from this option, must pass technical requirements for balancing service delivery by either prequalifying each asset separately or the overall portfolio. These prequalification obligations are generally related to the activation speed, the service provision interval and the ramp rate.

Moreover, online metering for resources which are participating in the balancing markets is required to predict flow changes in grid and system security. In case of small assets, this is seen as a general challenge to the business model of the aggregator, which has to cover also the fixed communication costs (€/month) for online metering. The relatively high cost of acquiring metering equipment induce high profitability risk, especially on smaller resources where the amount of flexibility and possible incomes for BSP are relatively small.

Figure 4 sums up the overall electricity balancing systems structure and relationships that exist between the main participants, ordered by time of occurrence (horizontal) and by actor (vertical).

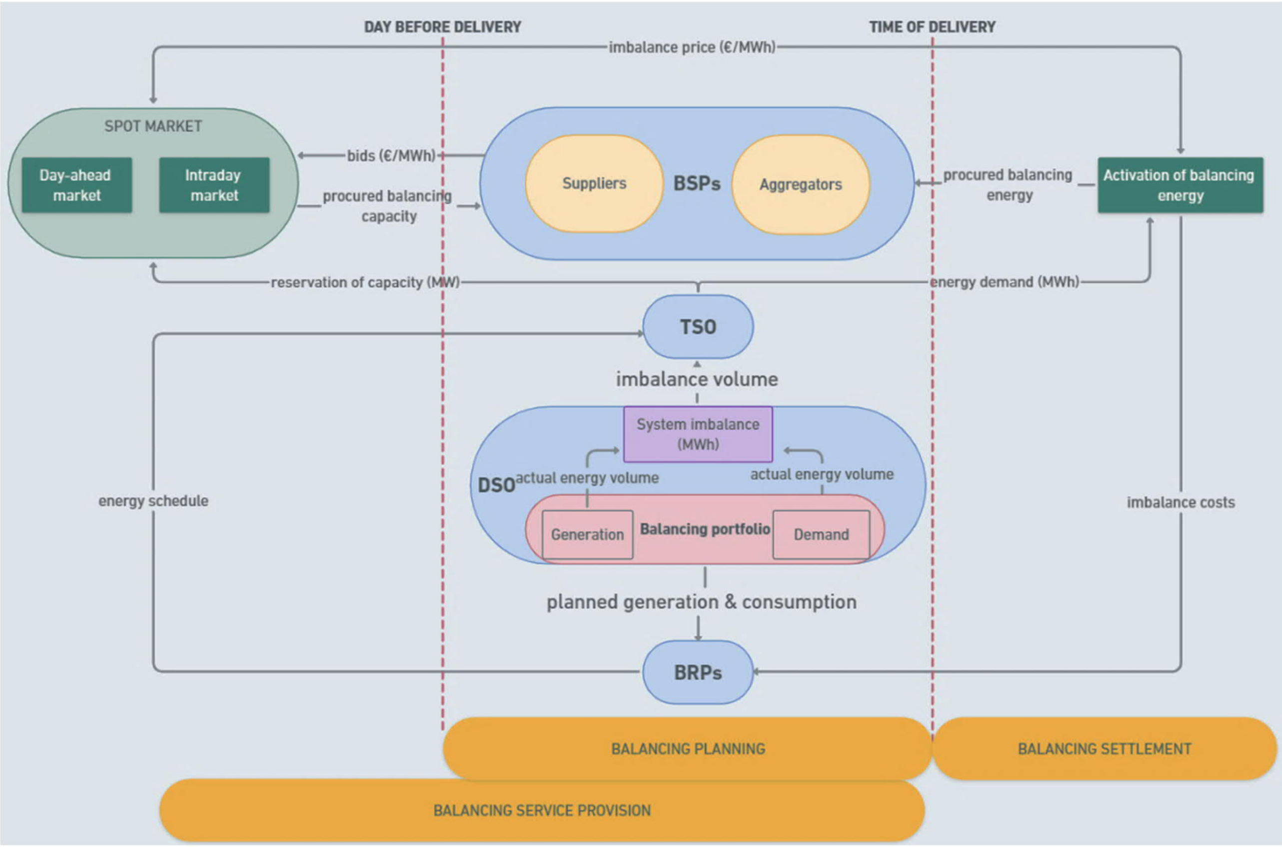



*Figure 4: Basic structure of the balancing market.*

# 3. Virtually Power Plant – VPP

## 3.1 VPP concept

As we have previously pointed out, in the countries where the TSOs allow the pooling, the virtual power plants (VPP) are an interesting opportunity for developing economic attractiveness of new technology. The VPP concept is based on the stimulation of clusters of “close” DERs (including RES, storage devices and loads) to respect an aggregate behaviour, compliant with the grid requirements. The idea is to allow the involvement of a small-scale distributed generators in balancing issues, voltage regulation and congestion resolution, avoiding strict requirements at each single point of connection [13].

A virtual power plant, thanks to the flexibility and heterogeneity of its portfolio, can realize an optimal management and control of a set of DER, in which all distributed generator units, loads and storage systems are coordinated together, considering electrical market signals and leading to profits for both stakeholders and network.

Moreover, fluctuating renewable energies are expected to benefit from the market-oriented operation mode in the virtual power plant. The selective and regulated shut down of renewable energies in times of negative electricity prices may lead to further cost savings. The utilization of temporary price fluctuations in the spot market and the demand-oriented provision of control power offer high additional revenue potential for flexible controllable technologies such as battery storage and CHP units [14].

In terms of VPP, Germany has already entered a commercial stage, while Italy is still in a demonstration stage due to the recent Virtually Aggregated Mix Units pilot project.

## 3.2 Germany

The VPP concept was developed in Germany when its vRES penetration in the grid became significant. The Figure 5 illustrates the constant need for flexibility throughout the all week. In the case presented, the wind dies down together with a drop in the generation of solar power. Thus, controllable conventional power plants have to cover a major portion of the demand within a few hours.

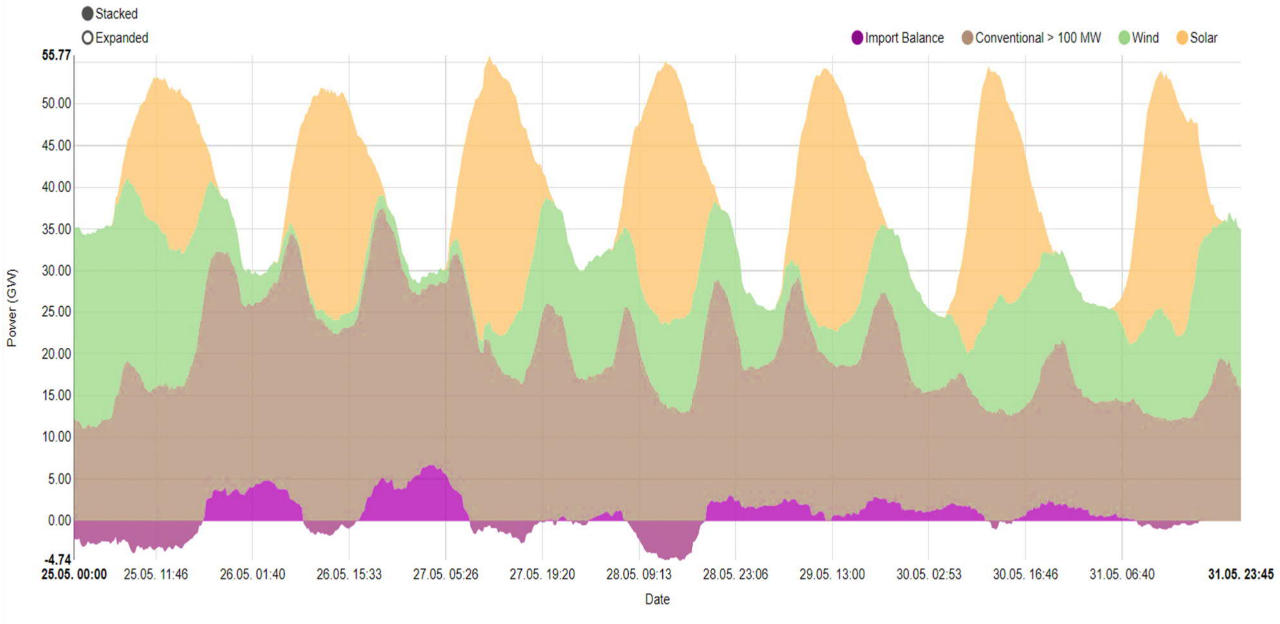



*Figure 5: Electricity production in Germany in a week in late spring 2020*[1].

The first research project on VPPs took place between 2008 and 2012 and was funded by the German Federal Ministry for Economic Affairs & Energy (BMWi). The mission confirmed that a VPP which was able to integrate vRES operated together with controllable resources, reduced by 15% the imbalances of the variable generation due to forecast errors.[2]

Their success, after 2012, was also prompted by the change in the renewable power support regulation which switched from a fixed feed-in-tariff model to a market-premium model. The VPP technology gave a perfect solution for the market integration of DER. Thanks to the direct connection to power assets for data acquisition, aggregators were able to optimize power forecasts and to perform a significant forecast improvement, that was detected after the implementation of VPPs in 2012.

Due to the legal, regulatory and market environment, VPPs are now quite common and in full commercial operation in Germany nowadays. One of the largest independent VPP operators in this region is Next Kraftwerke, who can boast massive capacities with prequalification for delivering the balancing products, subdivided as follow (early 2019) [15].

- FCR: 57 MW (mostly flexible biogas CHPs, electrolysis, and batteries);
- aFRR: 922 MW;

[1] https://www.energy-charts.de/power.htm?source=conventional&year=2020&week=22
[2] https://www.esig.energy/blog-virtual-power-plants-vpp-applications-for-power-system-management-example-germany/

- mFRR: 1,572 MW (FRR being mostly CHP and/or biogas).

The idea behind their VPPs proposal is to raise awareness of the opportunity of additional revenues or savings due to the power price volatility, that changes significantly moving from day-ahead markets to intraday market. In addition, greenhouse gases emissions can be reduced significantly through the market-oriented integration of renewable energies and efficient technologies.[3]

The asset owners have the possibility to adjust their schedules according to price forecast and trades the optimized schedules on the energy market, thanks to the aggregation into the VPP and the trading department of the operator.

Distributed generation units, active consumers, and energy storage are connected via information and communication technology (ICT) and aggregated into an intelligent plant network. The remote-control unit allows monitoring and steering of the asset in real time, considering all the specific parameters (ramp-up, modulation range, etc.). Furthermore, a merit order ranking of assets in VPP allows to automatically choose the cheapest plants in the portfolio to satisfy the desired power volume dispatchment.

The control system receives all the information of the networked units, power price exchange trends and the grid information of the system operator. On the day of the actual feed-in, live data continuously improve the forecast and enable the countering of the fluctuation of vRES.

Using intelligent algorithms, the control system can create individual optimized schedules in order to stabilize in real time the power grid. The remote control of power plants via VPP gave aggregators the flexibility to control the output of their portfolio based on price signals and the need of the TSOs. Flexible power generators such as CHPs, that can adjust their power production without external constrains, can be ramped up and down precisely to the quarter of an hour. Moreover, active power consumers, thanks to flexible arrangement called demand response, can orient their original schedule to provide grid stabilization factor and reduce power consumption costs by consuming their electricity when it is cheap, and the demand is low.

Thanks to the data transmitted to the aggregator servers, the VPP operator is able to offer suitable bid to grid frequency control auctions. Then, during a grid balancing call, the control system sends out

[3] https://www.next-kraftwerke.com/

the desired modulation order to all the units involved, after verifying all the restrictions from each networked asset in terms of availability, actual power and residual power capacity. In this way, the BSP can beat average prices on short-term markets and share the additional revenues with the asset owners, taking advantage of his better overall trading position.

The aggregators obtain from the TSOs capacity and energy payments for the ability to increase or decrease their production and consumption when there is need to balance the grid. Subsequently the tendering, the TSO sorts the bids by capacity fees and accepts offers until it reaches the required reservation of capacity. The accepted bids are ranked in increasing order by energy price to create a merit order curve, which is used in the balancing planning and settlement to activate the respective operators according to the current demand.

## 3.3 Italy

Italy is one of the historically closed countries regarding balancing markets. However, in the last few years Italy is undertaking important efforts to improve the access to balancing markets, aligning with other European markets. The Italian Regulatory Authority for Energy, Networks and Environment (ARERA) is trying to improve this situation with new pilot projects that allow a wider audience of market parties to provide flexibility service to the grid [12].

Since Delibera 300/2017/R/eel[4], the participation in the MSD[5] (Ancillary Service Market, which consists of a scheduling substage and Balancing Market, BM) is no longer an exclusive prerogative of large power plants (so-called “Relevant generation units”, with size not less than 10 MW) , but it has been opened to those facilities that present relatively small power capacity, non-programmable energy sources and active power consumers. These realities would be enabled to MSD on an aggregated basis, in compliance with appropriate geographical location criteria, contributing to form distributed dispatching points of consumption (UVAC) and generation (UVAP).

By 25th November 2018, UVAC and UVAP have been converted to UVAM (Unità Virtuali Abilitate Miste) in order to include in a single aggregate, the possibility of providing upward and downward balancing services.

[4] PRIMA APERTURA DEL MERCATO PER ILMSD ALLA DOMANDA ELETTRICA ED ALLE UNITÀ DI PRODUZIONE ANCHE DA FONTI RINNOVABILI NON GIÀ ABILITATE NONCHÉ AI SISTEMI DI ACCUMULO. ISTITUZIONE DI PROGETTI PILOTA IN VISTA DELLA COSTITUZIONE DEL TESTO INTEGRATO DISPACCIAMENTO ELETTRICO (TIDE) COERENTE CON IL BALANCING CODE EUROPEO.https://www.arera.it/it/docs/17/300-17.htm#

[5] MSD: mercato per il servizio di dispacciamento

In this new framework, for the first time in Italy the role of BSP has been introduced, as the holder of the UVAM and the entity responsible for the services negotiated on the MSD (see Figure 6). Each point included within the UVAM must be equipped with a “Peripherical Monitoring Unit” (UPM), an equipment capable of measuring the energy injected/withdrawn and sending the measurement data to the concentrator every 4 seconds (except for withdrawal points with modular power <1 MW and infeed points with modular power <250 kW for which the sending frequency is 60 seconds).[16]

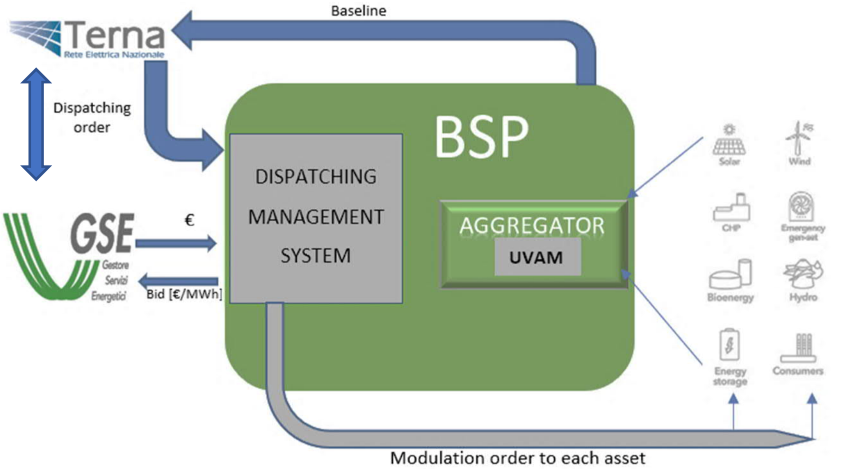



*Figure 6: BSP process layout*

Each BSP has the obligation to communicate on the day-ahead the so-called Baseline, i.e. the expected overall power schedule of all the assets included within the UVAM. The Baseline is then modified by the TSO (Terna) by means of a corrective factor, estimated on the basis of the fluctuation with the measured data. If the BSP bid is accepted, the corrected Baseline value is added to the accepted power capacity in the Ancillary Service Market (MSD), that is managed by the GSE on behalf of Terna. This determines the final power schedule of the UVAM, which leads to the verification of the correct execution of the movement requested by TSO. Finally, the BSP is required to communicate the partition coefficient of the quantities accepted on the MSD for each dispatching point.

In order to participate in the program, each asset holder has to daily communicate to the BSP the consumption and production forecasts for the UVAM Baseline definition. Moreover, it has to send regularly his availability to modulation so that the BSP is able to formulate the optimal bidding strategy.

The conveniences, that the Italian regulator will want to achieve through aggregation within an UVAM, are similar to those we have seen in the German VPP, i.e. growing valorisation of flexible plants, greater degrees of freedom for compliance with market constraints and maximization of the revenues.

Table 2 gives an overview of UVAM's characteristics, the services provided and the relative remuneration [16], [17].

| UVAM | |
|---|---|
| **Type of assets included** | Generation, withdrawal and accumulation units |
| **Minimum modulation capacity of the aggregate** | 1 MW |
| **Response time** | Response within 15 minutes from receiving the order |
| **Service delivery interval** | Ability to perform the modulation for at least 120 minutes |
| **Services provided** | • Congestion management<br>• Manual frequency restoration reserve (Tertiary control)<br>• Grid balancing services both in DAM and IDM |
| **Remuneration** | • Fixed availability price allocated through downward auctions with maximum bid of 30000 €/MW/year<br>• Flexible pay-as-bid price, to be applied only in case of activation of contracted capacity (with maximum strike price settled at 400 €/MWh) |
| **Bidding obligation** | • At least four consecutive hours in the range of 2 pm to 8 pm from Monday to Friday in order to benefit of the maximum remuneration (linear decrease of the fixed remuneration up to 50% in case of two hours bidding)<br>• No divisible bid allowed, which excludes the possibility of bidding partial allocated quantity |
| **Penalty** | • If the offer commitment is not verified positively for at least 70% of the days of the month, the fixed monthly remuneration is in any case equal to zero (termination of the contract occurs if this condition shows up for at least 1/6 of the month of validity)<br>• The UVAM loses the right of remuneration after the fifth modulation with a performance lower than 70% |

*Table 2: UVAM framework*

Despite being calling pilot projects they are completely integrated in the markets, with a participation of approximately 1000 MW today. The results of the annual term supply auctions for 2020 considering the two designed allocation area, represented in Figure 7, have shown a great interest by the stakeholders and the following results.

| Allocation Area | Total assigned power | Weighted average fixed availability price |
|---|---|---|
| **A** | 800 MW | 26.122,2 €/MW/year |
| **B** | 191,4 MW | 28.744,7 €/MW/year |

*Table 3: Average fixed availability price by allocation area*

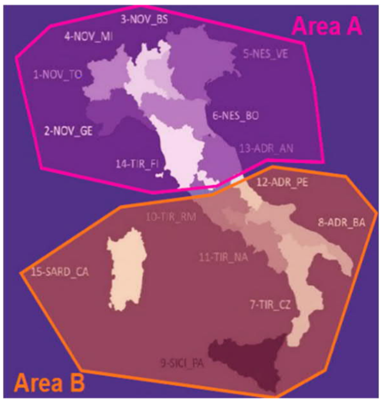



*Figure 7: Allocation area* [18].

Hence, the UVAM pilot project allows to exploit the power of generator unit that until now would not be authorized to participate in Ancillary Service Market (MSD). Figure 8 provides a scheme for better understanding this new opportunity.

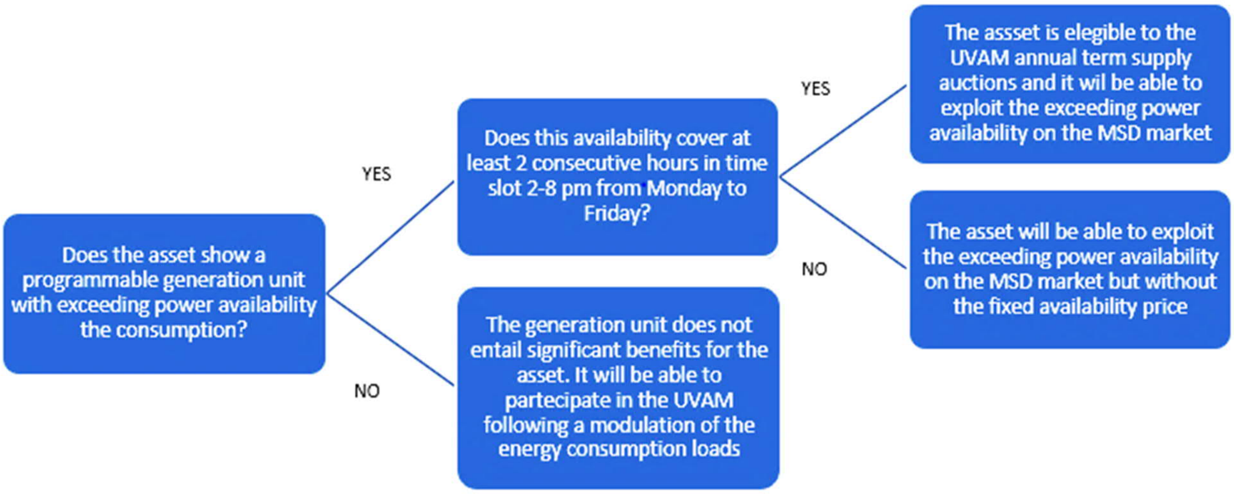



*Figure 8: UVAM opportunity for generation unit*

### 3.4 Comparison

The most perceptible feature of Germany's VPP business model compared to Italy is that it has already been successfully commercialised in a full scale of operation with a large amount of trading volume in the electricity market. In contrast, the pilot project found in Italy is in a demonstration stage and it has not been proved as commercially successful yet.

In Germany, there is no difference between conventional power plants and demand response (DR) or VPP. The market is uniform and does not distinguish wholesale power from balancing power/reserve control. There is no capacity market other than the balancing / reserve capacity market in Germany, differently from what we have seen in Italy with the annual term supply auctions for UVAM.

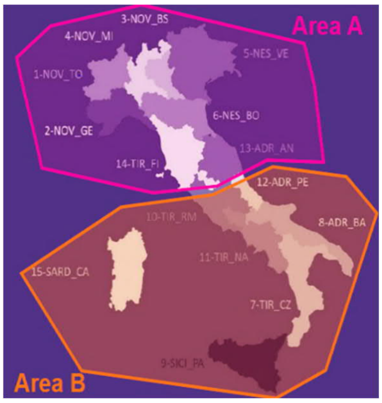
In Italy, the fixed availability price has a good attractiveness, especially in case of aggregation of clusters of small DERs which have to face a prequalification procurement for the first time. Moreover, since UVAMs are still in demonstration state their framework is designed in a precise way, which allows us to make a thorough analysis of the balancing market opportunities for new technologies, such as stationary fuel cell.

Therefore, the analysis on the possible future grid balancing role for SOFC, explored in the following sections, has been performed in the Italian scenario, taking advantage of the detailed UVAM framework.

# 4. Case Studies: overview

Starting from the COMSOS analysed market areas (described in Deliverable D5.3: Hotels, Supermarkets, Hospitals, etc.) in terms of daily load profiles across the year, we have analysed a SOFC power plant linked to a small supermarket in Italy, with a dispatch strategy as electricity led, which may successfully exploit its exceeding power availability thanks to the aggregation on a Virtual Power Plant. We have analysed two different scenarios in order to search a configuration that exploits the SOFC characteristics, minimizing the disadvantages. In fact, within the encouraging characteristics that suggest a positive entry into the grid balancing landscape, SOFCs are even penalized by cell degradation due to load fluctuation and by high capital expenditure.

We have considered a small supermarket with an electrical energy intensity of around 800’000 kWh/m$^2$ per year, which generally is associated to a 2000 m$^2$ sales area. To perform our simulations, we have decided to locate the resource in the south of Italy, precisely in city of Palermo (Sicily), because of the higher solar irradiation and also the higher average fixed availability remuneration (see Table 3: Average fixed availability price by allocation area




and Figure 7). Figure 9 shows the yearly electric load profile across the year.

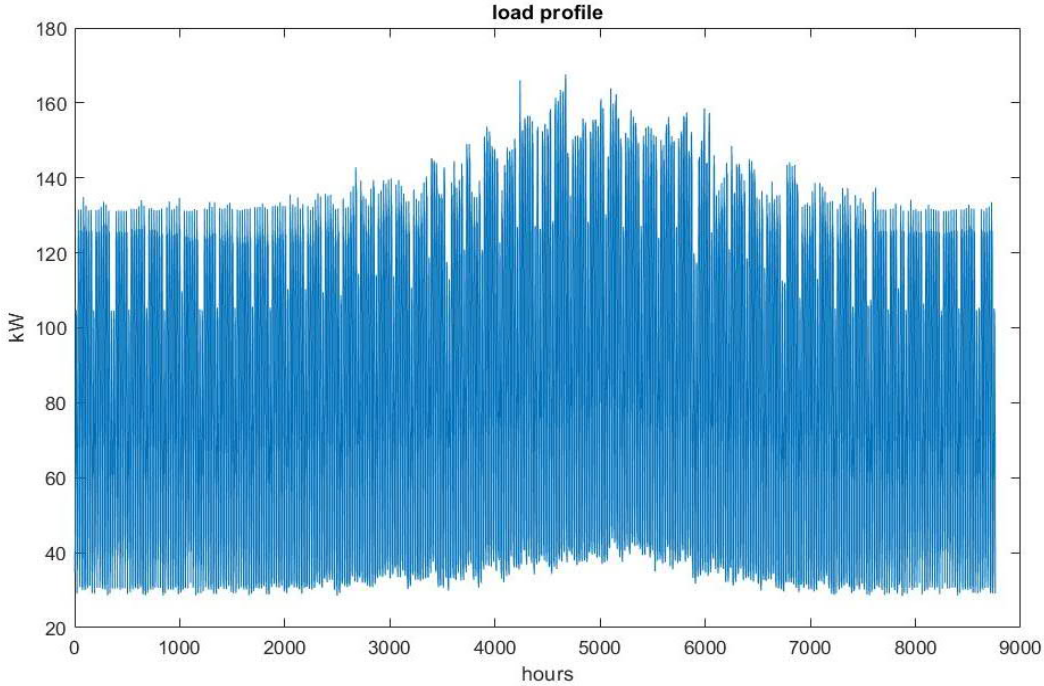



*Figure 9: Supermarket electric load profile.*

The idea was to create a prosumer who is able to provide grid balancing services, engaging successfully with the spot market. First semester of 2019 of the Italian UVAM pilot projects has in fact underlined the difficulty of submitting low bids due to high modulation cost and to the low reliability of the assets associated to the UVAM. The BSP tended to submit high bids to maintain the fixed remuneration right but without having actual interest in performing grid balancing. Figure 10 presents this trend. The difference between the bid submitted by the UVAM and the maximum selling price resulting from Balancing Market is significant [16].

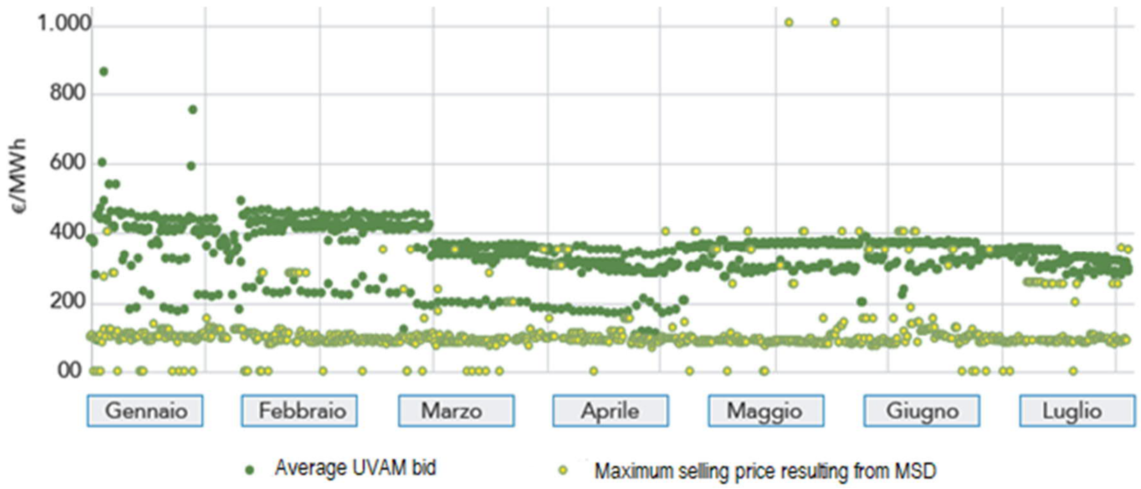



*Figure 10: Average UVAM bids (dark green points) and maximum selling price resulting from MSD in the allocation area A (light green points)* [16]

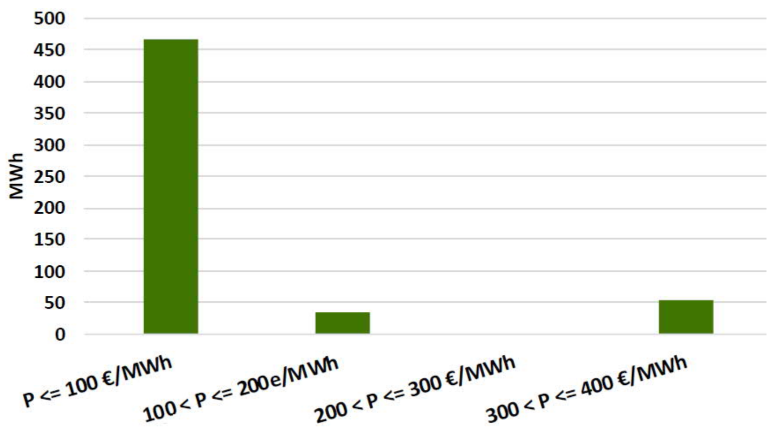



*Figure 11: Bid accepted by price range* [16]

Figure 11 points out the difficulty of having accepted bid near the strike price of 400 €/MWh. In fact, the main energy volume delivered by the UVAM is characterized by a price lower than 100 €/MWh

We have evaluated the performance of two different case studies, a stand-alone SOFC system, oversized respect to the base load in order to perform balancing services and a hybrid SOFC-PV system with a reduced oversizing but still acting in the grid balancing. Both models are evaluated for a full year of operation. The sub-component models are simulated in MATLAB® and the step-widths in the component models are in the range of one minute. The PV system energy production has been simulated with PVGIS.

## 4.1 Stand-alone SOFC

For the stand-alone SOFC case, we have designed a power plant composed by a nominal 180 kW SOFC system. We have decided to make the SOFC working at fixed power operation points in order reduce the daily number of ramps, starting from 30% of the installed nominal power. In case of dispatching order, the SOFC modules increase their output power to their nominal value in order to deliver the exceeding energy production to the grid. Table 4 provides the input definition for the model.

The base size of an SOFC module has been set to 60 kW (Convion case study) since this is already a relatively 'small' size compared to the VPP minimum modulation capacity (1 MW). Technical SOFC parameters are average values for D5.2 analysis not related to a specific manufacturer.

The SOFC operation, due to the high capacity installed, is managed in a load following mode, working with regular power steps, equal to 10% of the SOFC system nominal size.

| SOFC operation characteristics | | |
|---|---|---|
| **Operation type** | Electricity led | |
| **Electric load profile type** | Supermarket | |
| **Technical parameters** | **Value** | **Unit** |
| **SOFC system nominal size** | 3 x 60 | kW |
| **Ramp-up rate** | 1'800 | W/min per each module |
| **Ramp-down rate** | 3'000 | W/min per each module |
| **Modulation range** | 30-100 | % |
| **Power operation points** | 54,72,90,108,126,144,162,180 | kW |

*Table 4: Stand-alone SOFC model input*

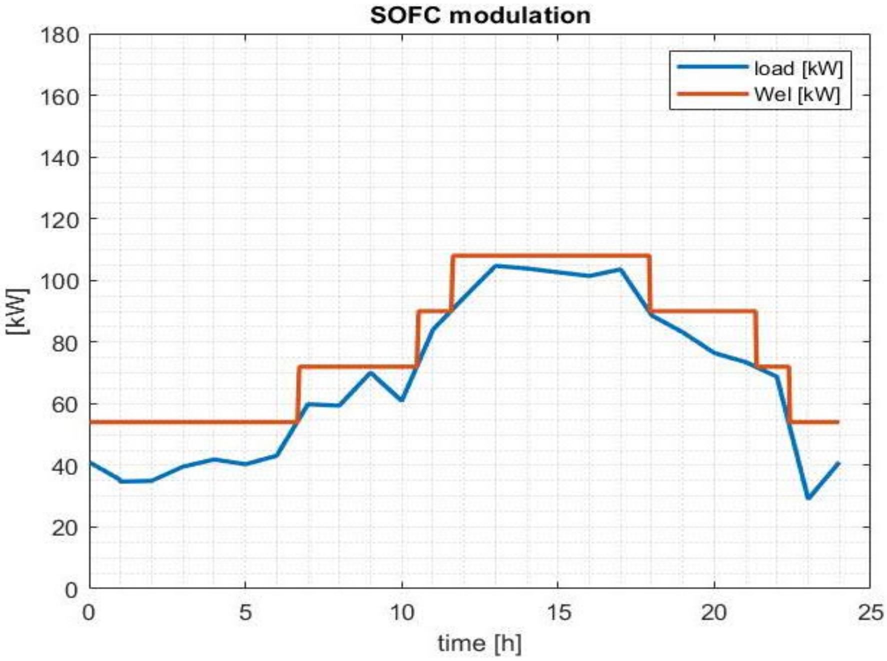



*Figure 12: Typical SOFC modulation and electric load in winter days.*

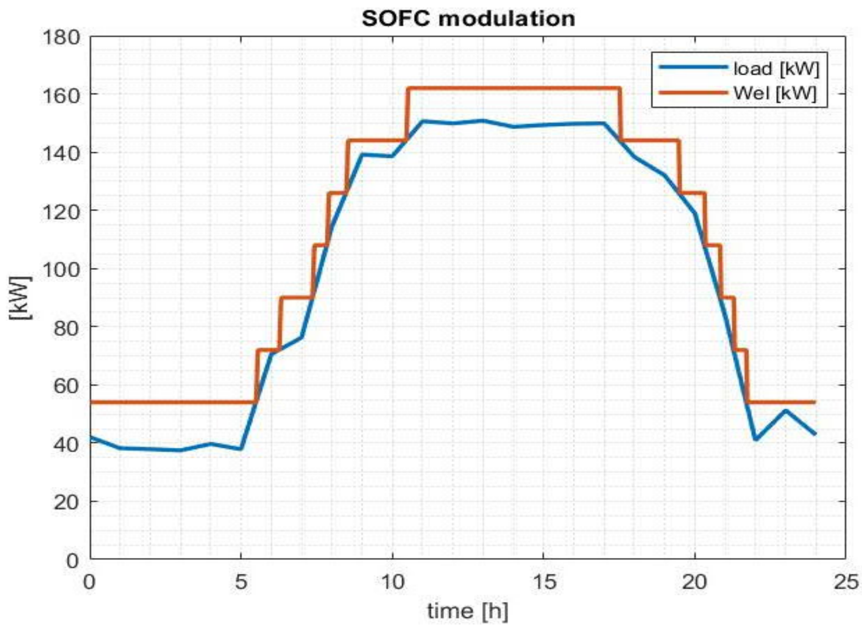



*Figure 13: Typical SOFC modulation and electric load in summer days.*

Figure 12 and Figure 13 show the typical SOFC modulation to satisfy the supermarket electrical load, without grid balancing purpose, during respectively winter and summer.

## 4.2 Hybrid SOFC-PV system

The limitation of the first case study is the need of a huge oversizing of the SOFC system in order to have some 'extra—power' to be given as capacity for grid balancing. When the SOFC is following the base load, the operating point is in fact very low (30%) which is not optimal for the system. We thus decided to evaluate a RES-CHP coupled system in order to reduce the SOFC oversizing. To simulate this second case study, we have designed a hybrid power plant, that couples a nominal 120 kW SOFC system with a peak 150 kW PV plant. For the considered supermarket case, there is no possibility to apply a tracking system, therefore a fixed crystalline silicon PV has been chosen, with optimized slope angle. Table 5 provides the input definition for the model.

| Power plant characteristics | | |
|---|---|---|
| **Electric load profile type** | Supermarket | |
| **SOFC operation type** | Electricity led | |
| **Radiation database** | PVGIS-SARAH | |
| **Location** | Palermo, Sicily, Italy | |
| **PV mounting type** | Fixed | |
| **PV technology** | c-Si | |
| **SOFC** | | |
| **Technical parameters** | **Value** | **Unit** |
| **System nominal size** | 2 x 60 | kW |
| **Ramp-up rate** | 1800 | W/min per each module |
| **Ramp-down rate** | 3000 | W/min per each module |
| **Modulation range** | 30-100 | % |
| **Power operation points** | 48, 72, 90, 108,120 | kW |
| **PV** | | |
| **Technical parameters** | **Value** | **Unit** |
| **Nominal power** | 150 | kWp |
| **System losses** | 14.0 | % |
| **Slope** | 31 | deg |
| **Azimuth** | 0 | deg |

*Table 5: Hybrid SOFC-PV system model input*

Figure 14 and Figure 15 show the typical SOFC modulation to satisfy the supermarket electrical load in a SOFC-PV hybrid power plant, without grid balancing purpose, during respectively winter and summer. With this configuration, it is possible to obtain a power availability exceeding consumption, without oversizing the SOFC system. With respect to the previous case study the nominal size of the SOFC system is reduced of 60 kW. Moreover, in this scenario, since the SOFC system cannot satisfy the peak demand on its own sometimes, in low irradiation period, may arise the necessity of drawing electricity from the grid.

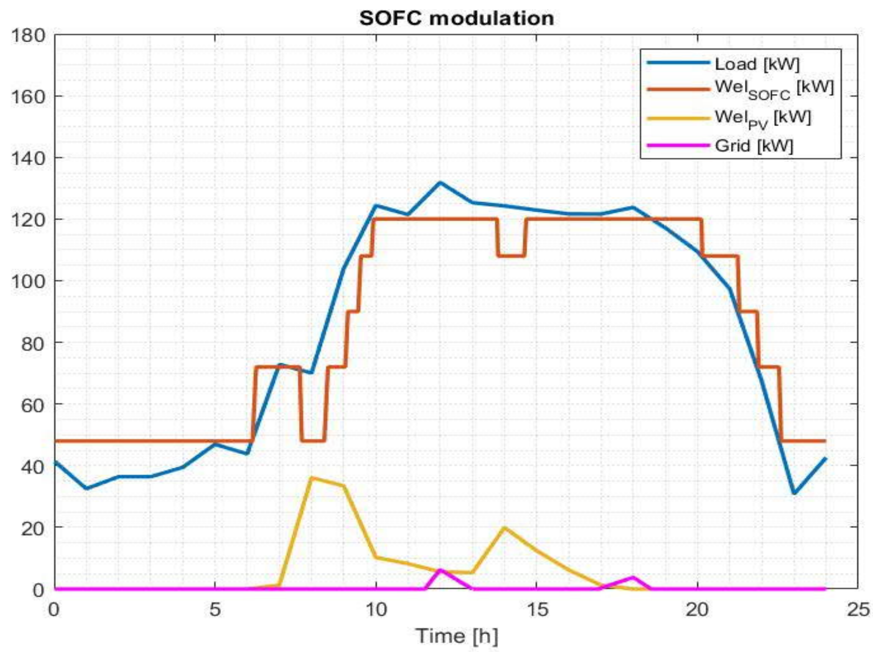



*Figure 14: Typical SOFC modulation, PV production and electric load in winter days.*

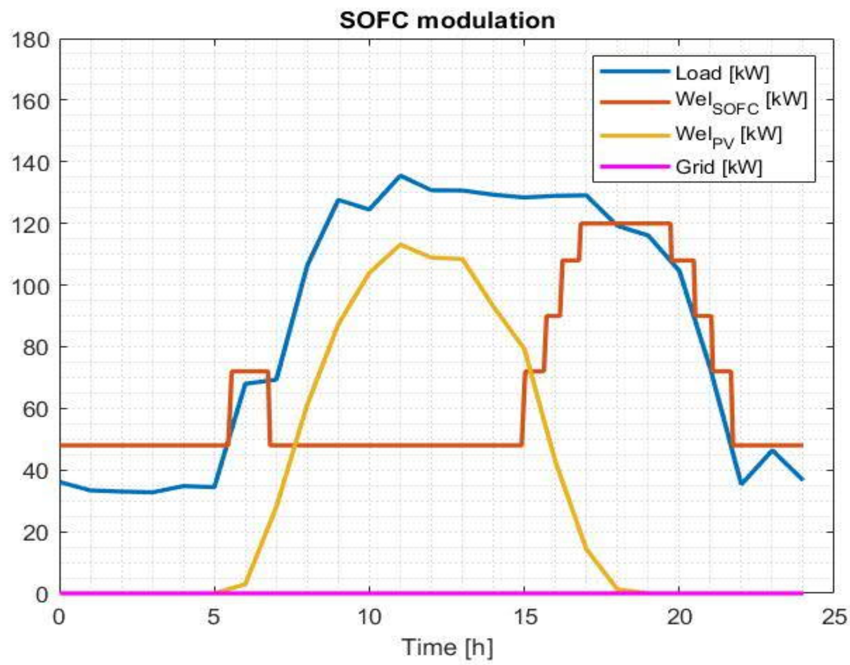



*Figure 15: Typical SOFC modulation, PV production and electric load in summer days.*

# 5. Cases study: results

## 5.1 Stand-alone SOFC

A stand-alone SOFC with over-sizing respect to the base load could successfully provide grid balancing service with suitable ramp-up time. In the presented case, the SOFC power plant, composed of 3 SOFC modules of 60kW each, linked to a supermarket load can increase its power output up to 80 kW within 15 minutes, which is the response time required for UVAM aggregation. The system has the ability to perform the modulation for at least 120 minutes with good reliability and high efficiency. Throughout the year, the SOFCs could provide from 20 kW exceeding power availability in summer, when the electrical demand is high due to the air conditioning, to 80 kW in winter, when the demand is lower. Figure 16 provides an example of correct modulation of 30 kW. The baseline is the expected power schedule of the asset included within the UVAM, that the BSP has to communicate to the TSO on the day-ahead stage. The electrical power is indeed the final power schedule of the SOFC asset, which leads to the verification of the correct execution of the movement requested by TSO in case of grid balancing order.

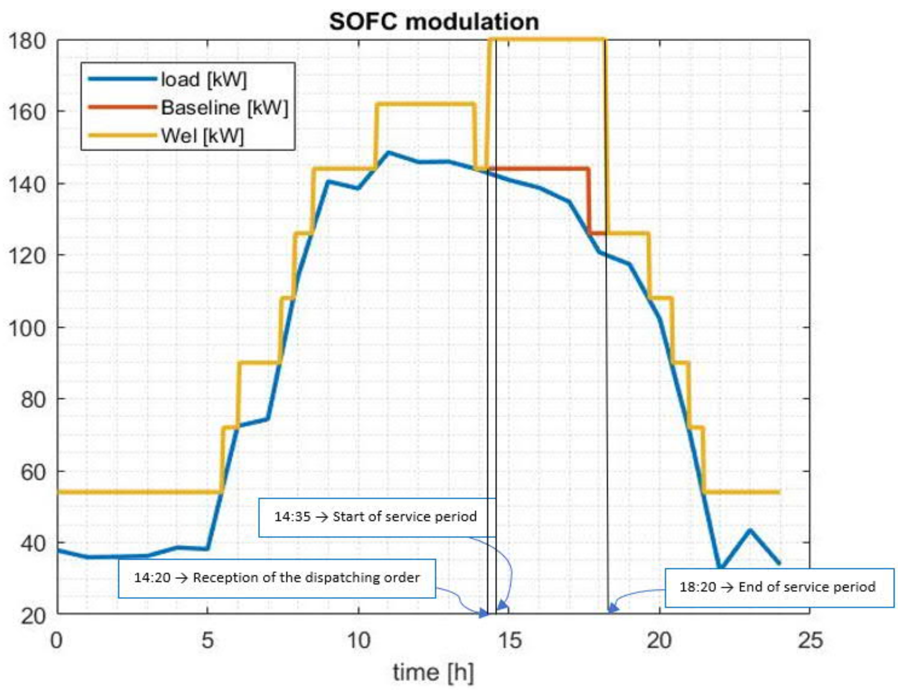



*Figure 16: Grid balancing with stand-alone SOFC*

As we can notice from the previous illustration, in order to take part into the grid balancing and to contribute within a Virtually Aggregated Mixed Unit, a CHP unit completely based on SOFC technology should be oversized, when its priority is the coverage of an electrical load with peaks in the same hours of the grid balancing services. In fact, in the time slot 2-8 p.m. when a dispatchment order may be received according to the UVAM bid obligation, the system is already stressed by a load peak. With this configuration, the SOFCs have also to work frequently at 30% of their nominal power, which leads to an unfeasible business case due to the resulting low production utilization rate. Moreover, the daily ramp-up and ramp-down range is very large, so the SOFC degradation is expected to be remarkable.

## 5.2 Hybrid SOFC-PV system

Due to the high degree of timely coincidence between solar irradiation and the period of high load demand in the supermarket area, PV panel production allows to reduce the residual demand and makes the SOFCs work at lower power output level during the daylight hours. This give to the system the flexibility needed in case of grid balancing dispatchment. In fact, within the UVAM bid obligation time period (from 2 pm to 8 pm), the SOFC modules may benefit from the lower residual demand and maintain the possibility to increase their power to accomplish grid balancing modulation.

In order to make suitable bids on the market, it is possible to use the flexibility of the SOFC to fulfil the balancing order while the PV production can be directly consumed. Therefore, with this configuration is possible to obtain a power availability exceeding consumption especially in the early afternoon, without oversizing the SOFC system.

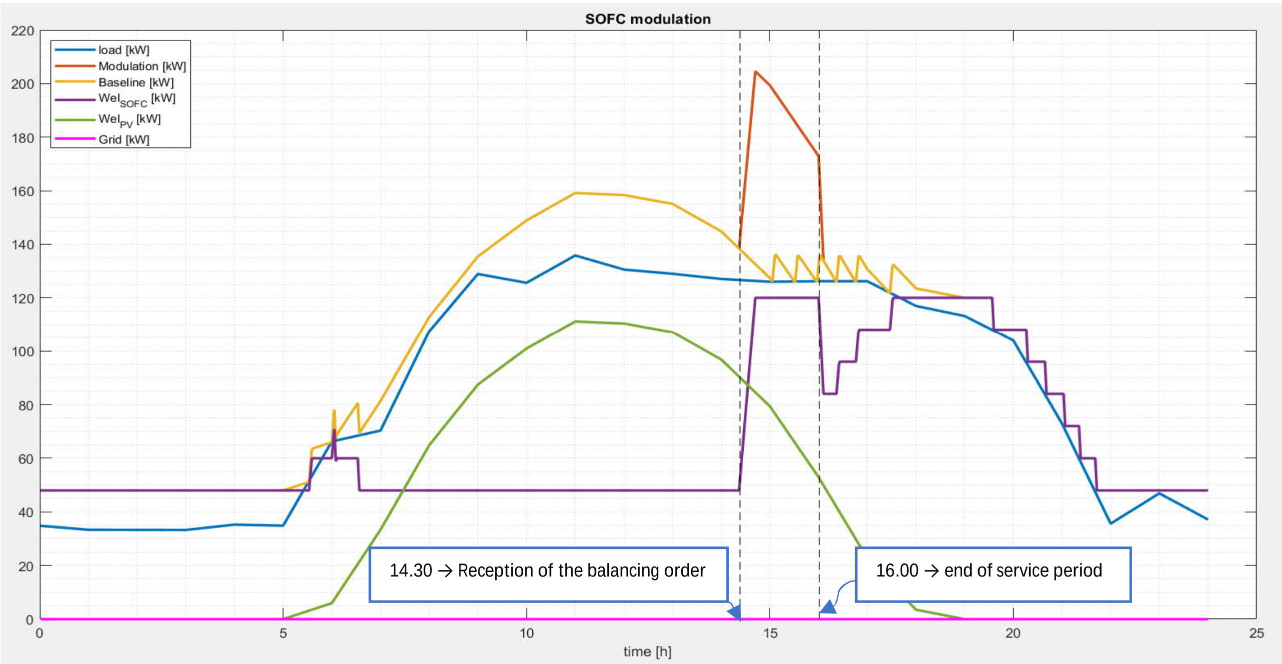



*Figure 17: Grid balancing with hybrid SOFC-PV system*

Figure 17 provides an example of correct modulation to fulfil grid balancing order by TSO. In the case presented, the SOFC modules remain at low power output thanks to the auto consumption of the PV production and they ramp up at their nominal power once the dispatching order is received.
Thanks to this configuration, it is possible to perform a correct minimum 10 kW modulation for 2 hours in case of a dispatching order in the ~70% of the cases. This result is important because it would allow the hybrid SOFC-PV system to virtually meet the UVAM-TSO commitment constraints (see Table 2: UVAM framework). The simulation has been performed with Monte Carlo method, where the start and the end of service period are generated randomly every day across the year from 2 p.m. to 4 p.m. considering a bid of two consecutive hours on the MSD and a minimum service delivering interval of 40 minutes. Figure 18 provides the outcome of the Monte Carlo simulation, where the average sample is presented with its error bar, representing the standard deviation.

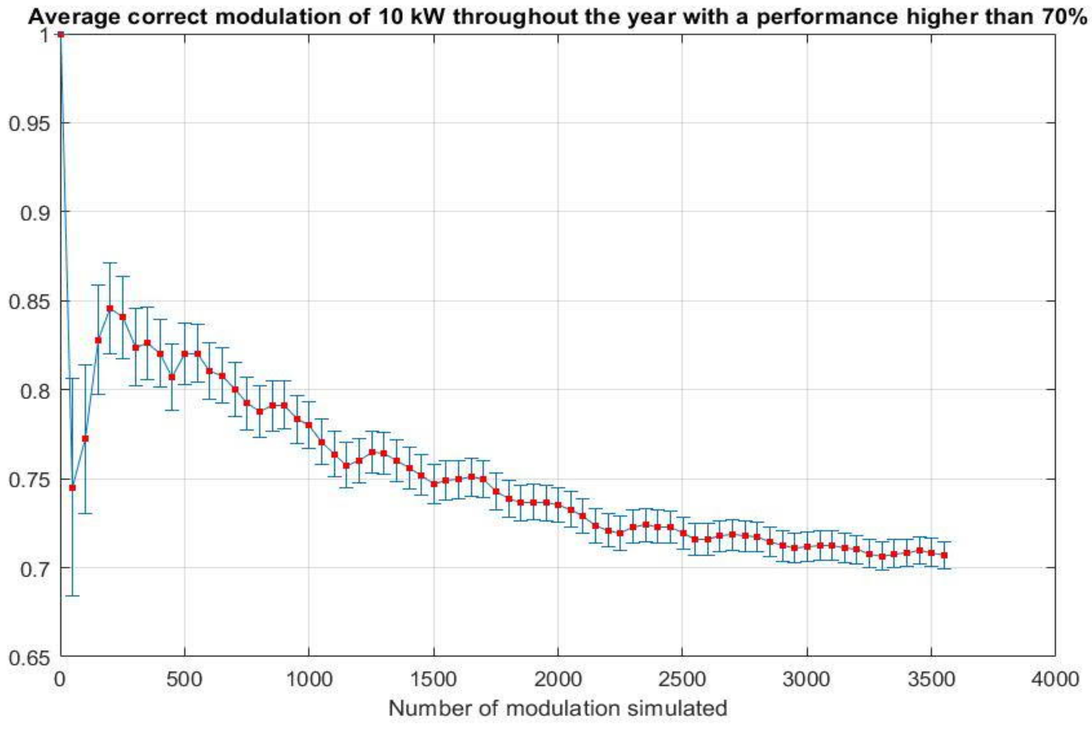



*Figure 18: Average correct modulation of 10 kW throughout the year with a performance higher than 70%*

# 6. Conclusions

The analysis of the possible integration of SOFC in Virtual Power Plants for grid balancing brought to the following conclusions:

- Grid balancing is an interesting opportunity for specific case studies where extra power is available from the CHP unit or load could be easily reduced, upon request. This is unfortunately not the case of the COMSOS approached markets, where self-consumption and load coverage is the priority and the aim of the installed CHP system.
- ComSos SOFC base-size (6, 25, 60 kW for Solidpower, Sunfire and Convion respectively) are quite small. In the analyzed case studies, minimum capacity from the plant was 10 kW. This means that, to reach the 1 MW minimum capacity of the VPP, 100 units like this would be required. The role (and the related incomes) related to these activities are thus reduced, because the extra capacity is usually low and linked with an oversized design.
- Being included in the VPP means to have an external entity (aggregator) which control the SOFC unit through a centralized control system: this could be non-optimal for minimization of degradation within the system.
- ComSos target markets (commercial sites, supermarkets, hotels, hospitals, sport centers, etc.) shows the highest energy requirement during the day, usually in the same time (2-8 pm) where grid balancing is requested: for this reason, with an SOFC-only, extra power can only achieved by a huge oversizing of the unit (currently not the best solution, due to the high CAPEX of the system).
- Most of the ComSos analyzed case studies are showing a constant base load which matches very well with an SOFC working at nominal power all the time. This scenario is not well-suited with modulation and extra-power for grid-balancing.
- Anyway, large-size SOFC hybrid solution (with PV and/or batteries) could be an interesting power generation unit able to perform grid balancing.
- Furthermore, dedicated large size SOFC units – not linked to COMSOS markets – but dedicated to grid balancing (without an end-user load to be satisfied) could be an interesting part of a VPP.

To conclude, small SOFC units alone are not necessarily sufficiently sized to be included in VPP’s to trade their flexibility. However, the bigger picture is that intermittency of renewable production may be best mitigated by involving a large number of small units in providing the necessary flexibility and while VPP's are one way, another way of doing this is by providing dynamic pricing and therefore incentivizing automatic demand response and other demand side arrangements possibly including SOFC-CHP.

As marketplace becomes bi-directional and consumption side becomes more responsive, cost optimization with increased level of quality of service in a given application often involves a hybrid of several technologies such as solar, battery, local CHP as well as thermal storage. If none of the pieces of such a system are sufficiently large to be part of the VPP, the entire building may still be and revenue from participation to a VPP may be part of the overall feasibility.

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