Politecnico di Torino

Department of Energy

Master of Science in Energy and Nuclear Engineering

Master of Science Thesis

The role of SOFC-based systems for prosumer integration in the balancing market: a techno-economic analysis

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Alla mia famiglia,
in particolare, alle mie nonne e
ai miei nonni
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Abstract

In the future, the high penetration of intermittent and unpredictable resources would introduce uncertainties until close to real-time, triggering the requirement for additional energy system reserve to be held. In this scenario, the development of efficient Virtual Power Plant (VPP) portfolios able to combine high responsiveness products and consumers involvement will be an important tool to allow Balance Responsible Parties (BRPs) to be balanced.

This master thesis aims to investigate the future role of Solid Oxide Fuel Cells (SOFCs) from which the transmission system operator (TSO) could, if necessary, extract flexibility by exploiting their ability to operate very efficiently at partial loads. In this way, the TSO can rely on a generator able to have fast ramp-up and ramp-down rates and efficiently meet short peaks of high production. At the same time, the asset owner can access a fixed and variable remuneration by adjusting its generation according to price forecast.

A techno-economic analysis has been performed for three different SOFC-based systems which are integrated within a supermarket with the aim of performing also grid balancing activities in the Italian Virtually Aggregated Mix Units (UVAM) pilot project framework. The results show that a hybrid SOFC-PV-BAT system could be the best solution in terms of reliability, efficiency and cost-effectiveness. It is able to unite financial profitability with UVAM bidding obligation constraints without oversizing the system for the sole purpose of performing grid balancing. The simulations have indeed proved that the system could allow in case balancing order a 30 kW modulation capacity on average, with an annual primary energy saving of 347 MWh and a payback time of 10 years.

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Symbol	Unit	Description
W_{inst}	kW	Installed capacity
W_{load}	kW	Electric power demand
Gas_{load}	kW	Gas demand
E_{el}	kWh	Electricity produced
E_{th}	kWh	Heat produced
η_{sys}	%	System efficiency
η_{el}	%	Electric efficiency
η_{th}	%	Thermal efficiency
$\eta_{el,avg}$	%	Yearly average efficiency
ε_{deg}	kW/kh	Degradation rate
η_{nom}	%	Nominal module efficiency
W_{el}	kW	Produced electric power
$\dot{Q}_{th}$	kW	Produced thermal power
$\dot{V}_{gas}$	Sm^3/h	Gas volumetric flow rate
Gas_{input}	Sm^3/y	Yearly gas input
LHV_{gas}	kWh/Sm^3	Gas lower heating value
$\dot{m}_{NOx}$	kg/h	NOx mass flow rate
$\dot{m}_{CO2}$	kg/h	CO_2 mass flow rate
ρ_{CO2}	kg/Sm^3	CO_2 density
k_{mod}	€	Cost of the modules
k_{rep}	€	Module replacement cost
$p_{op\&m}$	€	Operation and maintenance cost
k_{BOP}	€	Balance of plant cost
p_{BOP}	€/kW	Balance of plant price
$k_{C\&I}$	€	Commission & installation cost
$p_{C\&I}$	€/kW	Commission & installation price
Sub	€	Subsidies
R_{el}	€	Electricity revenues
R_{gas}	€	Gas revenues
p_{el}	€/kW	Electricity price
p_{gas}	€/kW	Gas price
k_{el}	€	Electricity cost
k_{gas}	€	Gas cost
$CAPEX$	€	Capital expenditure
$OPEX$	€	Operating expense
CF	€	Annual Cash Flow
DCF	€	Discounted Cash Flow
$RPBT$	y	Relative Payback Time
i	%	Inflation rate
d	%	Discount factor

List of Acronyms

BESS:	Battery Energy Storage System
BM:	Balancing Market
BRP:	Balance Responsible Party
BSP:	Balance Service Provider
CHP:	Combined Heat and Power
DAM:	Day-Ahead Market
DER:	Distributed Energy Resource
DR:	Demand Response
DSO:	Distribution System Operator
FC:	Fuel Cell
FCR:	Frequency Containment Reserve
FRR:	Frequency Restoration Reserve
ICT:	Information and Communication Technology
IDM:	Intra-Day Market
MCP:	Market-Clearing Price
MSD:	Mercato per il Servizio di Dispacciamento
PCR:	Primary Control Reserve
PV:	Solar Photovoltaics
SCR:	Secondary Control Reserve
SOC:	State of Charge
SOFC:	Solid Oxide Fuel Cell
SSP:	Scambio sul Posto
TCR:	Tertiary Control Reserve
TSO:	Transmission System Operator
UVAM:	Unità Virtuali Abilitate Miste
VOC:	Volatile Organic Compound
VPP:	Virtual Power Plants
RES:	Renewable Energy Sources

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 shown in 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 digitalisation [1].

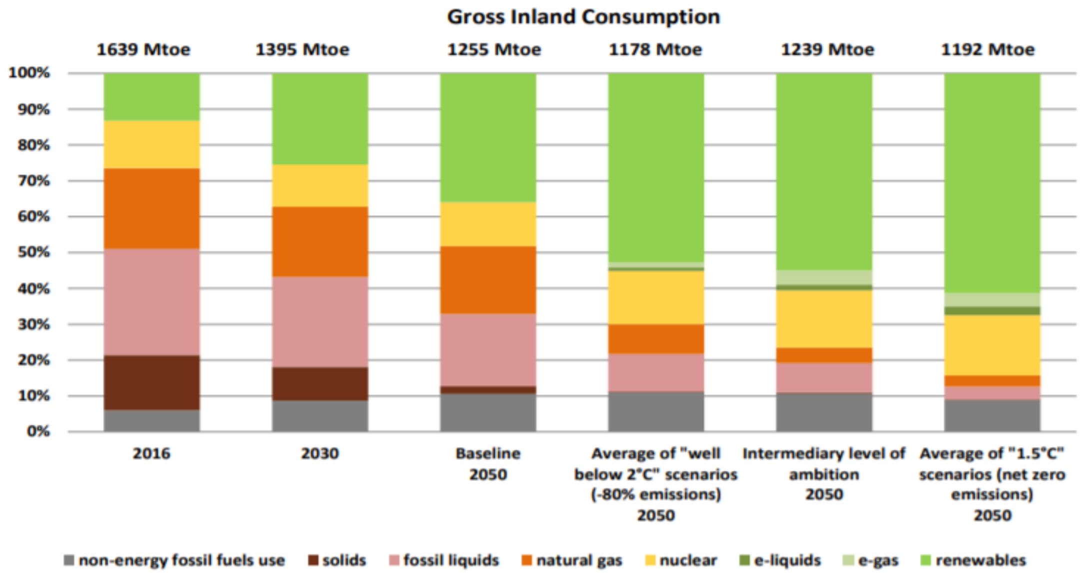


Figure 1: Gross European Inland Consumption scenarios [1]

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 the 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. At the same time, a small-scale non-programmable RES is authorised to inject power to the grid without a specific schedule. Over time, we will see essential attention on flexible sources and technologies, that shall provide the necessary 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 a 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 The ComSos Project

This work is part of ComSos - Commercial-scale SOFC systems - project, which is an EU funded project aimed to validate and demonstrate fuel cell based combined heat and power solutions in the mid-sized power range of 10-60 kW, referred to as Mini FC-CHP. The purpose is to strengthen the European SOFC industry world-leading position for SOFC products and to proof the advantages of introducing this technology to supply buildings in the commercial sector, like hospitals, supermarkets, hotels, sports centres, with heat and power. The technology and product concepts have been developed in Europe under supporting European frameworks such as the FCH-JU. The core of the consortium consists of three SOFC system manufacturers aligned with individual strategies along the value chain:[5]

- Convion Oy (Finland)
- SOLIDpower SpA (Italy)
- Sunfire GmbH (Germany)

The Politecnico di Torino has been tasked with leading "Exploitation and dissemination". "The main goal of this task is to analyse and quantify the mid and long-term market potential in different countries (EU and non-EU). To do so, a detailed techno-economic tool needs to be developed in order to perform business analysis and find which locations are the most preferred and what are the strengths and weaknesses of the SOFC-CHP application. At the end of the activity (techno-economic model of the technology, market analysis, business analysis) the outcome will be the development of a pathway for the commercialisation of the FC-based CHP solutions in the different market segments of the commercial environment."[5]

The following study 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 a focus on Italy and Germany, followed by a techno-economic analysis of three possible optimised case studies where a SOFC is integrated within a supermarket (ComSos case study) with the aim of performing also grid balancing activities. To perform this analysis, we start from data provided by Convion, Sunfire and SOLIDpower, regarding their three different electrical capacity technologies: Convion 60kW module, Sunfire 20kW module and SOLIDpower 12kW module.

1.4 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 (SOFCs), have proven to be highly efficient cogeneration systems (Combined Heat and Power, CHP) with an overall system efficiency up to 85-90%. They can combine the benefit in the 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 a considerable 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 the availability factor negatively and generates degradations phenomena within the cells (due to thermal cycles).

Furthermore, this technology basically eliminates all local pollutants (NO_x, SO_x, 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 constantly 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 5, 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 6, 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 [6], [7].
- *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 [6], [8].
- *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 certain ramp rates and for a minimum specified 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 recognised for the provision of the offered power

in a corresponding time interval, whereas the second compensates for the energy actually delivered [6].

- *Distribution system operators (DSOs)* are responsible for operating, ensuring the maintenance of and developing the distribution system in each area, in order to provide 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 [8].

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 [9].

TSOs must determine, ex-ante, and active, in real-time, the amount of capacity which needs to be earmarked as a 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, as we can see from Figure 2.

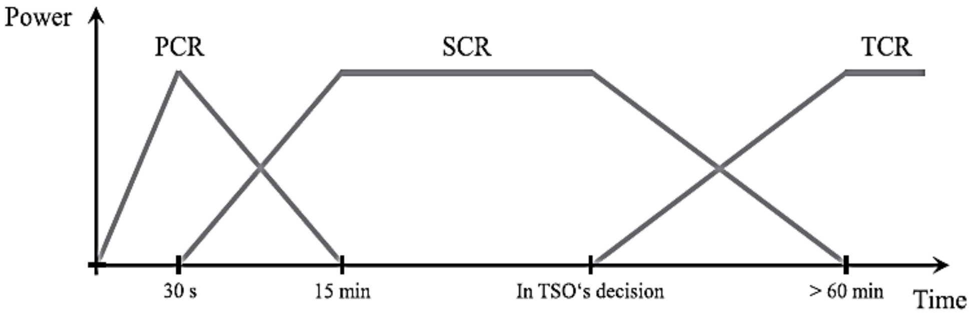


Figure 2: Starting and deployment times of primary (PCR), secondary (SCR) and tertiary control reserve (TCR) [10]

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 the 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 characterised by the most responsiveness technologies, that are able to reach the full activation within max 30 seconds [2], [6], [10].

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 [6], [10].

Finally, the *tertiary control reserve (TCR)*, which is also called manual frequency restoration reserve (mFRR), is the less responsiveness reserve characterised 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 standby generators and DER units with an end-user load to be satisfied [6], [10].

2.3 Short term market

The electricity market arrangement is generally based on three different short-term markets: 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) integrates new information that were not available at the day-ahead stage and adjusts 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 is additional remuneration of flexible capacity from the DAM to the IDM and BM, as we can see from Figure 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].

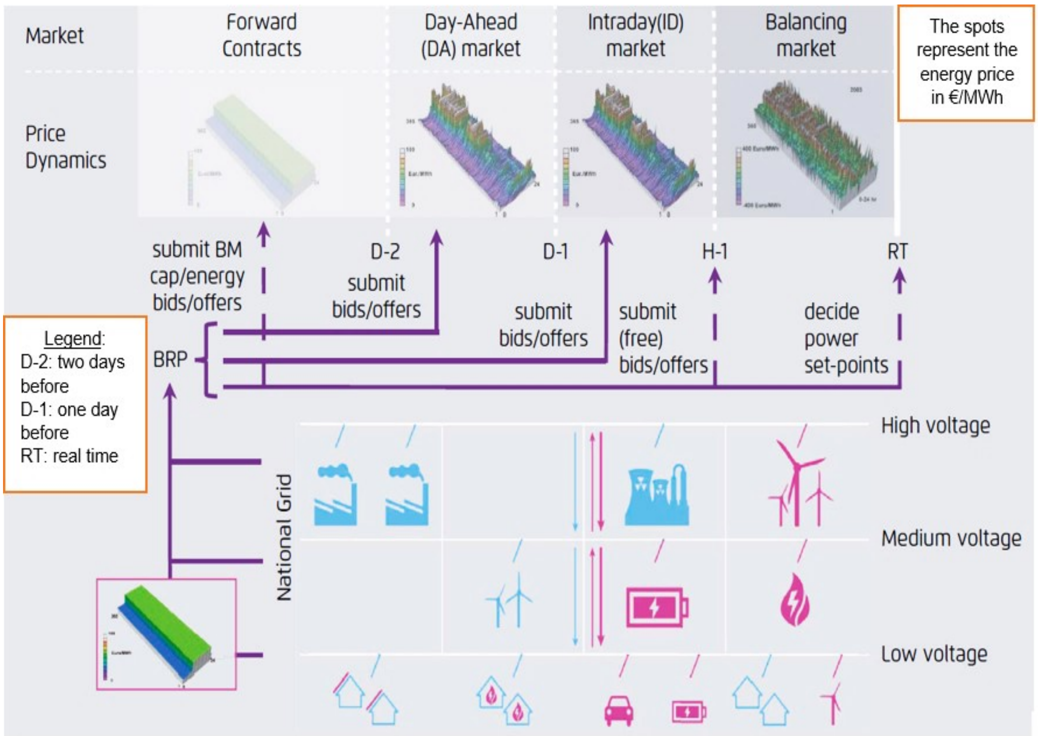


Figure 3: Typical organisation of electricity markets in Europe. Different generators and loads connected to the national grid and associated with a BRP are shown, ordered by voltage level. At the top, the price volatility evolution is presented moving from the DAM to RT [3]

The 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 a 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 the 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[11].

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 [12]. In this framework, the auction characteristics play an important role in the oncoming transition. For example, low frequency and following extended lead time (the period between the moment the auction is performed until the start of delivery of the product) can penalise 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 an extended period of time.

The bid features also affect the possibility of market accessibility. Lowering the minimum bid size can facilitate 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 into 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, Table 1 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.

	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; • aFRR: reaction in few secs, full activation within 5 mins; • 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; • aFRR: reaction in maximum 30 secs; full activation within 5 mins; • 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 an 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 pm.
aFRR		
Minimum bid size	1 MW	5 MW (1 MW increments)
Frequency of bidding	Daily	Daily
mFRR		
Minimum bid size	1 MW (200 kW increments)	5 MW (1 MW increments)
Frequency of bidding	Daily	Daily
Remuneration		
Pricing rule	• FCR: capacity payment; • aFRR and mFRR: PaB for capacity and energy, including start-up fee (€) for thermal generators	• FCR: uniform price method; • 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 [2], [13], [14]

In Italy, FCR products are currently not open to the market. The relevant generation units must provide it. In particular, if the asset is installed in the mainland, it must provide ±1.5% of its effective power to FCR. Plants in Sicily and Sardinia must provide ±10% of their effective power [13]. 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, generally characterised 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 through aggregation. Since 30th January 2020, the BSP of exclusively charging infrastructure for electric vehicles can operate in the market with a reduced minimum bid size of 200 kW. By the end of the year 2021, this licencing should be extended to all the other aggregators in order to preserve the principle of technology neutrality. This minimum bid size, initially dictated by system manageability needs, is indeed intended to be reduced thanks to the progressive evolution of the TSO's logic of dispatching [14].

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 a 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 [13].

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 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 permitted, 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 the grid and system security. In the 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).

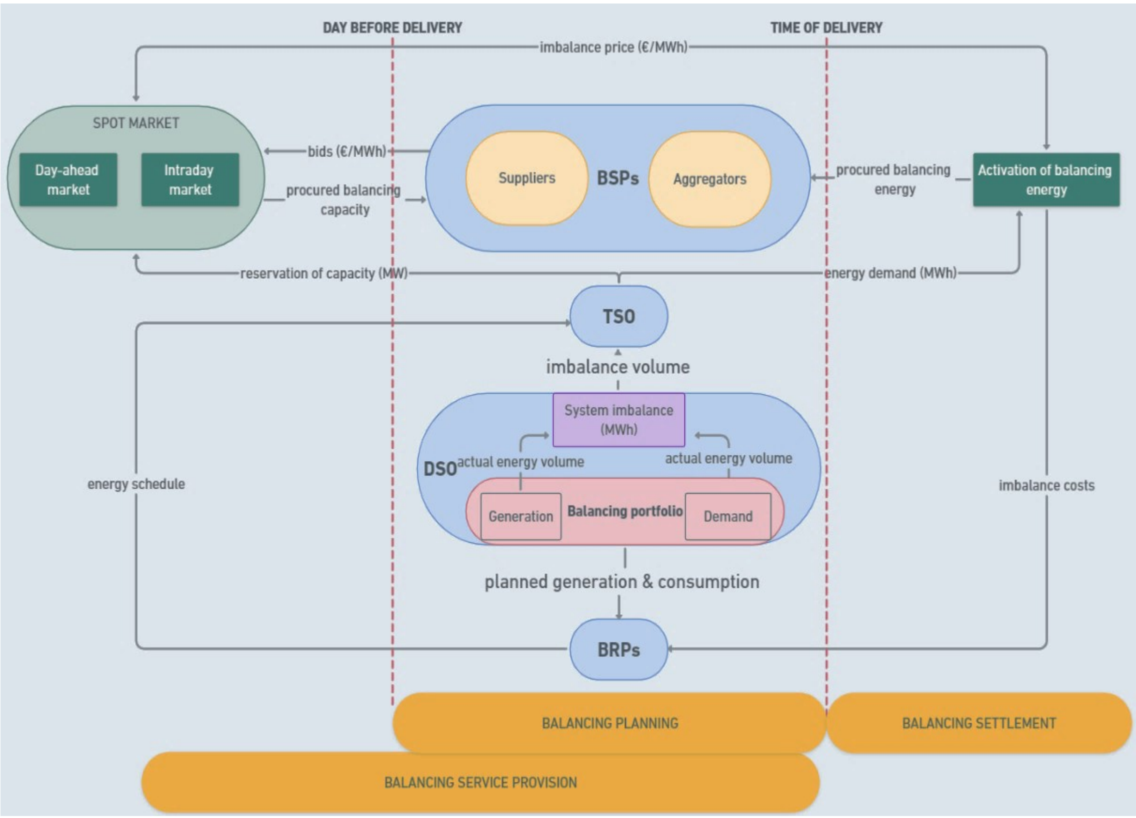


Figure 4: Basic structure of the balancing market

3 Virtual Power Plant

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 small-scale distributed generators in balancing issues, voltage regulation and congestion resolution, avoiding strict requirements at every single point of connection [15].

A virtual power plant, thanks to the flexibility and heterogeneity of its portfolio, can realise 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 utilisation of temporary price fluctuations in the spot market and the demand-oriented provision of control power offer high additional revenue potential for flexible and controllable technologies such as battery storage and CHP units [16].

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. Figure 5 illustrates the constant need for flexibility throughout 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.

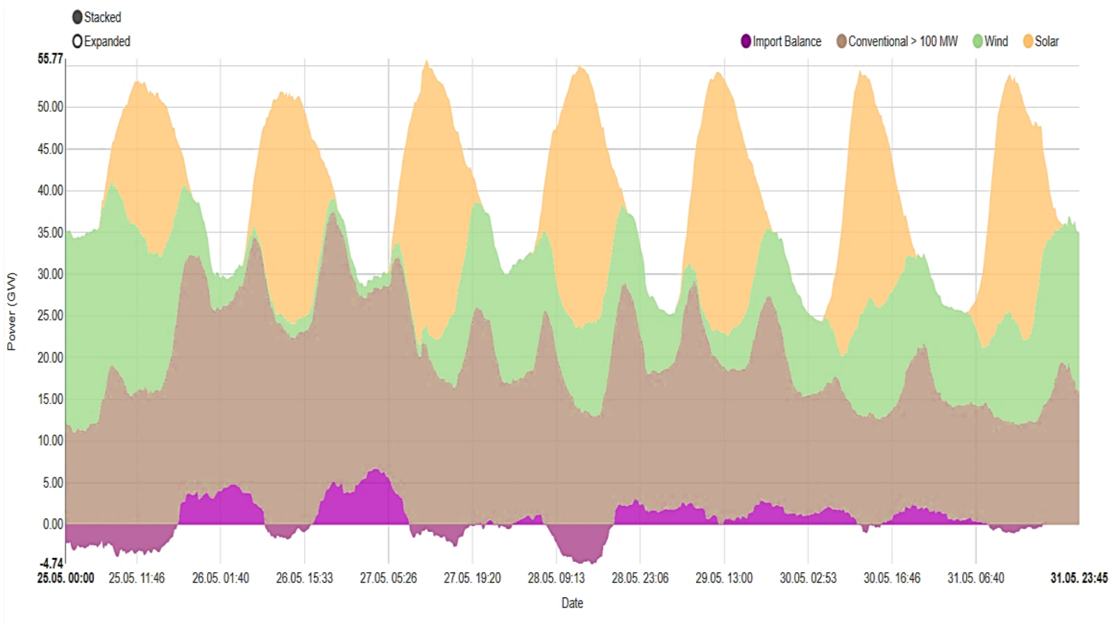


Figure 5: Electricity production in Germany in a week in late spring 2020 [17]

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 [18].

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 optimise 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): [19]

- FCR: 57 MW (mostly flexible biogas CHPs, electrolysis, and batteries);
- aFRR: 922 MW;
- 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 considerably through the market-oriented integration of renewable energies and efficient technologies [20].

The asset owners have the possibility to adjust their schedules according to price forecast and trade the optimised 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 optimised schedules in order to stabilise 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 a flexible arrangement called demand response, can orient their original schedule to provide grid stabilisation 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 bids to grid frequency control auctions. Then, during a grid balancing call, the control system sends out 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 a 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 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 [13]. Since Delibera 300/2017/R/eel [21], the participation in the MSD (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.

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).

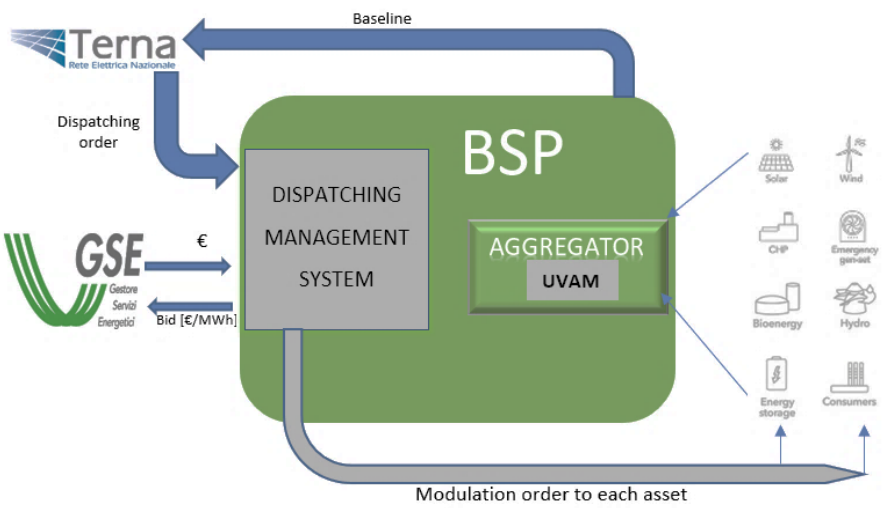


Figure 6: BSP process layout

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) through 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 a 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 maximisation of the revenues.

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

UVAM	
Type of assets included	Generation, withdrawal and accumulation units
Minimum modulation capacity of the aggregate	1 MW (200 kW increments)
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 • Manual frequency restoration reserve (Tertiary control) • Grid balancing services both in DAM and IDM
Remuneration	• Fixed availability price allocated through downward auctions with a maximum bid of 30000 €/MW/year • 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 the benefit of the maximum remuneration (linear decrease of the fixed remuneration up to 50% in case of two hours bidding) • 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) • The UVAM loses the right of remuneration after the fifth modulation with a performance lower than 70%

Table 2: UVAM framework [22], [23]

Despite being calling pilot projects, they are completely integrated into the markets, with a participation of approximately 1000 MW today. The results of the annual term supply auctions for 2020 (Table 3) considering the two designed allocation area, represented in Figure 7, have shown 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

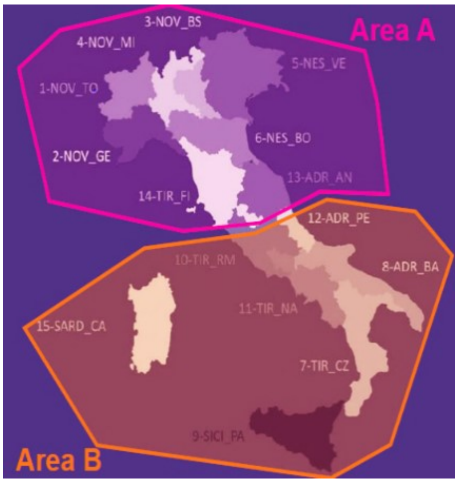


Figure 7: Allocation area [24]

Hence, the UVAM pilot project allows exploiting the power of the generator unit that until now would not be authorised to participate in MSD. Figure 8 provides a scheme for a better understanding of this new opportunity.

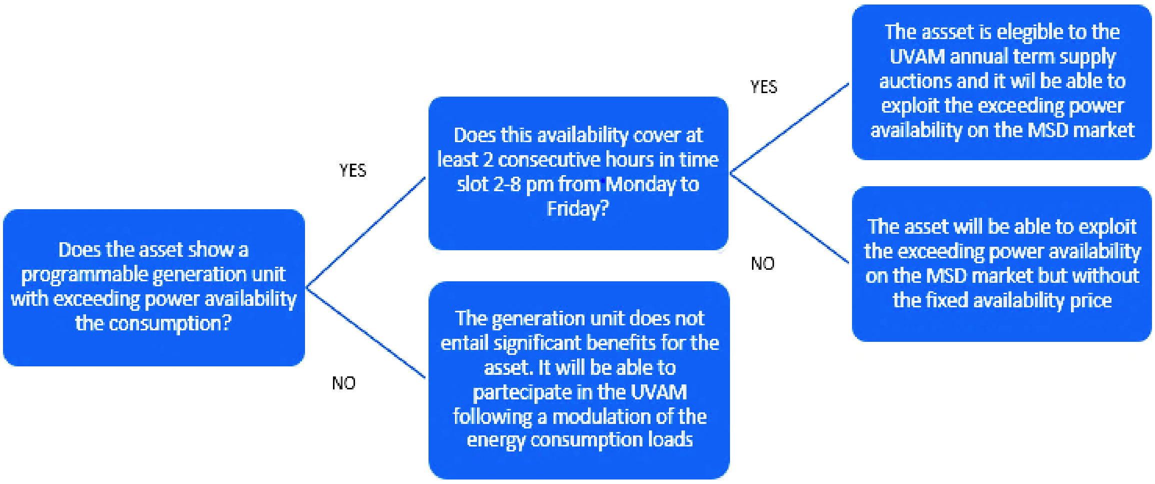


Figure 8: UVAM opportunity for generation unit

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 Methodology

The overall methodology of the dissertation is reported and described in this Chapter: the hypothesis, the procedures and the input data; which underlie the mathematical model built to evaluate the techno-economic impact due to the installation of a SOFC system to feed a supermarket building, in an investment period of 21 years. All the scenario presented are evaluated for a full year of operation, and the sub-component models are simulated in MATLAB® with a step-widths of one minute. The case studies analysed will be further specifically discussed in Chapter 5, in all their details and peculiarities, based on the hypothesis and the system control strategy presented in this Chapter.

4.1 Load profiles

Starting from the data of ComSos Deliverable 5.3 -Market analysis of CHP solutions applied in commercial applications-, we have analysed the energy consumption of different shops to replicate in a representative way the behaviour of the supermarket. The model is based on the daily and hourly load profile in order to characterise the operation of the SOFC system more in-depth and to make consideration to the actual grid balancing potential. The hourly load profiles database used for this model is the one available from the US Department of Energy, which is including a high number of commercial buildings profiles, among which many supermarkets. The database collects on an hourly basis the electric consumption and the heat consumption of supermarket, and their share among the different equipment and sections. The data collected are from 2004, and they refer to the same type of supermarket [25]. To represent the Italian case, the US scenario profiles have been modified to make up for the lack of data, considering the scaling coefficient between the two reality [26], [27].

We have considered a small supermarket with an electrical energy intensity of around 800,000 kWh per year, which generally is associated with a 2000 m^2 sales area. To perform our simulations, we have decided to locate the resource in the south of Italy, precisely in the city of Palermo (Sicily), because of the higher solar irradiance and also the higher average fixed availability remuneration (see Figure 7 and Table 3).

Figure 9 shows the yearly electric load profile across the year, while Figure 10 points out the difference between the winter and the summer daily electric load profile.

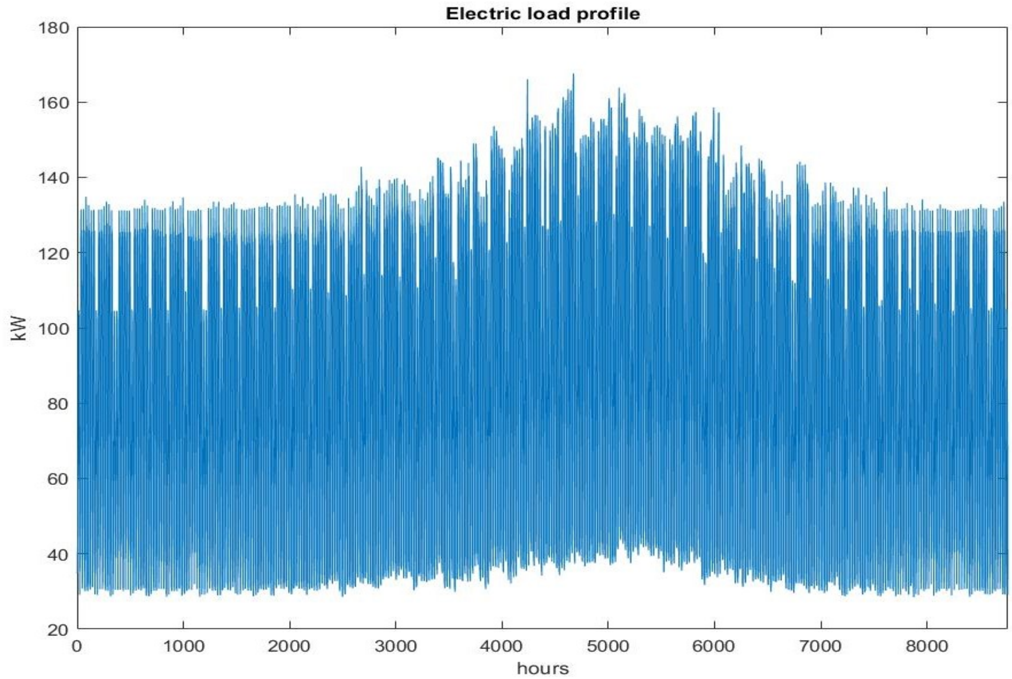


Figure 9: Supermarket electric load profile

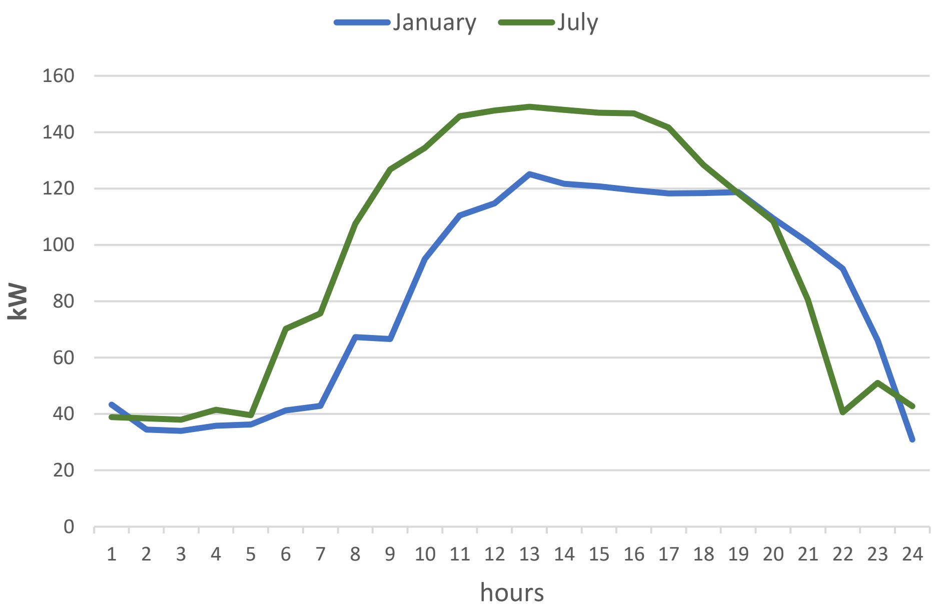


Figure 10: Daily average electric load profile in winter and summer month

The base load of the supermarket electric profile is around 40 kW throughout the year, and the peak load is associated with the middle hours of the day with peaks that can reach 160 kW in summer due to the high share of air conditioning. During winter, the electric load profile is slightly more consistent and power leap during the day is smoother.

We have also analysed the heat load in order to understand the potential of the heat produced as a coproduct of the SOFC cogeneration system. As we can see from Figure 11, the heat load is much more variable seasonally than the electric one. So, it may often happen that, for an extended period, a large part of the heat produced could be wasted, even if the SOFC is a cogeneration system highly biased towards the electric generation.

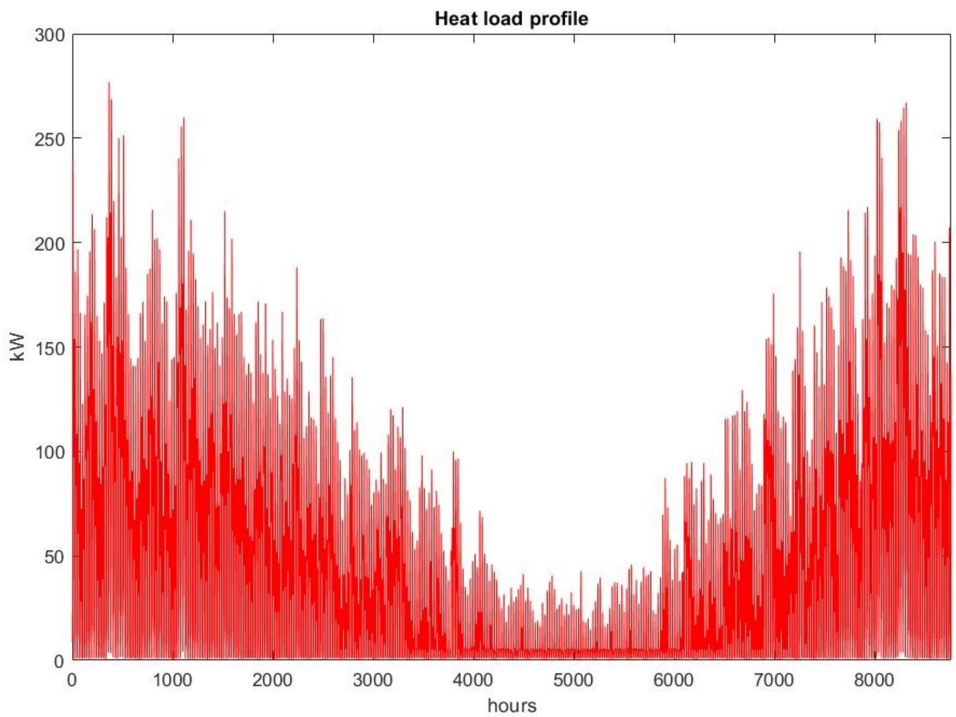


Figure 11: Supermarket heat load profile

4.2 Technical and economic performances

4.2.1 SOFC

The SOFC modules show technical performances slightly dependent on the manufacturing company and on the time scenario considered. In order to obtain a company independent analysis projected in a not-too distance future, where the SOFC systems have reached technological maturity, we decide to perform the study on the target scenario parameters of the average performances of the three ComSos partner manufactures (Convion Oy, SOLIDpower, Sunfire GmbH).

SOFC features, used in the model constructions, are presented below in Table 4.

Technical and Economic Information	Unit	Value
Electrical efficiency @ nominal size	%	60
Thermal efficiency @ nominal size	%	27
Modulation range	(min-max) %	30-100
Average system availability	%	100
System availability in hours	h/y	8760
Technical lifetime of the module	y	7
Start-up time	h	12
Shut-down time	h	12
Degradation rate	% / kh	0.3-0.5
NOx emission	mg/m^3	44
Manufacturing cost module target	€/kWe	2000
Manufacturing cost BoP target	€/kWe	1500
Operational cost	€/y	1700
Commissioning and installation cost	€/kW	100
	€/unit	6000

Table 4: SOFC technical and economic information [28]

Each fuel cell manufacture company has an average system availability around 97-99% when the system is considered fully running. In this simulation, the unavailability time is set to zero, as a hypothesis, in order to evaluate the grid balancing potential across all days of the year. Since the degradation rate is positively related to the modulation and thermal cycle, we have considered value in the range of 0.3 to 0.5, according to the case study features. As we can see from Figure 12, SOFC operation has its maximum efficiency when the system works at partial load, around 70% of the nominal power. The efficiency degradation becomes more marked if the load falls below 50% of the nominal power of the SOFC system.

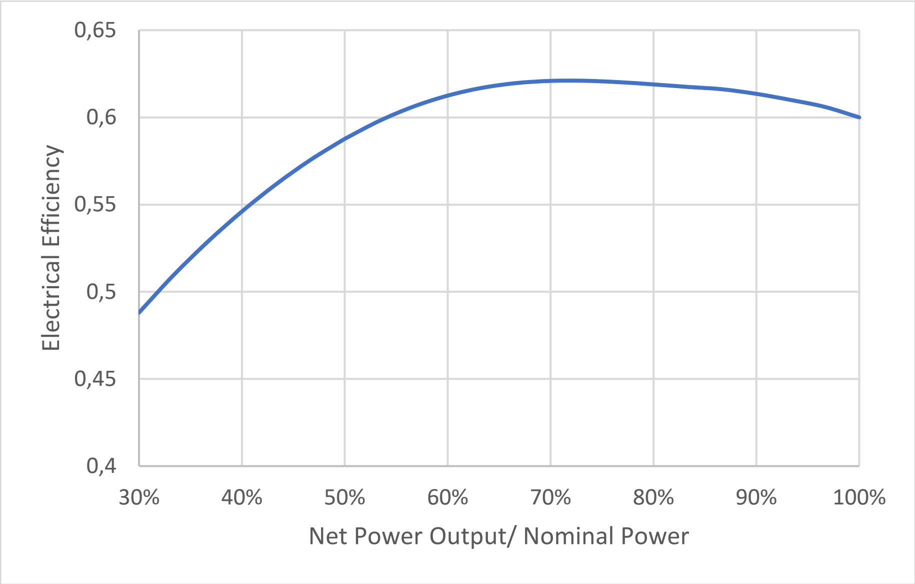


Figure 12: Electrical efficiency curve

To evaluate the degradation over the SOFC lifetime and the consequent variation of the electrical and thermal efficiency, a constant system efficiency, given by the sum of the electric and thermal efficiency, has been assumed [26], [27].

$$\eta_{sys} = \eta_{el} + \eta_{th} \qquad \textit{Eq. 1}$$

η_{el} decreases as a function of time, according to the degradation rate ε_{deg}, a parameter that expresses the reduction percentage in the electrical efficiency every 1000 working hours. At the end of each year, it is possible to evaluate the yearly nominal electrical efficiency reduction as in Eq. 2:

$$\Delta\eta_{el,nom} = \varepsilon_{deg} \cdot h \qquad \textit{Eq. 2}$$

Since it was assumed that the total efficiency remains constant all over the duration of the project, the thermal efficiency also undergoes a change while working hours increase, in the same rate of electrical efficiency but in the opposite way. Hence, η_{th}:

$$\eta_{th} = \eta_{sys} - \eta_{el} \qquad \textit{Eq. 3}$$

The electricity produced by the SOFC module is directly affected by the efficiency degradation, it is possible to rearrange the electrical efficiency curve implementing the following proportion:

$$\frac{W_{el,i}}{\eta_{el,i}} = \frac{W_{el,nom}}{\eta_{el,nom}} \qquad \textit{Eq. 4}$$

The thermal power obtained from the cogeneration system is evaluated, as illustrated in Eq. 5.

$$\dot{Q}_{th,i} = W_{el,i} * \frac{\eta_{th}}{\eta_{el,i}} \qquad \textit{Eq. 5}$$

Therefore, it is possible to evaluate the heat and the electricity produced yearly following Eq. 6 and Eq. 7 since $W_{el,i}$ and $\dot{Q}_{th,i}$ are evaluated on an hourly basis.

$$E_{th} = \sum_{i=1}^{8760} \dot{Q}_{th,i} \cdot 1h \qquad \textit{Eq. 6}$$

$$E_{el} = \sum_{i=1}^{8760} W_{el,i} \cdot 1h \qquad \textit{Eq. 7}$$

Since the evolution of hourly consumption of the whole years of the lifetime project is not available, it is assumed that the electricity and gas demands remain constant. The related technical parameters are calculated for each year only considering the annual data and their relationship with the previous year.

To simplify the calculations in the evaluation of the evolution of the SOFC performance, the average electric and thermal efficiency are used in calculating the power produced by the fuel cell. Starting from $\Delta\eta_{el,nom}$, it is possible to calculate the $\eta_{el,avg}$ as the average of the initial and the final efficiency of the project's year *j*, where the final value of first-year corresponds to the initial one of the second year and so on (Eq. 8).

$$\eta_{el,ave,j} = \frac{\eta_{el,ave,j-1} + \eta_{el,ave,j-1} - \Delta\eta_{el,nom}}{2} \qquad \textit{Eq. 8}$$

Once $\eta_{el,avg,j}$ for the corresponding year is known, it should be possible to evaluate the equivalent $\eta_{th,avg,j}$, $E_{th,j}$ and $E_{el,j}$ according to Eq. 9, Eq. 10, Eq. 11.

$$\eta_{th,avg,j} = \eta_{sys} - \eta_{el,avg,j} \qquad \textit{Eq. 9}$$

$$E_{th,j} = \frac{E_{th,j-1}}{\eta_{th,avg,j-1}} \cdot \eta_{th,avg,j} \qquad \textit{Eq. 10}$$

$$E_{el,j} = \frac{E_{el,j-1}}{\eta_{el,avg,j-1}} \cdot \eta_{el,avg,j} \qquad \textit{Eq. 11}$$

Since the stack has a lifetime lower than the total duration of the study, which corresponds to 21 year plant lifetime, the economic simulation is built in order to calculate the year in which the stacks must be substituted according to the technical lifetime of the modules. The substitution, for easiness, coincides with the end of the calendar year. All SOFC parameters are set to the initial values, without degradation penalisation. In this way, η_{el} and η_{th}, consequently, thermal and electrical power produced, show a cyclical trend of 7 years.

The inlet gas flow of the SOFC system is assumed as pure methane in order to simplify the number of electrochemical reactions involved. The methane flow rate is calculated as the ratio between the produced electric power and the product of the current electric efficiency and the lower heating value of methane (LHV_{gas}).

$$\dot{V}_{gas} = \frac{W_{el}}{\eta_{el} * LHV_{gas}} \quad \text{Eq. 12}$$

LHV_{gas} is considered constant at 8.79 kWh/Nm^3, in doing so $\dot{V}_{gas}$ depends only on the ratio between electric power and efficiency and, since the η_{el} and $\boldsymbol{W_{el}}$ are directly proportional in their evolution through the plant lifetime, it is constant for all the years of the simulation. Yearly gas flow rate is therefore calculated by summing the hourly volumetric flow rate throughout the whole year, as shown in Eq. 13.

$$Gas_{input} = \sum_{i=1}^{8760} \dot{V}_{gas} \quad \text{Eq. 13}$$

Finally, it is possible to calculate the pollutant emissions in terms of CO_2 and NO_x. In particular, the NO_x flow rate can be calculated directly from the parameter provided by the producer (Table 4), expressed in milligrams of NOx per kWh of produced electricity, as displayed in Eq. 14.

$$\dot{m}_{NOx} = NOx_{emissions} * W_{el} \quad \text{Eq. 14}$$

The CO_2 flow rate is calculated starting from the CO_2 produced by the reactions that take place within the fuel cell. Initially, CH_4 is subject to the steam reforming (Eq. 15) with CO and H_2 formation. Subsequently, the carbon monoxide reacts with H_2O molecule in a water gas shift reaction, by forming CO_2 (Eq. 16).

$$CH_4 + H_2O \rightarrow 3H_2 + CO \quad \text{Eq. 15}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{Eq. 16}$$

The previous reactions show a molar ratio between the reactant CH_4 and the product CO_2 of one, which means that also the balance between volumetric flow rates equals to one. Hence the carbon dioxide mass flow rate can be evaluated by multiplying $\dot{V}_{gas}$ by the density of carbon dioxide CO_2, equals to 1.842 kg/Nm3, as shown in Eq. 17.

$$\dot{m}_{CO_2} = \dot{V}_{gas} * \rho_{CO_2} \qquad \text{Eq. 17}$$

4.2.2 PV

Photovoltaic Geographical Information System (PVGIS) has been used to collect meteorological data from the Surface Solar Radiation Data Set - Heliosat (SARAH), a satellite-based climatology of the solar surface irradiance, the surface direct normalised irradiance and the effective cloud albedo [29]. Starting from the experimentally measured solar radiation for the location of Palermo and determining the average hourly power injected on the DC-Bus, it is possible to describe PV modules behaviour. PV energy is used to power the load and charge the batteries eventually (if foreseen in the case study) until they reach their maximum capacity after which part of the available PV power is fed into the grid, according to Eq. 18:

$$W_{PV} = W_{load} + W_{BAT,charge} + W_{grid} \qquad \text{Eq. 18}$$

The system control strategy considers the PV renewable energy a priority in energy supply on SOFC and battery pack, also having the user electrical load a priority on the battery pack, in case of battery charge [30]. Therefore, in the case of hybrid SOFC-PV system, the SOFC helps to back-up battery power and to meet the electricity demand of the user not satisfied by the PV, as described in Eq. 19.

$$W_{el,SOFC} = W_{load} + W_{BAT,charge} - W_{PV} \qquad \text{Eq. 19}$$

Regarding the PV panel characteristics, for the considered supermarket case, it is not possible to apply a tracking system. Therefore, a fixed crystalline silicon PV has been chosen, with optimised slope angle. Table 5 provides the input features in the definition of the model.

PV plant characteristics	
Electric load profile type	Supermarket
Radiation database	PVGIS-SARAH
Location	Palermo, Sicily, Italy
PV mounting type	Fixed
PV technology	c-Si
Replacement time	21 years
PV investment cost	1670 €/kW_P
Operation and maintenance cost	3% of the investment cost

Table 5: PV plant information [31]

4.2.3 BATTERIES

Lead-acid batteries and lithium-ion batteries have been identified to be the most mature, applicable and cost-competitive Battery Energy Storage System (BESS) solutions. It has been decided to select lithium-ion batteries due to the fluctuating power outages which require quick charging and discharging reactions occur. Moreover, they have a higher energy and power density; they are less sensible to deep cycle discharging and have higher efficiency, losing less energy while charging and discharging. In general, lithium-ion batteries can boast a longer nominal lifetime, with a replacement time around 87600 hours (10 years) [32]. Battery features, sed in the model constructions, are presented below in Table 6.

Technical and Economic Information	Unit	Value
Initial SOC	%	50
Minimum SOC	%	10
Maximum SOC	%	100
Charge and discharge efficiency	%	90
Replacement time	y	10
Li-ion investment cost	€/kWh	550

Table 6: Batterie pack technical and economic information [31]

The battery pack has been modelled into a MATLAB® environment as an ideal BESS with a charge and discharge efficiency of 90%, without taking into account the relative polarisation curve, the system operating voltage and the degradation of the State of Health (SOH) of the batteries.

4.3 Cash Flow evaluation

The cash flow evaluation is an important tool to present the outcome of economic analysis. A cash flow per share is useful to understand how expenditures, incomes and savings are structured, related to the installation of an innovative system for the energy. It assesses the value of an investment in the improvement of energy efficiency and the use of renewable energy.

The annual cash flow (CF) is obtained as the difference between the total cash inflows and the outflows, in terms of cost (K_{tot}), revenues (R_{tot}) and subsidies (Sub), as described in Eq. 20. Instead, the discounted cash flow (DCF) is the capitalisation of annual cash flow at the beginning of the project, an analysis which attempts to understand the value of an investment today, based on projections of how much revenues it will provide in the future. To obtain a DCF evaluation, it is necessary to multiply the annual cash flow with the discount factor, which define the reescalation of the future cash flow to the present condition, as shown in Eq. 21.

$$CF_y = R_{tot} + Sub + K_{tot} \qquad \textit{Eq. 20}$$

$$DCF_y = CF_y \cdot d \qquad \textit{Eq. 21}$$

Where the discount factor d is calculated as a function of the Weighted Average Cost of Capital (WACC), which evaluates the percentage of the initial investment covered by the debt and equity, as described in Eq. 22 and Eq. 23.

$$d = (1 + WACC)^{-(y-1)} \qquad \textit{Eq. 22}$$

$$WACC = \%e \cdot c_e + \%d \cdot c_d \cdot (1 - t) \qquad \textit{Eq. 23}$$

Where $\%e$ and $\%d$ are respectively the share of equity and the share of debt; c_e is the cost of equity, c_d is the cost of debt and t is the corporate tax rate.

In the absence of information on specific company's capital structure, in the economic analysis the WACC has been set to 8%, a precautionary value with respect to those indicated for the three-year period 2019-2021 by ARERA, regarding the infrastructure service in the electricity and gas sectors [33].

4.3.1 Costs

The cost can be divided into capital expenditure cost (CAPEX), operating expenditure cost (OPEX) and replacement cost. The CAPEX is the initial investment for the construction of the plant. It consists of various terms, depending on the type of system taken into consideration:

- manufacturing cost of the SOFC module, including a 10% manufacture company profit;
- SOFC Balance of Plant (BOP) cost, for all the supporting components and auxiliary systems;
- Li-ion BESS and PV panels capital cost;
- commissioning & installation cost.

$$CAPEX = k_{mod} + k_{BOP} + k_{BESS} + k_{PV} + k_{C\&I} \qquad \textit{Eq. 24}$$

The OPEX is related to the ordinary and necessary expenses that system need in order to operate each year. It consists of the cost of fuel for the SOFC modules, operational cost of SOFC system, operation and maintenance cost of the PV plant (if foreseen in the case study), as described in Eq. 25.

$$OPEX = Gas_{input} \cdot p_{gas} + p_{op\&m,SOFC} + p_{op\&m,PV} \qquad \textit{Eq. 25}$$

Moreover, since SOFC and BESS are characterised by a technical lifetime lower than the project duration, it is necessary to replace the SOFC module the battery pack, respectively every 7 and 10 years. The replacement cost of the fuel cell module k_{rep} is assumed equal to the manufacturing cost of the module, while the replacement cost of the BESS amounts to the Li-ion battery investment cost.

4.3.2 Revenues

Revenues are closely related to the savings, all the annual costs that the asset owner does not have to bear due to the installation of power plant since the energy produced by the system must not be purchased from the grid. They can be divided into electricity and gas revenues since the SOFC-CHP system is able to simultaneously provide heat and electricity to the supermarket, as shown in Eq. 26 and Eq. 27.

$$R_{el} = E_{el,self-used} \cdot p_{el} = \left(E_{load} - E_{grid}\right) \cdot p_{el} \qquad \text{Eq. 26}$$

$$R_{gas} = E_{th,self-used} \cdot p_{gas} \qquad \text{Eq. 27}$$

The yearly electrical and thermal energy that constitutes the system revenues are only the self-used part. In order to correctly evaluate this share, the energy production has been compared with the thermal and electric load of the supermarket on an hourly basis. The factor $E_{el,self-used}$ is constituted by the energetic contributions from all the generation and storage units involved in the case study, therefore, in some cases, it can be estimated as the electric load of the supermarket not meet from the grid contribution. The price of gas and electricity is seen as constant during the simulation period. In particular, it has been considered a gas price equals to 0.033 €/kWh, and an electricity price equals to 0.125 €/kWh, as reported in Eurostat dissemination for the first semester of 2020 [34], [35].

4.3.3 TEE

The subsidies actually available in Italy to support the energy transition are the "*Certificati Bianchi*", also known as "Titoli di Efficienza Energetica" (TEE), which are negotiable securities that certify the achievement of energy savings in the final uses of energy through the implementation of interventions to increase energy efficiency. This subsidy scheme shall be accessible to the high-efficiency cogeneration according to the conditions and procedures established by the Ministerial Decree of 5th September 2011. For recognition of operation in High-Efficiency Cogeneration, a given cogeneration unit must necessarily achieve a primary energy saving (PES) higher than the minimum pre-established values, differentiated according to the generation capacity of the unit itself, illustrated below [36]:

- PES ≥ 0.1 (10%) for cogeneration units with generation capacity at least equal to 1 MWe;
- PES> 0 for units with a generation capacity of less than 1 MWe (small and micro-cogeneration).

In particular, the PES is evaluated as described in Eq. 28.

$$PES = \left(1 - \frac{1}{\frac{CHPH_\eta}{RefH_\eta} + \frac{CHPE_\eta}{RefH_\eta}}\right) \cdot 100\% \qquad \textit{Eq. 29}$$

Where:

- $CHPH_\eta$ is the thermal efficiency of the cogeneration unit;
- $CHPE_\eta$ is the electrical efficiency of the cogeneration unit;
- $RefH_\eta$ is the reference efficiency value for separate heat generation;
- $RefE_\eta$ is the reference efficiency value for separate electricity generation;

For the evaluation of the primary energy saving in case unit powered by natural gas, such as SOFC, the Commission Delegated Regulation (EU) 2015/2402 states that the harmonised efficiency reference values for separate production of electricity ($RefE_\eta$) is 53.0% and the efficiency reference values for separate production of heat ($RefH_\eta$) is 84.0% [37].

In case of approved high-yield cogeneration systems with a $\eta_{sys} \geq 75\%$, GSE provides the energy efficiency certificates (TEE) that certify the energy savings achieved in the final uses of energy. For each Tonne of Oil Equivalent (TOE) of savings, equal to 5,327 kWh in case of electricity or 11,628 kWh in case of heat, a certificate (CB) is recognised, for all useful life established by the legislation for each type of project. Each TEE has a value of approximately 260 €/toe (updated to October 2020 [38]). It can be sold to electricity and natural gas dealers, who must purchase the missing securities on the market to comply with the obligation regarding annual saving. Revenue from the sale of the certificate is an incentive to stimulate investment in the improvement of energy efficiency.

The annual primary energy savings, expressed in MWh, achieved by the cogeneration unit, it is calculated as follows:

$$RISP = \frac{E_{CHP}}{\eta_{E\,rif}} + \frac{H_{CHP}}{\eta_{T\,rif}} - F_{CHP} \qquad \textit{Eq. 30}$$

Where:

- E_{CHP}: electricity produced by cogeneration unit.

- H_{CHP}: heat produced by cogeneration unit.
- F_{CHP}: power supply consumed to feed the cogeneration unit.
- $\eta_{E\,rif}$: conventional average efficiency of the Italian electricity production park assumed 46%.
- $\eta_{T\,rif}$: conventional average efficiency of thermal production in Italy assumed 90%.

Based on the primary energy savings calculated according to the formula described above (RISP), the cogeneration unit is entitled, for a specific year, to a number of certificates equal to:

$$CB = RISP * 0.086 * K \qquad \textit{Eq. 31}$$

Where K is a harmonisation coefficient, which varies according to the power of the cogeneration unit, in case of power below 1 MW is $K = 1.4$.

4.3.4 Net Metering -SSP-

Net metering is a mechanism that compensates consumers for the energy they export to the electricity grid. It allows the electricity produced to be fed into the grid, and then to be collected at a later time. It is an incentive system to enhance the energy not self-consumed according to a criterion of economic compensation with the value of the energy withdrawn from the grid, which therefore acts as an immense accumulator capable of returning the accumulated energy, usually produced with a different profile from that of the user, when we need it [39]. With concerns about climate change, net metering has been one way of accelerating the development of solar and wind generation, in the accomplishment of government policies regarding the continuous growth of renewable energy sources penetration.

In Italy, the net metering is known as "*Scambio Sul Posto*" (SSP), and it is available for the plant with the following features (neglecting the systems that have come on stream up to 31st December 2014) [39]:

- the total installed capacity of high-yield cogeneration systems is no greater than 200 kW;

- the total installed capacity of systems powered by renewable sources is no greater than 500 kW.

The user pays his zonal supplier for all his consumption, while the GSE calculates and pays the user a contribution on exchange account that consider the electricity fed into the network and restores the fairness of the exchange. The contribution disbursed by the GSE, to be paid on an annual basis, is calculated at market prices on the share of energy exchanged, as shown in Eq. 32:

$$CS = min(O_E; C_{EI}) + CU_{sf} \cdot E_S \qquad \textit{Eq. 32}$$

Where:

- CS is the contribution on exchange account [€];
- O_E is the cost incurred annually for the purchase of electricity withdrawn, evaluated as the product between the amount of electricity withdrawn from the grid and the National Marginal Price ("*Prezzo Unico Nazionale*" -PUN-) [€];
- C_{EI} is the value of the electricity fed into the grid (determined on the basis of the hourly zone prices that are formed on the day-ahead market) [€];
- CU_{sf} is the annual flat rate unit exchange fee [c€/kWh];
- E_S is the annually exchanged energy [kWh].

The PUN and the C_{EI} reference prices, which are an hourly and zonal average of the variable prices recorded day by day on the Electricity Market, varies between 4 and 6 c€/kWh. CU_{sf}, which reimburses part of the fixed costs paid in the bill by the final use, ranges from 5 to 20 c€/kWh [40]. To perform the analysis, in conformity with these terms, it has been decided to enhance the electricity introduced and later withdrawn from the grid through a price of 0.15 €/kWh, whereas the price for the electricity fed into the grid and not withdrawn has been set to 0.05 €/kWh.

4.3.5 Grid Balancing

Since the purpose of this study is to create a prosumer who is able to provide grid balancing services, engaging successfully with the spot market, the grid balancing revenues have to be taken into account in the cash flow evaluation. The 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 with the UVAM. The BSP tended to submit high bids to maintain the fixed remuneration right but without having actual interest in performing grid balancing [22]. The difference between the bid submitted by the UVAM and the maximum selling price resulting from Balancing Market is significant, and Figure 13 shows this trend.

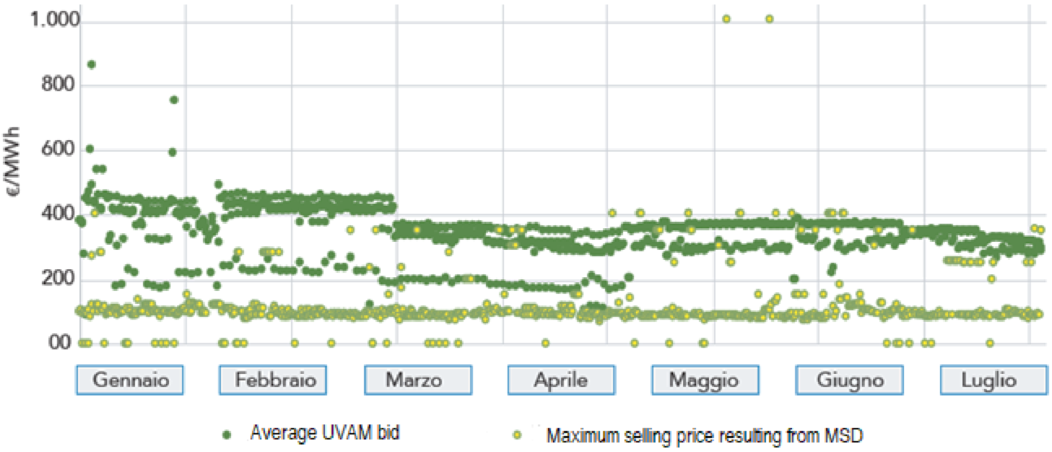


Figure 13: Average UVAM bids (dark green points) and maximum selling price resulting from MSD in the allocation area A (light green points) [22]

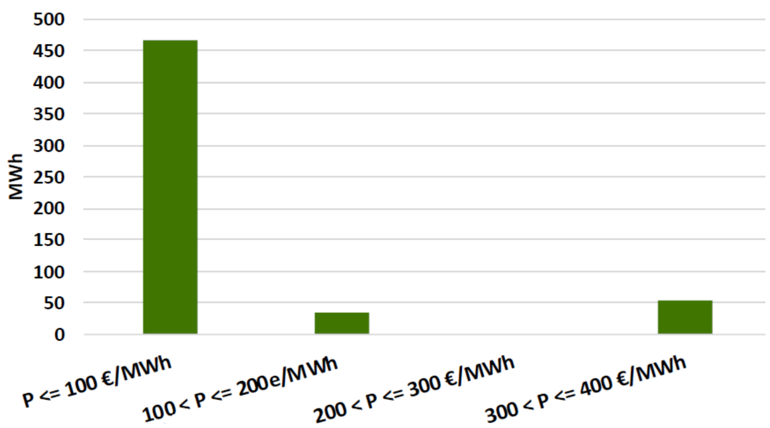


Figure 14: Bid accepted by price range in the first semester of 2019 [22]

Figure 14 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 characterised by a price lower than 100 €/MWh. Moreover, to set up the model a contract type between the BSP and the asset owner has been considered in conformity with the ones typically used in the actual market. Taking into consideration the actual trend of UVAM pilot project, Table 7 provides the assumptions definition for the model in terms of average bid size, yearly hours of accepted bids and contract type decisions on the fixed and variable remuneration.

Grid Balancing Information	Unit	Value
Average bid price	€/MWh	150
Yearly hours of accepted bid	h/y	400
Fixed remuneration	€/MWh	30000
Revenue stream asset owner business model	% fix	70%
	% var	80%

Table 7: Grid Balancing model input

5 Case Studies: Overview

Three different case studies have been evaluated in order to perform balancing services, and they have been compared with the base load scenario, which is currently the most studied SOFC system solution as evidenced by the ComSos Deliverable 5.3.

5.1 Base Load

The base load scenario is modelled to satisfy the minimum required power value, the so-called base load, of the supermarket load profile. SOFC capacity is selected in order to have a system that does not need the modulation, because it produces only a minimum fraction of the necessary electricity, at any time of day. The SOFC system is composed of three nominal 12 kW modules (SOLIDpower manufacturing), for a total nominal size plant of 36 kW. The system is designed to work at its maximum load in a continuous way, as pointed out in Figure 15.

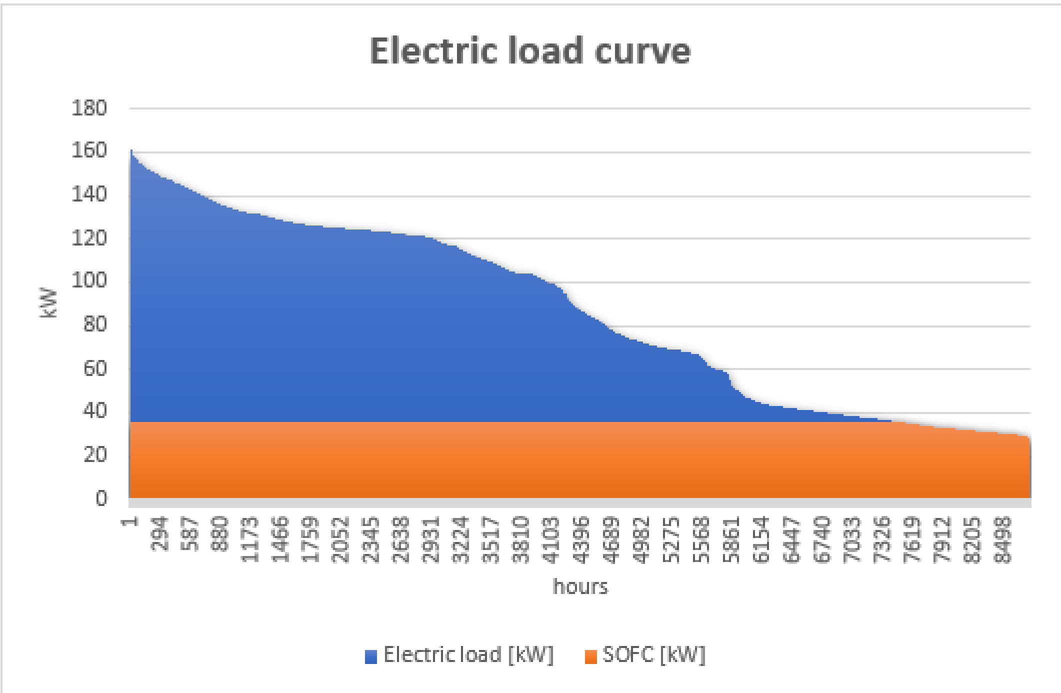


Figure 15: Electric load curve

This configuration allows the system to minimise the degradation rate of SOFC modules because the SOFCs can constantly work without daily ramp-up or ramp-down. For this reason, ε_{deg} is set equals to 0.3 %/kh.

5.2 Stand-alone SOFC

For the stand-alone SOFC case, we have designed a power plant composed of a nominal 180 kW SOFC system. We have decided to make the SOFC working at fixed power operation points in order to reduce the daily number of ramps, starting from 30% of the installed nominal power. In the case of dispatching orders, the SOFC modules increase their output power to their nominal value to deliver the exceeding energy production to the grid. Table 8 provides the input definition for the model.

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

The SOFC operation, due to the high capacity installed, is managed in a stepped load-following mode, working with regular power steps, equal to 10% of the SOFC system nominal size. This assumption has been set in order to reduce the number of modulations during the day, at the cost of having an electricity suplus.

SOFC operation characteristics		
Operation type	Electricity led	
Electric load profile type	Supermarket	
Technical parameters	**Unit**	**Value**
SOFC system nominal size	kW	3 x 60
Ramp-up rate	W/min per each module	1’800
Ramp-down rate	W/min per each module	3’000
Modulation range	%	30-100
Power operation points	kW	54,72,90,108,126,144,162,180
Degradation rate	%/kh	0.5

Table 8: Stand-alone SOFC model input

Figure 16 and Figure 17show the typical SOFC modulation to satisfy the supermarket electrical load, without grid balancing purpose, during respectively winter and summer.

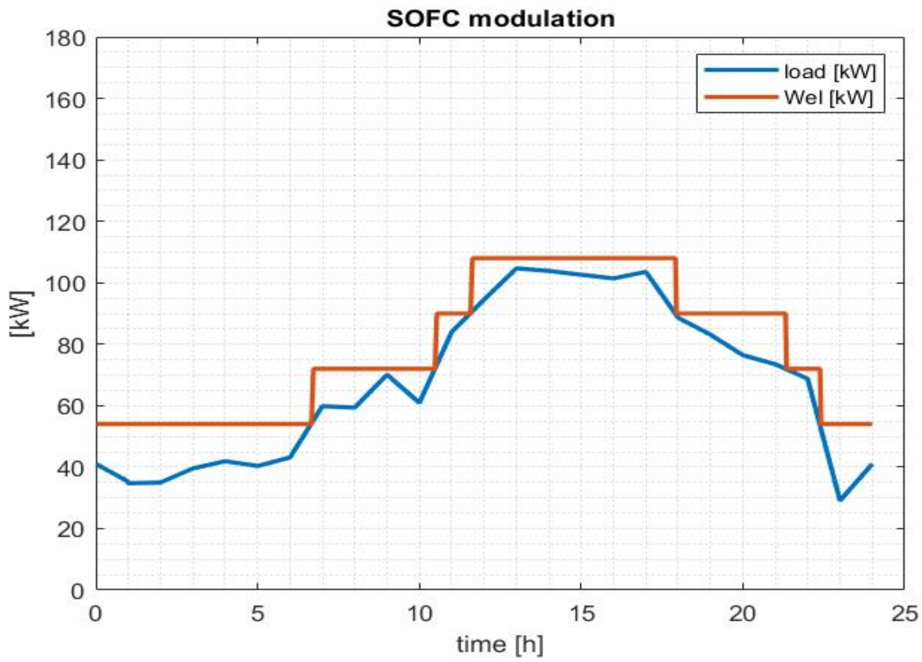


Figure 16: Typical SOFC modulation and electric load in winter days

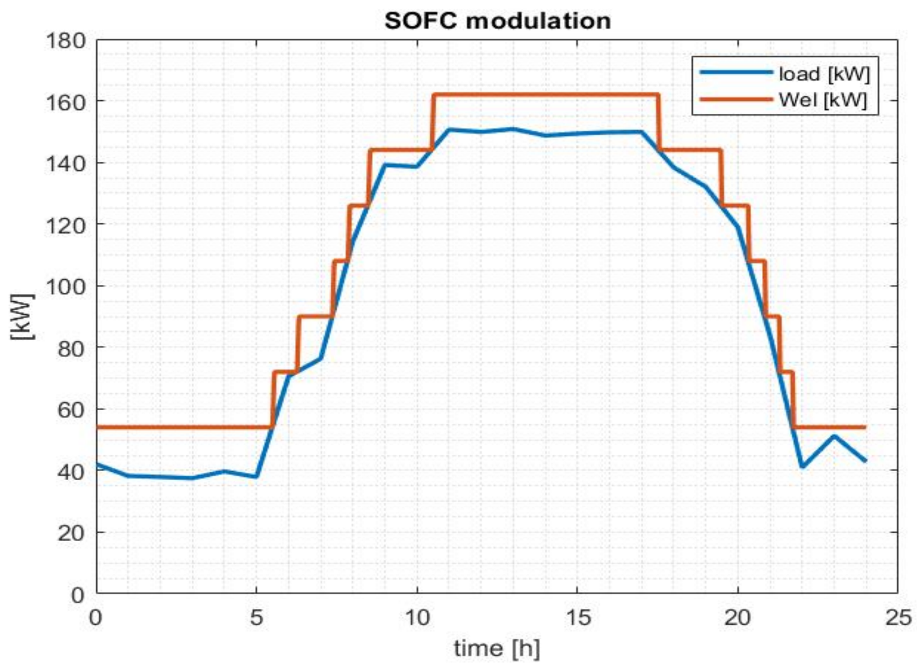


Figure 17: Typical SOFC modulation and electric load in summer days

5.3 Hybrid SOFC-PV system

The limitation of the second case study is the need for 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 baseload, the operating point is 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. Table 9 provides the input definition for the model.

	Technical parameters	**Unit**	**Value**
SOFC	System nominal size	kW	2 x 60
	Ramp-up rate	W/min per each module	1800
	Ramp-down rate	W/min per each module	3000
	Modulation range	%	30-100
	Power operation points	kW	48, 72, 90, 108,120
	Degradation rate	%/kh	0.4
PV	Nominal power	kWp	150
	System losses	%	14.0
	Slope	deg	31
	Azimuth	deg	0

Table 9: Hybrid SOFC-PV system model input

Figure 18 and Figure 19 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.

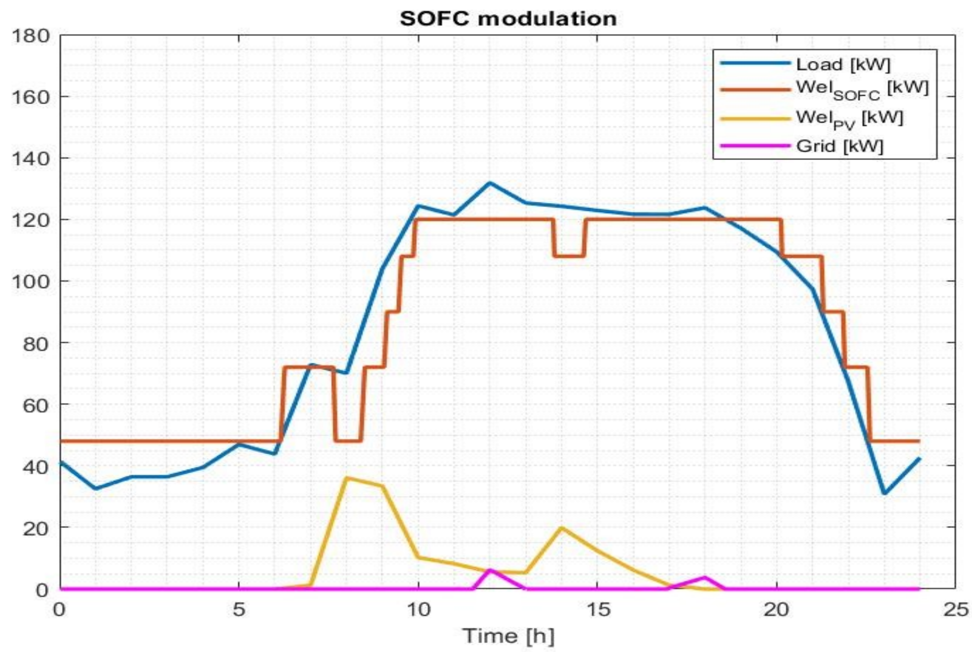


Figure 18: Typical SOFC modulation, PV production and electric load in winter days

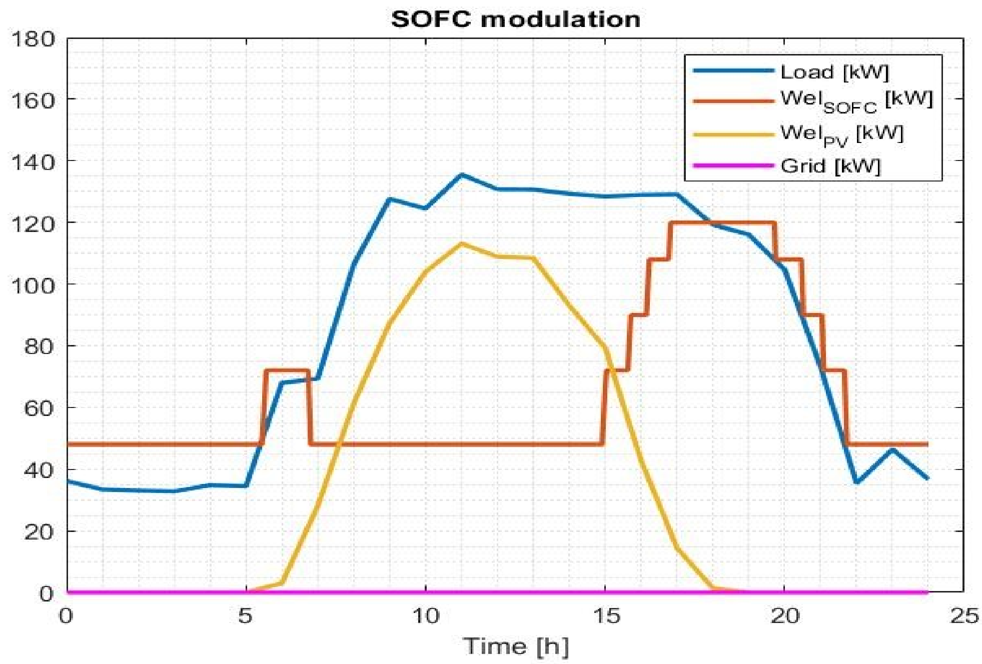


Figure 19: Typical SOFC modulation, PV production and electric load in summer days

With this configuration, it is possible to obtain a power availability exceeding consumption, without oversizing the SOFC system. Concerning the previous case study, the nominal size of the SOFC system is reduced by 60 kW. Moreover, in this scenario, since the SOFC system cannot satisfy the peak demand on its own sometimes, in low irradiance period, may arise the necessity of drawing electricity from the grid.

5.4 Hybrid SOFC-PV-BAT system

In this third case study, we analyse a further optimisation of the SOFC oversizing with a hybrid power plant equipped with a Battery Energy Storage System (BESS). The RES-CHP coupled system is composed of a peak 150 kW PV plant and a nominal 60 kW SOFC system, which can operate on average at the nominal load since it is sized about the supermarket baseload. Figure 20 shows the conceptual configuration to be simulated, where the arrows define the interactions between the different components, while the colour tone highlights the intensity of the electricity exchanged during the year. The energy feds into the grid are also divided into two types: "*Scambio Sul Posto*" (SSP) and grid balancing according to the enabled service.

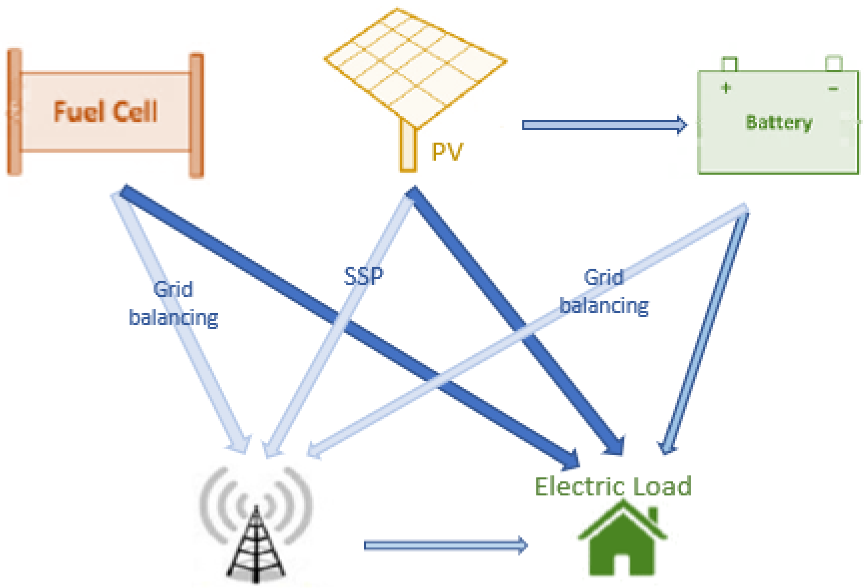


Figure 20: Working principle of SOFC+PV+BAT power system

Table 10 provides the input definition for the model.

	Technical parameters	Value	Unit
SOFC	System nominal size	kW	60
	Ramp-up rate	W/min per each module	1800
	Ramp-down rate	W/min per each module	3000
	Modulation range	%	75-100
	Power operation points	kW	45,50,60
	Degradation rate	%/kh	0.3
PV	Nominal power	kWp	150
	System losses	%	14.0
	Slope	deg	31
	Azimuth	deg	0
BESS	Storage capacity	kWh	80

Table 10: Hybrid SOFC-PV-BAT system model input

With respect to the previous case studies, the nominal size of the SOFC system is only 60 kW. The SOFC module always works very close to the nominal capacity, which allows storing the surplus of energy in the battery during the night and during the middle of the day. The PV power-plant specs have been designed to maximise the renewable energy delivered to the electric load over the whole year. Although this may lead to some losses during summer, it allows for better usage of PV power during wintertime and low solar radiation period. The solar-generated electricity is almost completely used for self-consumption, except for a small amount that is stored in the BESS or in the grid thanks to the SSP mechanism. The battery pack capacity, 80 kWh, has been chosen to approximately provide the system with enough power to perform a minimum 20 kW grid modulation order correctly, even in case of no solar radiation and simultaneous peak load power. Figure 21 represents an electric scheme of the system, where all the components are connected in parallel on the same DC-bus [30].

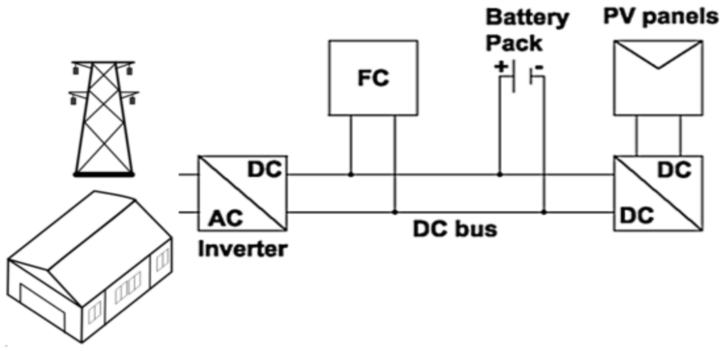


Figure 21: Hybrid system for power generation [30]

In this scenario, since the SOFC system is not oversized, the peak demand cannot be satisfied, particularly with regards to late afternoon and low irradiance period. The grid compensation allows matching the electricity demand at every moment. Figure 22 shows the typical system modulation to satisfy the supermarket electrical load in a SOFC-PV hybrid power plant without grid balancing purpose. Figure 23 and Figure 24 show respectively the share of self-consumed electricity and the battery State of Charge (SOC) profile during an ordinary day.

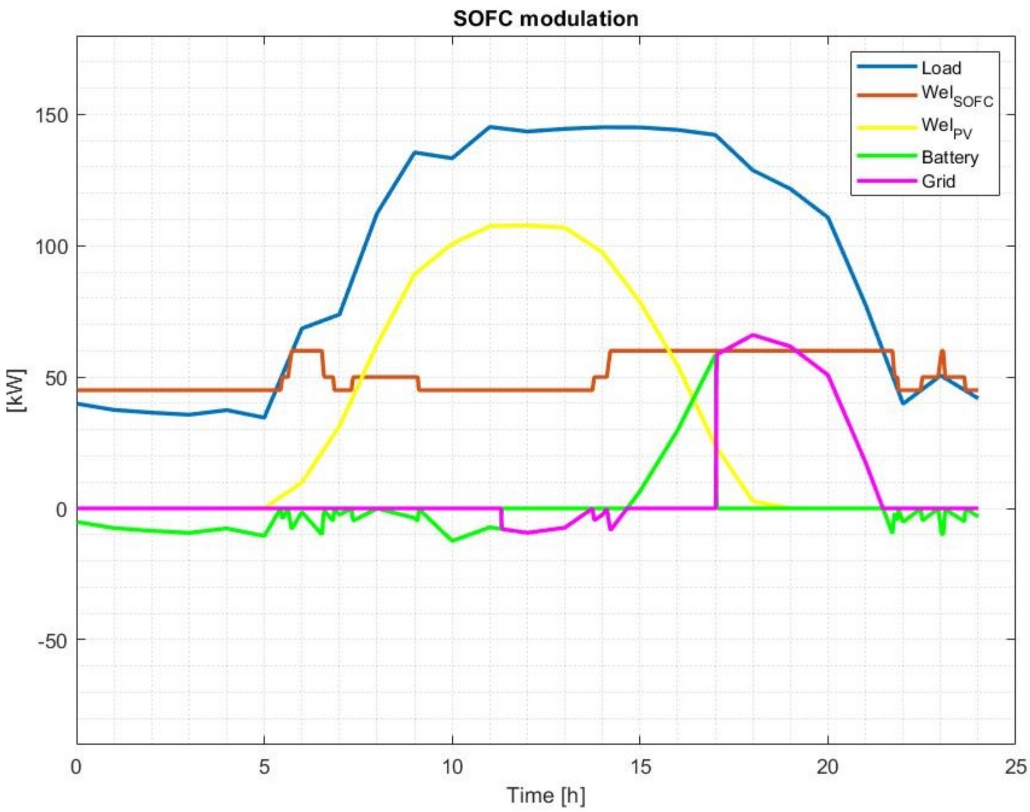


Figure 22: Hybrid SOFC+PV+BAT system generation profile

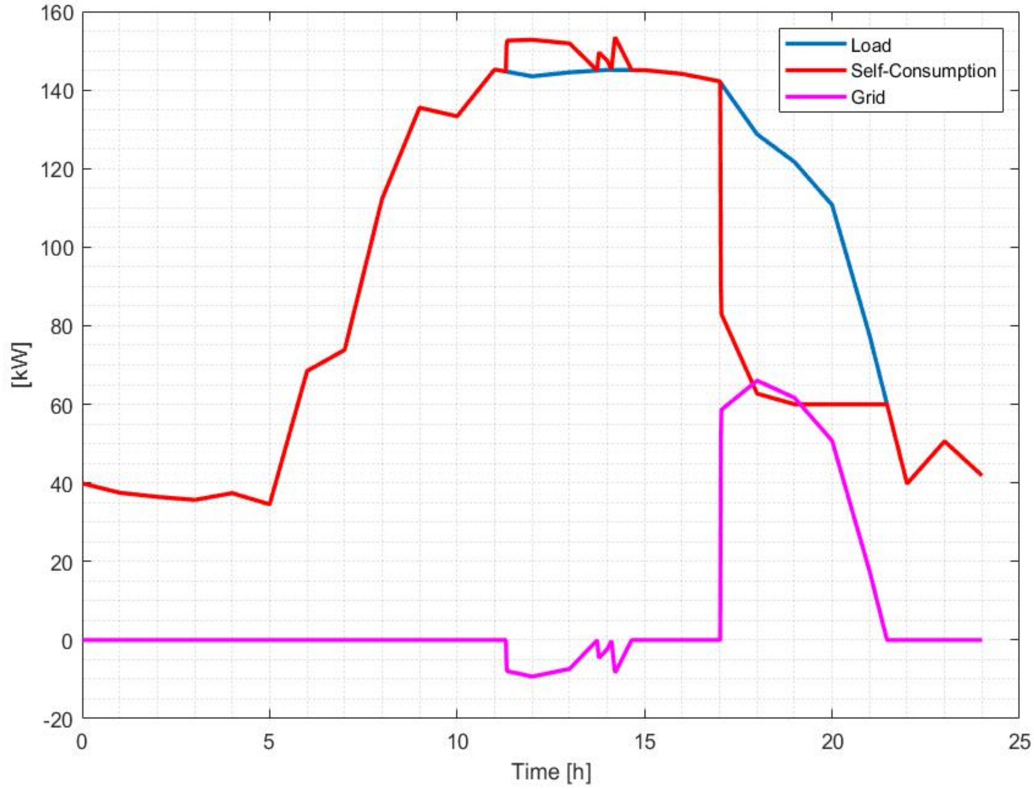


Figure 23: Share of self-consumed electricity and grid compensation

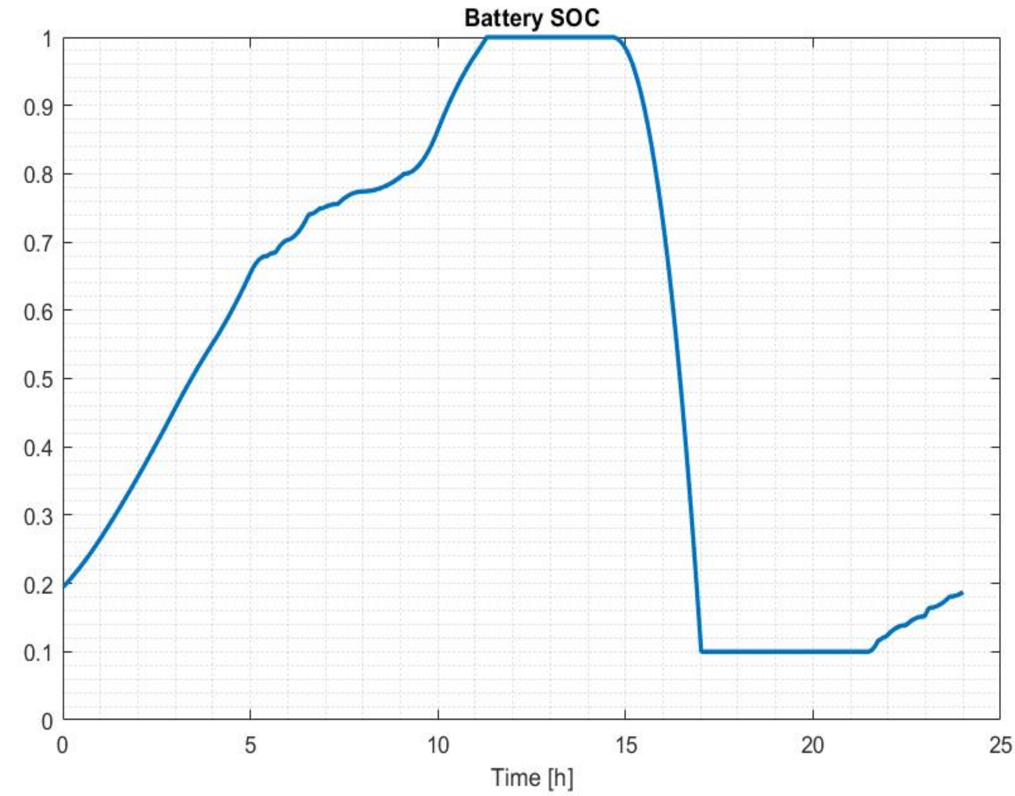


Figure 24: Daily SOC profile

Figure 25 and Figure 26 show the differences between typical hybrid SOFC-PV-BAT system modulation during respectively winter and summer. As we can see from the comparison between the two graphs, during winter, the grid compensation is higher, and the battery is activated to satisfy the electrical load in advance of the summer case.

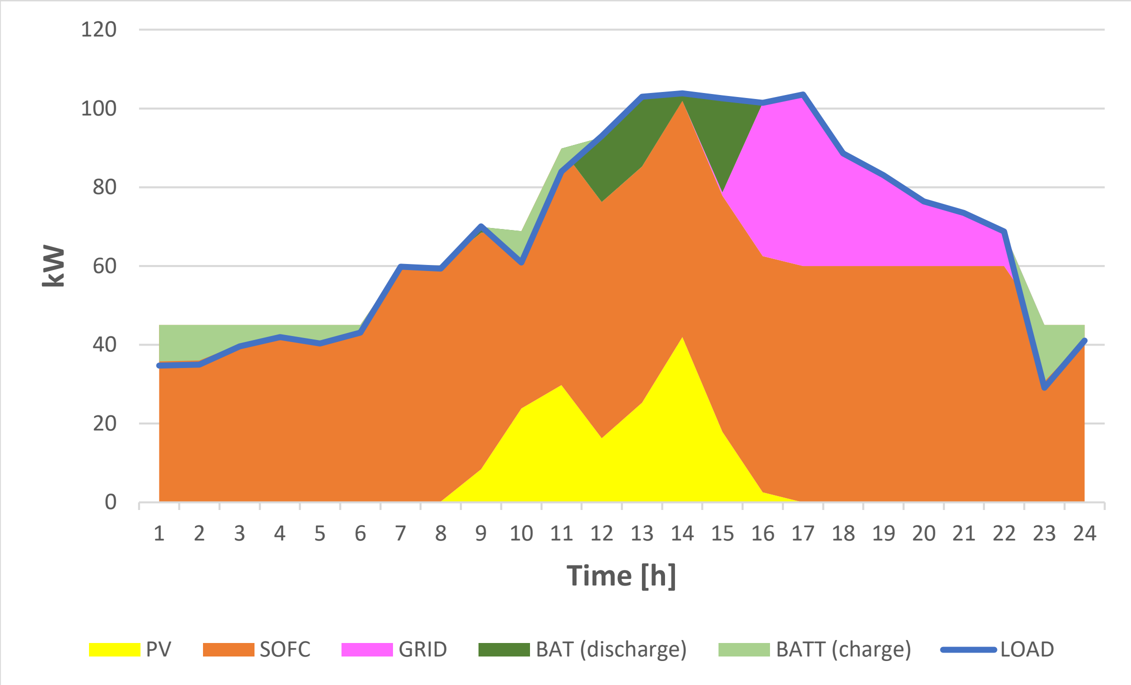


Figure 25: Share of electricity generation during winter days

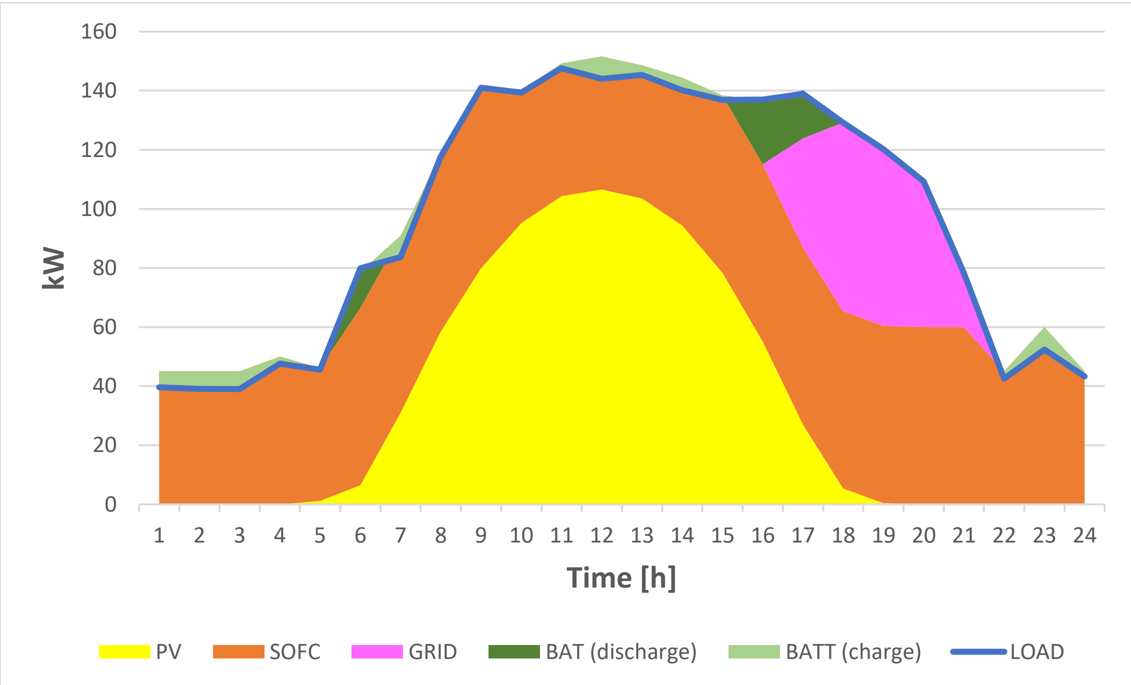


Figure 26: Share of electricity generation during summer days

6 Case studies: results

6.1 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 27 provides an example of a correct modulation of 30 kW. The Baseline is the expected power schedule of the asset included within the UVAM that the BSP must 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.

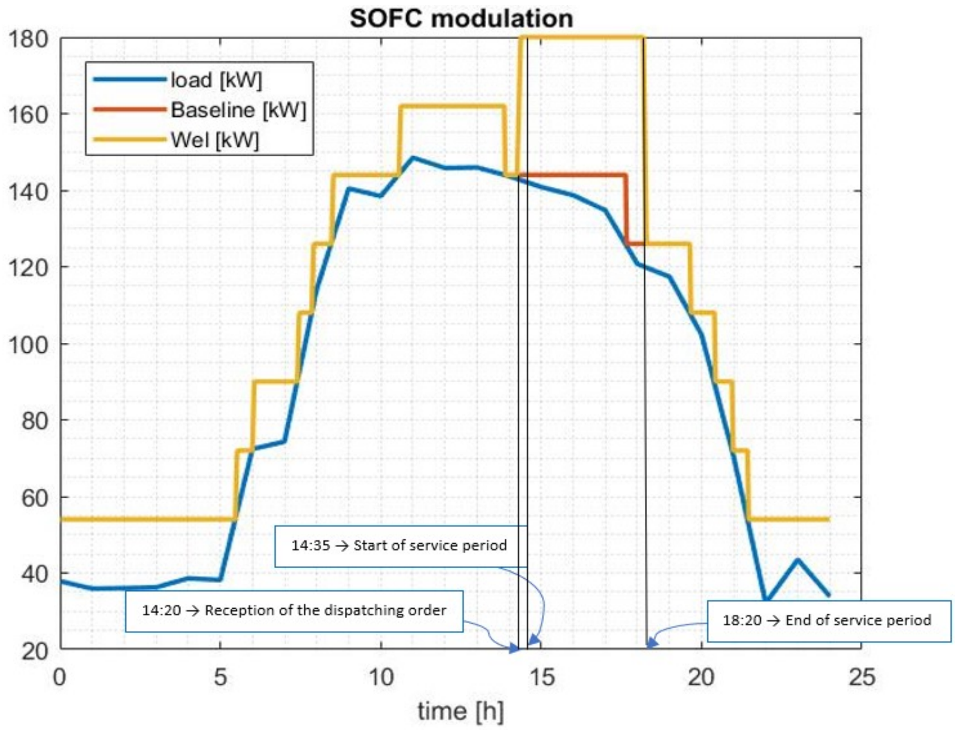


Figure 27: Grid balancing with stand-alone SOFC

As Figure 27 illustrates, 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 to meet the electrical need with peaks in the same hours of the grid balancing services. In fact, in the time slot 2–8 pm when a dispatching 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 ranges are very large, so the SOFC degradation is expected to be remarkable. For these reasons, in the cash flow evaluation, it has been considered a degradation rate of 0.5 %/kh and an annual average contribution in the UVAM bid size of 45 kW, considering the different capacity availability throughout the year.

6.2 Hybrid SOFC-PV system

Due to the high degree of timely coincidence between solar irradiance 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 gives the system the flexibility needed in case of grid balancing dispatching. 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.

This hybrid power system allows the SOFC modules to work at higher efficiency with a reduced modulation range of 40% to 100% of the nominal power. However, the daily modulation still interests a wide variety of power operation points which leads to a consistent degradation rate, set to 4 %/kh.

Figure 28 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.

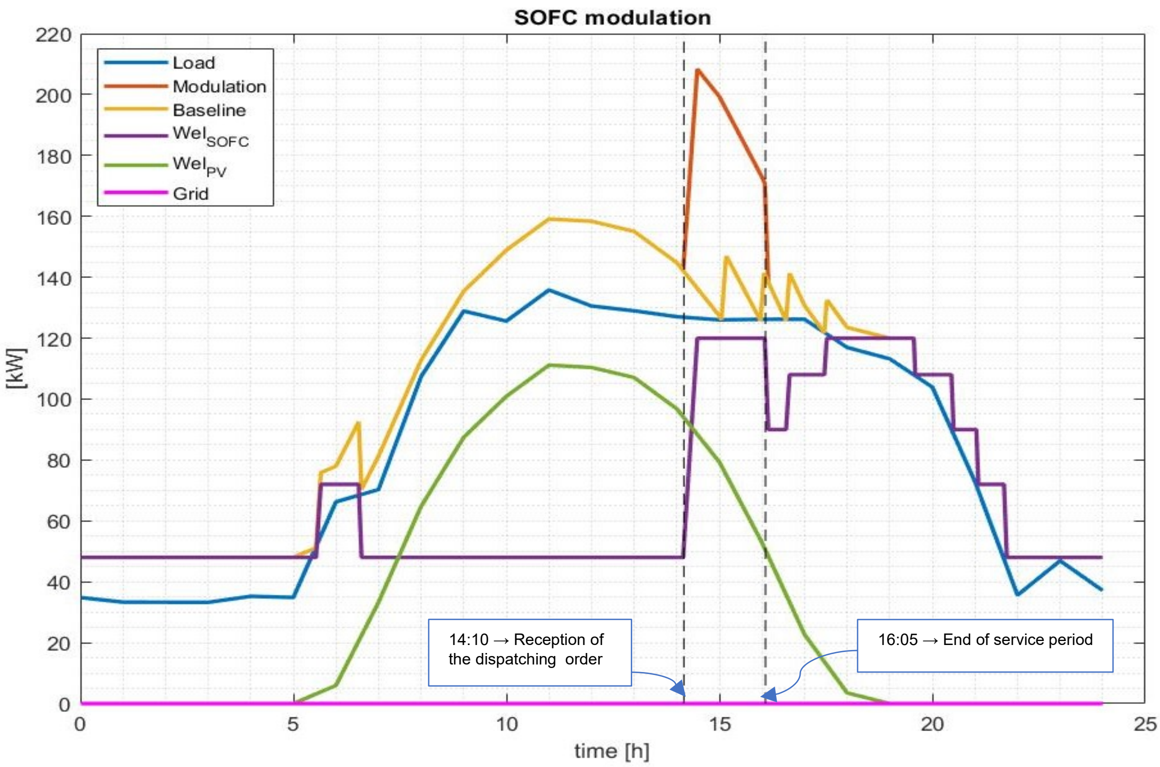


Figure 28: Grid balancing with hybrid SOFC-PV system

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 pm to 4 pm considering a bid of two consecutive hours on the MSD and a minimum service delivering interval of 40 minutes. Figure 29 provides the outcome of the Monte Carlo simulation, where the average sample is presented with its error bar, representing the standard deviation. Once the adequacy of the system in providing balancing service has been proven, the cash flow evaluation is performed by considering an annual average contribution in the

UVAM bid size of 20 kW. The power availability exceeding consumption is actually high, around 30-40 kW, during summer, thanks to the high share of PV production.

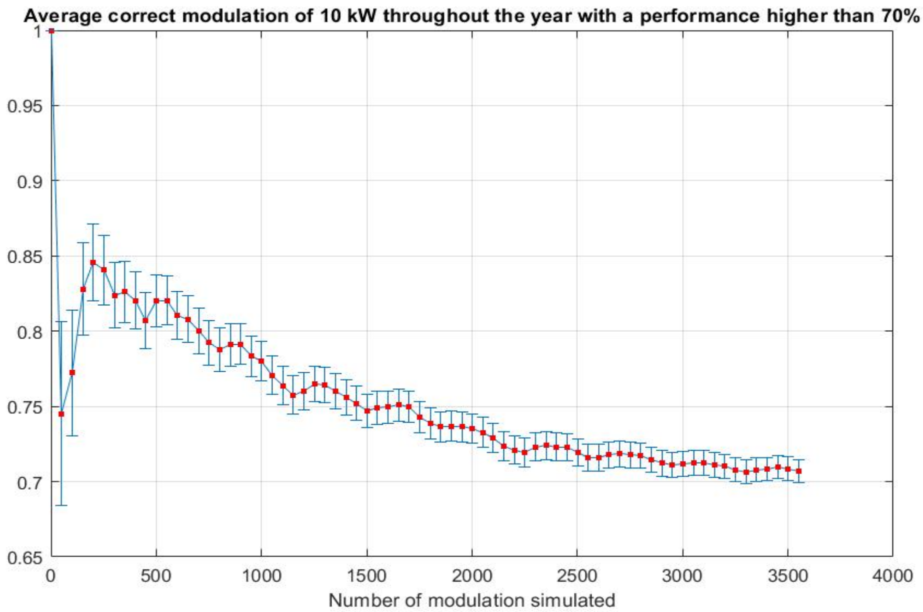


Figure 29: Average correct modulation of 10 kW throughout the year with performance higher than 70%. On the Y-axis is the percentage of modulation successfully completed, and on the X-axis is the number of modulations simulated uniformly throughout the year

In real management, there are, however, additional uncertainties compared to the study done. The analysis has been performed retrospectively so that the starting data are actual. The quantity made available by the plant, in this study, was indeed calculated starting from the real generation data from PVGIS-SARAH database. In reality, the generation of the PV array is based on weather forecasts which add a further degree of uncertainty. In doing so, it could be possible to offer an amount of energy in the markets that may not be available, thus reducing the possibility of revenues compared to this base case.

6.3 Hybrid SOFC-PV-BAT system

The hybrid SOFC-PV-BAT system has, differently from the previous two power plant, two sources of flexibility. Both SOFC and BESS have the ability to respond to change in supply according to grid need. The power capacity required to perform grid balancing is shared between the two technology, always ensuring high responsiveness, high efficiency and clean energy. The grid balancing capacity is strongly affected by the solar irradiance because the system is not oversized. During peak load periods, the PV array must cover part of the electrical load in order to avoid the need for grid compensation. When no radiation is available, the Li-ion battery packs and the solid oxide fuel cell are in charge of the load supply. This redundant flexible system allows a self-sufficient operation for couples of hours but cannot ensure grid balancing service since it is not suited for electricity surplus.

Figure 30 provides a practical example of how a modulation order may be handle by the hybrid system thanks to the modulation of the SOFC and the BESS. The dashed lines represent the baseline profile without the need for grid balancing. When the battery or the grid profiles become negative, it means that the hybrid SOFC-PV system is storing the electricity surplus form the fuel cell and the PV array, with priority to BESS.

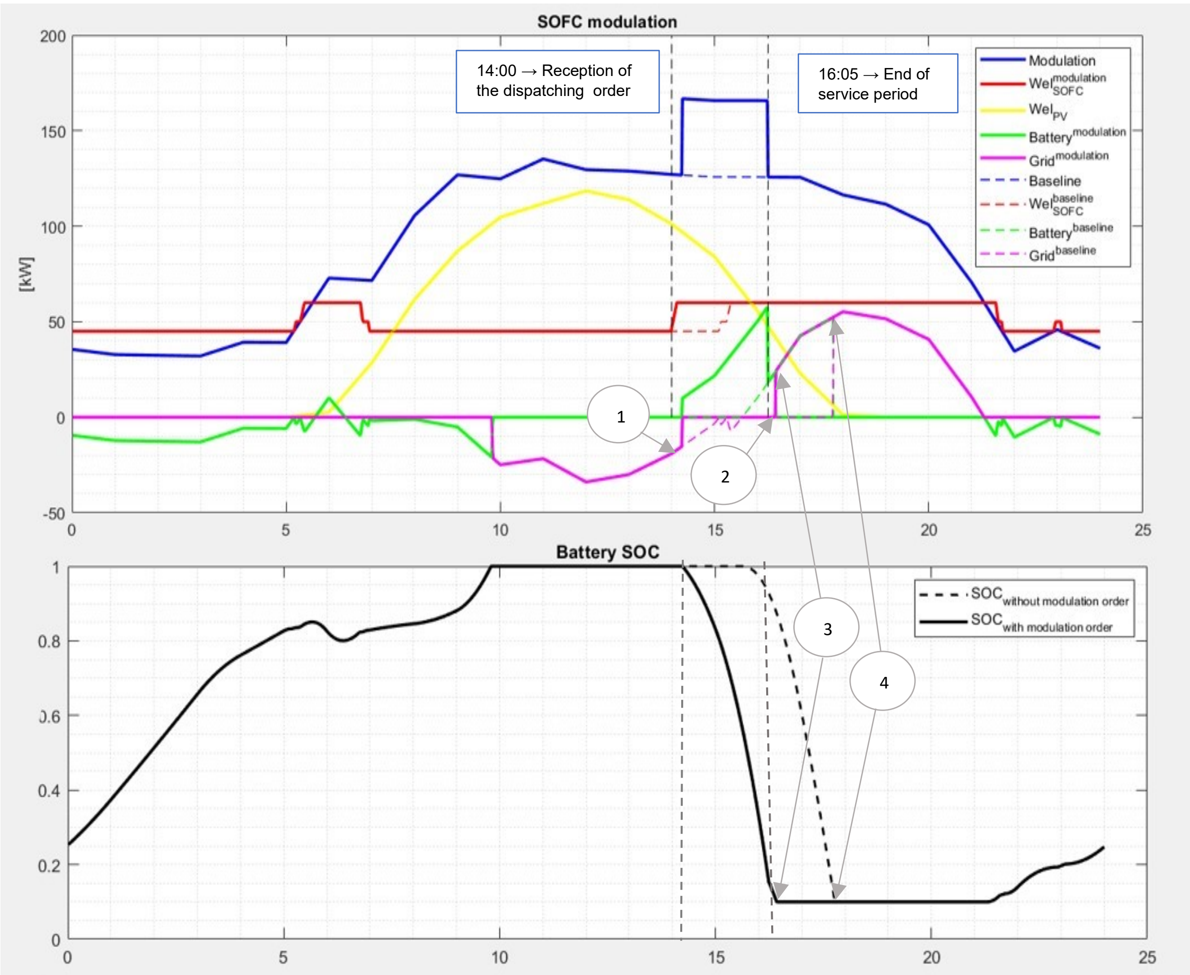


Figure 30: Grid balancing with hybrid SOFC-PV-BAT system

Four significant moments are highlighted. In moment 1, the UVAM receives the dispatching order from the TSO, taking into consideration the bids submitted to the MSD. The aggregator sorts all modulation orders to the assets that have become available within the VPP. From that moment, the SOFC have fifteen minutes to ramp up and reach the nominal power while the BESS stays in standby mode as long as the SOFC-PV system is able to meet the energy needs. In 2, the dispatching order from the TSO is interrupted. The system is only in charge of the load supply, but differently from the baseline profile, the SOC of the battery pack is already close to the minimum and BESS is nearly used up. The moments when the batteries are cut off according to balancing and baseline mode are respectively 3 and 4, which differ from each other by 95 minutes.

The time difference between these two modes allows the hybrid system to take part in the MSD. Thanks to the advance in the use of the stored energy, it is indeed possible to provide balancing service in the early afternoon when the solar irradiance is still consistent. This hybrid SOFC-PV-BAT system does not include oversized components. SOFC work efficiently near the nominal power, reducing the degradation related to continuous ramp-up and ramp-down. The battery pack is sized in order to store part of the electricity surplus coming from the PV array and SOFC. Still, it does not provide an accumulation of electricity exceeding the daily demand. With this configuration, the asset owner will earn a triple benefit: the SOFC works continuously at high-efficiency point, the percentage of self-consumed electricity is enhanced, and he can also take advantage of the grid balancing remuneration.

6.4 Comparison

In the three case studies presented, we have analysed different way of consumers empowerment by providing balancing signal and financial incentives to adjust their use of demand-side resources such as their distributed generation or storage capabilities. Active energy consumers involved in the electricity market are so-called prosumers because they both consume and produce electricity. Under explicit UVAM schemes, they receive a direct payment to modify their generation upon aggregator request. Table 11 summarizes the grid balancing features of each case study.

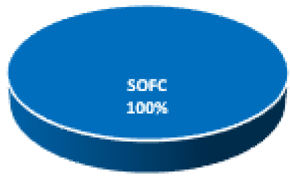
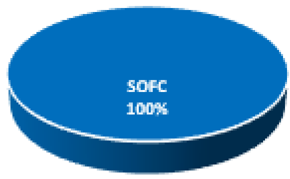
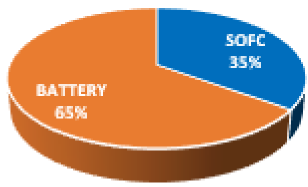
Case study	Features		Share of balancing flexibility
Stand-alone SOFC	SOFC installed capacity	180 kW	
	Average bid size contribution	45 kW	
	Availability	2-8 pm	
Hybrid SOFC-PV	SOFC installed capacity	120 kW	
	Average bid size contribution	20 kW	
	Availability	2-4 pm	
Hybrid SOFC-PV-BAT	SOFC installed capacity	60 kW	
	Average bid size contribution	30 kW	
	Availability	2-5 pm	

Table 11: Case studies comparison

In the stand-alone SOFC case study, the distributed generation unit totally consists of solid oxide fuel cell modules. Since the system is oversized in relation to the yearly load, the grid balancing capacity is much greater than that of the other case studies. It could constitute a valuable asset for a VPP since SOFC shows high responsiveness, high-efficiency operation and low overall balancing cost. Moreover, the system allows obtaining power availability exceeding consumption in all the UVAM bid obligation period (from 2 pm to 8 pm), which leads to a further degree of freedom in submitting valuable offers on the MSD. On the other hand, it might be disproportionally expensive for the asset owner, since it could be hard for him to recoup his investment.

With a hybrid SOFC-PV system, the balancing order would always be met by the SOFC, but part of the electric load of the supermarket would be taken charge of by the photovoltaic array. In this case study, the flexibility capacity can be provided only in the first hours of the UVAM obligation period since the PV production rapidly decreases as minutes increase. This system could be an interesting asset for an aggregator that has in its portfolio technologies which are able to interact positively with its features, such as industrial and commercial demand response. However, it remains the fact that the configuration is able to perform a correct minimum 10 kW modulation for 2 hours in case of a dispatching order in the ~70% of the cases.

Finally, the third case study presents the same features of the RES-CHP coupled system for an aggregators point of view in terms of duration and starting time. However, the hybrid SOFC-PV-BAT system is generally more reliable due to the implementation of a BESS and, above all, it is much more cost-efficient from the asset owner point of view.

7 Economic evaluation results

In this Chapter, the economic evaluation results related to the three case studies are presented and compared with the baseload scenario, which acts as a reference. The costs and revenues assessment are estimated in constant currency, without considering the inflation. The cash flow evaluation is performed in base year currency, considering negligible inflation rate, equals to zero ($i = 0\%$).

Figure 31 provides the contribution of each generation source, energy storage and compensation system of the grid in order to meet the annual electrical needs of the supermarket. The percentages shown in the following graphs represent the shares of electricity imported by each system for a total of 757'363 kWh/year. The grid compensation does not include the share of withdrawn electricity from the grid through the net metering policy (SSP), which is evaluated as the electrical surplus fed into the grid and used at a later time. The electricity surplus that comes from high irradiance period during summer or from the not precise electricity led operation mode of the SOFC system is shown on the box in the upper right. To reduce the amount of ramp-up and ramp-down, the SOFC modules work in fixed power steps which leads to electricity surplus that may exceed the grid compensation demand, in case of an oversized system such as in the second and third case study. This electricity exceeding consumption is enhanced by feeding into the grid with a minimum guarantee price, settled at 0.05 €/kWh.

The baseload of the supermarket electricity is 32 kW. The electricity need throughout the year is higher than 36 kW more than 80% of the time. In this case, the SOFC modules cover 40% of the yearly electricity demand.

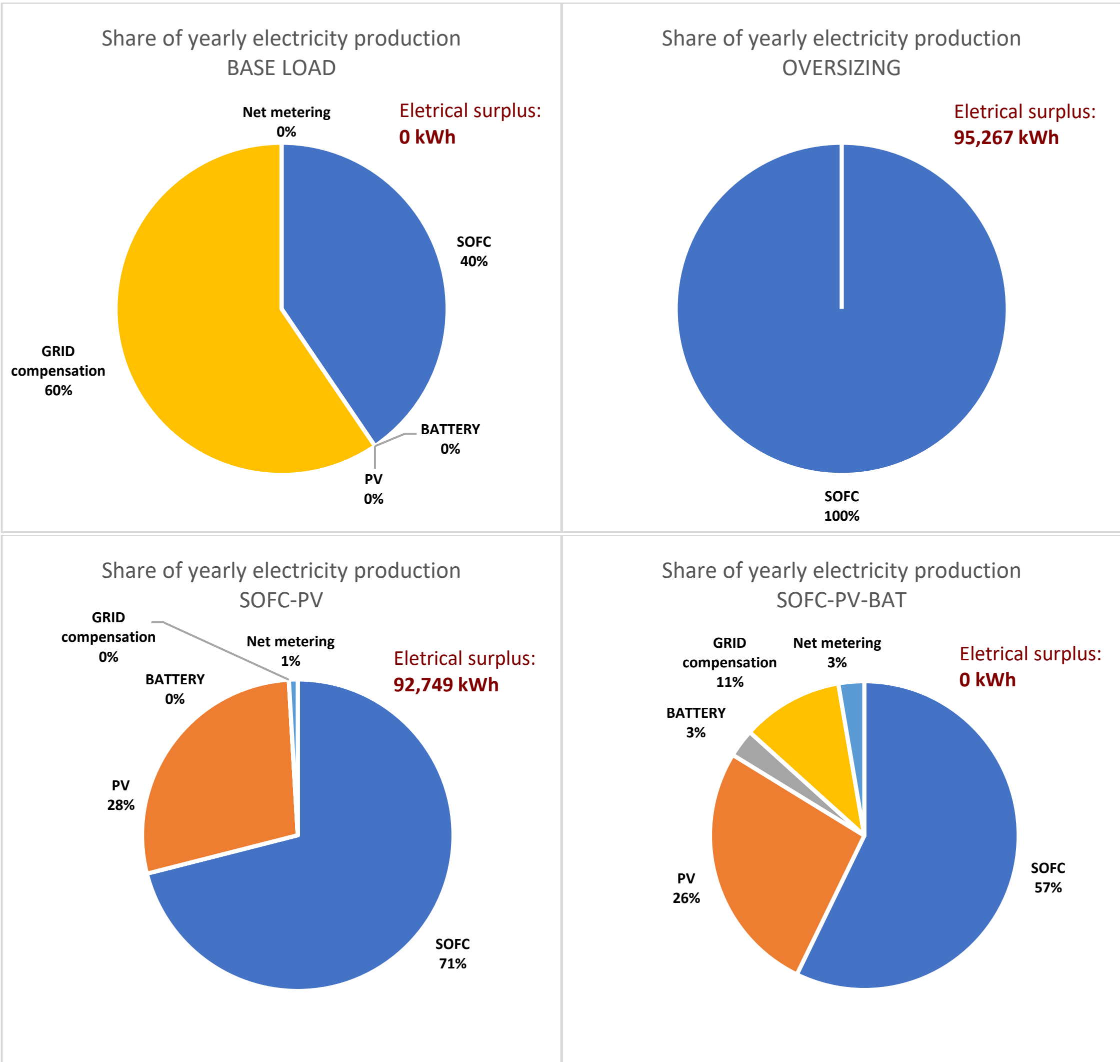


Figure 31: Share of yearly electricity production

Moreover, another disadvantage that occurs in case of oversizing is the increased heat wasted due to the low time-coincidence between the period of high heat demand and the one of high electrical need. It goes from around 38’000 kWh_t for the baseload case study to more than 146’000 kWh_t for the oversizing scenario. This tendency further reduces the benefit of the cogeneration unit, which cannot enhance the heat produced through self-consumption. Table 12 points out these considerations according to the outcomes of the simulations. The percentages of the total production regarding the heat waste increase significantly with the increasing of the SOFC installed capacity due to the high amount of heat wasted during summer. Without an appropriate infrastructure, there is no possibility to recover this energy with a strong seasonal trend. This leads to a reduction of the primary energy saving (PES) achieved by the High-Efficiency Cogeneration.

	Heat production [kWh_t/year]	**Share of annual heat demand**	**Heat wasted [kWh_t/year]**	**Percentage of the total production**
Base load	108,817	20%	37,940	34%
Oversizing	320,095	48%	146,236	45%
SOFC-PV	231,705	38%	93,337	40%
SOFC-PV-BAT	160,574	28%	60,624	37%

Table 12: Heat production

The investment cost and the revenues reflect these considerations, and according to the hypothesis presented in Chapter 5 and 6, they are shown in Table 13. The CAPEX includes the costs for the stack and/or Li-ion replacement. All the parameters are kept constant with the exception of the electricity and gas savings, which are annually updated according to efficiency degradation that occurs in the SOFC modules (Eq. 10 and Eq. 11). For this reason, the entries of the list regarding energy savings and revenues are expressed as an average value over 21 years using the system.

	Unit	**Case study**			
		Base load	***Oversizing***	***SOFC-PV***	***SOFC-PV-BAT***
CAPEX	€	301,200	1,494,00	1,240,500	792,500
OPEX	€/y	18,800	52,001	45,626	34,448
Electricity savings	kWh/y	290,135	757,363	703,267	624,170
Heat savings	kWh/y	81,876	209,729	172,995	117,085
Electricity revenues	€/y	36,334	83,352	87,908	78,021
Gas revenues	€/y	2,694	6,921	5,709	3,864
Subsidies	€/y	6,606	9,167	12,325	10,093
SSP	€/y	-	4,764	4,997	3,269
Balancing revenues	€/y	-	3,105	1,380	2,070

Table 13: CAPEX, OPEX and average values of energy savings and revenues

Very indicative is the fact that the subsidies disbursed through white certificates are lower for the oversizing case study, although the installed SOFC modules have a greater total capacity. This is since almost half of the heat generated in cogeneration is dispersed due to bad timing with the heat load, furthermore, always working at partial load, the overall efficiency of the system is also significantly affected. The SOFC-PV-BAT system, shows, compared to the ones analysed in order to provide grid balancing, a higher percentage incidence of subsidies with respect to the initial investment as result of an annual primary energy saving of 347 MWh.

The outcomes of the economic evaluation expressed in Table 13 contribute to defining the cumulative cash flow performed in base year currency, shown in Figure 32.

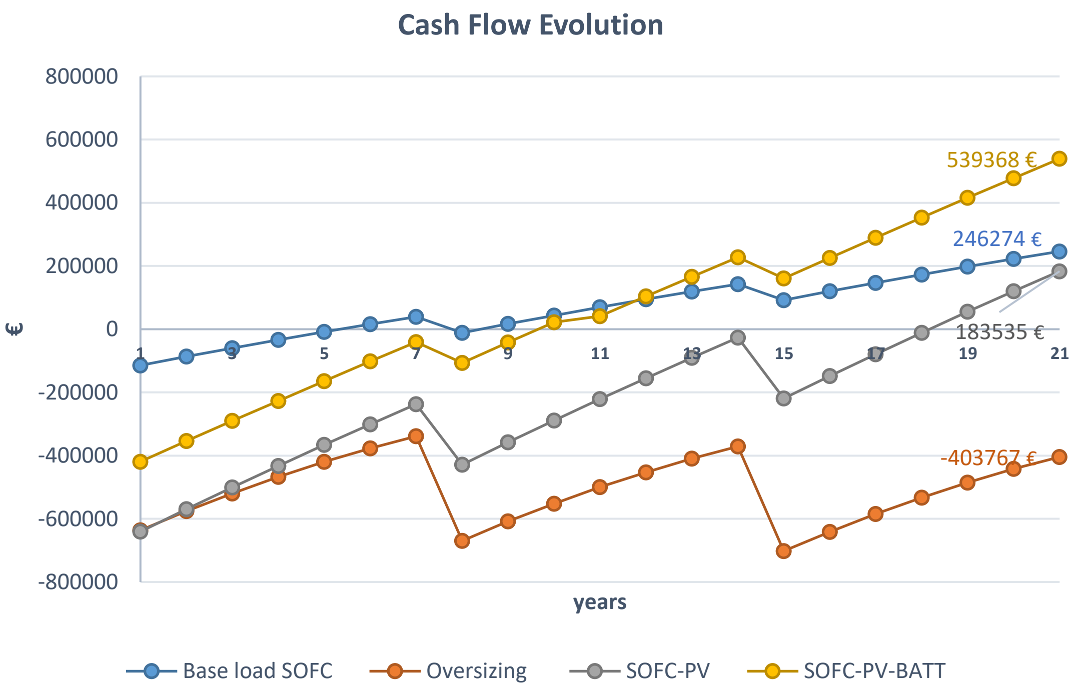


Figure 32: Cash flow evolution

Every seven years, at the end of the stack lifetime, the asset owner has to invest part of the initial capital expenditure in replacing the stacks of the SOFC system, which widely conditions the possibility of obtaining positive net cash flows in those years. This leads to significant penalisation for those systems that show high SOFC installed capacity and low capacity utilization rate, such as oversizing and SOFC-PV systems.

According to the cash flow evaluation, the Payback Time (PBT), which represent the period required to recover the initial cost of the investment, is lower than the project duration of 21 years in the most cases. The base load scenario is the first to reach the PBT after little more than five years, followed by the SOFC-PV-BAT system with a PBT of approximately ten years and finally followed by SOFC-PV system which achieves the PBT after eighteen years. On the contrary, the oversizing system does not lead to substantial revenues which may justify the capital expenditure.

The slope of the curve is mostly determined by the annual electricity revenues of the system, as reported in Figure 33, which are related to yearly electricity production and the SOFC efficiency degradation. Even if the oversizing system is able to meet all the annual electricity demand, according to Figure 31, the occurrence of high performance degradation leads to a rounded curve profile which limits the earning opportunity.

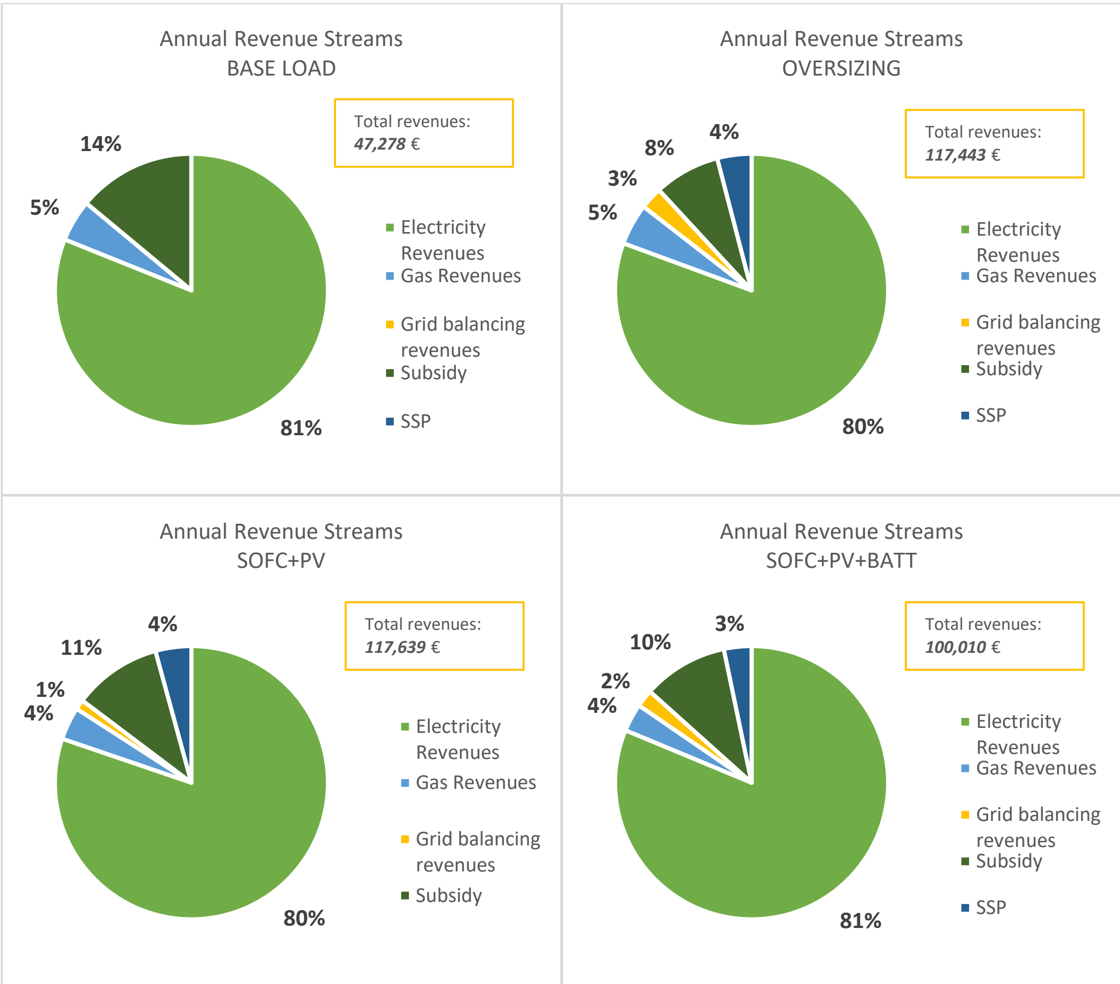


Figure 33: Annual revenue streams related to the first-year operation

The revenues coming from grid balancing service are minor with respect to the incoming cash flow. Therefore, they must be considered as additional but not determinant share to condition decisions regarding the size of the plant. Subsidies through white certificates constitute, on average, 10% of the total annual revenues. The share of revenues from electricity savings, through self-consumption of the produced electricity, constitutes four-fifths of the total incomes and, therefore, it must be valued as a fundamental parameter to obtain a favourable PBT.

The trend of the discounted cash flow (DCF) is then analysed for the most convenient system, i.e. SOFC-PV-BAT case study. As shown in Figure 34, the present value of expected future cash flows is above the current cost of the investment, which could lead to the opportunity of resulting in positive returns. The exceptions with respect to the marked increasing trend of the curve are attributable to the replacement of the battery pack during the 10th year and the replacement of the SOFC stacks in the seventh and fourteenth year.

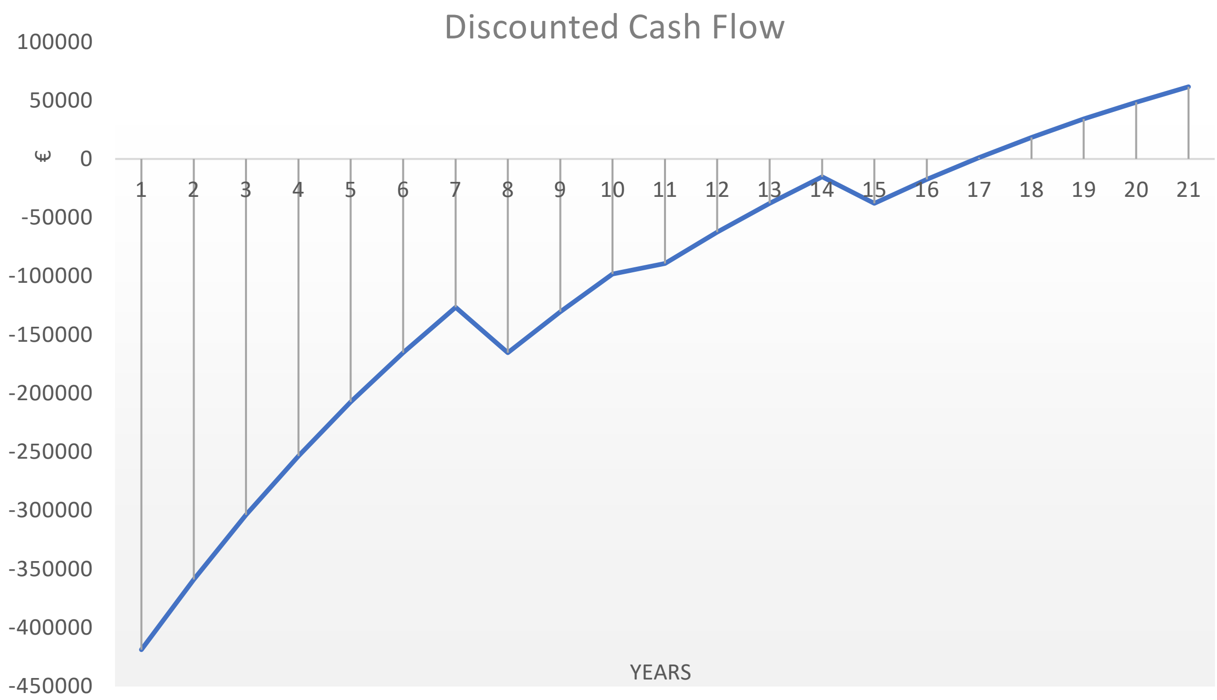


Figure 34: Discounted cash flow evaluation for SOFC-PV-BAT system

8 Comparative results

8.1 Environmental impact

A Solid Oxide Fuel Cell is able to eliminate all local pollutants (NOx, SOx, VOC) and particulates emissions. Natural gas-powered stationary fuel cells can also substantially reduce CO_2 emissions as a highly efficient conversion of low-carbon natural gas (lower emitted tons of CO_2 per kWh). Moreover, they are perfectly suitable for carbon capture without substantial additional cost because of streams separation of fuel and oxidant by plant design.

It has been discussed in Chapter 2 that the operating reserve requirements and the need for flexibility at high levels of penetration of vRES generation increase significantly above those in the conventional systems. Additional active reserves are delivered through an increased amount of plant operating part loaded, i.e. less efficiently, and/or through plants with higher costs and CO2 content, leading to an increase in real-time system management costs and environmental impact [41]. Moreover, if the flexibility capacities are not adequate to absorb intermittent generation, the TSO may have no other option but to curtail the amount of intermittent generation, which would lead to a further threat to the achievement of a more environmentally-friendly system.

An electrical grid based on the DERs and consumers involvement would be the best solution to schedule the optimal provision of reserve and response services, taking into account the capabilities and costs of potential providers of these services, including efficiency losses of part loaded plant and start-up costs. In this scenario, technology such as SOFC could be an important asset not only in terms of flexibility resource but also regarding pollutant emission. To this purpose, the case studies previously analysed are compared with each other and to the conventional system present in the Italian scene.

Concerning the greenhouse gases (GHGs) and other atmospheric pollutants emission in the energy industry, the Italian National Institute for Environmental Protection and Research (ISPRA) published in 2019 a detailed report, where the emissions were analysed through the breakdown of determining factors [42]. Table 14 provides the GHG emission factor from the electricity sector expressed in $gCO_{2,eq}$/kWh, including the generation from renewable sources, and the emission factors, expressed in quantity of emitted CO2 and NOx per kWh, of the cogeneration pool from fossil sources. The former is used to evaluate the GHG emission from the grid compensation electricity; the latter is used for the calculation of the emissions from the conventional system.

Pollutant	Sources	Type of production	Unit	Value
CO_2	All including RES	Electricity	g/kWh	308
	Conventional cogeneration system	Electricity	g/kWh	433
		Heat	g/kWh	215
NO_x	Conventional cogeneration system	Electricity/Heat	g/kWh	0.23

Table 14: Emission factors related to Italian energy production in 2017

A comparison is made between the emission from a SOFC-based and a conventional system in producing the same amount of energy, which is specifically the share of annual energy (combined heat and power) demand covered by the SOFC-based system in the different case studies. Figure 35 and Figure 36 provide the possibility in reducing the emissions thanks to the analysed power plants, respectively in terms of tons of CO_2 and kilograms of NO_x.

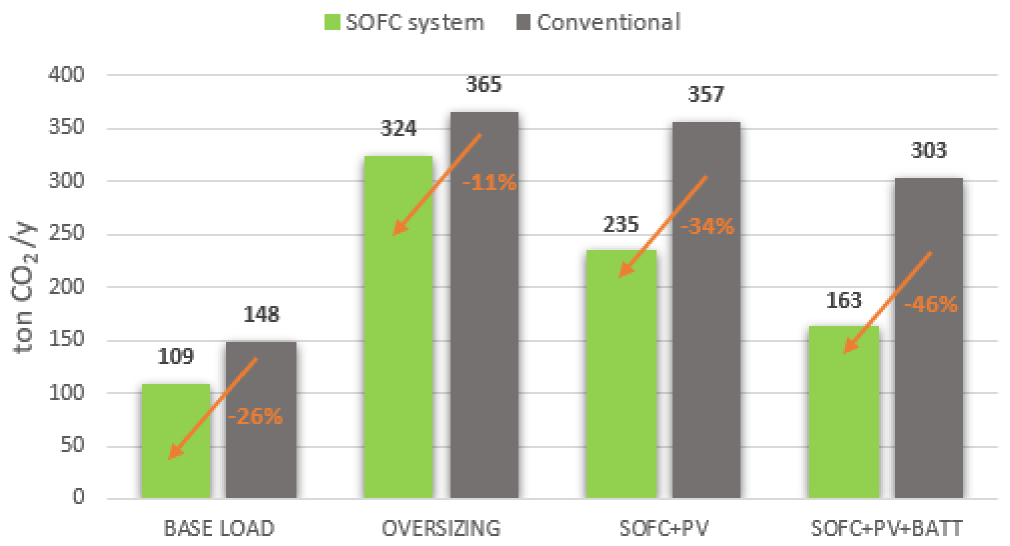


Figure 35: Comparison between yearly CO_2 emissions from conventional and SOFC-based systems

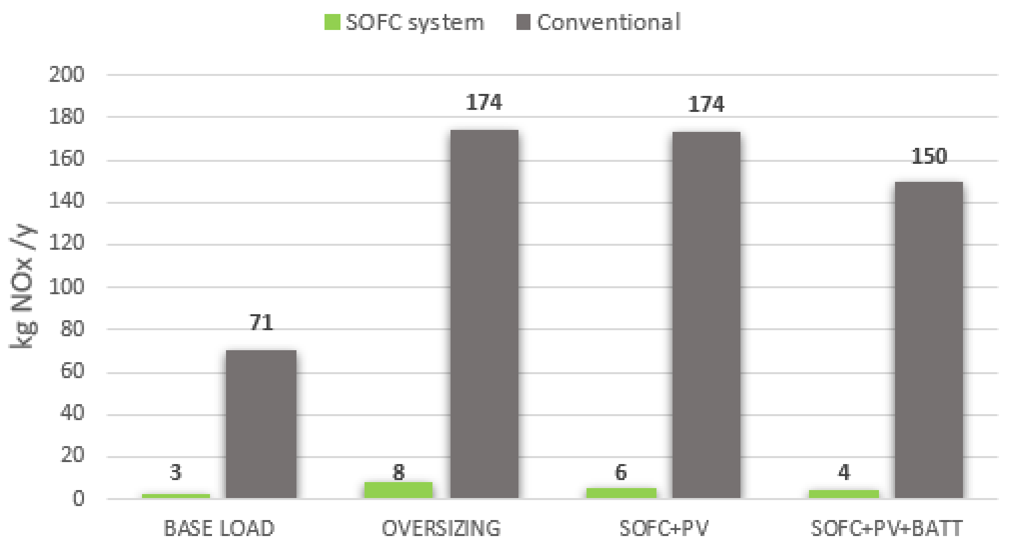
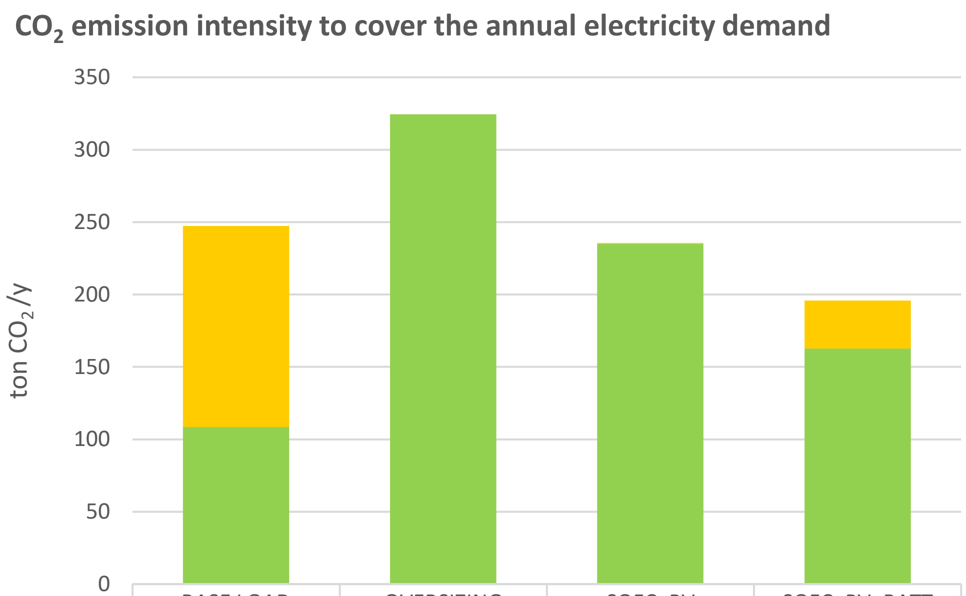


Figure 36: Comparison between yearly NO_x emissions from conventional and SOFC-based systems

Each system is able to cut more than 90% of the NO_x emissions, a result that would significantly increase the quality of the air in areas with high population densities. Concerning the emissions of carbon dioxide, a decrease can be observed compared to the conventional system for every case study. The baseload operation guarantees a percentage of emission savings of 26%, which is entirely to refer to the SOFC highly efficient conversion of low-carbon natural gas. For the oversizing system, the avoided emissions are lower due to the less efficient operation of the SOFC modules which are forced to work at partial load for the majority of the time. For the case of the hybrid system, such as RES-CHP and RES-CHP-BESS, the percentage of CO_2 emission savings ranges from 34% to 46%. The further reduction with respect to the baseload reference case would be attributed both to the efficient conversion within the SOFC and to the production of electricity from renewable sources.

Finally, the different case studies are compared against each other and ranked according to annual CO_2 emission savings in order to meet the entire supermarket electricity requirement, taking into account both the share of the power plant and that of the grid compensation, for which an emission rate of 308 gCO_2/kWh was considered.



	BASE LOAD	OVERSIZING	SOFC+PV	SOFC+PV+BATT
CO2 grid [ton CO2]	139	0	1	33
CO2 plant [ton CO2]	109	324	235	163

Figure 37: CO_2 emission intensity to cover the annual electricity demand of the supermarket

As shown in Figure 37, the CO_2 emission intensity to cover the annual supermarket electricity demand is the lowest for the SOFC-PV-BAT system which efficiently integrates different technologies both from a technical and an ecological points of view. It shows a global CO_2 emission ratio of 258 gCO_2/kWh, which is well below the actual emission factor related to Italian energy production.

8.2 Electrical efficiency

Continuous SOFC stack operation with constant power output generally results in a gradual degradation in performance during long-term operation. However, SOFCs can suffer to a greater degree from changes in operating conditions. Due to thermal expansion mismatch between the different components, the cells can suffer from mechanical degradation mechanisms, such as delamination and crack formation with simple thermal cycling. Changes in the atmosphere can result in more serious degradation. Possible degradation mechanisms can occur at the catalyst level, where Pt-free Nickel clusters enhance the electrochemical reactions. They include Ni agglomeration, Ni oxidation and Ni precipitation at electrolyte grain boundaries; which are accelerated by the presence of constant power modulation. All these phenomena lead to a decrease in electrode activity and consequent cell performance degradation during cycling [43].

The different system solutions analysed in the previous chapters consider both the efficiency curve and the degradation rate of the SOFC stacks throughout the project lifetime of 21 years, taking into account the fuel cell performance degradation due to ageing and cycling. Figure 38 provides an overview of the evolution of the different systems in terms of average electrical efficiency and SOFC load.

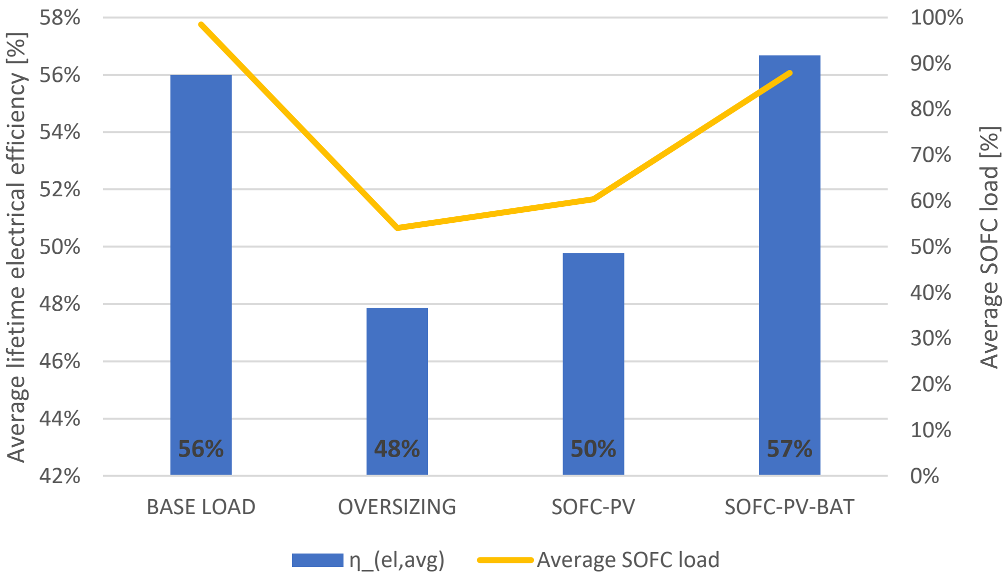


Figure 38: Average lifetime electrical efficiency and SOFC load

The electrical efficiency decreases significantly if the average SOFC load is considerably lower than the nominal value, such as for the oversizing and SOFC-PV systems, due to the simultaneous effect of the degradation phenomena and the efficiency curve penalisation. Whereas the base load and the SOFC-PV-BAT systems show a higher average lifetime electrical efficiency due to their constant power output operation. The integration of a BESS allows the system to work at higher efficient power points, according to Figure 12: Electrical efficiency curve, which eventually leads to the highest $\eta_{el,avg}$ among the analysed systems, equals to 56.7%.

This result ensures for the SOFC-PV-BAT system, which has been previously evaluated as the best solution in terms of economic investment and pollutant emissions, a higher relative amount of subsidies through the TEE incentive mechanism. The annual primary energy savings, expressed in MWh, achieved by the cogeneration unit, is indeed not deeply affected by the occurrence of SOFC efficiency degradation. This would lead to a higher number of "*Certificati Bianchi*" under the same installed electric power capacity throughout the project lifetime.

9 Conclusions

Virtual Power Plant, such as the Italian "*Unità Virtuali Abilitate Miste*" (UVAM – Virtually Aggregated Mixed Units), may become in the next few years an essential facility in the grid balancing market scene. Its peculiarity of being a network of decentralized medium-scale power units will exploit the possibility of meeting increasingly short peaks of high modulation without being affected by the lack of long-term security of supply. On the contrary, as the penetration of variable and unpredictable renewable energy resources increases, the peaks of large production from conventional power plants become shorter in duration and more frequent. In this way, these units become decreasingly cost-effective, thus enabling the development of a wider audience of balancing market parties.

Stationary fuel cells, such as Solid Oxide Fuel Cells, may have a role to play in this scenario. They 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. Moreover, they can tolerate a considerable degree of modulation, even below 50%, which allows the Transmission System Operator to be able to count, when necessary, on a very efficient and flexible capacity reserve distributed throughout the territory. The techno-economic potential of the SOFC-based systems has been investigated under realistic operation conditions by integrating them within an Italian supermarket and varying the components of the power plant. Three different system configurations have been used and compared with the baseload scenario, which is currently the most studied SOFC system solution [25]: stand-alone SOFC, hybrid SOFC-PV and SOFC-PV-BAT systems.

The economic benefits of grid balancing have proved to be inadequate to justify a large oversizing of the SOFC, however many advantages have been observed in the case of integration, within the SOFC modules, of PV panels and battery energy storage systems. This hybrid configuration allows the plant to minimize CO_2 emissions, enhance the average lifetime electrical efficiency and optimise the earning potential from the economic investment. A SOFC-PV-BAT system has proved to be a valuable asset for a UVAM portfolio since it may modulate its power output according to the grid requirement. The flexibility redundancy, which is given by the SOFC module and BESS, allows promptly responding to the TSO signals. The drawback is mostly related to the need for reducing the residual demand of the supermarket load by PV production in order to exploit the SOFC and BESS capacity in case of a dispatching order from the TSO. The aggregator must therefore be able to adapt the assets schedules in its network in an effective way, taking into account for each system the availability, the actual power output and the residual power capacity. However, the existing UVAM pilot project framework does not allow the possibility of submitting bids on the MSD for a portion of the quantity assigned during the auction for annual supply. This obligation may disturb the aggregation of multiple resources, by making the VPP unable to offer the remaining available capacity on the market if some of its assets are unavailable. The request to insert a partial remuneration, if it is not possible to reach the assigned capacity in the bidding obligation period, could provide a valid incentive to promote the DER involvement in the balancing market.

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Bibliography

[1] European Comission, “A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.”

[2] K. Poplavskaya and L. de Vries, “Distributed energy resources and the organized balancing market: A symbiosis yet? Case of three European balancing markets,” *Energy Policy*, vol. 126, pp. 264–276, Mar. 2019, doi: 10.1016/j.enpol.2018.11.009.

[3] C. Redl, D. Pescia, V. Rious, N. Hary, and M. Saguan, “Refining Short-Term Electricity Markets to Enhance Flexibility.” [Online]. Available: www.agora-energiewende.de.

[4] T. I. Strasser, S. Rohjans, and G. M. Burt, “Methods and Concepts for Designing and Validating Smart Grid Systems.” [Online]. Available: www.mdpi.com/journal/energies.

[5] ComSos, “Commercial scale SOFC systems,” 2018. https://www.comsos.eu/.

[6] L. Hirth and I. Ziegenhagen, “Balancing power and variable renewables: Three links,” *Renewable and Sustainable Energy Reviews*, vol. 50. Elsevier Ltd, pp. 1035–1051, 2015, doi: 10.1016/j.rser.2015.04.180.

[7] R. A. C. van der Veen and R. A. Hakvoort, “The electricity balancing market: Exploring the design challenge,” *Util. Policy*, vol. 43, pp. 186–194, Dec. 2016, doi: 10.1016/j.jup.2016.10.008.

[8] European Comission, “Concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (Text with EEA relevance),” 2009.

[9] G. Delille, B. François, and G. Malarange, “Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system’s inertia,” *IEEE Trans. Sustain. Energy*, vol. 3, no. 4, pp. 931–939, 2012, doi: 10.1109/TSTE.2012.2205025.

[10] M. Resch, “Impact of operation strategies of large scale battery systems on distribution grid planning in Germany,” *Renewable and Sustainable Energy Reviews*, vol. 74. Elsevier Ltd, pp. 1042–1063, 2017, doi: 10.1016/j.rser.2017.02.075.

[11] A. Berrada, K. Loudiyi, and I. Zorkani, “Valuation of energy storage in energy and regulation markets,” *Energy*, vol. 115, pp. 1109–1118, Nov. 2016, doi: 10.1016/j.energy.2016.09.093.

[12] V. Bobinaite, A. Obushevs, I. Oleinikova, and A. Morch, “Economically efficient design of market for system services under the Web-of-Cells architecture,” *Energies*, vol. 11, no. 4, Apr. 2018, doi: 10.3390/en11040729.

[13] A. Pinto-Bello, "The smartEn Map European Balancing Markets Edition," 2018. [Online]. Available: www.smarten.eu.

[14] ARERA, "Documento per la consulatazione 201/2020/R/eel, Orientamenti relativi alla partecipazione dei veicoli elettrici al MSD, per il tramite delle infrastrutture di ricarica dotate di tecnologia vehicle to grid," 2020.

[15] M. Giuntoli and D. Poli, "Optimized thermal and electrical scheduling of a large scale virtual power plant in the presence of energy storages," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 942–955, 2013, doi: 10.1109/TSG.2012.2227513.

[16] M. Loßner, D. Böttger, and T. Bruckner, "Economic assessment of virtual power plants in the German energy market — A scenario-based and model-supported analysis," *Energy Econ.*, vol. 62, pp. 125–138, Feb. 2017, doi: 10.1016/j.eneco.2016.12.008.

[17] "Electricity Production | Energy-Charts." https://energy-charts.info/charts/power/chart.htm?l=en&c=DE (accessed Oct. 23, 2020).

[18] "Virtual Power Plants (VPP): Applications for Power System Management - Example Germany - ESIG." https://www.esig.energy/blog-virtual-power-plants-vpp-applications-for-power-system-management-example-germany/ (accessed Oct. 23, 2020).

[19] Y. Ninomiya, J. Schröder, S. Thomas, and W. Institute, "Comparative study-Digitalization and the Energy Transition: Virtual Power Plants and Blockchain Report on analysis in Japanese FY 2018: The role and status of Virtual Power Plants and blockchain technology," 2019.

[20] "Virtual Power Plant | Power Trader | Aggregator." https://www.next-kraftwerke.com/ (accessed Oct. 23, 2020).

[21] ARERA, "Deliberazione 5 Maggio 2017 300/2017/R/EEL -Prima apertura del MSD alla domanda elettrica ed alle fonti di produzione anche da fonti rinnovabili non già abilitate nonchè ai sistemi di accumulo-," 2017.

[22] V. Chiesa, D. Chiaroni, S. Franzò, F. Frattini, and A. Di Lieto, "ELECTRICITY MARKET REPORT -L'apertura del MSD oltre i progetti pilota: quali ricadute per il sistema paese?-." [Online]. Available: www.energystrategy.it.

[23] ARERA, "TESTO INTEGRATO DEL DISPACCIAMENTO ELETTRICO (TIDE)-ORIENTAMENTI COMPLESSIVI-Documento per la consultazione Mercato di incidenza: energia elettrica." [Online]. Available: www.arera.it.

[24] ENEL X, "Demand Response: nuove opportunità dal mercato dell'energia," 2019.

[25] M. Gandiglio, M. Santarelli, M. Sciaulino, G. Giolitti, and T. Hakala, "ComSos - Deliverable number 5.3- Market analysis of CHP solutions applied in commercial applications," no. 5, 2019.

[26] G. Giolitti, “Analysis of the hotel sector as a potential market for fuel cell-based cogeneration systems.,” Politecnico di Torino.

[27] F. Accurso, “Techno-economic evaluation of SOFC-based cogeneration systems for the hospital sector.,” Politecnico di Torino.

[28] M. Gandiglio, M. Santarelli, M. Sciaulino, G. Giolitti, and T. Hakala, “ComSos - Deliverable number 5.2- Techno-economic models of the considered SOFC-based CHP systems,” no. 5, pp. 1–11, 2019.

[29] K. Cieslak and P. Dragan, “Comparison of the existing photovoltaic power plant performance simulation in terms of different sources of meteorological data,” *E3S Web Conf.*, vol. 49, pp. 1–8, 2018, doi: 10.1051/e3sconf/20184900015.

[30] G. Bruni, S. Cordiner, M. Galeotti, V. Mulone, M. Nobile, and V. Rocco, “Control strategy influence on the efficiency of a hybrid photovoltaic-battery-fuel cell system distributed generation system for domestic applications,” *Energy Procedia*, vol. 45, pp. 237–246, 2014, doi: 10.1016/j.egypro.2014.01.026.

[31] L. Gracia, P. Casero, C. Bourasseau, and A. Chabert, “Use of hydrogen in off-grid locations, a techno-economic assessment,” *Energies*, vol. 11, no. 11, 2018, doi: 10.3390/en11113141.

[32] BMWi, “Markets for Battery Storage.”

[33] ARERA, “Deliberazione 6 Dicembre 2018 639/2018/r/ AGGIORNAMENTO DEL TASSO DI REMUNERAZIONE DEL CAPITALE INVESTITO PER I SERVIZI INFRASTRUTTURALI DEI SETTORI ELETTRICO E GAS, PER GLI ANNI 2019-2021,” vol. 2015, pp. 1–13, 2021.

[34] Eurostat, “Gas prices (from 2007 onwards).” https://ec.europa.eu/eurostat/cache/metadata/EN/nrg_pc_202_sims_it.htm (accessed Oct. 30, 2020).

[35] Eurostat, “Electricity prices (from 2007 onwards).” https://ec.europa.eu/eurostat/cache/metadata/EN/nrg_pc_204_sims_it.htm (accessed Oct. 30, 2020).

[36] GSE, “Cogenerazione ad alto rendimento,” no. Vi, pp. 1–18, 2013.

[37] European Comission, “REGOLAMENTO DELEGATO (UE) 2015/2402 DELLA COMMISSIONE del 12 ottobre 2015,” vol. 2014, no. 8, pp. 328–384, 2007, [Online]. Available: http://www.confcommercio.cs.it/spaw2/uploads/files/allegati.pdf.

[38] GME-Gestore Mercati Energetici, “GME - Esiti dei mercati - TEE - Mercato TEE.” https://www.mercatoelettrico.org/It/Esiti/TEE/TEE.aspx (accessed Oct. 30, 2020).

[39] Gestore dei Servizi Energetici, “Servizio di scambio sul posto,” 2019.

[40] "GME - Esiti dei mercati - MGP - esiti." https://www.mercatoelettrico.org/It/Esiti/MGP/EsitiMGP.aspx (accessed Oct. 31, 2020).

[41] D. Holding, N. Frydas, and G. Doyle, "Impact Assessment on European Electricity Balancing Market," *Manag. Serv. Qual.*, 2013, doi: 10.1108/09604520910943161.

[42] ISPRA, "Fattori di emissione atmosferica di gas a effetto serrra nel settore elettrico nazionale e nei principali Paesi Europei," 2019.

[43] M. Hanasaki *et al.*, "SOFC Durability against Standby and Shutdown Cycling," *J. Electrochem. Soc.*, vol. 161, no. 9, pp. F850–F860, 2014, doi: 10.1149/2.0421409jes.