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# Smart microgrid: how to reduce costs and $CO_2$ emissions in wineries and vineyards

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**Abstract.** The wine sector is greatly threatened by climate change, but is also one of its contributors. In vine-growing and wine-making activities, energy is one of the main sources of $CO_2$ emissions, as well as a significant economic cost. Wine companies often turn to the production and use of renewable energy, usually photovoltaics, as a means of reducing their emissions and operating costs. However, there are several hindrances when it comes to efficiently manage all the energy flows that exist in vineyard and winery. A proposed solution for this is the integration of all generation and consumption points (generators, batteries, pumps, loads, etc.) into a microgrid managed by a smart controller. This controller uses advanced techniques, such as Model Predictive Control, Genetic Algorithms, Internet of Things (IoT) and Artificial Intelligence (AI) to optimise the economic savings and emissions reduction. The solution has been developed and used in a real case study in a winery and vineyard located in a semi-natural environment, as part of the European LIFE CLIMAWIN project. The main objective is to reduce the use of fossil fuel, decrease emissions, maximise renewable energy utilisation and achieve an operational cost reduction, while assuring a fully autonomous operation in a more observable manner. Results already show a reduction of between 16-42% in both fossil fuel consumption and greenhouse gas emissions.

## 1. Introduction

The wine sector is greatly threatened by the effects of climate change. According to the “State of the World Vine and Wine Sector in 2024” report by the International Organisation of Vine and Wine (OIV), data highlight the significant impact of climate change on the EU wine regions, with vineyards facing a wide range of climatic disruptions. Nevertheless, vine-growing and wine-making activities also contribute to climate change.

Although the wine companies are gradually becoming more aware of their responsibility towards sustainability, mitigation measures are still being adopted very slowly and with great variability of criteria [1]. The first step to deploy a mitigation plan is to know which are the main sources of emissions. For this, it is required to calculate the carbon footprint of the wine company activity [2, 3]. According to some studies and life cycle analyses [4-7], energy is usually the second main source of emissions, following packaging. It is also a significant economic cost for the wine company.

Energy is related to a number of processes that occur in the grape-growing and wine-making activity, mainly through fuel consumption and electricity use from the grid. In vineyards, energy is needed for pumping and pressurising irrigation water. Wineries use electricity for process cooling, air conditioning, machinery, lighting, office automation, etc.

The production and use of renewable energies is often adopted by winery companies as means of reducing their emissions and operating costs [8-12]. Usually, this renewable generation relies on photovoltaics, due to the good availability of the solar resource and a good predisposition of the locations. What is more, these locations (specially vineyards) are often isolated. The electricity grid does not reach them, and their connection is difficult and expensive. In these cases, diesel-photovoltaic hybrid generators can be used [11]. However, for them to adequately work, off-grid generators must be close to the consumption points. But this conventional solution does not allow for energy optimisation [13]: when energy production does not match the demand, it is lost, since it can't be used and there is nowhere to evacuate it. Therefore, photovoltaic energy for vineyard irrigation pumping is unused outside the irrigation season, while that for wineries is very underused outside the post-harvest season. This means missing the potential opportunity for economic savings and emissions reduction. Batteries do not solve the problem either, as it is only profitable to store energy for a few hours. On the other hand, integrating multiple generators and remote consumption points presents a number of problems regarding grid stability and quality of supply. Energy management is difficult and requires advanced techniques.

The proposed solution relies on the integration of all generation and consumption points into a microgrid managed by a smart controller [14-16]. This controller uses advanced technologies, such as Model Predictive Control, Genetic Algorithms, Internet of Things (IoT) and Artificial Intelligence (AI). The main objective is to reduce the use of fossil fuel, decrease emissions, maximise renewable energy utilisation and achieve an operational cost reduction, while assuring a fully autonomous operation in a more observable manner.

The microgrid and smart controller have been developed and used in a real case study in a winery and vineyard located in a semi-natural environment, as part of the European LIFE CLIMAWIN project.

This paper explains the configuration and functioning of the proposed solution, in the context of the case study. It shows the first obtained results regarding emissions and operational costs reduction.

## 2. Methodology

Outline for the methodology followed to develop the proposed solution is shown in Figure 1.

After the revision of the state of the art, in terms of microgrid technology and smart control techniques, and the selection and analysis of the case study, two parallel workflows are developed.

The first one consists of the modelling and simulation of the microgrid system, in order to study its operation and validate the control algorithms. To do so, the control strategy to be used by the energy manager has been proposed. Two different models have been implemented in the softwares PowerFactory (quasi-dynamic simulation) and Matlab-Simulink (dynamic simulation). The system behaviour has been simulated under different control strategies.

The second workflow consists of the physical implementation of the microgrid elements and control algorithms. Regarding the energy management, there has been a conceptualisation and a programming stage.

Additionally, experimental bench tests have been carried out to demonstrate the feasibility of the developed control strategy.

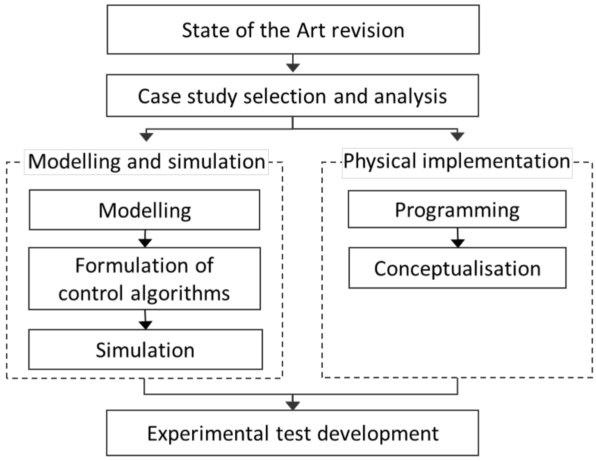


**Figure 1.** Outline of methodology.

## 3. Case study

The proposed solution has been implemented in the premises of the winery and vineyard of Bosque de Matasnos, located in a semi-natural environment in Burgos, in the Ribera del Duero Denomination of Origin area in Spain (Figure 2). It counts with 123.4 hectares of native forest, 53.3 hectares of rainfed cereal and 67 hectares of vineyard.


**Figure 2.** Bosque de Matasnos location.

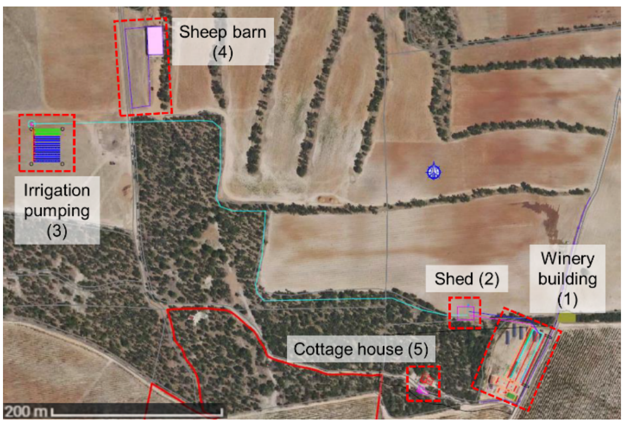


**Figure 3.** Distribution scheme of the consumption centres.

The whole place has no connection to the electric grid. In the past, energy was mostly reliant on fossil fuels. In 2020, the owners installed a photovoltaics system for direct pumping (extracting the groundwater to irrigate the vineyard parcels). Since then, vineyard irrigation worked by a hybrid system combining photovoltaics and a diesel generator set. The building of the winery was built in the location in 2023. To cope with its demand, a photovoltaic stand-alone system with energy storage in batteries was installed for the whole winery premises, reducing the use of fossil fuels. In addition to the pre-existing pumping facilities for vineyard irrigation, and a residence used by the winery owner, there is also a new pumping station, together with a sheep barn. All this leads to a significant increase in electricity demand and the need for a better security of supply.

There are five electricity consumption centres (Figure 3). Each of them is univocally associated to a single network segment or bus, and all of them are formed in a radial configuration. All nodes are electrically separated from each other by up to more than one kilometre.

The consumption nodes are as follows:

- Winery building (1) and ancillary premises. This is the central generation node and grid generation.
- Shed (2). This is the central pumping, water treatment and ancillary equipment.
- Pre-existing irrigation pumping (3). Generation.
- Sheep barn (4).
- Cottage house (5).

Main loads (Table 1) correspond to the industrial processes in the winery (100 kW), water pumping (74 kW), water treatment (27.6 kW) and farm machinery and processes (27.6 kW). These loads are considered unmanageable, as they are subordinated to agricultural and viticultural criteria.

**Table 1.** Electric loads.

| Bus | Type | Power [kW] |
|---|---|---|
| Winery building (1) | Industrial loads | 100 |
| Shed (2) | Water treatment | 27.6 |
| | Irrigation pump | 37 |
| Irrigation pumping (3) | Irrigation pump | 37 |
| Sheep barn (4) | Farm loads | 27.6 |
| Cottage house (5) | Residential loads | 9.2 |

The implemented microgrid integrates all the electricity demands for both winery and vineyard, as well as all the systems for electric production and distributed storage. It also incorporates an advanced system for the intelligent management of deferrable loads, manageable generation and electricity storage.

## 4. Microgrid topology

The exposed topology suggests the introduction of a distributed system based on sub-networks (physical and virtual agents). This is because a large part of the elements that make up the microgrid are non-manageable and non-linear, making a complete centralised approach less viable.

Due to their spatial proximity, simplicity of aggregation and critical nature, two physical agents and a central one have been configured. The characteristics of its distributed energy resources (DERs) are shown in Table 2.

**Table 2.** Characteristics of the agents that make up the microgrid. Pp: peak power; Pn: nominal power; Pch: charge power; Pdis: discharge power; Pset: setpoint power.

| Agent | Photovoltaics | | Battery storage system | | | Genset | |
|---|---|---|---|---|---|---|---|
| | $P_p$ [kW] | $P_n$ [kW] | $P_{ch}$ [kW] | $P_{dis}$ [kW] | C [kWh] | $P_n$ [kW] | $P_{set}$ [kW] |
| Central (1) | 179.8 | 150 | 90 | 90 | 450 | 150 | 120 |
| Pump (3) | 67.8 | 50 | 12 | 12 | 138 | 0 | 0 |
| House (5) | 7.1 | 8 | 12 | 12 | 192 | 0 | 0 |

The following sections explain in more detail the configuration of the central agent formed by the winery premises (1), the local agent formed by the vineyard irrigation pumping (2) and the other local agent formed by the cottage house (5).

### 4.1. Winery premises central agent

It constitutes the central agent and grid-forming node of the distributed microgrid. This is because of the multicluster unit, which combines the rest of the elements and enables operation of the stand-alone system.

Regarding the DERs, this central agent counts with photovoltaic generation, energy storage and a back-up genset.

A photovoltaics (PV) field is mounted on the roof of the winery building with an east-west orientation (Figure 4). It has a total peak power of 179.8 kWp and nominal power of 150 kW. The three grid inverters, located in the facilities room inside the main building, convert the direct current produced on the photovoltaic modules to alternating current, which is the current required by the winery loads. The grid inverters maximise and optimise the power generation of the PV modules. They monitor the PV system energy yield, the electrical activity and possible signals in case of any problems.

The energy storage system consists of five clusters of low voltage Lithium-ion batteries, with inverter-chargers. Total power is 90 kW, and 450 kWh of capacity. The inverter-chargers are able to create a stable virtual three-phased grid through the batteries that allows the coupling of the grid inverters of the photovoltaic systems. The inverter-chargers also convert the direct current coming from the battery system into alternating current, used by all the electrical devices in the winery premises. What is more, the surplus energy produced by the grid inverters in alternating current is absorbed by the inverter-chargers and converted to direct current to charge the batteries.

**Figure 4.** Photovoltaics field on the winery building roof.

On the other hand, the energy storage system in batteries provides stability to the microgrid. It provides the required power for the inverter-chargers to create the grid. The battery system stores the surplus electrical energy produced by the photovoltaic modules. It is charged during the hours of greatest photovoltaic production and makes this energy available during the hours or periods of less solar radiation or during the night-time. This way, the use of diesel generator in times with low solar radiation is minimised.

All these equipment is located in the facilities room (Figure 5) in the winery building, alongside with the switchboards and the rest of the electronic and electric equipments (electric panels and cabinets, copper wiring, small electrical materials, such as electrical protections, wattmeters, etc.)

Additionally, a back-up diesel genset provides the required power whenever the PV and battery systems are not able to. It has a total power of 150 kW. It charges the batteries when there is a lack of solar irradiance and, therefore, there is no photovoltaic production, and when the state of charge (SOC) of the battery is below a preset value. It also operates if the power demand is higher than the maximum power value that can be delivered by the battery system.

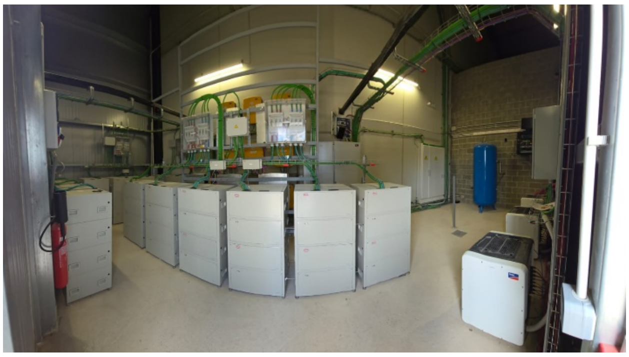

**Figure 5.** Panoramic photograph of the facilities room in the winery building: central agent.

### 4.2. Irrigation pumping agent

One of the physical agents consists of the irrigation pumping.

The oldest photovoltaic system is located close to the vineyards (Figure 6). It consists on a PV field of a total peak power of 67.8 kWp mounted on the ground on a fixed concrete structure facing south. The power is limited to 50 kW. The grid inverter, located inside the irrigation shed, converts the direct current produced on the photovoltaic modules to alternating current, which is the current required by the water pumping irrigation system. The grid inverter maximises and optimises the power generation of the PV modules. It monitors the PV system energy yield, the electrical activity and possible signals in case of any problems.

It is planned to include a small battery energy storage system, with total power of 12 kW and 138 kWh of capacity. This battery is intended to increase storage capacity and improve power quality, minimising voltage deviations and zone loading.

**Figure 6.** Photovoltaics field close to the vineyard.

### 4.3. Cottage house agent

The last physical agent is the cottage house. It counts with a small PV system for residential loads.

It is also planned to include a small battery energy storage system, with total power of 12 kW and 192 kWh of capacity. This battery allows to change the operating mode to work independently, in the event of a grid generation system outage.

## 5. Smart control system

The last component of the microgrid is the smart control system, which aggregates the information and manages the energy flows in order to maximise the production and use of renewable energy and minimise the use of diesel, maintaining the genset only as a back-up system.

### 5.1. Communication and monitoring

In order to implement the smart control system, it is required to deploy sensors in the generation and storage systems along with a number of grid-analysers.

The acquisition and visualisation of the information from the microgrid operation is monitored via the data manager communications centre, which maximises the performance of the system components in real time and keeps them in perfect sync. This device makes it possible to quickly monitor the battery system state of charge, energy consumption, photovoltaic generation and diesel generator usage. Additionally, the monitoring system tracks alerts, diagnostic checks and allows to resolve problems remotely. All of this information can be remotely visualised in PC and mobile and tablet devices by accessing to the data manager software or app.

### 5.2. Smart Control topology

The microgrid control topology follows a distributed multi-agent scheme (Figure 7). Its basic principle hinges on a set of self-optimising agents behaving as standalone manageable systems and communicating with a central coordinating entity, effectively constituting a set of microgrids connected to the mains in a similar manner to that of a distribution microgrid.

The physical agents are formed by a group of distributed resources (DERs) connected to the same bus, while virtual agents are constituted by a group of DERs not necessarily connected to the same bus, but which are aware of the existence of other agents. At a control level, both behave as standalone and controllable units. There is a point of common coupling (PCC) through which the energy exchange takes place. This point is common to any agent.

The coordinator, or central agent, on the other hand, is a purely virtual entity that manages the overarching elements, such as the grid forming inverters. Unlike a regular agent, this entity is aware of all them. However, its knowledge stops at their point of connection. The coordinator also implements a special subset of agents (control agents) that to varying degrees share the coordinator's awareness, functioning as standings for the overarching elements or other more abstract concepts such as grid-quality.

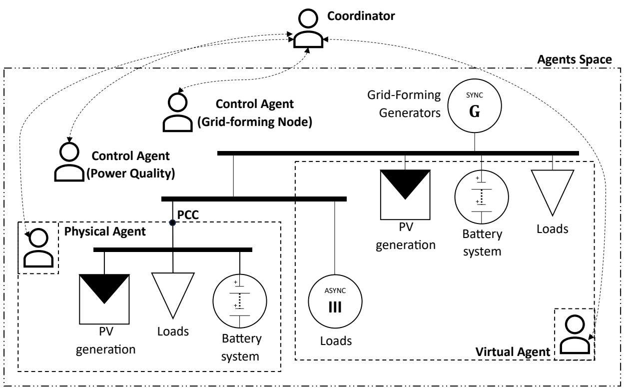


**Figure 7.** Graphical scheme of the multi-agent control topology.

### 5.3. Control operation scheme

A set of costs is applied to all energy imports and exports at the point of common coupling, similar to conventional distribution grids. To ensure proper operation, the coordinator must establish the agents' set of costs for imports and exports. To do so, the coordinator periodically enters a negotiation with the agents. It sends information regarding possible sets of costs and in turn receives data on the expected imports and exports, alongside with the estimated operational costs for each of them. Part of this information is then made public to the control agents. They may respond with an infeasibility or a new compound cost. This process is repeated until convergence is reached. At the point of convergence, a final set of costs is determined and published to the rest of the agents.

Since the set of costs constitutes the gross of the information exchange from the coordinator towards the agents, the latter are free to optimise themselves in whichever manner see fit. The distributed agents follow the model predictive control directives for their optimisation. This also offers the advantage of shifting the computational load from the coordinator towards the agents during negotiation, effectively parallelising the optimisation processes.

## 6. Simulation of operation

The microgrid system is modelled and simulated to analyse its operation and validate the control scheme. Two different models have been studied: quasi-dynamic and dynamic simulation. Quasi-dynamic models are viable for simulating long periods, while dynamic models are best suited for simulating the actual behaviour of the control scheme and microgrid components response. The latter are able to simulate transient behaviours, but have greater computational costs.

The expected long-term behaviour of the microgrid is obtained by means of a quasi-dynamic simulation, using the software PowerFactory. The microgrid components (generators, storage systems and electrical lines equivalents) have been implemented into the model through their manufacturer and equipment model (if available in the software's database) or by introducing their characteristics as in their datasheet. Previously estimated loads have been parametrised through a timeseries yearly and in a per quarter hour basis. Unknown loads have been parametrised through their peak power and according to the generally approved profiles for residential, agricultural breeding, and continuous commercial loads respectively.

Regarding the smart control scheme, the software Matlab-Simulink has been used. The model used in these simulations implements every distributed energy resource (generators, batteries, pumps, loads, etc.) through an equivalent model of the same characteristics. In example, generators operating under the same conditions at the same bus, batteries on a master-slave configuration or close-by loads that hang from the same bus get combined into a single electrical equivalent, the implementation of which reduces computational load whilst having no significant effect on the quasi-dynamic simulation's accuracy. Quasi-dynamic behaviour of commercial control systems in the grid have been modelled and parametrised in accordance with their actual quasi-dynamic behaviour and current settings.

According to the results of the simulations in Simulink, dynamic behaviour of the smart control system has been introduced in PowerFactory software through a simplified scheme of the high-level and low-level control.

The simulations in PowerFactory have been carried out through a whole non-leap year on ten minutes steps, considering the typical meteorological year (TMY) as well as the temperature and time dependant behaviour of the different elements. On the other hand, simulations in Matlab-Simulink have been carried out though variable integration steps for typical days.

## 6.1. Simulation case studies

The following case studies have been considered:

- Genset Only (GSTO). This case study models the microgrid considering a traditional genset only off-grid installation. The whole of demand is met by the current back-up diesel generators which work at variable setpoint. The purpose of this case study is to serve as baseline to the introduction of renewable generation as well as to provide a qualitative perspective on further results.
- Centralised microgrid control (CMGC). This case study models the microgrid after the renewable contribution has been introduced. In this simulation the quasi-dynamic behaviour of the grid-forming node has been evaluated at every step, in turn coordinating the generator dispatch. This case study serves as baseline for the smart control system and provides quantifiable data on the impact of the renewable generation.
- Multi-agent + Metaheuristic Coordinator (MAMC) [17-19]. This case study models the microgrid after the introduction of the decentralised scheme. Iterating over the previous case, this simulation introduces the smart control system and its negotiation events on an hourly basis and on a sequential calculation. Both the prediction and control horizons have been set to 24h. This case study provides a first look into the capabilities of the control scheme.

## 6.2. Simulation results

Simulation results (Table 3) show a reduction in the operating hours of the diesel genset with the CMGC and a further reduction with the MAMC case studies. It is demonstrated that fuel consumption is minimised to back-up uses. Hence, a significant reduction in GHG emissions and other contaminants is achieved (m $CO_2$).

The installation of renewable resources is expected to provide a yearly reduction of equivalent $CO_2$ emissions upwards of 255 ton $CO_2$eq/year. This is equivalent to a 74.9% reduction compared to the “genset only” base case. The introduction of the smart controller is expected to further this trend up to 280 ton $CO_2$eq/year, equivalent to a 29% reduction compared to the centralised control. Furthermore, the introduction of this smart control is expected to improve the grid quality by decreasing the maximum absolute voltage deviation (drops or raises) seen for at least 5% of the time (Δu) by 0.7%. This is equivalent to a 17.1% reduction.

**Table 3.** Comparison of simulation results for each case study.

| Case study | Reference | | | | | |
|---|---|---|---|---|---|---|
| | m $CO_2$ | | | Δu | | |
| | GSTO | CMGC | MAMC | GSTO | CMGC | MAMC |
| **GSTO** | 1.000 | 3.981 | 5.599 | 1.000 | 1.641 | 2.692 |
| **CMGC** | 0.251 | 1.000 | 1.407 | 0.610 | 1.000 | 1.641 |
| **MAMC** | 0.179 | 0.711 | 1.000 | 0.371 | 0.609 | 1.000 |

Table 4 shows the renewable fraction and overall energy efficiency per system. Efficiency has been calculated considering the primary energy of diesel and the electrical energy of the renewable sources.

**Table 4.** Simulated renewable fraction and efficiency for each case study.

| Case study | Renewable fraction | Efficiency |
|---|---|---|
| Genset Only **(GSTO)** | 0.00% | 22.04% |
| Centralised Microgrid Control **(CMGC)** | 71.70% | 52.69% |
| Multi-agent + Metaheuristic Coordinator **(MAMC)** | 78.32% | 61.88% |

## 7. Conclusions and further work

In the context of the LIFE CLIMAWIN project, a microgrid has been implemented in the Bosque de Matasnos winery and vineyard. This microgrid integrates and manages all energy flows. A smart control system has been developed to optimise its operation. This system is based in a multi-agent control scheme with centralised coordination.

The control algorithms of this smart control scheme have been tested and validated through simulations and experimental setup in bench.

The results of the simulations show that, under quasi-dynamic simulation, the proposed control scheme is able to reduce greenhouse gas emissions between 16-42%. This is between 13.5 and 35.3 ton $CO_2$eq/year. In economic terms, the reduction in operating costs is between 7,308 and 19,184€/year (considering a diesel cost of 1.45€/litre). This means a reduction in fixed costs of 7,717€, due to the avoidance of oversizing power lines. The control system allows considering network parameters in the management of resources, managing voltage levels and line loads appropriately.

Regarding the investment in the case study in Bosque de Matasnos, it is recovered in an 8 to 10 years period of time. However, these figures are dependant of the fossil fuel cost variability. In both cases, the levelized cost of energy (LCOE) is at reasonable values 20 years ahead, similar to those of the SPOT market in 2024. Both represent a significant reduction of the LCOE with respect to the base case.

Further works include testing the prototype in the case study location, standardisation of control equipment and acceleration of the algorithm. Further development on the control algorithms is expected in the form of system optimisation, bug fixing and fine parameter tuning, as data acquired will throw light on its actual behaviour.

Other possible lines of work are the implementation of control systems based on neural networks and fuzzy logic with and without stochastic considerations, as well as the consideration of consensus-based multi-agent systems.

## 8. Acknowledgment

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## 9. Abbreviations

The following abbreviations have been used in this paper:

AI – Artificial Intelligence

CMGC – Centralised Microgrid Control case study

DER – distributed energy resource

GHG – greenhouse gases

GSTO – Genset Only case study

IoT – Internet of Things

kW – kilowatt (power)

kWh – kilowatt hour (energy)

kWp – kilowatt peak (peak power)

LCOE – levelized cost of energy

MAMC – Multi-agent + Metaheuristic Coordinator case study

PV – photovoltaic

SOC – state of charge (of a battery)

TMY – typical meteorological year

## 10. References

1. J. Carroquino, N. García-Casarejos, P. Gargallo. J Clean Prod **244**:118874 (2020)
2. V. Russo, A.E. Strever, H.J. Ponstein. Int J Life Cycle Assess **26**, 1374–1390 (2021)
3. A. Laca, S. Gancedo, A. Laca, M. Díaz. Environ Sci Pollut Res **28**:1204–1223 (2021)
4. H.J. Ponstein, A. Meyer-Aurich, A. Prochnow. J Clean Prod **212**:800–809 (2019)
5. K.L. Steenwerth, E.B. Strong, R.F. Greenhut, L. Williams, A. Kendall. Int J Life Cycle Assess **20**:1243–1253 (2015)
6. A. Navarro, R. Puig, E. Kılıç, et al. J Clean Prod **142**:1661-1671 (2016)
7. M. Mainar-Toledo, M. Palmero, M. Díaz-Ramirez, I. Mendioroz, D. Zambrana-Vasquez. Energies **16**, 6589 (2023)
8. C. Gopal, M. Mohanraj, P. Chandramohan, P. Chandrasekar. Renew. Sustain. Energy Rev **25**:351–370 (2013)
9. N. García-Casarejos, P. Gargallo, J. Carroquino. Energy Procedia **153**:438–443 (2018)
10. N. García-Casarejos, P. Gargallo, J. Carroquino. Sustain. **2018**;10(9) (2018)
11. J. Carroquino, R. Dufo-López, J.L. Bernal-Agustín. Renew Energy **76**:566-74 (2015)
12. A. Chel, G. Kaushik. Agron Sustain Dev **31**:91–118 (2011)
13. T. Sebbagh, R. Kelaiaia, A. Zaatri, T. Bechara, L. Abdelouahed. Clean Technol Environ Policy **20**:2365–2373 (2018)
14. A. Cecilia, J. Carroquino, V. Roda, R. Costa-Castelló, F. Barreras. Energies **13**(6):1454 (2020)
15. B. Amrutha Raju, S. Vuddanti, S.R. Salkuti. Energies **14**:5459 (2021)
16. S. Sen, V. Kumar. IEEE Syst J **17**:546–557 (2023)
17. R.B. Amrutha, S. Vuddanti, R.S. Surender. Energies **14**:5459 (2021)
18. J. Hu, Y. Shan, J.M. Guerrero, A. Ioinovici, K.W. Chan, J. Rodriguez. Renew. Sustain. Energy Rev **136**:110422 (2021)
19. J.A. Basantes, D.E. Paredes, R.L. Jacqueline, et al. Energies **16**:2912 (2023)