Smart Microgrid Management: a Hybrid Optimisation Approach

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Abstract

Background: The association of distributed generators, energy storage systems and controllable loads close to the energy consumers gave place to a small-scale electrical network called microgrid. The stochastic behavior of renewable energy sources, as well as the demand variation, can lead in some cases to problems related to the reliability of the microgrid system. On the other hand, the market price of electricity from mainly non-renewable sources becomes a concern for a simple consumer due to its high costs.

Method: In this work, an energy management system was developed based on an innovative optimization method, combining linear programming, based on the simplex method, with particle swarm optimisation algorithm. Two scenarios have been proposed to characterise the relation price versus gas emissions for optimal energy management. The objective of this study is to find the optimal setpoints of generators in a smart city supplied by a microgrid in order to ensure consumer comfort, minimising the emission of greenhouse gases and ensure an appropriate operating price for all smart city consumers.

Results: The simulation results have demonstrated the reliability of the optimisation approach on the energy management system in the optimal scheduling of the microgrid generators power flows, having achieved a better energy price compared to a previous study with the same data.

Conclusion: The energy management system based on the proposed optimisation approach gave an inverse correlation between economic and environmental aspects, in fact, a multi-objective optimisation approach is performed as a continuation of the work proposed in this paper.

Keywords: Microgrid; Smart Sustainable Cities; Energy Management System; Particle Swarm Optimisation; Linear Programming

1 Introduction

The considerable increase in population is followed by an inflation in demand and the human energy consumption can become a large-scale problem. The main problem is the consumption growing of electrical energy which leads to the rising of electricity cost and also to environmental impact mainly when the energy is from conventional sources. According to the International Energy Agency (IEA), in 2018 the production of electricity based on fossil fuels (gas and oil) was estimated at 64% of the total electricity production in the world, while the contribution of renewable sources was estimated at only 26% (hydroelectricity 16%, wind 5%, biomass 3%, solar 2%) and 10% of the production was from nuclear power plants. The world has
experienced a historic peak in greenhouse gas emissions related to the fossil fuel-based production, with 33.1 billion tons of $CO_2$ being released into the atmosphere. As a result, in 2018 the planet’s temperature was more than 1°C warmer than the 19th century average according to the U.S. space agency (NASA). Therefore, the world community made several efforts by orienting the production from renewable energies, especially in the challenge of decreasing global warming [1]. Even though they are inexhaustible and largely available, the stochastic effect of renewable energies leads to innovative methods in order to get the best benefit from them. The utilization of these sources as decentralised generators are the better option for reducing greenhouse gas (GHG) emissions and losses in the energy transport system [2, 3].

To increase the penetration of renewable energies and solve the problems associated with the conventional electrical system such as losses in the transport and distribution networks, the microgrid concept has been introduced to ensure a reliable production in a small scale, by making the place of consumption a place of production [4, 5].

The microgrid is defined as a low-voltage distribution network including various distributed generators (micro-turbines, fuel cells, photovoltaic, wind-turbines, among others), together with storage devices and controllable loads that can operate interconnected or isolated from the main distribution network. Microgrids become a component of smart grids, where a load management system is used to balance the energy generation and consumption [6, 7]. The optimal energy management system can effectively optimize, improve efficiency, provide flexibility, controllability and economic viability of power system operation [8].

A local production from several energy sources gives place to the concept of multi-source. The optimal management of a multi-source system economically and environmentally is a growth research area especially after the objective established by the European Union (EU) to confront the climate change in the framework for action on climate and energy for the period of 2021-2030. The key targets are: reduction of greenhouse gas emissions by at least 40% (from 1990 levels), increasing the contribution of renewable energy to at least 32% of final energy consumption and improving energy efficiency by at least 32.5%. Several management systems strategies have already been proposed, for instance, the authors in [9, 10] developed a mixed-integer programming (MILP) method to deal with the optimal energy control of distributed generators for a small microgrid. In [11] a genetic algorithm (GA) was proposed to achieve an optimisation strategy for hybrid energy systems. In [12] the author proposed a new approach based on artificial fish swarm algorithm (AFSA) to solve the problem of optimal planning of available sources in a microgrid community. In [13] four optimisation approaches have been developed and compared for microgrid source scheduling. The author used the direct search method, particle swarm optimisation (PSO), lambda logic, and lambda iteration. The PSO showed better performance between the four adopted management strategies. In the work performed in [14] the author presented day-ahead optimised scheduling using a harmony search (HS) and differential evolution (DE) algorithms. In [15] an optimal real time energy management was developed to minimise costs and gas emissions and also to encourage renewable generation, by using binary particle swarm optimisation
method (BPSO). In [16] the author proposes an optimal energy management in the presence of a high penetration of renewable energy, a novel model was introduced to deal with the challenging constraint of the supply-demand balance raised by the intermittent nature of renewable energy sources. In this study, the conventional generation costs, utilities with adjustable loads, distributed storage costs were taken into and, additionally, the worst-case transaction cost was included in the objective function.

Seyed et al. proposed in [17] a distributed energy management system called alternating direction method of the multiplier (ADMM) in order to jointly schedule the central controller as well as local controllers. The algorithm considers optimal power flow equations within the distributed energy management problem.

In [18] the author proposed an energy management strategy for a smart city based on load scheduling. Two PSO algorithms were developed in two steps to find the optimal operating set-points. The first PSO algorithm led to the optimal powers set-points of all microgrid generators that can satisfy the non-shiftable needs of the smart city demand with a low operating cost, while the second PSO algorithm aimed at scheduling the shiftable city demand in order to avoid peak hours when the operating cost is high.

Initial integration of information communication technology (ICT) into city operations have promoted telecity, information city, and digital city concepts. Later, the conception of IoT has founded the smart cities, which support the city operations intelligently with minimal human interaction [19]. However, smart cities and sustainable cities have given rise to the 'smart sustainable city' referred to a city that is supported by the pervasive presence and massive use of ICT technology, enable the city to control available resources in a safe, sustainable and efficient way to improve economic and societal outcomes [20, 21]. In this context, the work presented in this paper consists in an architecture extension of the one proposed in [18] by adding a storage system to the distributed generators of the microgrid destined to supply a smart city (photovoltaic system, wind generator and micro-turbine) with connection of the entire microgrid with the utility grid. A combined management strategy between linear programming (LP) based on the simplex method and particle swarm optimisation (PSO) has been adopted to ensure optimal dispatch of the microgrid sources, according to the load-demand of the smart city, while ensuring an optimal energy cost and considering the minimization of GHG emissions. This study presents an innovative optimization approach proposed to ensure an optimal energy management in microgrids using energy storage and load control devices, essential pillars that contribute to the development and evolution of microgrids.

This paper is organised as follows. Section 2 presents an overview of a microgrid community. In Section 3 the energy storage systems is modelled. In Section 4, the problem formulation is presented and the objective function with constraints are formulated. Section 5 explains the adopted energy management strategy with description of the optimization algorithms used. Simulation results for two scenarios of the energy management system are performed and compared in Section 6. Section 7 concludes the study and proposes guidelines to future works.
2 Microgrid Description

The system proposed in this study consists of a combination of photovoltaic generators, a wind turbine farm and a conventional micro-turbine system. Because of the stochastic effect of renewable sources and the limited capacity of the micro-turbine, it is included a storage system in order to ensure the continuous balance between supply and demand and minimize the amount of curtailed energy from renewable resources. The microgrid is connected to the main grid, even so it may have the possibility to be explored off-grid, in case of not required, malfunction or failure of the main grid, the connection is ensured through a transformer and common coupling point (PCC) as indicated in Figure 1. By this way, the main grid acts as a buffer, when the sources and the exploitation procedures into the microgrid are not enough. So, regarding the economic and environmental criteria, the renewable energy sources can provide energy to loads and/or charge the battery. Excess energy, after satisfying local demands, can be fed into the main grid to reduce the total operating costs and reduce the emissions from conventional generation, or it can be exchanged with other microgrids.

In this study case, the battery is dimensioned to assist local load for one hour, and the stored energy cannot be sold to the main grid for safety reasons, reliability and continuity [22]. The energy management system (EMS) will allow an optimal scheduling of distributed generators (DG) and the energy storage system (ESS) by respecting economic and environmental constraints.

![Figure 1 The architecture of the microgrid](image)

The power limits for each DGs and storage device are shown in Table 1, where $P_g$ represents the power delivered by the main grid, $P_{WT}$, $P_{PV}$ and $P_{MT}$ are the power delivered by the wind turbine, photovoltaic system and micro-turbine, respectively. Finally, $P_{SD}$ is the energy associated to the storage device. The main grid can exchange with the microgrid a maximum power of 95kW. In order to reduce the
number of start-up/shutdown and for maintenance reasons [18], the micro-turbine (MT) is present at all times either by its minimum power of 6kW or by the necessary power of load that is limited to 30kW. The battery is used to supply the shiftable part of the load, being its maximum capacity of 15kWh.

| Microgrid system | $P_g$ | $P_{WT}$ | $P_{PV}$ | $P_{MT}$ | $P_{SD}$ |
|------------------|-------|----------|----------|----------|---------|
| $P_{min}$ (kW)   | 0     | 0        | 0        | 6        | -7.5    |
| $P_{max}$ (kW)   | 95    | 80       | 40       | 30       | 15      |

Table 1 Maximum and minimum limits for microgrid production units

Figure 2 shows the daily variation of the power delivered by the renewable generators, namely photovoltaic and wind turbine. The determination of the optimal size of distributed generators is beyond the scope of this paper, therefore the power data delivered by the distributed generators are taken similar to the microgrid proposed in study [18].

Figure 2 The daily power profile from renewable sources [18]

The types of loads in the proposed microgrid are smart home loads, composed of a main fixed part called non-shiftable load, and a secondary part comprising shiftable load that could be shed to avoid a high price of energy at the consumption peaks. The behaviour of non-shiftable and shiftable loads is shown in Figure 3. The loads are connected through sensors and communication technologies, in an internet of things (IoT) based approach, allowing the sensing and transmission of real-time data, which enables decision-making according with specified objectives. This gives to the customer the possibility to program their demand, independently, by taking as reference the instantaneous operating cost delivered by the manager of the microgrid [23]. For this purpose several strategies have already been proven to be effective in load scheduling: the use of fuzzy logic for the optimal management and loads programming in a smart house [24], and many other metaheuristics have allowed moderate consumption planning such as Genetic Algorithm, as proposed
in [25], and PSO presented in [26]. Also, Artificial Neural Network algorithm based forecasting model was developed in [27]. After the load analysis, the most common approach is to perform load shedding to avoid consumption peaks and, consequently, excessive costs. In [16] a PSO algorithm was proposed for this task, achieving a better performance when compared with a standard management.

The contribution of this paper is to ensure the supply of both shiftable and non-shiftable devices, instantaneously, i.e., assuring feeding the essential loads when needed, while assuring the minimisation of the operation costs. A storage system was introduced in the microgrid system to optimise the operating costs and ensure a minimum GHG emission rate followed by the production sources. This operation is ensured by an energy management system (EMS), based on a mixed optimisation method (LP-PSO). To demonstrate the influence link between price and emission, two scenarios are proposed. The first scenario takes into account the optimisation of energy costs as a primary goal, while the second one takes the environmental effect by increasing the utilization of renewable energy sources.

3 Modeling of the Energy Storage System

To optimise the microgrid scheduling, a proper model must be developed for the energy storage system (ESS) [28]. However, there are several types of storage systems: supercapacitors, electrochemical batteries, superconducting magnetic energy storage, compressed air energy storage and flywheel energy storage [29]. These devices have different characteristics, including response times, storage capacities and peak current capabilities, which are applied for different purposes with different time-scales [30]. Electrochemical batteries are selected in this study due to their popularity of storing electrical energy for a long time and capacity.

The ESS system used in this microgrid consists of a bank of electrochemical batteries, connected in series to increase the voltage level and in parallel to increase the
current level \[31\]. The energy stored in the ESS is used as a state variable by the management system. To properly model the ESS, several factors must be considered, such as the capacity and charge/discharge rates. In order to increase the lifespan of the storage system, deep discharges should be avoided. So, considering that \(E(t)\) represents the battery stored energy at time \(t\), the charging and discharging operations are given by:

\[
\begin{align*}
E(t+1) &= E(t) - \Delta t P_c(t) \eta_c, & \text{charging mode} \\
E(t+1) &= E(t) - \frac{\Delta t P_d(t)}{\eta_d}, & \text{discharging mode}
\end{align*}
\]  

(1)

where \(P_c(t)\) and \(P_d(t)\) are the charging and discharging powers of the battery at time \(t\); \(\Delta t\) is the interval of time considered, and finally, \(\eta_c\) and \(\eta_d\) are the charging and discharging efficiencies.

4 Problem Formulation

The aim of the proposed management system is to find the optimal power operation points for distributed generators, storage system and the main grid with respect to economic and environmental constraints.

4.1 Cost Minimization

The definition of the cost function is of most relevance approach. It depends on several parameters, mainly the type of architecture of the microgrid \[32\]. Several functions have already been used, in \[33\] the cost of exploitation from the distributed resources and the storage system were considered constant during the day and selling/buying prices of the main grid were different, while in \[28, 34, 35\], the cost of the distributed resources and the storage system was considered dynamic throughout the day. Also, the cost of selling/buying energy supplied by or injected into the grid varies during the day, being the main objective of the cost function to satisfy the load demand during the day in the most economical way. So, in each hour \(t\) the cost can be calculated as:

\[
C(t) = \sum_{i=1}^{N_g} U_i(t) P_{DGi}(t) B_{DGi}(t) + \sum_{j=1}^{N_s} U_j(t) P_{SDj}(t) B_{SDj}(t) + P_g(t) B_g(t) \tag{2}
\]

where \(N_g\) and \(N_s\) are the total number of generators and storage devices, respectively. \(B_{DGi}(t)\) and \(B_{SDj}(t)\) represent the bids of \(i^{th}\) DG unit and \(j^{th}\) storage device at hour \(t\). \(P_g(t)\) is the active power which is bought (sold) from (to) the utility grid at hour \(t\) and \(B_g(t)\) is the electricity price of the utility grid at hour \(t\). \(U_i(t)\) and \(U_j(t)\) are the operation mode of the \(i^{th}\) generator and the \(j^{th}\) storage device (ON or OFF), respectively. The energy bids of the elements that constitute the microgrid as well as the hourly grid electricity price are known parameters defined according to \[18\], while \(P_{DGi}, P_{SDj}\) and \(P_g\) are the variables that are identified to solve the following problem:
\[ \text{CT} = \min C(t) \quad (3) \]

### 4.2 GHG Emissions Evaluation

Emissions include the polluting gases responsible for the greenhouse effect such as nitrogen oxides (\(NO_x\)), sulfur dioxide (\(SO_2\)), and carbon dioxide (\(CO_2\)) [34]. Table 2 presents the emission factors for non-renewable sources as defined in [28].

| EF        | Micro-turbine (Kg/MWh) | Grid (Kg/MWh) |
|-----------|-------------------------|---------------|
| CO\(_2\)  | 724                     | 922           |
| NO\(_X\)  | 0.2                     | 2.295         |
| SO\(_2\)  | 0.00136                 | 3.583         |

The quantity of GHG Emissions at time \(t\) is given by:

\[
EM(t) = \sum_{i=1}^{N_g} U_i(t) P_{DG_i}(t) EF_{DG_i}(t) + P_g(t) EF_g(t) \quad (4)
\]

where \(EF_{DG_i}(t)\) and \(EF_g(t)\) are GHG emission factors which described the amount of pollutants emission in kg/MWh for each generator and utility grid at hour \(t\), respectively.

The total quantity of GHG emissions in kg during a period of time \(T\), can be determined by:

\[
\text{EMT} = \sum_{t=1}^{T} EM(t) \quad (5)
\]

### 4.3 Power Balance Constraint

The total power generation has to meet the total demand (including storage) and transmission losses. The active power balance is the precondition for a stable operation, in terms of frequency stability. The transmission losses are considered numerically low, being neglected in this study. Thus, the power balance constraint assumes the following form:

\[
\sum_{i=1}^{N_g} P_{DG_i}(t) + \sum_{j=1}^{N_s} P_{SD_j}(t) + P_g(t) = P_L(t) \quad (6)
\]

being \(P_L(t)\) the total electrical load demand at hour \(t\). And knowing that the power of the battery \(P_{SD_j}(t)\) can be positive in case of discharging or negative in the case of charging where it is considered as a load.

### 4.4 Electrical Limits of Generators Constraint

The generators must not operate beyond their limits and, in addition, the energy exchanged between the microgrid and the main grid are limited. The active power
output of each DG and the main grid are limited by lower and upper bounds as follows:

\[
P_{\text{DG}i}(t) \leq P_{\text{DG}i}(t) \leq P_{\text{DG}i}^{\text{max}}(t) \tag{7}
\]
\[
P_{\text{SD}j}(t) \leq P_{\text{SD}j}(t) \leq P_{\text{SD}j}^{\text{max}}(t) \tag{8}
\]
\[
P_{g}(t) \leq P_{g}(t) \leq P_{g}^{\text{max}}(t) \tag{9}
\]

where \(P_{\text{min}}(t)\) and \(P_{\text{max}}(t)\) are the minimum and the maximum powers of the distributed generator (DG), storage device (SD) and the grid (g) at the time \(t\), respectively.

### 4.5 Storage System Limits Constraint

Battery must remain within the limits of its capacity and its charging/ discharging is limited by a maximum rate that must not be exceeded

\[
E_{\text{min}}(t) \leq E(t) \leq E_{\text{max}}(t) \tag{10}
\]

\[
\begin{cases}
-P_c(t)\eta_c \leq P_{c}^{\text{max}} & \text{charging mode, } P_c(t) < 0 \\
\frac{P_d(t)}{\eta_d} \leq P_{d}^{\text{max}} & \text{discharging mode, } P_d(t) > 0
\end{cases} \tag{11}
\]

where \(E_{\text{min}}(t)\) and \(E_{\text{max}}(t)\) are the minimum and maximum energy levels of the battery, respectively, and \(P_{c}^{\text{max}}\) and \(P_{d}^{\text{max}}\) are the maximum rates of charge/discharge of the battery that must be respected in each operation.

### 5 Proposed Management System

In order to be economically and ecologically reliable, two constraints must be considered in the optimisation problem associated to the costs and emissions issues. The proposed microgrid is composed of two conventional sources (micro-turbine and the main grid) responsible for GHG emissions mainly \(CO_2\), \(SO_2\), and \(NO_x\) with different rates. The energy management program, proposed in this study, is established considering two types of loads: non-shiftable and shiftable. The non-shiftable part can be fed by the two renewable sources PV’s and WT’s, the micro-turbine and also the grid. The shiftable part is provided by the storage batteries as first priority with the remaining power from the previous four sources after feeding the non-shiftable part of load. The energy management system (EMS) depends mainly on a mixed optimization using linear programming (LP) based on the simplex method, and a particle swarm optimization (PSO) method.

In order to consider both economic and environmental criteria, two management scenarios are proposed:

**Scenario 01:** The supply of non-shiftable part of load, is supported by the four main generators previously identified: photovoltaic, wind-turbine, micro-turbine and grid,
depending on the state of charge of the storage system. The supply of the shiftable part of load is provided by the storage battery as a first priority. But, in the case where the storage system has reached its minimum state of charge, the compensation is provided by the remaining power after supplying the non-shiftable part of the load.

**Scenario 02**: This approach will mainly take into account the environmental criterion. Although the power supply of the non-shiftable loads is provided by the four main sources, the supply of the shiftable loads is assured by the ESS, but, in the case that the battery bank achieves its minimum state of charge, the lack will be compensated by the remaining power from renewable sources: photovoltaics and wind turbines, if the energy from renewable sources is insufficient for this operation, the non-supplied part will be shifted out to off peak hours.

### 5.1 Optimisation Techniques

This study presents two optimisation techniques to solve the problem presented in section 4, the simplex method and the Particle Swarm Optimization (PSO) approach, detailed below.

#### 5.1.1 Simplex Method

The simplex method is an algorithm for solving linear optimisation problems, its procedure consists in moving from a feasible solution to another, at each step, by improving the value of the objective function. The method is completed after a finite number of these transitions [36].

Two characteristics of the simplex method have led to its acceptance as a computational tool. The first one is the robustness of the method which allows to solve any linear problem: it detects redundant constraints in the optimisation problem; it identifies cases where the objective value is unlimited; it solves problems with multi-local solutions; it is a self-initiated method used either to generate an appropriate and feasible solution, or to show that the problem has no feasible solution. On the other hand, the simplex method offers much more than optimal solutions. It shows how the optimal solution depends on the problem data (cost coefficients, constraint coefficients and right-hand-side data) [36].

#### 5.1.2 Particle Swarm Optimization Algorithm

The PSO is a stochastic optimisation technique that finds the optimal solution using a population strategy iteratively to improve a candidate solution. This method was originally developed by Eberhart and Kennedy in 1995 and it is based on the dynamic behaviour of animals moving in compact groups [37]. PSO depends on a population of simple particles where each particle is considered as a potential solution to the problem [38]. The particles communicate between them in all search space in order to build a solution to the problem posed, by taking advantage of their collective experience. Each particle has a memory of its best position or experience, known as best personal value ($P_i$), and also the best experience of all the particle swarm denoted as global best ($G$) [39].

First of all, a random number of particles are evaluated in the search region, then each particle changes its position in this space according to its own current location
(X_i), previous velocity (V_i), best personal value (P_i) and global best value (G). With some random perturbations, the velocity of each particle is modified iteratively according with the best position. The next step starts again after updating the position (X_i) of each particle. In this process, the swarm as a whole, is able to find the optimal solution [22]. As the particles interact with each other, they progress towards the optimal solution as expressed in Equation (12) [40].

\[
\begin{align*}
X_i(t+1) &= X_i(t) + v_i(t+1) \\
v_i(t+1) &= C_0 v_i(t) + C_1 r_1(P_i(t) - X_i(t)) + C_2 r_2(G(t) - P_i(t))
\end{align*}
\] (12)

The personal best \(P_i(t)\) and the global best \(G(t)\), are updated at each iteration until the global minimum is reached, \(r_1\) and \(r_2\) are random parameters between \([0,1]\). The personal best \(P_i(t)\), associated with the particle \(i\), is the best position that the particle has visited since the beginning of the evolution. Considering a minimisation function, \(f(x)\), the best personal position at the moment, \(t + 1\), is calculated as follows:

\[
\begin{align*}
P_i(t+1) &= P_i(t), \quad f(X_i(t+1)) \geq f(X_i(t)) \\
P_i(t+1) &= X_i(t+1), \quad f(X_i(t+1)) < f(X_i(t))
\end{align*}
\] (13)

The best global position at time \(t\) is defined as follows:

\[G(t+1) = \min_i(P_i(t+1))\] (14)

5.2 Energy management system procedure
The importance of linear programming is illustrated in the first part of execution of the energy management program by using the simplex method as an optimal scheduling tool for the distributed generators that supply the non-shiftable loads. The main highlighted constraint is the assurance of continuous power supply to these loads by the three microgrid distributed generators: photovoltaic, wind turbine, micro-turbine and main grid, while respecting the power limits of each one of them, respectively, \(P_{\text{max}}^{\text{DG1}}\) and \(P_{\text{max}}^{\text{g}}\). In the second step, the PSO is intended to manage the charging and discharging process of the storage system dedicated to supply the shiftable part of the load while respecting the limits constraints (4.5). The initial departure points of the PSO particles are the optimal set point values delivered by the linear programming (LP) algorithm used to schedule the generators of the microgrid to feed the non-shiftable part of the load. Figure 4 illustrates the process of the proposed energy management system.

6 Numerical Results and discussion
This section presents the numerical results of the EMS applied to reduce the cost and the GHG emissions in a time span of 24 h of operation. The microgrid comprises three power sources, two being renewable, the photovoltaic system, the wind turbine and a non renewable source, a micro-turbine. Additionally, the microgrid comprises an energy storage system and it is also connected to the utility grid, which may
act as a buffer, supplying or absorbing the energy from the imbalances into the microgrid loads and sources.

Two scenarios are proposed to supply the microgrid consumers. The first takes into account the economic criterion and the second the environmental criterion, both of them allow to illustrate the price/emissions relation, as described in previous section.

After cost minimisation by means of objective function (3), the quantity of emissions is evaluated by the second function (5). The application of the energy management system allowed the calculation of the optimal set points for the distributed generator (DG’s) and storage system (ESS) of the microgrid through the combined (LP-PSO) strategy (Figure 4), assuring a power balance between supply and demand, i.e, at all times, the sum of the optimal power points generated by the microgrid sources and the main grid is equal to the power demand from the microgrid consumers and the energy required for charging the storage system in case of need.

The parameters of the selected PSO are as follows: search dimension = 1, population size = 60, number of iteration = 100, c1 = 2, c2 = 2 and w = 0.78, the performance and reliability of the optimisation algorithms are proven by the good choice of the optimal power set points.
Tables 3 and 4 present the solutions found for the first and second scenarios identifying the energy sources and considering the load needs for each hour (all values are in kW) and PV, WT, MT and ESS represents the optimal power setpoints of the microgrid generators and storage system obtained by the implementation of the energy management system.

The results of Table 3 show that for each hour, the set points of the cheapest sources are the most important, while in the Table 4 remarks a high use of renewable sources.

Table 3 Optimal scheduling of DGs and storage for the first scenario. Total operation cost= 102.69 Euro. Total emissions= 807.40 kg.

| Time | PV  | WT  | MT  | ESS | GRID   | LOAD |
|------|-----|-----|-----|-----|--------|------|
| 01   | 00  | 41  | 06  | 05  | 00     | 52   |
| 02   | 00  | 34  | 06  | 10  | 00     | 50   |
| 03   | 00  | 39  | 06  | 05  | 00     | 50   |
| 04   | 00  | 43  | 06  | 02  | 00     | 51   |
| 05   | 00  | 00  | 06  | 5.5556 | 44.444 | 56   |
| 06   | 00  | 00  | 06  | -8.3333 | 65.3333 | 63   |
| 07   | 00  | 00  | 06  | -8.3333 | 72.3333 | 70   |
| 08   | 00  | 00  | 06  | -8.3333 | 77.3333 | 75   |
| 09   | 2.36 | 51.9733 | 30  | -8.3333 | 00     | 76   |
| 10   | 7.92 | 42.080 | 30  | 00   | 00     | 80   |
| 11   | 31   | 17   | 30  | 00   | 00     | 78   |
| 12   | 39.2 | 4.8   | 30  | 00   | 00     | 74   |
| 13   | 42.6 | 0.0859 | 30  | -0.6859 | 00     | 72   |
| 14   | 38.8 | 00   | 23.20 | 10  | 00     | 72   |
| 15   | 32.48 | 00   | 28.52 | 15  | 00     | 76   |
| 16   | 19.8 | 27.9778 | 30  | 2.2222 | 00     | 80   |
| 17   | 4.4  | 00   | 06  | -8.3333 | 82.9333 | 85   |
| 18   | 00   | 00   | 06  | -8.3333 | 90.3333 | 88   |
| 19   | 00   | 00   | 06  | -8.3333 | 92.3333 | 90   |
| 20   | 00   | 00   | 06  | -8.3333 | 89.3333 | 87   |
| 21   | 00   | 72.2743 | 06  | -0.2743 | 00     | 78   |
| 22   | 00   | 57   | 06  | 08   | 00     | 71   |
| 23   | 00   | 54   | 06  | 05   | 00     | 65   |
| 24   | 00   | 42   | 06  | 08   | 00     | 56   |
According to the available power and daily energy bids, it is clear that the photovoltaic power is fully exploited because of its encouraging price, but the presence of this source depends on its potential that is available only during the day. So, this gives the opportunity for wind energy to be exploited. The advantage with this source is that it is potentially available during night and its price is relatively low during this period which justifies its wide use.

During the day, the insufficient power of the photovoltaic source leads to a compensation by one of the two conventional sources: from the grid or the micro turbine, depending on their unit operating price.

The LP method is responsible for the scheduling of the microgrid generators needed to supply the non-shiftable part of load by the mean of the energy management system. The use of the storage system is intended to supply as a priority the shiftable part of the load. The management of the battery charge/discharge as well as the supply of the shiftable part of load is ensured by the PSO algorithm while respecting the battery limit constraints.

In [18] the shiftable part of the load is driven at times when the energy price is low. This will lead to the disconnection of some home-application when they are part of the shifted load, and therefore, the comfort of the users can be affected. Instead of shifting the load when the energy price is low, the cheaper energy can be used for charging the ESS, this energy will be used to power the shiftable part of the load. The parts of loads that were supposed to be shifted will be maintained and powered by the energy of the battery, which price depends on the low prices of the sources used to charge it. Therefore, get the best benefit from the cheapest energy sources available on the microgrid.

Table 4 Optimal scheduling of DGs and storage for the second Scenario. Total operation cost=109.42 Euro. Total emissions= 672.87 kg.

| Time | PV | WT | MT | ESS | GRID | LOAD |
|------|----|----|----|-----|------|------|
| 01   | 00 | 41 | 06 | 05  | 00   | 52   |
| 02   | 00 | 34 | 06 | 10  | 00   | 50   |
| 03   | 00 | 39 | 06 | 05  | 00   | 50   |
| 04   | 00 | 43 | 06 | 02  | 00   | 51   |
| 05   | 00 | 4.444 | 06 | 5.5556 | 40 | 56   |
| 06   | 00 | 08 | 06 | -8.3333 | 57.3333 | 63   |
| 07   | 00 | 10 | 06 | -8.3333 | 62.3333 | 70   |
| 08   | 0.400 | 11.6 | 06 | -8.3333 | 65.3333 | 75   |
| 09   | 2.36 | 51.9733 | 30 | -8.3333 | 00   | 76   |
| 10   | 7.92 | 42.080 | 30 | 00   | 00   | 80   |
| 11   | 31 | 25 | 22 | 00  | 00   | 78   |
| 12   | 39.2 | 25 | 9.8 | 00  | 00   | 74   |
| 13   | 42.6 | 20 | 10.0859 | -0.6859 | 00 | 72   |
| 14   | 38.8 | 00 | 23.20 | 10  | 00   | 72   |
| 15   | 32.48 | 00 | 28.52 | 15  | 00   | 76   |
| 16   | 19.8 | 27.9778 | 30 | 2.2222 | 00   | 80   |
| 17   | 4.4 | 25 | 06 | -8.3333 | 57.9333 | 85   |
| 18   | 0.400 | 22.6 | 06 | -8.3333 | 67.3333 | 88   |
| 19   | 00 | 10 | 06 | -8.3333 | 82.3333 | 90   |
| 20   | 00 | 15 | 06 | -8.3333 | 74.3333 | 87   |
| 21   | 00 | 72.2743 | 06 | -0.2743 | 00   | 78   |
| 22   | 00 | 57 | 06 | 08  | 00   | 71   |
| 23   | 00 | 54 | 06 | 05  | 00   | 65   |
| 24   | 00 | 42 | 06 | 08  | 00   | 56   |
The dispatching optimal power setpoint of microgrid generators for the first and the second scenarios are illustrated in figures 5 and 6, respectively.

Figure 5 Hourly dispatch set-points of microgrid generators for the first scenario.

During the hours when the energy price is relatively low, it can be seen that the battery is being charged at the limits of its maximum charge rate (the charging of the storage system is shown by negative values). By adapting this approach, the total price of energy comparing with results presented in [18] was reduced to 102.69 Euro.

Figure 6 Hourly dispatch set-points of microgrid generators for the second scenario.

Figure 6 and Table 4 describe the power flow behavior in the microgrid for the second scenario explained previously. It should be noted that the set points of the energy from the main grid and micro-turbine have been reduced while the set points of the renewable sources: photovoltaic and wind energy are more important due to their massive exploitation imposed by the strategy of the energy management system (EMS) that promotes the environmental aspect in this part. Therefore, the rate of greenhouse gas emissions has been significantly reduced.

Figure 7 illustrates the comparison of the hourly variation of the energy prices for a 24 h operating time in the microgrid obtained by the scheduling elaborated by
the energy management system based on the hybrid optimization approach LP-PSO for both scenarios. It can be seen that the hourly variation of energy prices for the first scenario is lower than the second one. This behavior results from the different management strategies elaborated in the two scenarios, since during the day, the management system of the first scenario will favour the use of energy from sources with a reduced energy price according to the load demand by the consumers and the energy required for charging the storage system, while the management system of the second scenario aims at encouraging a higher use of renewable sources in order to reduce the increase of GHG emissions.

![Figure 7](image)

*Figure 7* Day profile of the obtained operating cost.

The evaluation of the emissions is obtained for both scenarios. Figure 8 shows a comparison of the hourly variation in greenhouse gas emissions (GHG) for the two scenarios proposed in the microgrid. The emissions come mainly from the energy produced by the micro-turbine and the main grid, which is considered produced from fossil resources. The management system in the second scenario encourages the use of renewable sources, which results in a considerable reduction in GHG emissions as can be seen in Figure 8.

![Figure 8](image)

*Figure 8* Daily profile of the obtained emissions.
For reduction of emissions, it is observed that the price has increased to 109.42 Euro and GHG emissions have been reduced to 672.87 kg per day. So, the inverse relation is consequently obtained between the two criteria. This will go towards a second approach of multi-objective optimisation where price and emissions are both targeted to be optimised, i.e, a dependent optimisation relation between the two objectives.

Table 5 Comparison between both scenarios.

| scenario | Total operation cost (Euro) | Total emissions (kg) |
|----------|-----------------------------|---------------------|
| 01       | 102.69                      | 807.40              |
| 02       | 109.42                      | 672.87              |

7 Conclusions and Future Work

In this paper, an energy management system has been proposed for the optimal scheduling of the microgrid generators taking into account the controllability of scheduled loads. The configuration of the microgrid represents an extension of the architecture proposed in [18], the management system takes as main targets the optimisation of the price and the reduction of the GHG emission rate, by using a hybrid optimisation approach LP-PSO strategy. The results demonstrate the reliability of the proposed energy management system (EMS) in the optimal scheduling of the microgrid generators power flows, having achieved a better energy price compared with the previous study with the same data, presented in [18]. The uni-objective approach gave an inverse relation between the economic and environmental constraints. Starting from this result, a multi-objective approach is going to be presented as future work by taking the price and emissions as a dependent optimisation target. Differently to the uni-objective approach that gave an optimal point, the multi-objective optimisation will deliver a set of optimal solutions (Pareto front), that will represent scenarios, of which the best compromise between price and emission is selected to give the optimal scheduling of microgrid generators.

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