Energy 165 (2018) 385–398

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A MILP methodology to optimize sizing of PV - Wind renewable energy systems

Regina Lamedica [a,*], Ezio Santini [a], Alessandro Ruvio [a], Laura Palagi [b], Irene Rossetta [c]

[a] SAPIENZA University of Rome, Dept. of Astronautical, Electrical, and Energy Engineering, Rome, Italy
[b] SAPIENZA University of Rome, Dept. of Computer, Control, and Management Engineering, Rome, Italy
[c] Rete Ferroviaria Italiana S.p.A., Rome, Italy

ARTICLE INFO

Article history:
Received 9 April 2018
Received in revised form
22 August 2018
Accepted 12 September 2018
Available online 5 October 2018

Keywords:
Industrial power plant
Mixed-integer linear programming
Optimization
Renewable energy systems

ABSTRACT

This paper proposes a methodology that is based on mixed-integer linear programming (MILP) to calculate the optimal sizing of a hybrid wind-photovoltaic power plant in an industrial area. The proposed methodology considers the: i) load requirements; ii) physical and geometric constraints for the renewable plants installation; iii) operating and maintenance costs of both wind and PV power plants; and the iv) electric energy absorbed by the public network.

The power demand variation associated with the production cycles is considered by using a stochastic simulation tool. To consider both the load and seasonality variability, and to adapt the methodology to the actual operational use of the power plant, the optimization is performed separately for each month of the year. Then, an integrated economic analysis is discussed. The methodology is adopted to analyze an industrial plant in the Rome area used as a train depot and for maintenance purposes. The results, which combine the needs of the plant activity with the availability of renewable energy, enabled the determination of optimal solutions and the relevant savings achievable.

1. Introduction

In recent years, there has been an exponential increase in the attention given to energy saving and realizing a reduction of pollution caused by fossil fuels. Many studies have focused on issues related to the rational management of the load in order to reduce energy absorption from the network [1–6]. The use of measurement campaigns and control actions is important to obtaining this target, together with new solutions for real-time decision models in industrial load management [7]. The production of energy (even if partially) using renewable energy Sources (RESs) is an important feature of modern companies. In addition to the economic benefits, each industrial structure should carefully consider environmental issues and the reduction of greenhouse gas emissions (Kyoto Protocol, 1997).

1.1. Italian scenario

Over the last two decades, the Italian electricity market has undergone continuous changes and developments. The privatization of the market (three steps in years 1996, 2003, 2009) has been followed by the introduction of European incentives for production from RESs. The rapid development of the latter has significantly changed the structure itself of the electricity market. In Italy, between 2013 and 2016 RESs are rapidly grown. In 2016, electric energy production was almost 106 TWh including 23 TWh of solar (PV) and 17 TWh of wind energy [8].

1.2. RES and microgrids

The Italian policy has encouraged the growth of RESs in order to support the use of clean energy in the European green economy context. Nowadays, owing to this policy, many old industrial facilities are introducing renewable sources, in a framework that will combine energy saving and energy production in the future development of microgrids (MGs).

Large-scale RES production has to be integrated with power systems in order to improve system operation, reliability, environmental sustainability, and economic benefits [9].

The sizing of different RESs and their relevant coordination are two basic aspects for the correct operation of MGs. The economic

* Corresponding author.
E-mail address: regina.lamedica@uniroma1.it (R. Lamedica).

https://doi.org/10.1016/j.energy.2018.09.087
0360-5442/

Acronyms

A_b	Area Occupied By a Wind Turbine
A_{max}	Area For Wind Turbines
C_{eolic}, C_{pv}	Unit Installation Cost of a Wind Turbine and PV Panel
$C_{PV\ O\&M}$	Unitary Operating And Maintenance Cost Of A Photovoltaic Panel
$C_{eolic\ O\&M}$	Unitary Operating And Maintenance Cost of A Wind Turbine
$C_{\ O\&M}$	Total Operating and Maintenance Cost
$C^*_{i,tot}$	Overall Installation Cost
$C_{network\ energy}$	Unit Cost of The Purchased Energy
F_n	Cash Flows At Period N
HSWSO	Hybrid Solar-Wind System Optimization Sizing
I (IRR)	Internal Rate Of Return
I_{mp}	Maximum Module Current
$Impp$	Rated Current Of PV Panel
I_{sc}	Short-Circuit Current of PV panel
ki	Temperature Coefficient Related To Isc
kp	Temperature Coefficient At Module Power Max - Pmax
kv	Temperature Coefficient At Open Circuit - Voc
γ	Sun Elevation At Noon On The Horizon In Winter Solstice
L	Longitudinal Dimension Of The Solar Module
LCE	Levelized Cost Of Energy
LLPs	Loss Of Load Probability
LPSP	Loss-Power Supply Probability
MG	Micro Grid
MPPT	Maximum Power-Point Tracking System
n	Investment Lifespan
P_{dcn}	Rated DC Power
PDFs	Probability Distribution Functions
P_{max}	Maximum Module Power
P^i_{eolic}	Wind-turbine power production, i-th Interval
P^i_{load}	Power Demand, i-th Interval
P^i_{pv}	PV Power Production, i-th Interval
$Pmpp$	Rated Power Of PV Panel
Q	The Ministerial Rate (Italian Laws)
R	Amortization Rate
RES	Renewable Energy Source
RSM	Response Surface Methodology
S_l	Area for Solar Panel Installation
$Umpp$	Rated Voltage PV Panel
V_{mp}	Maximum Module Voltage
V_{oc}	Open-Circuit Voltage
V_r	Residual Value At The End Of The Time Period
β	Solar Module Tilt Angle
θ	Solar Module Orientation Angle

and operational considerations state limits on the total number of RESs that can be installed in electric power systems. Considerations related to the land use, power system reliability, and electricity market design are among the many issues that impose constraints on the total deployment of renewables, with particular reference to non-programmable sources, i.e., mainly wind and solar energy [10,11].

One of the most critical aspects of RESs is the energy-production forecast, which depends on geographical and climatic parameters. To overcome this difficulty, many solutions have been proposed, such as modelling the uncertainty using fuzzy confidence intervals [12,13], by using suitable probability distribution functions (PDFs) [14] or the autoregressive moving average model (ARMA) model for PV power systems [15], even by using Markov chain rules [16]. Often, the authors did not consider the probabilistic aspects, but they used simple output functions for the energy produced by the RESs [17], or they consider the production from PVs that are always under maximum power-point tracking system) conditions [15]. Moreover, most of the studies use a sequence of steady-state situations within a time interval (typically 1 h), depending on the PV and wind models [18,19].

1.3. RES and optimization

Once a forecasting model is available, the design of an MG can be modelled as an optimization problem, and solved using suitable algorithms. Over the past few decades, the application of computer simulations to solve complex engineering systems has emerged as a promising method. To deal with different types of optimization problems, a large number of optimization methods have been developed [20]. The use of a mathematical model gives an overall view of complex systems such as industrial MGs. Its use is justified whenever there are many possible alternative choices, at which time it is necessary to analyze all of them, in order to determine the best one, or at least an approximation to the "best" within a given tolerance. This approach is complementary to a ground-rule approach, which relies on "common sense" rules that are issued by someone with experience and mature judgment in the sector. This allows effective decisions to be made, and guarantees the optimal choices in competition with human experts.

Many studies have been performed to select the model that leads to a coherent and realistic solution for MG sizing using different algorithms.

Some studies rely on existing optimization software, such as HOMER [21], while others develop their own optimization methodologies. Static and dynamic renewable performances are optimized in Ref. [22], and a multi-objective model to minimize both cost of energy as well as the total greenhouse gas emissions of the system is shown in Ref. [23]. Reference [24] deals with the optimal size of a hybrid PV-wind system for different values of loss of load probability (LLPs) based on the available solar energy and wind speed; Reference [18] describes a configuration that can achieve the desired loss power supply probability (LPSP) with a minimum annualized cost of system. In Ref. [25], a comparison study on two design optimization models (single and multi-objective) for renewable energy systems in low-energy buildings and zero-energy buildings was reported. In Ref. [26], the authors developed a model to optimize the sizes of different components of hybrid solar-wind power-generation systems. The hybrid solar-wind system optimization sizing (HSWSO) model consists of three modules: the model of the hybrid system, the model of loss of power supply probability (LPSP), and the model of the levelized dost of energy (LCE). The LPSP technique has been also used in Ref. [27], where for a given loss probability, different combinations of PV modules, wind turbines, and battery banks are determined. In Ref. [19], the authors used the response surface methodology (RSM) to determine the optimal size of an autonomous PV-wind integrated hybrid energy system. In most cases, genetic algorithms (GA) were used to determine the solution of the proposed model [21].

Gas, particle swarm, among others in general evolutionary methods, fit the class of heuristics that are widely used in the engineering framework for their ease of implementation. Heuristics methods are often used when a complete formulation is not explicitly available, and/or when the dimension of the addressed problem is so large that an optimal solution may be not computable within the given computational time. However, such methods do not provide any kind of certification of the quality of the solution, which in turn may largely depend on the parameter settings.

Thus, when the mathematical model fits the class of linear programming (LP) or mixed-integer linear programming (MILP), these methods and more generally population-based methods, are not the best suited for the solution of the corresponding problems.

To this end, some authors propose models using LP or MILP class for power grids. See Ref. [28] for a review, and e.g., [29,30] to obtain the LP model for the minimization of the component size and of total investment cost.

The use of MILP models allows us to consider standard software for the solution of the problem. Algorithms that can produce a certified optimal solution of LP, ILP, and MILP are widely available, and are implemented in standard software, both commercial and open source. Interested readers can refer to the classical reference [31] and the up-to-date [32] for ILP models and related algorithms.

Further, it is necessary to consider the intrinsic stochastic behavior of renewable energy, as in Ref. [24], and the uncertainty of the electric load demand.

In this paper, a model to determine the optimal size of the wind and PV apparatuses of a power plant is proposed; the model is in the MILP class.

An integrated economic analysis of the investment through the net present value (NPV) method is also performed, which allows the convenience of the proposed system to be evaluated over its lifetime.

The structure of the paper is as follow. Section 2 presents the main novelties of the proposed methodological approach, In Section 3, the MILP problem is defined. Sections 4 and 5 report the automatic procedure and the case study of an industrial area, respectively. Then, Section 6 shows the results obtained, and section 7 concludes the paper.

2. Novelty of methodological approach

A methodology that is used to systematically determine the optimal size of PV-wind renewable plants is defined.

Indeed, the use of a mathematical model that is embedded within a simulation framework, taking into account specific constraints of the industrial area and load variability during the day in different years, is proposed.

The proposed approach aims to jointly determine both optimal sizes of the renewable plants and the amount of network energy from the grid that satisfies load requirements by minimizing the sum of the daily cost of the energy purchased and the daily operating and maintenance costs of RESs.

The main novelties of the proposed approach are that the electric load profile for a typical day of the year is considered, and that the optimal sizing is determined by accounting for the trend during the daytime over a season. The analysis was performed for each month of the year to provide optimal solutions for industrial plants that are characterized by power demand, which fluctuates widely during the year (e.g., sea villages that operate from May to October, high-mountain MGs that are populated three months in winter and two months in summer, oil platforms, archaeological parks), considering also the RESs availability. The proposed methodology can be applied to industrial plants that are not qualified as prosumers and/or that are equipped with energy storage. The procedure is implemented in a user-friendly platform in MATLAB®.

An industrial plant located in Rome area was chosen to verify the SW applicability.

3. Methodologic approach

The models of the RESs plant take into account the non-programmable energy that is produced, and depends on multiple factors such as the installation site, month, hour of the day, and weather conditions. Weather conditions are assumed to be equal over different years (hypothesis justified by the study of Italian historical data). The considered data that are employed for the case study were imported from an existing on-line database.

3.1. Wind-power plant model

The typical shape of the wind-turbine power curve chosen by the Authors is reported in Refs. [33–36].

3.2. PV power plant model

To estimate the PV energy production, several factors, such as solar radiation, as well as the exposition of modules and system efficiency have been considered, as reported in Refs. [18], [37–39].

To obtain realistic values of the energy produced according to the weather condition and season, parameters reported in Refs. [4,40] were considered in the model.

3.3. Load profile

The load profile has to be defined from the power demand vs. time. The model requires a vector of power absorption, and the values are considered to be constant at each time step.

The load profile can be obtained using both a measurement campaign, if the industrial site exists, and the knowledge of the power demand of similar plants if the system is in the planning phase.

To consider the load variability, starting from the values listed in the vector, the procedure performs a random extraction, creating new load profiles.

3.4. Definition of the MILP model

The number of wind turbines and PV panels represents the solution of the MILP problem, identifying respectively the first and second set of decision variables (unknowns). These values cannot be negative.

The optimization model requires as an input the main RESs characteristics, the local geographical restrictions, and the load profile. The investment budget that is expected for the RES installations is taken into account.

The full set of decision variables identified in the mathematical model are:

- x_1, the integer number of the wind turbines;
- x_2, the integer number of PV panels;
- $x_3, \ldots, x_{N+2}$, the energy purchased from the network at each interval $i = 1, \ldots, N$, where the day is discretized.

The values of power-load absorptions are stored in a vector, and each value is specific for one of the N intervals in which the day is discretized. Having 1440 min in a day, the time interval discretization is 1440/N min.

Consequently, N time intervals are also considered for energy exchanges with the public network; the corresponding constraints to balance renewable production and load demand have to be defined. The number of variables depends on the number of intervals, N. If N is large, the model accuracy increases. The value of N chosen by the authors is 96, corresponding to a discretization interval of 15 min, which is considered a good compromise between accuracy and computer times. This value was used in the case study (Section 6).

The definition of the MILP model requires the mathematical formalization of the objective function and of the restrictions as linear equalities or inequalities, which establish the relationships between the decision variables and the input data.

3.4.1. Objective function

The objective function is defined by the overall cost, i.e., the sum of the operating and maintenance costs of the wind and PV power plants [€/kW] and the purchase cost of network energy [€/kWh]. It can be assumed that these costs are proportional to the number of elements of the plants as well as to the quantity of the energy purchased by the network. Hence, the costs are represented by a linear function involving $x_1, x_2, x_3, \ldots, x_{N+2}$ variables. Because the total has to be minimized, the objective function is (3):

$$\min_x \left(C_{eolic\ O\&M} * x_1 + C_{PV\ O\&M} * x_2 + \sum_{i=3}^{N+2} C_{network\ energy} * x_i \right) \tag{3}$$

where:

$C_{eolic\ O\&M}$ is the unit operating and maintenance cost of a wind turbine;
$C_{PV\ O\&M}$ is the unit operating and maintenance cost of a photovoltaic panel;
$C_{network\ energy}$ is the unit cost of the purchased energy, which is assumed to be independent of the time interval.

3.4.2. Constraints

The decision variables, together with data, must satisfy some technological, economic, and geometric constraints. Mathematically, these constraints are expressed by linear equalities and inequalities involving the variables.

– *Energy absorption*

With the hypothesis that the energy can only be purchased from the public network, the energy value must be not negative. The constraint is in (4):

$$x_i \geq 0 \quad i = 1, \ldots, N+2 \tag{4}$$

– *Balance between renewable production and load demand*

In the *i*-th time interval, the balance between renewable production and the load demand is expressed by equation (5).

$$\left(P^i_{eolic} * x_1 + P^i_{pv} * x_2\right) * \frac{\mathrm{m}}{\mathrm{N}} + x_{i+2} = P^i_{load} * \frac{\mathrm{m}}{\mathrm{N}} \quad (i = 1, \ldots, N) \tag{5}$$

where
m is the number of minutes in a day (1440);
P^i_{eolic}, P^i_{pv}, and P^i_{load} are respectively the wind-turbine power production, PV power production, and load power demand in the *i*-th time interval.

– *Economic constraints*

To consider the cost limitations of wind turbines and PV panels, constraints have been considered, assuming a maximum available budget that should not be exceeded. Mathematically, the expression is a linear inequality involving only x_1 and x_2, which ensures that the initial installation cost of wind turbines and PV panels does not exceed the fixed budget (6):

$$C_{eolic} * x_1 + C_{pv} * x_2 \leq budget \tag{6}$$

where
C_{eolic} is the unit installation cost of a wind turbine; C_{pv} is the unit installation cost of a PV panel.

– *Geometric constraints*

These constraints refer to some geometrical details. With respect to the wind-energy production, a constraint arises owing to the limited available ground area for the installation of the wind turbines (7):

$$x_1 * A_b \leq A_{max} \tag{7}$$

where

A_b is the basic ground area occupied by a wind turbine;
A_{max} is the available area.

The second constraint concerns the available installation space for the PV power plant (8):

$$x_2 \leq \frac{(S_l - 3)}{L} * N_{rows\ of\ panels} \tag{8}$$

where

S_l is the larger side of the available area for the installation of solar panels [m];
L is the longitudinal dimension of each panel (in meters).
$N_{rows\ of\ panels}$ is the number of rows of installed panels.

In (8), s_l decreases by 3 m in order to consider the maintenance corridors, a central one of 1 m, and two other corridors, both 1 m and located along the larger side.

To avoid shading of the solar panels, and consequently, a significant reduction in their energy production, the correct number of rows of panels $N_{rows\ of\ panels}$ was calculated using (9):

$$\begin{cases} N_{rows\ of\ panels} = \dfrac{(s_l - 3)}{D} \\ D = L \cos\beta \left(1 + \dfrac{\tan\beta}{\tan\gamma}\right) \end{cases} \tag{9}$$

where
s_l is the smaller side of the available area for the installation of solar panels.

In addition, the smaller side should be reduced by 3 m in order to take into account the presence of corridors.

Equation (8) leads to expression (10):

$$x_2 \leq \frac{(S_l - 3) * (s_l - 3)}{L^2 * \cos\beta \left(1 + \frac{\tan\beta}{\tan\gamma}\right)} \tag{10}$$

3.4.3. MILP model equations

In the MILP model, there are therefore N+2 variables and 3*N + 3 constraints. Equations (11)–(15) summarize the model.

$$\min_x\left(C_{eolic\ O\&M}*x_1 + C_{PV\ O\&M}*x_2 + \sum_{i=3}^{N+2} C_{network\ energy}*x_i\right) \quad (11)$$

$$\left(P^i_{eolic}*x_1 + P^i_{pv}*x_2\right)*\frac{\mathrm{m}}{\mathrm{N}} + x_{i+2} = P^i_{load}*\frac{\mathrm{m}}{\mathrm{N}} \quad i = 1, \ldots, N \quad (12)$$

$$x_1*A_b \le A_{max} \quad (13)$$

$$x_2 \le \frac{(S_l - 3)*(s_l - 3)}{L^2* \cos\beta\left(1 + \frac{\tan\beta}{\tan\gamma}\right)} \quad (14)$$

$$C_{eolic}*x_1 + C_{pv}*x_2 \le budget \quad (15)$$

The model considers x_1, x_2 as integers, and enforces the non-negative solution as in Eq. (16)

$$x_i \ge 0\ i = 1, \ldots,\ N+2 \quad (16)$$

The optimal solution of the problem can be obtained by using exact standard algorithms for MILP [31]- [32], which are implemented in most commercial software. Exact methods algorithms for MILP are approximate implicit enumeration methods of branch-and-bounds or Branch-and-Cut type. The convergence of such methods to an optimal solution of the MILP is fully understood, as discussed in Ref. [31]- [32]. Note that LP and MILP can be solved to global optimality, in that no better value of the objective can be reached, by properly setting the parameters of the algorithm. They also provide a certification of the accuracy of the obtained solution.

In MATLAB® implementation, the routine of the Optimization Toolbox "intlinprog" has been used.

3.5. Investment evaluation and economic analysis

The investment evaluation was conducted by calculating the net present value (NPV).

The effectiveness of the investment is evaluated by summing the various expenses and incomes, and reporting these quantities to the same reference time through the discounting mechanism, as in Eq. (17).

$$NPV = F_0 + \frac{F_1}{(1+i)} + \frac{F_2}{(1+i)^2} + \ldots + \frac{F_n}{(1+i)^n} \quad (17)$$

where

n is the life span of the investment; F_n represents the cash flows (to evaluate the profitability of industrial investment) at the n-th period; i is the internal rate of return (IRR), and it is chosen iteratively relatively to the length of the investment and to its economic availability.

This method requires the definition of a-priori "n" and "i" and it leads to these considerations:

- $NPV>0$: the investment will give an economic profit;
- $NPV=0$: the investment transaction will return in n years the capital and interests at i rate;
- $NPV<0$: the investment is not convenient because it will return an economic loss.

Therefore, the investment is convenient only if NPV> 0. Different investments can be compared using this technique, and the one with the greater NPV is the natural choice.

The cash-flow calculation requires the MILP solutions to relate revenues and the operational/maintenance cost of RESs. From each simulation, the optimal sizing of the renewable plants is obtained ($x^{*,month}$).

The optimization analysis is performed, month-by-month, for a full year. The number of wind turbines and PV panels is selected by choosing the maximum value obtained among the results. Hence, the parameters that were considered are (18):

$$x_{1,ref} = \max_{month=1,\ldots,12} x_1^{*,month} \quad x_{2,ref} = \max_{month=1,\ldots,12} x_2^{*,month} \quad (18)$$

where

$x_{1,ref}$ is the number of wind generators;
$x_{2,ref}$ is the number or PV panels.

The cash flow is expressed using the following relationship (19):

$$F = (i-p)\left(Revenues - C^*_{O\&M}\right) + p*A - C^*_{i,tot} \quad (19)$$

where

i is the interest rate;
p is the coefficient used to consider the taxes;
A is the annual amortization.
$C^*_{O\&M}$ and $C^*_{i,tot}$ are respectively the operating and maintenance cost and total installation cost, considering $x_{1,ref}$ and $x_{2,ref}$ which have the following expressions (20) (21):

$$C^*_{O\&M} = C_{eolic\ O\&M}*x_{1,ref} + C_{PV\ O\&M}*x_{2,ref} \quad (20)$$

$$C^*_{tot} = C_{eolic}*x_{1,ref} + C_{pv}*x_{2,ref} \quad (21)$$

Revenues correspond to the cost of the energy saved in a year; they are calculated as the difference between the energy produced by RESs and the energy absorbed by the load.

The annual amortization estimation was calculated using (22):

$$A = r*C_{i,tot} = q \quad (22)$$

where:
r is the devaluation rate;
$C_{i,tot}$ is the overall installation cost of the wind turbines, PV panels, and interface inverters.

The A value coincides with the rate "q" (the value is set equal to 9%). In Italy, the parameter represents the amortization percentage of the cost of capital goods used for commercial activities, arts, and professions, and it was established by the Ministry of Finance by Ministerial Decree dated 31 December 1988, and was amended by Ministerial Decree dated 28 March 1996. It has been in force since May 16, 1996.

4. Case study

The Rome subway has three lines, and has a total length of 53 km. The oldest is the line "B," which is about 19-km long, and opened in 1955 (the extension from stations "Termini" to "Rebibbia" in 1990); the line has a junction "B1" opened in 2012) that is about 4-km long. Line "A", which opened in 1980, is about 18-km long. The line "C" is the newest; only the section between "Pantano" and "San Giovanni" stations has been in operation since 2014. Each Rome subway line is equipped with large available areas where metro train depots are located and maintenance activities are carried out.

The power plant chosen for the application of the proposed MILP model is the large facility "Officina Magliana" in which maintenance activities on metro trains of line "B" are performed.

In “Officina Magliana,” there are activities that involve the assembling and disassembling of mechanical and electrical components of the rolling stock, including profiling and lathing of the rims with the lathe in the pit [41].

“Officina Magliana” has a medium-voltage supply with a dedicated substation equipped with MV/LV (20 kV - 0.4 kV) transformers. The complete industrial plant consists of ten buildings, as shown in Fig. 1.

The budget available by the transport Company for the investment is 300,000 €; the operating and maintenance costs chosen are shown in Table 2 [42].

The cost of the purchased energy depends on the agreement with the local electric distributor. The current electric energy cost was assumed equal to 0.18 €/kWh (Italian energy price for energy delivered by the MV network).

4.1. Electric load profiles

The instrument used for the measurement campaigns is the Chauvin Arnoux CA 8335 network analyzer, which can measure and log many quantities simultaneously, as well as transient waveforms and inrush currents. The measurement uncertainty is between ± 0.3 and ± 2.5% (including the error for the current sensors), depending on the measured variables.

The thermal power plant, the building maintenance, the refectory building, the bar, and offices are the monitored electrical loads. A lighting tower that is located in the area, a constant power consumption of 63 kW has been measured from 6 p.m. to 6 a.m. Fig. 2(a), (b), and 2(c) show the electrical demand of loads monitored on three working days.

The power measurement of the thermal power (Fig. 2(a)) ranges between 27 kW and 32 kW owing to the switch on/off operation of compressors that are installed in the area. The power consumption on the refectory, bar, and office (Fig. 2(b)) ranges between 13 kW and 42 kW. However, the maximum consumption is recorded on each day from 7 a.m. to 17 p.m. owing to working activities. The power request by the building of maintenance (Fig. 2(c)) ranges between 55 kW and 105 kW. In this case, the trend varies daily. The maintenance activities are carried out every 24 h with an unscheduled program.

Using these measurements, the proposed procedure creates randomly varying daily load profiles, as illustrated in Section 3.3.

Table 1
“Officina Magliana” localization and characteristic data.

Latitude [°]	41.82
Longitude [°]	12.44
Azimuth angle [°]	314
Height of the sun in winter solstice [γ]	24
Average wind speed [m/s]	3.81
Height from ground corresponding to the average wind speed value [m]	12
Soil roughness coefficient	3.5
Available area for wind power plant [m^2]	15
Available area for PV power plant [m^2]	8000
Tilt angle of solar panels [β]	16
Reflection coefficient	0.13
Feeder Ampacity [A]	370

Table 2
Objective function coefficients.

	PV System	Wind System
Daily operating & maintenance costs [€/kW]	0.052[a]	0.095[a]

[a] Data are referred to 2016.

4.2. RES data

The main characteristics of PV and wind generators are listed in Table 3.

5. Results

The proposed method was implemented in the Matlab® programming language. The software operates as a batch procedure. A graphical interface was implemented to simplify the data input. The outputs describe numerically the industrial area and the RES machines. The charts shown below represent the main output of the software.

01 Maintenance by external executing company	06 Control Tower
02 Building maintenance	07 Roof wagons maintenance
03 Offices, Refectory, Bar, Changing Room	08 Thermal plant
04 Ecological Island	09 Electrical component storehouse
05 Warehouse	10 Blowing and washing

Fig. 1. “Officina Magliana” depot/maintenance and repair site. The characteristic parameters of the “Officina Magliana” are listed in Table 1.

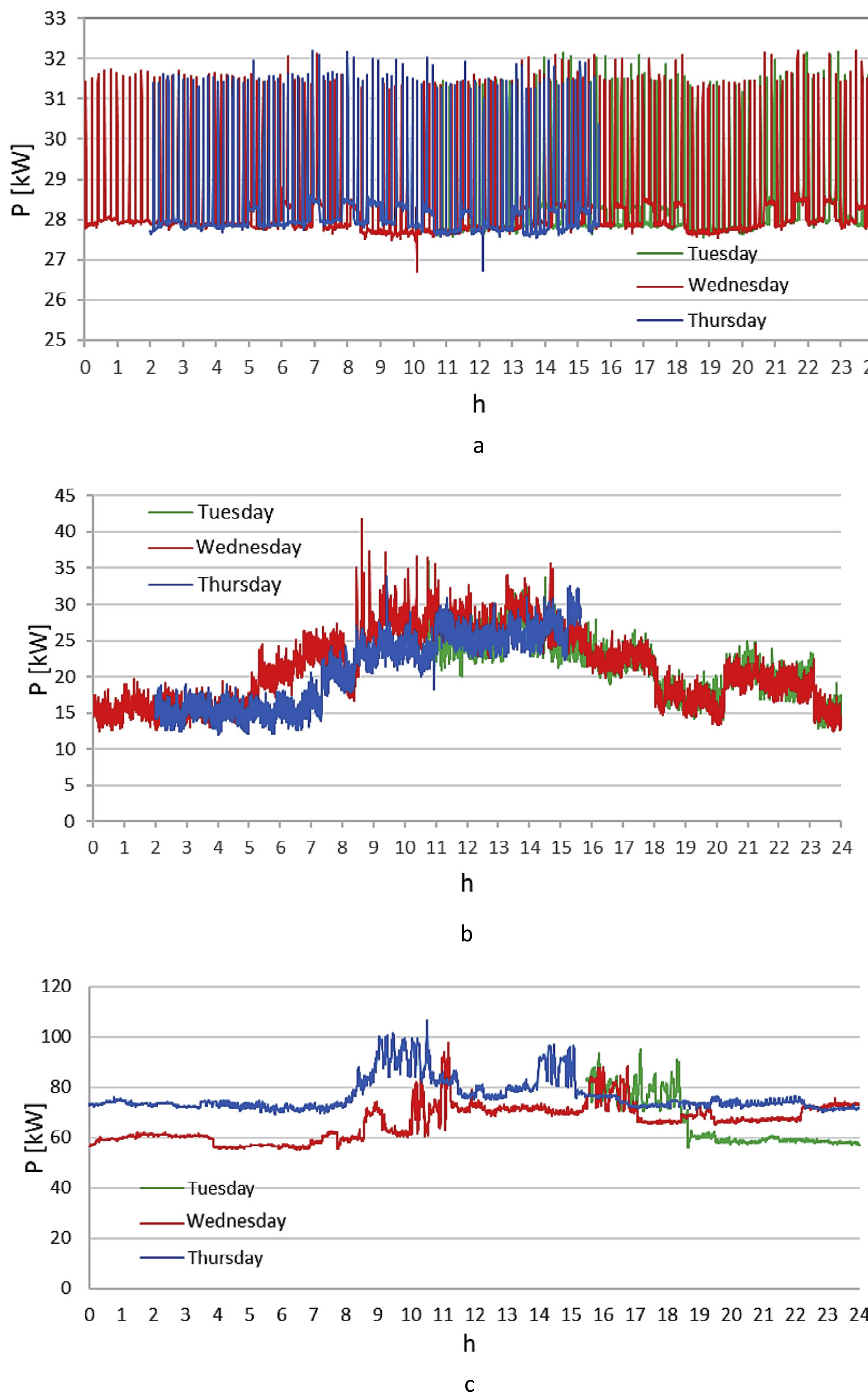


Fig. 2. (a) Thermal power plant power demand vs. time of the day; 3(b) Refectory, bar, and office power demand vs. time of the day; 3(c) Building maintenance power demand vs. time of the day.

Table 3
Electric and mechanics characteristic of a 220-W solar panel.

PV panel		
	Rated power (Pmpp) [W]	220
	Rated voltage (Umpp) [V]	27.91
	Rated current (Impp) [A]	7.88
	Open-circuit voltage (Uoc) [V]	36.55
	Short-circuit current (Isc) [A]	8.23
	Efficiency [%]	13.8
	Power tolerance	0%–5%
	Maximum voltage [V]	1000 (EU)
	Operating temperature	−40 °C to +85 °C
	Temperature coefficient (Voc)	−0.32%/°C
	Temperature coefficient Pmax	−0.35%/°C
	Temperature coefficient (Isc)	−0.04%/°C
	NOTC	51.5 ± 3 °C
	Dimensions (L × L × A) [mm]	1.639 × 982 × 35
	Price of each panel	200 €
Wind Generators		
	Rated Power	5 kW
	Tower height	15 m
	Price	1300 €/kW

5.1. Monthly optimized results

The optimization results for the 12-month period are reported in Figs. 3–6, with each set of figures being relevant to the four seasons.

Fig. 3(a)–(c) show that during the winter season, only the wind-turbine gives results from the optimization. In fact, during these months (very similar to the others), low PV production is expected; obviously, the procedure recommends that PV plant installation be avoided. Based on the optimization, the use of three wind turbines is the proposed solution.

Hence, only the wind plant provides the energy from RESs and the relevant revenues.

The wind generation provides up to 15% of the total energy requested by the loads, and only for short periods during the day.

Fig. 4(a), (b), and 4(c) show the energy profiles during the spring season. The energy produced by the PV power plant increases relative to winter. In April (Fig. 4(a)), the use of only one wind turbine and 631 solar panels is proposed. During this month, the wind speed is not very high (3 m/s); it is less than in other months. The average energy received from the public network on a given day decreases from 33.58 kWh to 26.92 kWh.

In May (Fig. 4(b)), three wind turbines and 415 solar panels are obtained by the optimization procedure. The large number of panels is also owing to the low wind-power plant production, according to the unfavorable wind speed. The average network energy absorption decreases from 33.60 kWh before optimization to an average received energy of 26.30 kWh after optimization. Both the energy efficiency and the revenues are higher than in the winter months, and this is owing to the increase of the average wind speed (3.79 m/s), which is also present during the night when the PV system is not generating electricity.

In June, the number of recommended panels is slightly higher than in May. This is also related to the further increase in wind speed (3.95 m/s). The network energy absorption decreases from 33.73 kWh to 26.5 kWh.

The results for the summer season are similar to those obtained during spring. The more favorable weather conditions in July (Fig. 5(a)), involve a reduction of the solar panels (405, in May, there are 415) and the network's average energy absorption on a given day decreases (25.8 kWh, in May: 26.3 kWh). In August (Fig. 5(b)), the weather conditions are not the most favorable; therefore, the procedure recommends a larger number of panels, i.e., 611. The network's daily average energy absorption decreases from 33.63 kWh to 25.69 kWh. In September (Fig. 5(c)), the number of panels is slightly higher than in August. The network's average daily energy absorption decreases from 33.64 kWh to 25.26 kWh. Further, during the autumn season, the optimization solution recommends the use of three turbines.

In October (Fig. 6(a)), the number of recommended PV panels is the highest for the whole year owing to the low energy production of the solar panels during cloudy days in autumn, and to the low energy production of the wind power plant. The network's daily average energy absorption decreases from 33.62 kWh to 28.3 kWh.

In November, as in the other autumn months of Fig. 6, the procedure does not propose PV panels; their production is almost zero. The average recorded wind speed is 3.5 m/s. The network's daily average energy absorption decreases from 33.69 kWh to 33 kWh.

In December, no PV panels were recommended. The average wind speed is 4.29 m/s, which is much higher than all of the winter months. The average energy absorption from the network on a given day decreases from 33.69 kWh to 32.6 kWh.

Table 4 reports the main results obtained for one month of each season: January for winter, May for spring, July for summer, and October for autumn. The associated costs of the RESs are also presented.

5.2. Economic analysis

The results obtained for the 12-month period are the input data for the economic analysis. The amortization assessment and the NPV evaluation are therefore performed (Section 3.5).

Considering the PV plant peak power and wind-rated power (142 kW and 12 kW, respectively), from the equations of paragraph 3.5, the annual operating and maintenance costs are calculated as 3217 €; the total annual revenues are 28,418 €.

Table 5 shows the amortization cost, the overall installation cost ($C_{i,tot}$), and the residual value at the end of the year (V_r). When V_r in Eq. (21) becomes negative, amortization is concluded.

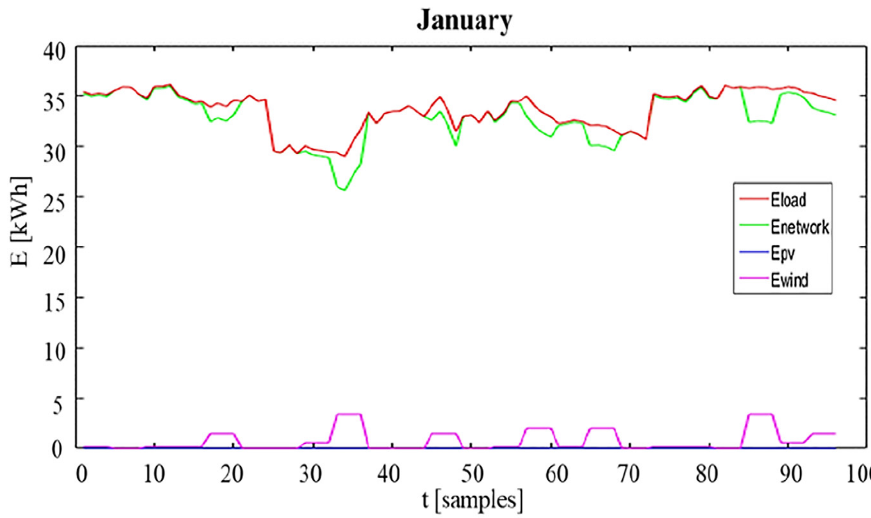
$$V_r = C_{i,tot} - n{*}A \tag{21}$$

Table 6 reports values of revenues, amortization, $C_{i,tot}$, operating and maintenance costs ($C_{O\&M}$), cash flows, and NPV over 25 years.

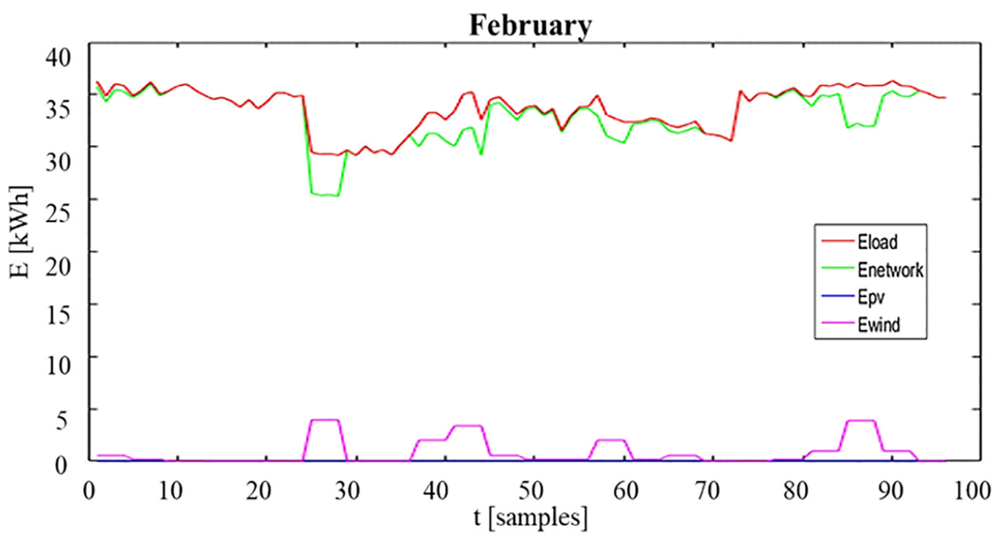
Fig. 7, which was derived from Table 6, illustrates the NPV values for wind and PV plants over a 25-year period. As can be seen in the graph, after 11 years, the NPV reaches a positive value, and a return on investment (RoI) is obtained.

6. Conclusions

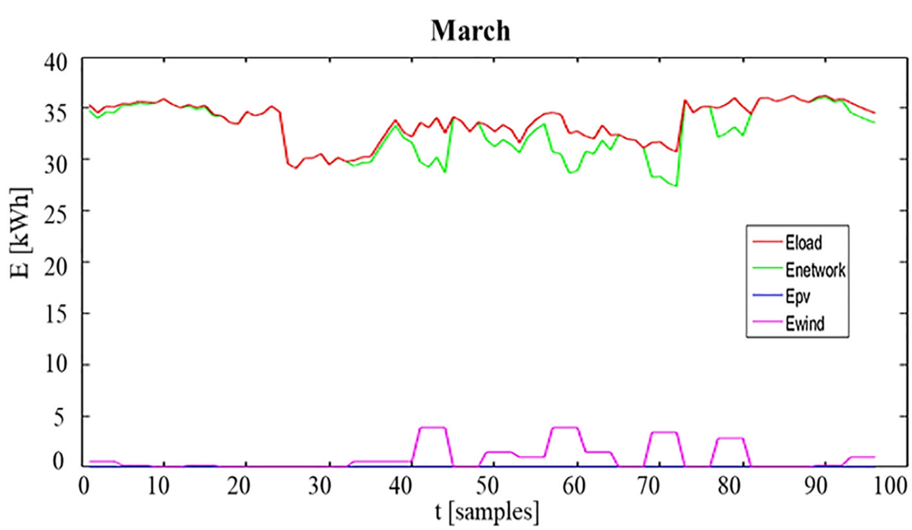
A procedure that is based on an MILP formulation has been proposed to determine the optimal sizing of both PV and wind energy plants, starting from the knowledge of the power required by the loads and the site geographical location. The monthly/seasonality optimization of renewable generation has been performed, and considers inhomogeneous seasonal energy consumption. The procedure was applied to a real industrial plant located in the Rome area, and the obtained results show the usefulness of the methodology to identify the optimal choice, which combines the needs of the industrial plant with the RES availability and the achievable savings.



a



b



c

Fig. 3. Energy profile of RES, network, and load profile on a typical working day in winter.

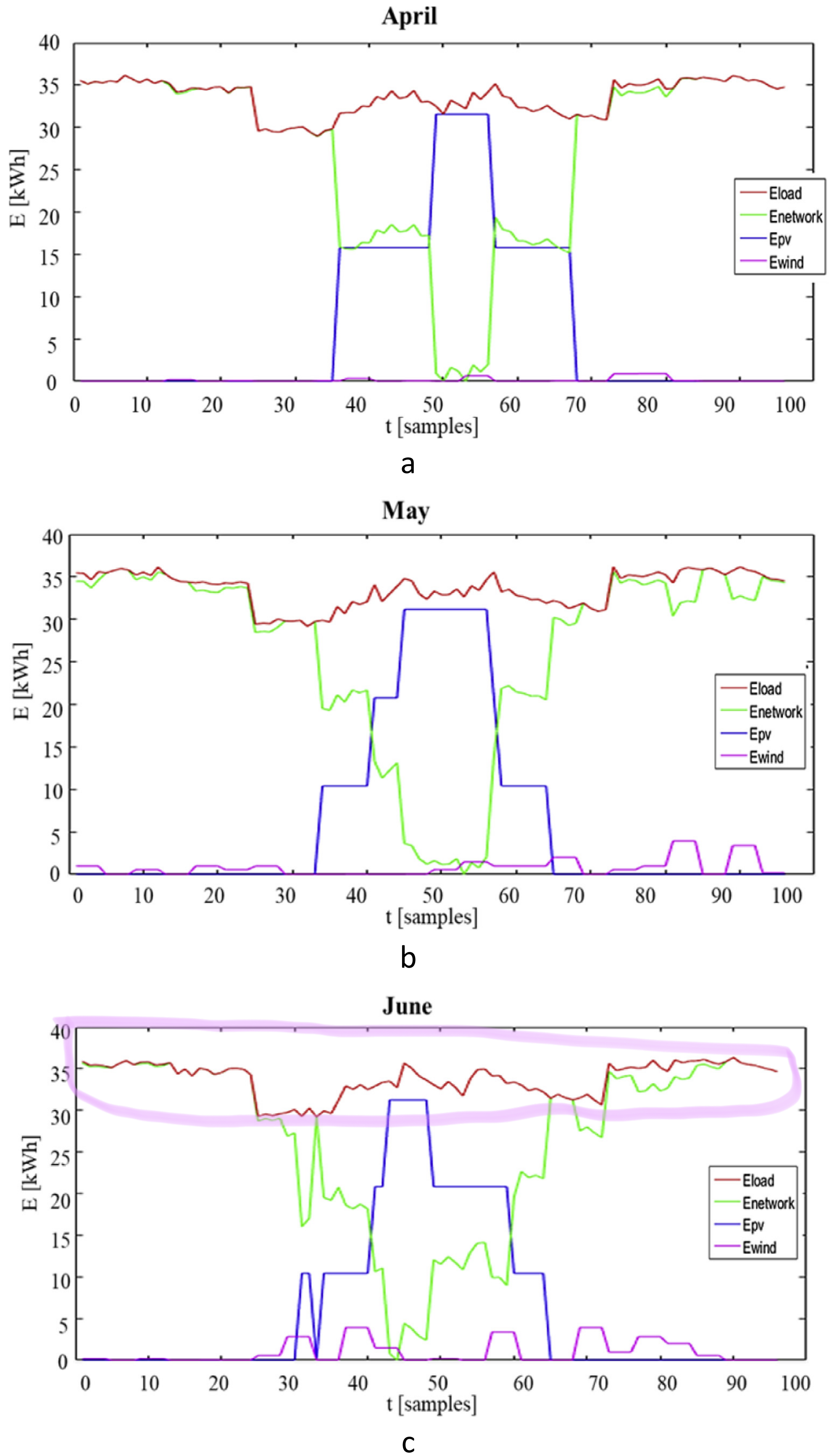


Fig. 4. Energy profile of RES, network, and load profile in a typical working day in spring.

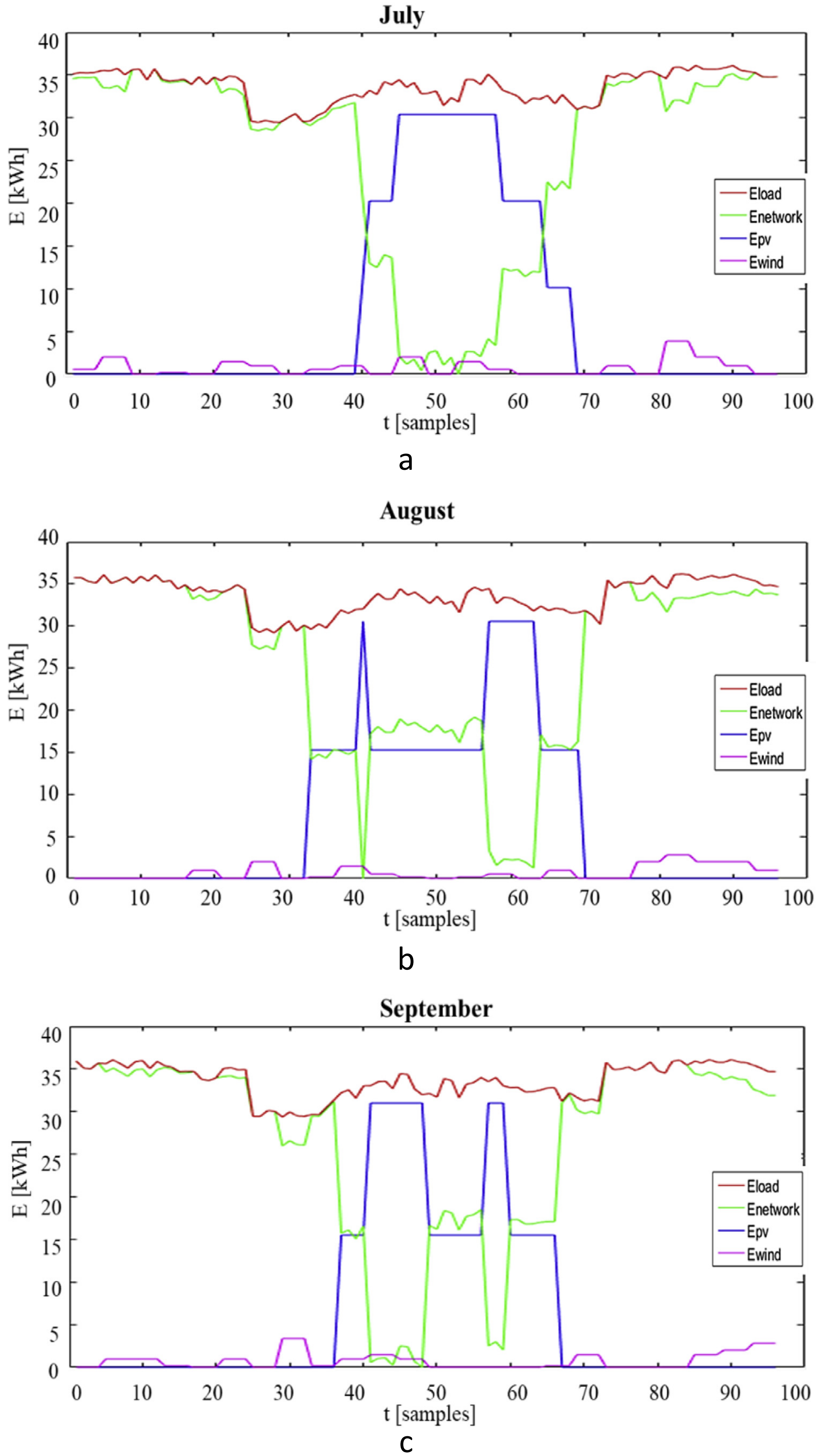


Fig. 5. Energy profile of RES, network, and load profile on a typical working day in summer.

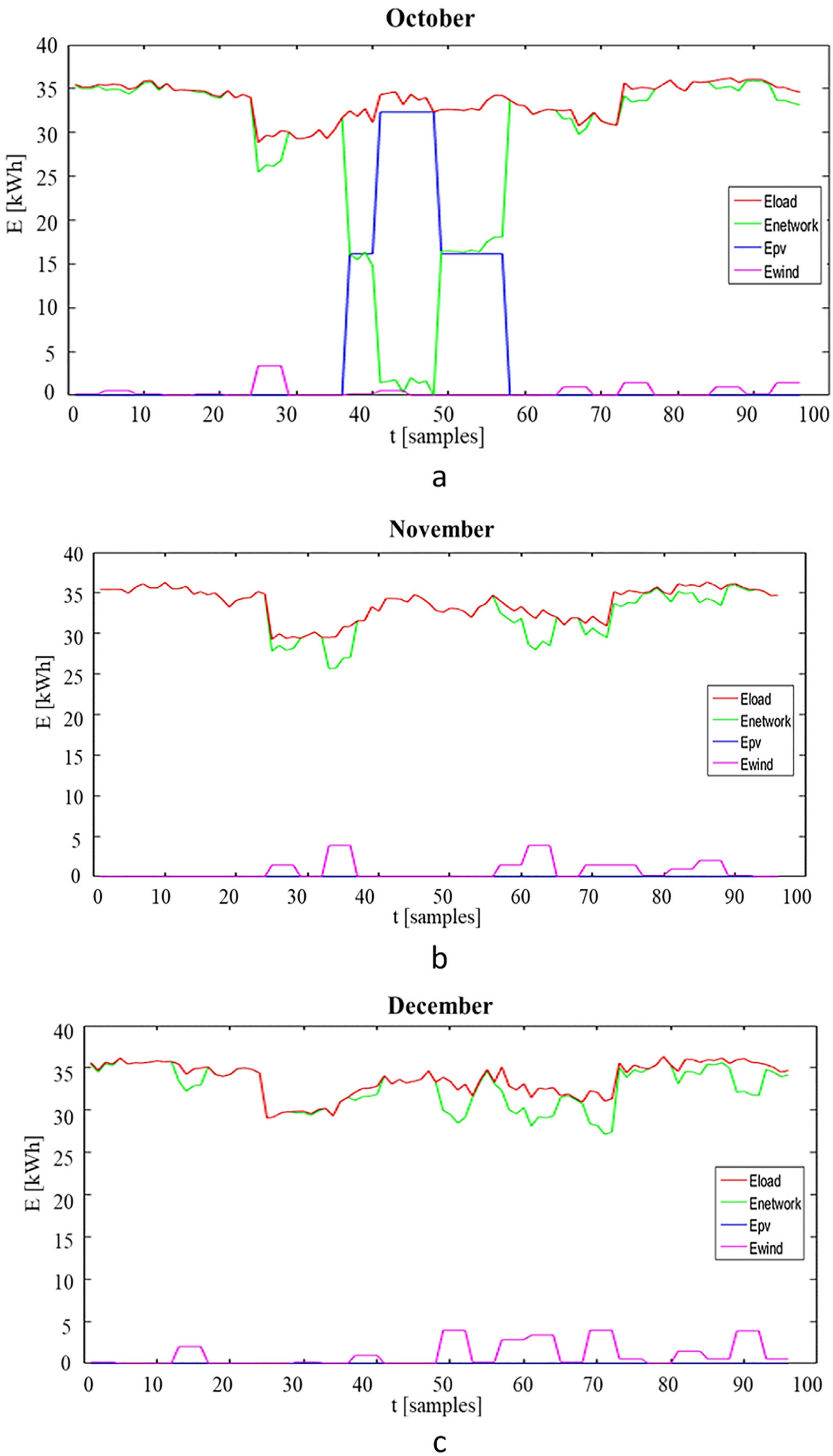


Fig. 6. Energy profile of RES, network, and load profile on a typical working day in autumn.

Table 4
Optimization results for January, May, July, and October.

	January	May	July	October
N° of 5 kW wind turbines	3	3	3	3
N° of 220-W panels	0	415	405	646
N° solar panels rows	0	29	29	29
N° solar panels per row	0	14	14	22
Daily expense for energy purchase without RES [€]	582	581	581	581
Optimized daily expense for the energy purchase [€]	569	455	445	489
Total optimized daily expense [€]	571	461	451	498
Daily revenues [€]	13	126	135	92
Monthly revenues [€]	393	3900	4200	2851
Daily O&M costs of wind system [€]	1	1	1	1
Daily O&M costs of solar system [€]	0	5	5	7

Table 5
Values of amortization (A), and V_r.

Year	A	$C_{i,tot}$	V_r
	[€/year]	[€]	[€]
1	16803	186700	169897
2	16803	186700	153094
3	16803	186700	136291
4	16803	186700	119488
5	16803	186700	102685
6	16803	186700	85882
7	16803	186700	69079
8	16803	186700	52276
9	16803	186700	35473
10	16803	186700	18670
11	16803	186700	1867

Table 6
Values of revenues, amortization, $C_{i,tot}$, $C_{O\&M}$, cash flows, and NPV over 25 years.

Year	Revenues	$C_{i,tot}$	A	$C_{O\&M}$	Cash Flows	NPV
	[€/year]	[€]	[€/year]	[€/year]	[€/year]	[€]
0	0	186700	0	0	−186700	−186700
1	28419	0	16803	3218	21590	−165840
2	28419	0	16803	3218	21590	−145686
3	28419	0	16803	3218	21590	−126213
4	28419	0	16803	3218	21590	−107399
5	28419	0	16803	3218	21590	−89221
6	28419	0	16803	3218	21590	−71657
7	28419	0	16803	3218	21590	−54688
8	28419	0	16803	3218	21590	−38292
9	28419	0	16803	3218	21590	−22451
10	28419	0	16803	3218	21590	−7146
11	28419	0	16803	3218	21590	7642
12	28419	0	0	3218	14365	17148
13	28419	0	0	3218	14365	26333
14	28419	0	0	3218	14365	35207
15	28419	0	0	3218	14365	43781
16	28419	0	0	3218	14365	52065
17	28419	0	0	3218	14365	60069
18	28419	0	0	3218	14365	67803
19	28419	0	0	3218	14365	75274
20	28419	0	0	3218	14365	82493
21	28419	0	0	3218	14365	89468
22	28419	0	0	3218	14365	96208
23	28419	0	0	3218	14365	102719
24	28419	0	0	3218	14365	109010
25	28419	0	0	3218	14365	115088

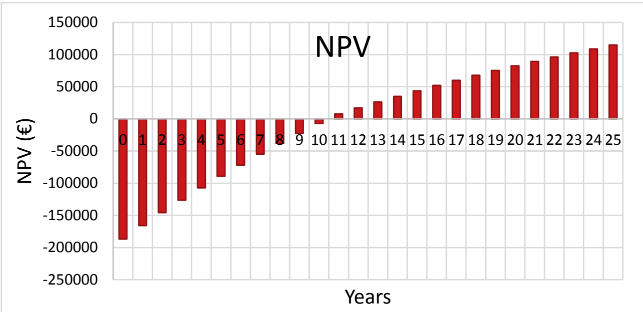


Fig. 7. NPV profile over 25-year period.

The procedure is suitable for any generic industrial site, including those that do not operate all year long. The integrated technical-economic procedure is useful for correctly defining the investments according to the different Company's objectives.

Acknowledgements

The authors would like to thank ATAC S.p.a (The city of Rome Transportation Company) for facilitating the measurement campaign at an industrial plant.

References

[1] Grasselli U, Lamedica R, Ruvio A. Management policies for residential and tertiary users: a measurement campaign. In: International symposium on power electronics, electric drives, automation and motion 2014; 18-20 June 2014. https://doi.org/10.1109/SPEEDAM.2014.6872118.
[2] Graditi G, Ippolito MG, Lamedica R, Piccolo A, Ruvio A, Santini E, Siano P. Innovative control logics for a rational utilization of electric loads and air-conditioning systems in a residential building. Energy Build 2015;102:1–17. https://doi.org/10.1016/j.enbuild.2015.05.027.
[3] Dagdougui H, Minciardi R, Ouammi A, Robba M, Sacile R. Modeling and optimization of a hybrid system for the energy supply of a "Green" bulding. Energy Convers Manag 2012;64:351–63.
[4] Lamedica R, Santini E, Teodori S. Electrical loads management in a smart building supplied by PV sources in power scenario. Int Rev Econ Educ 2014;9(5). https://doi.org/10.15866/iree.v9i5.4216.
[5] Ogunjuyigbe ASO, Ayodele TR, Akinola OA. User satisfaction-induced demand side load management in residential buildings with user budget constraint. Appl Energy 2017;187:352–66. https://doi.org/10.1016/j.apenergy.2016.11.071.
[6] Lešić Vinko, Martinčević Anita, Vašak Mario. Modular energy cost optimization for buildings with integrated microgrid. Appl Energy 2017;197:14–28. https://doi.org/10.1016/j.apenergy.2017.03.087.
[7] Yu Mengmeng, Lu Renzhi, Ho Hong Seung. A real-time decision model for industrial load management in a smart grid. Appl Energy 2016;183:1488–97. https://doi.org/10.1016/j.apenergy.2016.09.021.
[8] Ministry of economic development. General directive for security for supply and energy infrastructure, the national energy situation in Italy. 2016.
[9] Lv T, Ai Q. Interactive energy management of networked microgrids-based active distribution system considering large-scale integration of renewable energy resources. Appl Energy 2016;163:408–22. https://doi.org/10.1016/j.apenergy.2015.10.179.
[10] Behboodi Sahand, Chassin David P, Crawford Curran, Djilali Ned. Renewable resources portfolio optimization in the presence of demand response. Appl Energy 2016;162:139–48. https://doi.org/10.1016/j.apenergy.2015.10.074.
[11] Wang Xiaonan, Palazoglu Ahmet, Nael H, El-Farra. Operational optimization and demand response of hybrid renewable energy systems. Appl Energy 2015;143:324–35. https://doi.org/10.1016/j.apenergy.2015.01.004.
[12] Morales R, Sàez D, Marìn LG, Nuñez A. Microgrid planning based on fuzzy interval models of renewable sources. In: 2016 IEEE international conference on fuzzy systems. FUZZ-IEEE); 24-29 July 2016. https://doi.org/10.1109/FUZZ-IEEE.2016.7737706.
[13] Coelho Vitor N, Coelho Igor M, Coelho Bruno N, Reis Agnaldo JR, Enayatifar Rasul, Souza Marcone JF, Guimarães Frederico G. A self-adaptive evolutionary fuzzy model for load forecasting problems on smart grid environment. Appl Energy 2016;169:567–84. https://doi.org/10.1016/j.apenergy.2016.02.045.
[14] Atia R, Yamada N. Sizing and analysis of renewable energy and battery system in residential microgrid. IEEE Trans Smart Grid May 2016;7(3).
[15] Sansa I, Villafafila R, Bellaaj NM. Optimal sizing design of an isolated microgrid using loss of power supply probability. In: 2015 6th international renewable energy congress (IREC); 24-26 March 2015.
[16] Cervone A, Carbone G, Santini E, Teodori S. Optimization of the battery size for PV systems under regulatory rules using a Markov-Chains approach. Renew Energy 2016;85(January):657–65. Elsevier.
[17] Urias MEG, Sanchez EN, Ricalde LJ. Electrical microgrid optimization via a new recurrent neural network. IEEE Syst J Sept. 2015;9(3).
[18] Hongxing Y, Wei Z, Chengzhi L. Optimal design and techno-economic analysis of a hybrid solar-wind power generation system. Appl Energy 2009;86:163–9. https://doi.org/10.1016/j.apenergy.2008.03.008.
[19] Ekren O, Yetkin Ekren B. Size optimization of a PV/wind hybrid energy conversion system with battery storage using response surface methodology. Appl Energy 2008;85:1086–101.
[20] Nguyen Anh-Tuan, Reiter Sigrid, Rigo Philippe. A review on simulation-based optimization methods applied to building performance analysis. Appl Energy 2014;113:1043–58.
[21] González Arnau, Riba Jordi-Roger, Rius Antoni, Puig Rita. Optimal sizing of a hybrid grid-connected photovoltaic and wind power system. Appl Energy 2015;154:752–62.
[22] Eldessouky AS, Gabbar HA. Microgrid renewables dynamic and static performance optimization using genetic algorithm. In: 2015 IEEE international conference on smart energy grid engineering (SEGE); 17–19 Aug. 2015.
[23] Katsigiannis YA, Georgilakis PS, Karapidakis ES. Multiobjective genetic algorithm solution to the optimum economic and environmental performance problem of small autonomous hybrid power systems with renewables. IET Renew Power Gener 2010;4(5):404–19. https://doi.org/10.1049/iet-rpg.2009.0076.
[24] Khatib T, Mohamed A, Sopian K. Optimization of a PV/wind micro-grid for rural housing electrification using a hybrid iterative/genetic algorithm: case study of Kuala Terengganu, Malaysia. Energy Build 2012;47:321–31. https://doi.org/10.1016/j.enbuild.2011.12.006.
[25] Lu Y, Wang S, Zhao Y, Yan C. Renewable energy system optimization of low/zero energy buildings using single-objective and multi-objective optimization methods. Energy Build 2015;89:61–75.
[26] Yang H, Lu L, Zhou W. A novel optimization sizing model for hybrid solar-wind power generation system. Sol Energy 2007;81:76–84.
[27] Yang HX, Lu L, Burnett J. Weather data and probability analysis of hybrid photovoltaic-wind power generation systems in Hong Kong. Renew Energy 2003;28:1813–24.
[28] Bienstock D. Electrical transmission system cascades and vulnerability: an operations research viewpoint. SIAM-MOS Series on Optimization; 2015.
[29] Kasukana K, Vermaak HJ, Numbi BP. Optimal sizing of a hybrid energy plant using linear programming. Johannesburg, South Africa: IEEE PES PowerAfrica Conference and Exposition; 09–13 July 2012.
[30] Kneiske TM, Braun M, Hidalgo-Rodriguez DI. A new combined control algorithm for PV-CHP hybrid systems. Appl Energy 2017;xxx. xxx–xxx In press, https://doi.org/10.1016/j.apenergy.2017.06.047.
[31] Wolsey, Laurence A. Integer programming, vol. 42. New York: Wiley; 1998.
[32] Jünger Michael, et al., editors. 50 years of integer programming 1958-2008: from the early years to the state-of-the-art. Springer Science & Business Media; 2009.
[33] ISO IEC 61400.
[34] http://www.societaelettricaitaliana.it/documents/MINIEOLICO_SEI-MD_5KW.pdf.
[35] Manwell James F, McGowan Jon G, Anthony L. Rogers wind energy explained: theory, design and application editore. John Wiley and Sons Ltd Anno; 2009.
[36] Segyro JV, Lambert TW. Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. J Wind Eng Ind Aerod 2000;85:75–84.
[37] The Italian UNI 10349: heating and cooling of buildings, Climate Data: methods to divide the hourly solar irradiance into the direct and diffuse fraction and to calculate the radiant energy received from a fixed surface, however inclined and oriented;.
[38] ENEA - National Agency for New Technologies, Energy and Sustainable Economic Development data bank solar radiation: http://www.solaritaly.enea.it/CalcComune/Calcola.php.
[39] Karatepe E, Boztepe M, Colak M. Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells. Sol Energy 2007;81:977–92.
[40] Cervone A, Santini E, Teodori S, Zaccagnini D. Impact of regulatory rules on economic performance of PV power plants. Renew Energy 2015;74:78–86. Elsevier.
[41] Capasso R Lamedica, Podestà L, Ruvio A, Sangiovanni S, Lazaroiu GC, Maranzano GA. A measurement campaign in a metro-train deposit/maintenance and repair site for PV production optimal sizing. In: 15th conference on environment and electrical engineering. IEEE EEEIC; 2015.
[42] NREL – National Renewable Energy Laboratory: https://www.nrel.gov/analysis/tech-lcoe-re-cost-est.html.