Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2018) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

Applied Energy Symposium and Forum, Renewable Energy Integration with Mini/Microgrids, REM 2018, 29–30 September 2018, Rhodes, Greece

Wind, solar and battery micro-grid optimal sizing in Tilos Island

Jean-Laurent Duchaud[a]*, Gilles Notton[a], Alexis Fouilloy[a], Cyril Voyant[b]

[a]SPE Laboratory – UMR CNRS 6134, University of Corsica, France
[b]PIMENT Laboratory, University of La Reunion, France

Abstract

This paper presents a flexible power plant modeling associated with a Multi-Objective Particle Swarm Optimization in order to obtain the optimal size of each plant component. The modeling can be adapted to a wide range of energy sources, storages and loads. The methodology is applied to a Wind Turbine / Photovoltaic array / Battery bank configuration located in Tilos, Greece. The optimization is set up to minimize the system cost and the energy imported from non-renewable sources. The results form a Pareto front representing the trade-off between the equipment cost and the micro-grid autonomy. An optimal solution for a given energy importation cost is detailed as an example.

Keywords: Hybrid power-plant; Particle swarm optimization; Techno-economic study

1. Introduction

Energy production and distribution in non-interconnected areas are often costly and not environmental friendly. This is especially true for islands [1] where the plants heavily rely on fossil fuel or on undersea cables, causing important power losses. Local energy production from renewable sources can help to reduce the energy cost and its environmental impact. To supply power to the consumers at all times, renewable energy power plants should include an energy storage system due to the intermittent nature of the sources [2]. Coupling wind and solar power can also help reduce the production variability [3].

* Corresponding author. Tel.: +336 89 02 36 57.
E-mail address: duchaud_jl@univ-corse.fr

Such a power plant is expensive and can easily be not profitable if improperly sized [4], [5]. This problem has often been studied in the literature [6] with different algorithms such as Genetic Algorithm [7], [8] or Particle Swarm Algorithm [9], [10]. However each of these references focuses on a specific power plant configuration.

The methodology presented in this paper uses a 12-variable modeling applicable to a wide range of micro-grid configurations [11]. It uses a Multi Objective Particle Swarm Optimization (MOPSO) algorithm [12], [13] to minimize the system cost [14] and the dependence to external energy sources. This external energy cost is used after the optimization to obtain the best plant configuration for a given location and consumption profile.

The algorithm is used to size a wind and solar power plant associated with a battery bank in Tilos Island, Greece. The next section describes the flexible plant modeling, how it is configured for the case studied, its power sources, the energy conversion components, the energy management strategy and the economic assumptions. Section 3 briefly presents the optimization problem and the MOPSO algorithm. Finally, the optimization results are presented in Section 4.

2. Plant Modeling

2.1. Flexible plant modeling

The modeling used in this paper is designed to be modular. It can simulate a wide range of plant configurations made of one or two Renewable Energy Systems (RES) and one External Storage System (ESS). The plants modeled have to supply a load either at all times or with a Loss of Power Supply tolerance. They can be connected to a main grid or a controllable source like a Diesel Generator if the RES power is not sufficient and may or may not export the exceeding energy produced. This flexibility is offered by nine Generic Conversion Systems (GCS) that can be enabled or disabled depending on the configuration modeled.

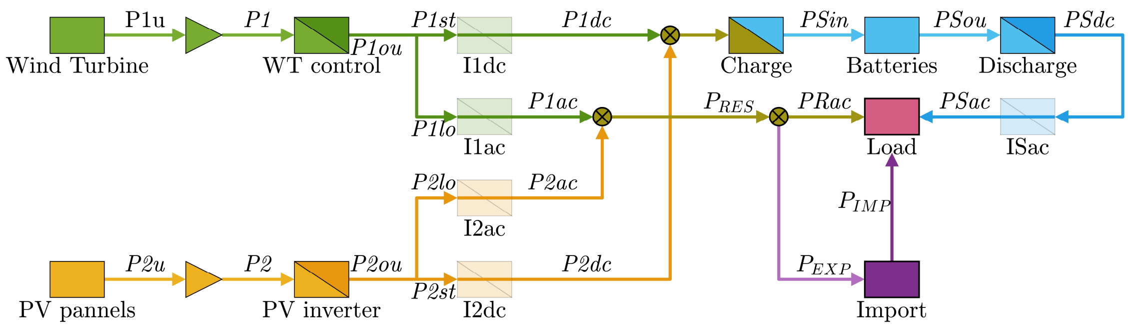
Fig. 1 presents the algorithm setup for the plant used as an example in this paper. It is made of a Wind Turbine, a Photovoltaic array and a Sodium Nickel Chloride battery bank. The plant is located in Tilos, Greece, and has to supply power to approximately 800 inhabitants [15]. In case the RES are not sufficient to power the load, energy can be produced by a Diesel Generator or imported via an undersea cable from Kos, a nearby island.

2.2. Renewable Energy Systems

The Wind Turbine and the PV panels power output is computed from meteorological weather data measured in-situ. The computations are done before the optimization with a unitary installed power then the output is multiplied by the actual installed power. In addition to these RES, the plant can use an undersea cable or a Diesel Generator to import power.

Fig. 1. Algorithm setup for the plant configuration.

2.3. Generic Conversion Systems



Generic Conversion Systems (GCS) are the backbone of the plant modeling. They are used to model the plant components such as power electronics like inverters or rectifiers; a fuel cell and an electrolyzer; water pumps and turbines or a battery charge efficiency. By activating or deactivating some GCS, the algorithm can be adapted to the configuration wanted.

They act as a limiter, which represents the maximum permissible power for the component and a gain that models the component efficiency. This gain can be fixed or function of the input power. The optimization algorithm will find the optimal maximum power (i.e. size of the component) according to the objectives defined.

In our case (Fig. 1), *I1dc*, *I1ac*, *I2dc*, *I2ac* and *ISac* are deactivated. *WT control* represents the Wind Turbine power electronics doing the AC/AC conversion, set up with a constant 96% efficiency. The power produced by the PV panels is converted to AC by inverters. *PV inverter* models these components with an efficiency curve extracted from the datasheet of a commercial inverter. Finally *Charge* and *Discharge* represent the battery bank power electronics. They are setup with a 70% roundtrip efficiency and their maximum power is defined by the storage capacity with a 1.6 C charge rate [16].

2.4. Power management

The optimization algorithm needs values representing the plant performances in order to find the best solution. To evaluate the performances of a given plant, its behavior is simulated for a period of time with weather and consumption data. This period should at least be one year to avoid seasonal phenomenon and be representative of the location.

Since the optimizer will simulate a great number of configurations, the power management algorithm must be simple enough to be run quickly. In our case, the power produced by the Wind Turbine is converted to the grid voltage and frequency by *WT control*. In the same way, the power from the PV panels is converted via *PV inverter*. These power are used to supply the load. If the RES power is greater than the consumption, the remaining power is routed to *Charge* to be converted to DC and stored in the battery bank. If the batteries are full, the energy is exported to the main grid if possible. If the RES are not enough to power the load, the batteries are discharged and converted to AC through *Discharge*. In case that is still not enough, the remaining energy is imported from the grid or the Diesel Generator. Finally, if the import power limitation does not allow to supply the load, there is a Loss of Power Supply and the plant is penalized by the optimizer.

The power exchanges are integrated and normalized for 365 days to obtain the annualized energy consumed by the load E_{CA}, the imported energy from non-renewable sources E_{IA}, the renewable energy used E_{UA} and the exceeding energy produced E_{EA}. The amount of imported energy E_{IA} is used in the optimization as an objective to be minimized. The other values are stored for post-treatment.

To prevent the algorithm from returning a costly solution with almost no energy imported, an economic criterion need to be also minimized.

2.5. Economics

Estimating the cost of a power plant is a difficult task due to the number of economic parameters at stake and their variability. The cost for installed PV panel for example decreased by 83% in seven years [17]. They also depend on the supplier, the location and the labor cost and are subject to change quickly. The values used come from [17] and [18] for PV panels and inverters, from [19] for Wind Turbines and from [18] and [20] for the batteries. The authors insist that this paper focuses on the modeling and the optimization methods and that the costs used are purely indicative.

Each component has an installation cost C_I that depends on its size. The number of replacement N_R is derived from the equipment lifespan L_s and the study duration D_S set here as 25 years. The buying cost is then the N_R times the installation cost adjusted by the actualization rate τ_A that represents the yearly cost variation. The buying cost is divided by the study duration to obtain an annualized cost:

$$C_{BA} = \sum_{k=0}^{N_R} \frac{C_I(1-\tau_A)^{L_S}}{D_S} \tag{1}$$

The annual maintenance cost is assumed to be a fraction τ_M of the installation cost. The annualized cost for a given equipment is finally:

$$C_A = C_{BA} + C_I \tau_M \tag{2}$$

The Annualized Cost of System (ACS) is then obtained by summing the annualized cost of each equipment. The ACS is used as the second objective to minimize in the optimization. Since it conflicts with the energy imported, the optimization results will form a Pareto front.

3. Particle Swarm Optimization

The optimization problem aims to minimize the Annualized Cost of System (ACS) and the imported energy E_{IA} under the constraints that the Lost of Power Supply Probability ($LPSP$) is null. It can be formulated as follows:

$$\text{Find } x^* \text{ in } X \text{ such as } \begin{cases} x^* = arg\ min_{x \in X}[ACS(x), E_{IA}(x)] \\ LPSP(x^*) = 0 \end{cases} \tag{3}$$

Where x is the vector defining the Wind Turbine nominal power, the PV array peak power, the PV inverter rated power and the battery bank capacity and X the study domain.

This four-parameter optimization problem is solved using a Multi-Objective Particle Swarm Optimization (MOPSO) [13], [21]. It is a gradient-free stochastic algorithm that can solve large scale problems. It works by moving the particles x, representing plant configurations, in the study domain. The particle speed is derived from the plant performances: ACS and E_{IA} so they converge to the optimal solution, if any. The algorithm returns a list of non-dominated plants forming a Pareto front.

4. Optimization results

The solutions given by the algorithm are represented by the dark blue line in Fig. 2. Each point in the graph represents an optimal plant with its ACS and the imported energy percentage: E_{IA}/E_{CA}. The blue circle denotes the actual configuration installed and the thinner lines represent the Wind Turbine nominal power (green), the PV array peak power (yellow) and the battery bank capacity (light blue).

These results indicate that the principal energy source should be the wind. Above 25% imported energy, the plant solely relies on the wind and on the importations without solar power or storage. Below this threshold, increasing the PV array size becomes profitable. However, since this power is not available at night, it should be associated with a bigger storage. This increases drastically the cost and gaining in autonomy becomes expensive.

The optimal solution depends now on the cost of producing energy with the Diesel Generator and on the energy importation cost. These costs may vary every hour and should be treated separately. For the sake of illustration, they are supposed equal and constant so the results can be plotted in a 3D graph.

Let C_B be the energy buying cost (i.e. the importation and the diesel cost). For each plant, the production cost C_p can be defined as the ratio between the money spent in one year and the energy consumed:

$$C_p = \frac{ACS + C_B E_{IA}}{E_{CA}} \tag{4}$$

For a given C_B, the plant in the Pareto front that minimizes C_p is plotted in red in Fig. 3. In the end, assuming C_B allows to find the optimal component size of the plant, defines the ACS, the imported energy and the production cost. Fig. 4 synthetizes these results on the same figure. For example, for $C_B = 220$ €/MW.h, the optimal plant is made of a 1 MW Wind Turbine, a 200 kWp PV array with associated with inverters accounting for 350kW nominal power and a 400 kW.h power bank. This plant offers 80% energetic autonomy and a production cost of 87 €/MW.h. This configuration is marked by a red circle in Fig. 2. It uses more wind power and less storage than its actual counterpart for slightly better performances.

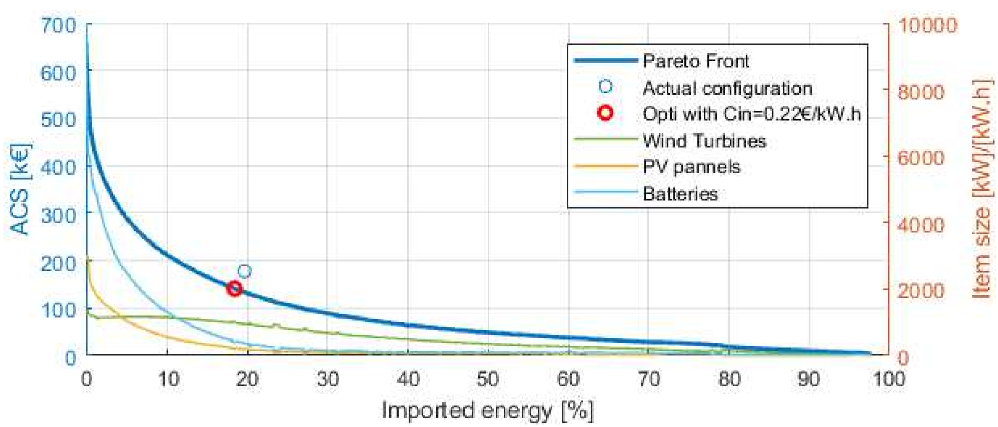


Fig. 2. Algorithm optimization result for a Wind Turbine / Photovoltaic array / Battery bank configuration in Tilos.

5. Conclusion

The algorithm presented in this paper is able to optimize the component sizes of a hybrid renewable power plant associated with a storage. The plant model can be adapted to various configurations and takes into account the non-linear cost of the equipment and power dependent efficiencies. A Multi Objective Particle Swarm algorithm is used to solve the optimization problem.

The algorithm has been applied to a Wind Turbine / Photovoltaic array / Battery bank power plant in Tilos Island, Greece. To avoid assuming an energy importation cost before the optimization, the objectives are to minimize the Annualized Cost of System and the imported energy. Once the Pareto front is obtained, the optimal solution for different importation costs can be computed. The solution consists on the size of each plant component (WT size, PV installed power, inverter nominal power and storage capacity), the ACS, the imported energy and the energy production cost.

This algorithm has successfully solved the optimization problem. It can be improved by implementing a better energy management strategy [22], the possibility to use multiple storages, more precise power sources models or the eventual storage aging. Furthermore, the economic parameters for the components buying and maintenance costs need to be refined to give more realistic solutions.

Acknowledgements

This work was carried out in the framework of the Horizon 2020 project TILOS. The authors would like to thank the European Union and the Corsican Territorial Collectivity for the financial support.

References

[1] G. Notton, “Importance of islands in renewable energy production and storage: The situation of the French islands,” *Renew. Sustain. Energy Rev.*, vol. 47, pp. 260–269, Jul. 2015.

[2] M. Black and G. Strbac, “Value of storage in providing balancing services for electricity generation systems with high wind penetration,” *J. Power Sources*, vol. 162, no. 2, pp. 949–953, Nov. 2006.

[3] L. Stoyanov, G. Notton, and V. Lazarov, “Balance of Solar and Wind Energy Sources,” *Ecol. Eng. Environ. Prot.*, vol. IV, no. 1, pp. 65–76, 2015.

[4] M. Alsayed, M. Cacciato, G. Scarcella, and G. Scelba, “Multicriteria Optimal Sizing of Photovoltaic-Wind Turbine Grid Connected Systems,” *IEEE Trans. Energy Convers.*, vol. 28, no. 2, pp. 370–379, Jun. 2013.

[5] E. Waffenschmidt, “Dimensioning of Decentralized Photovoltaic Storages with Limited Feed-in Power and their Impact on the

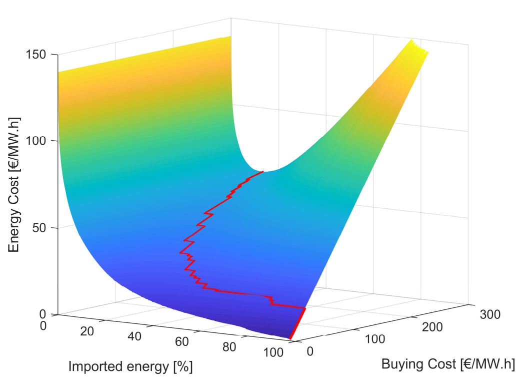


Fig. 3. Energy production cost depending on the optimal solution and the buying cost. The red line denotes the minimal production cost for each buying cost.

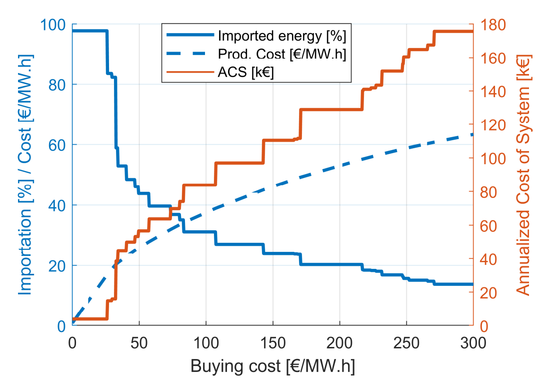


Fig. 4. Annualized Cost of System, Imported Energy and Production Cost versus the Buying Cost.

Distribution Grid," *Energy Procedia*, vol. 46, pp. 88–97, 2014.

[6] A. H. Fathima and K. Palanisamy, "Optimization in microgrids with hybrid energy systems – A review," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 431–446, May 2015.

[7] T. Ma, H. Yang, L. Lu, and J. Peng, "Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization," *Appl. Energy*, vol. 137, pp. 649–659, 2015.

[8] H. Yang, W. Zhou, L. Lu, and Z. Fang, "Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm," *Sol. Energy*, vol. 82, no. 4, pp. 354–367, 2008.

[9] A. K. Bansal, R. A. Gupta, and R. Kumar, "Optimization of hybrid PV/wind energy system using Meta Particle Swarm Optimization (MPSO)," in *India International Conference on Power Electronics 2010 (IICPE2010)*, 2011, pp. 1–7.

[10] N. Phuangpornpitak, W. Prommee, S. Tia, and W. Phuangpornpitak, "A study of particle swarm technique for renewable energy power systems," in *Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010)*, 2010, pp. 1–6.

[11] J.-L. Duchaud, G. Notton, C. Darras, and C. Voyant, "Multi-Objective Particle Swarm optimal sizing of a renewable hybrid power plant with storage," *Renew. Energy*, vol. 131, pp. 1156–1167, Feb. 2019.

[12] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proceedings of ICNN'95 - International Conference on Neural Networks*, 1995, vol. 4, pp. 1942–1948.

[13] J. Aubry, "Optimisation du dimensionnement d'une chaîne de conversion électrique directe incluant un système de lissage de production par supercondensateurs : application au houlogénérateur SEAREV," ENS Cachan, 2011.

[14] A. Kaabeche, M. Belhamel, and R. Ibtiouen, "Optimal sizing method for stand-alone hybrid PV / wind power generation system," *Rev. des Energies Renouvelables SMEE'10 Bou Ismail Tipaza*, pp. 205–213, 2010.

[15] G. Notton, M.-L. Nivet, D. Zafirakis, F. Motte, C. Voyant, and A. Fouilloy, "Tilos, the first autonomous renewable green island in Mediterranean: A Horizon 2020 project," in *2017 15th International Conference on Electrical Machines, Drives and Power Systems (ELMA)*, 2017, pp. 102–105.

[16] IRENA, "Electricity Storage and Renewables : Costs and Markets To 2030," International Renewable Energy Agency, Abu Dhabi, 2017.

[17] R. Fu, D. Feldman, R. Margolis, M. Woodhouse, and K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017," 2017.

[18] IRENA, "Renewable Power Generation Costs in 2017," International Renewable Energy Agency, Abu Dhabi, 2018.

[19] X. T. Chadee and R. M. Clarke, "Wind resources and the levelized cost of wind generated electricity in the Caribbean islands of Trinidad and Tobago," *Renew. Sustain. Energy Rev.*, vol. 81, no. June 2016, pp. 2526–2540, 2018.

[20] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 569–596, Feb. 2015.

[21] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," in *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, 1995, pp. 39–43.

[22] J.-L. Duchaud, G. Notton, C. Darras, and C. Voyant, "Power ramp-rate control algorithm with optimal State of Charge reference via Dynamic Programming," *Energy*, vol. 149, pp. 709–717, Apr. 2018.