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Joint cost of energy under an optimal economic policy of hybrid power systems subject to uncertainty☆

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ABSTRACT

Economical optimization of hybrid systems is usually performed by means of LCoE (levelized cost of energy) calculation. Previous works deal with the LCoE calculation of the whole hybrid system disregarding an important issue: the stochastic component of the system units must be jointly considered. This paper deals with this issue and proposes a new fast optimal policy that properly calculates the LCoE of a hybrid system and finds the lowest LCoE. This proposed policy also considers the implied competition among power sources when variability of gas and electricity prices are taken into account. Additionally, it presents a comparative between the LCoE of the hybrid system and its individual technologies of generation by means of a fast and robust algorithm based on vector logical computation. Numerical case analyses based on realistic data are presented that valuate the contribution of technologies in a hybrid power system to the joint LCoE.

1. Introduction

The energy production based on renewable resources has been continuously increasing over the last decades due to the several advantages it reports. As the presence of distributed generation has increased, its integration into the main grid has become a critical point in order to preserve and guarantee the stability and quality of the mains grid. In this sense, electrical hybrid systems are a good option for connecting renewable energy production into the mains grid in a reliable and profitable manner.

As a definition, hybrid systems integrate different types of distributed generators in order to feed a local load [1]. These systems usually comprehend both renewable and non renewable energy sources and can incorporate storage systems. Among the research lines of hybrid systems, this paper deals with the optimization of the energy production from an economic point of view. Many works deal with the economic optimization of both standalone and grid connected hybrid systems. Regarding to standalone systems, in Ref. [2] cloud cover modeling is addressed in a standalone PV-battery system using Markov transition matrix of the clearness index. Another proposal can be found in Ref. [3] where an economic analysis of PV/diesel hybrid system with flywheel energy storage is performed. This economic analysis considers the power generation, energy cost, and net present cost. A stand-alone PV–wind–diesel system with batteries storage is also economically optimized in Ref. [4] by means of a multi-objective optimization that holds the LCoE (levelized cost of energy) and the equivalent carbon dioxide LCE (life cycle emissions) as objectives to be minimized.

According to grid connected hybrid systems [5], recently proposed a planning technique using multi-objective optimization formulation for a sustainable hybrid system including photovoltaic, wind turbine and battery energy storage systems. In this work, the objectives of the optimization function are the LCoE, embodied emissions of energy and the *reliability* generation. Apart from this, there is another proposal in Ref. [6] where a storage system is added to a private electricity facility with the aim of reducing the electricity bill. The work in Ref. [7] addresses the performance of a hybrid renewable system (consisting of a variable speed ICE and a

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solar device) for variable electricity prices by means of an optimized management strategy. Bortolini et al. proposed another optimized hybrid system (photovoltaic system with battery energy storage) in Ref. [8]. This work deals with a model which optimizes the LCoE of a hybrid system and minimizes the LCoE of the system.

Taking into account the proposals found in the literature, economical optimizations of hybrid systems usually consider the Levelized Cost of Energy (LCoE). Although, the calculation of this LCoE is usually performed in a deterministic manner disregarding the uncertainty of the renewable sources. In Ref. [5] this uncertainty is modeled by means of method of moments. However, this method can be only applied with variables with a normal distribution. In addition, the LCoE of the whole hybrid system is normally calculated as the sum of the LCoE of the individual technologies, which is not a suitable method when uncertainty is involved. This paper aims to deal with these deficiencies and find an optimal policy for a hybrid power system under uncertainty.

The featured MG (microgrid) in this paper has three main generation technologies—small wind turbine, gas microturbine, and the main grid proper—entailing different conceptual approaches [9]. First, wind energy is a representative of a renewable-based energy source with a global installed capacity of almost 400 GW at the end of 2014 [10]. Its main characteristic is the uncertain, and somehow uncontrollable, power production level. Alternatively, thermal-based generation offers a remarkably higher certainty in power, but at the cost of more greenhouse gas emissions and increased operating costs. Both technologies are thus complementary, and in a MG they directly or indirectly affect the OPEX (operation expenditures). On the one hand, firing the thermal generation requires fuel consumption, with OPEX subject to the evolution of the gas price. Alternatively, renewable-based energy has almost negligible OPEX, but the uncertain power produced may make necessary buying power from the main grid. Though indirectly, this obviously has an impact on the MG OPEX. Supporting both technologies to increase reliability, the mains grid contributes to the OPEX also in a stochastic way.

This paper proposes a computation of the LCoE based on the premise that the MG has two major OPEX sources: gas and electricity purchases. Because gas and electricity prices do not necessarily follow correlated paths, the LCoE will vary depending on the energy mix; which ultimately will be driven by the mismatch between wind generation and load demand. This paper shows a computation of the LCoE based on an optimal policy, under which the OPEX is sought to be minimum by adequately switching between gas and electricity as a response to the power deficit originated by the load-generation mismatch. The energy mix, and hence the OPEX, is sought to be optimal.

The main contributions of this paper are:

i. Foremost it demonstrates that the cost of energy in a hybrid system subject to different kinds of uncertainty cannot be simply extrapolated from the sum of costs of individual technologies.
ii. This is but a consequence of fact that stochastic variables cannot be directly summed. (At most if they were independent, they may be convoluted, but not directly summed [11].) To solve the problem, this paper features Monte Carlo experiments ensuing from a decomposition of the problem model into several; encompassing the uncertainties in the prices, loads, and wind power in auto-regressive models while retaining seasonal components.
iii. Compounding the problem, the existence of several technologies competing in costs makes it relevant to formulate an optimal policy to ensure that the cost of exploiting the hybrid system is minimal. But the classic approaches to optimization fail to be useful in this case because of the high dimensionality of an hourly scale problem over a year, repeated over a large number of Monte Carlo samples. This paper shows an alternative approach to find the optimal policy on the basis of vector logical operations, which gives both speed and simplicity at the time of determining the optimal scheduling of generating units.
iv. Finally, this paper confronts several scenarios from realistic data to analyze the contribution of hybrid systems to the LCoE formation; particularly comparing them with the sole import of electricity from the grid.

The paper is structured as follows. After an introduction explaining the main scopes and highlights of the work, a deep description of the hybrid system model is presented. In this description, LCoE concept is detailed and the implemented models are described: electricity price model, microturbine and gas price models, characterization of the load and wind power model. Later, the proposed optimal policy is presented which is discussed by means of a number of case analysis. Finally, the conclusions that are drawn from the article are presented.

2. Model characterization

2.1. Levelized cost of energy

The levelized cost of energy is the energy cost—in real euros—of building and operating a power-generating plant over its assumed financial life. In individual generating plants the components of the LCoE are readily interpreted. The building costs (hereafter CAPEX, for CApital EXpenses) consist of the expenditures incurred in the building of the plant. This paper considers that the CAPEX is expended only once, though in practice—depending on the technology lead time—it could be spread over a number of years.[1] Differently the term OPEX (for OPerating Expenses) covers the costs incurred in operating the plant every year over its lifetime. In this paper without loss of generality the OPEX is reduced to the fuel expenses.

The definition of LCoE has a built-in flexibility that allows for different interpretations and levels of detail; see for instance [12] and references therein. In this paper the definition employed is

$$LCOE = \frac{I_0 + \sum_{t=1}^{T} C_t e^{-rt}}{\sum_{t=1}^{T} E_t e^{-rt}}, \tag{1}$$

where

T is the financial lifetime of power-generating asset;
I_0 is the initial (capital) expenditures, the CAPEX;
C_t are the annualized costs of operation at year t, the OPEX;
E_t is the energy produced at year t; and
e^{-rt} is the *discount factor* at an interest rate equal to r, which discounts the yearly cash flows back to the present.

This formulation is readily applied to single generation units. Specifically, if the yearly produced energy is assumed to be constant over the entire lifetime (that is, $E_t = E$ for $t = 1, \ldots, T$), then

[1] *Overnight* costs is a way of reformulating I_0 when the expenditures are distributed over several years. It is a term employed in energy generation literature that essentially discounts back the distributed CAPEX to obtain one only equivalent expenditure. In practice, therefore, considering the cost accumulated in the first year does not represent a problem.