# Evaluation of the Levelized Cost of Energy Method for Analyzing Renewable Energy Systems: A Case Study of System Equivalency Crossover Points Under Varying Analysis Assumptions

Cory R. A. Hallam and Carolina Contreras

***Abstract*—A modified levelized cost of energy (LCOE) model was created to determine the economic crossover point (measured in €/barrel of oil) between a traditional diesel power-generating facility and a hybrid closed-loop wind–hydro energy system on the island of El Hierro. This island represents the first system-of-systems coupled wind and pumped-storage hydroelectric facility in the world aimed at achieving energy independence for an island. LCOE models were developed using fixed baseline oil prices of 30, 40, and 50 €/barrel, which is the price range when the construction project was undertaken. The percentage change of the Spanish consumer price index and industrial price index were used to assess the effect of changing oil prices on the LCOE. This paper involved on-site investigation of the technical and financial elements of the project and resulted in an LCOE model that includes investment, operation and maintenance, emissions, and land costs. Sensitivity analyses were carried out at varying inflation and discount rates. Results indicate that the economic crossover point between the energy production systems to be below the current world oil price and within the range of prices when the project was initiated. Increasing inflation rates reduces the crossover point by increasing future costs associated with the diesel system, and increasing discount rates raises the crossover point by discounting future costs associated with diesel fuel expense. Under constant dollar analysis, the LCEO model robustly highlights system equivalency points; however, the inclusion of discount rate challenges this robustness by introducing the potential for gaming the analysis in favor of one technology over another.**

***Index Terms*—Cost of energy, diesel power, economics, energy, hydroelectric power, life cycle, power production, renewable energy, sensitivity analysis, wind power.**

## I. Introduction

ENERGY plays an important role in every nation's development and industrialization [1]–[3]. To meet electricity demand, fossil fuels have traditionally been the main source of electric energy production [4]–[8]. The U.S. Department of Energy's "International Energy Outlook, 2011" projects world electricity demand to increase from 505 to 770 quadrillion Btu between 2008 and 2035 [5]. This growth in demand is projected to be covered by multiple sources, including coal, natural gas, liquid fuels, nuclear, and renewable sources such as wind, solar, hydropower, biomass, and geothermal. Despite the introduction of renewable energy technologies, fossil fuels will continue supplying the majority of the world's energy needs. According to the International Energy Agency's "World Energy Outlook," fossil fuels contributed approximately 80% of the total primary energy supply in 2002 and are expected to contribute 82% of the total primary energy supply by 2030 [6].

The predominant use of oil, coal, and natural gas exposes societies to an array of political, economic, and environmental risks. Today, there exists empirical evidence to support the fact that swings in oil prices caused by the oil–gross domestic product effect pose threats to the world's economy by raising inflation and unemployment and by dampening macroeconomic growth [9], [10]. In addition, emissions from fossil fuels have been identified as problematic due to the risk associated with their potential environmental damage from greenhouse gases (i.e., $CO_2$, CO, $NO_x$, etc.) [11]–[14]. Since initial investigations began in the early 1970s, a scientific consensus has emerged to point out that increasing greenhouse gas concentrations in the atmosphere have their roots in human activity, primarily through burning fossil fuels, which tend to warm the planet and to drive the process of climate change [15]. According to the Intergovernmental Panel on Climate Change, current climate models predict that continued emissions from anthropogenic greenhouse gases beyond the sequestration capacity of natural systems will result in increased temperatures and more frequent extreme climate events [8]. These projected future effects can impede human access to the basic elements of life such as water, food, and habitat [16].

In light of the adverse economic, environmental, and political consequences that dependence on fossil fuels entails, renewable energy sources such as solar, wind, and hydropower for electricity generation have shown excellent potential as supplementary sources for conventional systems that produce electricity based on fossil fuels [3], [17]–[20]. Renewable energy technologies provide a means of electricity generation that offers economic independence from fossil-fuel suppliers, the potential for political stability by eliminating fossil-fuel-source

Manuscript received December 17, 2012; revised May 14, 2013 and September 30, 2013; accepted October 26, 2013. Date of publication December 6, 2013; date of current version March 2, 2015.

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Digital Object Identifier 10.1109/JSYST.2013.2290339

supply dependence, and ecological sustainability [8], [21], [22]. However, transitioning to technologies that provide a greater proportion of renewable power to the grid has been impeded by economic barriers associated with their elevated acquisition and installation cost, compared with fossil-fuel-based energy production technologies [23]. Furthermore, the combination of multiple energy production technologies, systems, and operational controls expands these projects into larger scale system-of-system problems [24], [25].

In more remote locations, or areas of low grid connectivity, one of the most significant economic barriers to renewable energy systems has been initial installation cost, when compared with traditional diesel systems [4], [26]–[28]. The diesel systems tend to cost more over time to operate; however, their upfront costs are lower than renewable energy installations. While comparable wind installations have high upfront costs, their source of energy is free; thus, they have very low operating costs in the long run [29], [30]. In systemically analyzing comparable projects and establishing renewable energy policy, the levelized cost of energy (LCOE) methodology can be used to measure the total financial cost of producing electricity on a per kilowatthour basis between the two systems over the life of the projects [22], [23], [29], [30]–[34].

Among the myriad of renewable energy sources, wind power has been identified as a major source in future energy supply scenarios [35]–[40]. The European Union has set a 20% renewable energy target for the year 2020, with 33% of that being contributed by wind energy [28], [39]. Wind generating technology has been championed in areas without access to interconnected electricity grids, where grid extension is prohibitively costly or where the cost of fuel for engine-driven generators of electricity increases with location remoteness [41], [42]. As a clear case of transitioning from traditional diesel power to hybrid renewable energy, a small island belonging to Spain has made the switch first in the world.

The island of El Hierro, which is part of the Spanish Archipelago of the Canary Islands, has been implementing an island-wide sustainable development plan since 1997. The energy portion of this plan has been focused on the implementation of a hybrid closed-loop renewable energy system for electricity power supply composed of a wind farm and a pumped-storage hydroelectric facility as an alternative for replacing the island's current diesel power-generating facilities. The three primary objectives driving the hybrid closed-loop energy system are as follows:

1) pursue renewable energy sources as a major component of the island's development and identity (sociopolitical reason);
2) reduce the long-term cost associated with increasing oil prices and, thus, the input energy cost for diesel fuel (economic reason);
3) grow the region's engineering prowess in designing and building renewable energy systems (technological reason).

In view of the above objectives, this paper provides a methodology for analyzing the LCOE to determine the economic crossover point (measured in €/barrel of oil) of energy production projects to determine at what input prices of oil they appear economically equivalent (which is called the crossover point). This methodology is applied to the El Hierro project as a retrospective analysis and is potentially expandable to multiple system analyses using its normalizing criteria. The later characteristic allows systems of varying life spans to be compared and contrasted on a cost per generated kilowatthour basis. The LCOE model developed herein includes the effect of changing oil prices (the independent variable) on the cost variables by accounting for their percentage change as a function of either the Spanish consumer price index (CPI) or industrial price index (IPI).

## II. Overview

### A. The Wind–Hydro Hybrid Solution

Within the context of sustainable energy development projects, the Island of El Hierro 100% renewable energy supply project aims to create an island where electricity needs are met with 100% renewable energy sources. Using wind turbines coupled to a pumped-storage hydroelectric facility, the government of El Hierro hopes that the island will be independent of fossil fuels for normal operations in the near future. They are also considering a long-term policy to expand renewable energy use in the island to include solar options, both thermal and photovoltaic.

The island of El Hierro is located at 27.72 °N, 18.024 °W; El Hierro is the western and southernmost island in the Canary Islands archipelago, and at 269 km$^2$, it is the smallest and the least populous with 10 892 inhabitants. Like all of the Canary Islands, El Hierro suffers from near total dependence on fossil fuels to supply its electricity needs. The current electricity demand on the island is met by nine diesel engines connected in parallel with installed power of 12.7 MW located at Llanos Blancos on the western side of the island. According to the Cabildo El Hierro, in 2010, the electricity demand of the island was estimated to be 44.6 GWh.

In order to maximize the use of the available wind resources on the island of El Hierro, engineers developed a hybrid closed-loop wind–hydro electric system concept. The system in its simplest form can be described as using a wind farm as the main source of energy production and a system of two connected water reservoirs that will be used as a supplementary source of energy. By using surplus energy from the wind farm, water from a lower reservoir is pumped into an upper reservoir. The system mitigates the risk of intermittent and variable wind power output with the highly predictable characteristics of a hydro system. The reservoirs essentially form a "rechargeable battery" using potential energy storage, thereby permitting maximum use of the wind resource by decoupling the temporal dependence of customer load demand from the wind generation cycle [23], [43], [44]. As an additional unique characteristic of the system, surplus energy beyond the need of customers and the capacity of the reservoirs is offloaded directly to a local desalination plant that converts seawater to potable water, which is a necessary process on the island and a unique feature of this hybrid system design.

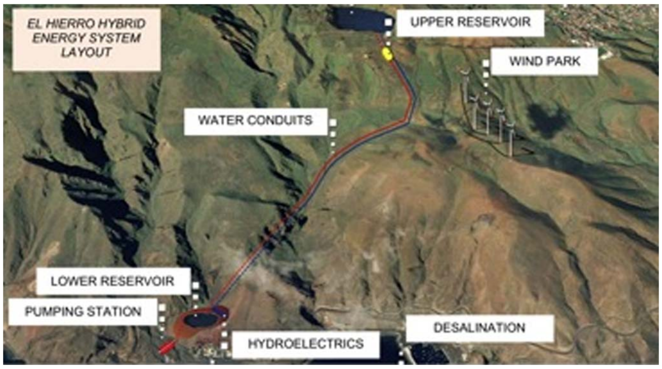


Fig. 1. El Hierro Island hybrid closed-loop wind–hydro electric system overview (source: http://www.goronadelviento.es/).

According to the island's administrators, with population growth, the installed hybrid closed-loop wind–hydro electric system is intended to produce up to 70% of the island's energy requirements with plans for further expansion to photovoltaic installations and solar thermal collectors to provide the remaining in later years. The existing diesel plant will not be decommissioned but rather act as an installed backup system. Fig. 1 provides a schematic overview of El Hierro's hybrid closed-loop wind–hydro electricity system. As illustrated in the schematic overview, Table I presents a summary of the components of the wind–hydro system included in the construction.

From an environmental standpoint, the hybrid closed-loop wind–hydro electric system is expected to provide environmental benefits to the island by preventing the emissions of 600 ton of $SO_2$, 18 700 ton of $CO_2$, and 400 ton of $NO_x$ annually. These estimates come from the projected fuel savings of 6000 ton of diesel fuel annually, which is approximately equal to 40 000 barrels of oil.

## B. Levelized Cost of Energy

The LCOE is defined as the sum of all costs incurred over the lifetime of a given generating technology divided by the energy produced [30], [45]. Therefore, LCOE provides the price at which energy must be sold to break even over the life cycle of the project [32]. The specific advantage of the LCOE method is that it computes the present day cost in dollars per kilowatthour produced by a given generation technology over its life cycle. The resulting LCOE metric can be then compared with other electricity generating technologies, regardless of the specific life span of each installed technology [31], [45]. As such, it is widely seen as the best summary measure for evaluating the overall competitiveness of different electricity generation technologies [28]. The main formula used to calculate the LCOE is expressed as follows [31]:

$$\text{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Lifetime Energy Production}}. \tag{1}$$

Equation (1) can be rewritten in terms of cost variables to obtain the general equations used to calculate the LCOE, as shown in the following [22], [31], [33], [45]:

$$\text{LCOE} = \frac{\text{TLCC}}{\sum_{t=0}^{T} (\text{AEP}_{\text{net}})_t} \tag{2}$$

$$\text{LCOE} = \frac{\sum_{t=0}^{T} (I + \text{O\&M})_t / (1+d)^t}{\sum_{t=0}^{T} (\text{AEP}_{\text{net}})_t} \tag{3}$$

where TLCC represents the total life cycle cost, $T$ the total life of the project, $t$ is the year, $\text{AEP}_{\text{net}}$ is the net annual energy production in year $t$, $d$ is the discount rate, $I_t$ is the investment costs in year $t$, and $\text{O\&M}_t$ are the operating and maintenance costs in year $t$. The summation symbols in (2) and (3) start from zero to include the costs incurred at initiation of the project. Both systems were designed to meet the anticipated annual demand of the island grid (44.6 GWh), and this serves as the basis for the $\text{AEP}_{\text{net}}$. The diesel system can produce on demand to meet the daily need and consumes diesel fuel for this response. The wind system can provide load up to a maximum value but may experience peak load periods above its wind capacity, requiring the use of the hydraulic reservoirs to augment the energy delivery. In times of excess production, the system refills its upper reservoir, which will be later used to supply hydropower as part of its $\text{AEP}_{\text{net}}$. The ability to drive power directly to the desalination plant during overproduction also counts as fulfilling a portion of $\text{AEP}_{\text{net}}$ as the desalination plant requirements are part of the total island load. Without the ability to store or use the excess energy produced, the wind system would be designed significantly larger to meet the peak demand and could experience periods of no power in the rare event of a still air mass.

# III. Economic Model Methodology

## A. Modified LCOE Model

The economic model used in this paper utilizes a modified version of the LCOE model over those presented in (2) and (3). The modified model is designed to help highlight the price sensitivity of electricity generated by El Hierro's diesel system and by the wind–hydro hybrid system. The modified model is as follows:

$$\text{LCOE} = \frac{\sum_{t=0}^{T} (I + \text{O\&M})_t * (1+d)^{-t} * (1+i)^t}{\sum_{t=0}^{T} (\text{AEP}_{\text{net}})_t} \tag{4}$$

where $i$ represents the inflation rate.

The cost portion of the equation can be further expanded. The investment cost $I$, includes engineering, procurement, construction, and decommissioning costs. The O\&M costs can be split into fixed and variable costs. The fixed O\&M costs will include scheduled maintenance, administrative costs, and land purchase/lease, whereas the variable O\&M costs will include fuel, unscheduled maintenance, and potential emission costs ($CO_2$ and $NO_x$). Identifying the land, fuel, and emission costs separately from the total other O\&M costs can help investigate the sensitivity of the LCOE model to these variables, and

TABLE I
EL HIERRO ISLAND HYBRID CLOSED-LOOP WIND–HYDRO ELECTRIC SYSTEM COMPONENTS

| **Wind Farm** | **Hydro Pumping stations** (Connecting upper and lower reservoirs) |
|---|---|
| • Wind Farm area is 2 Hydroelectric Turbines 740 $m^2$ 7,000 $m^2$<br>• 11.5 MW Installed power<br>• 5 x 2.3 MW Enercon E-70 generators<br>• Annual hourly equivalent of 3128 hours, or a capacity factor of 35.7%<br>• Estimated annual energy production of 40.36 GWh | • Hydro Pumping Station area is 825 $m^2$<br>• Upper Reservoir area is 56,600 $m^2$<br>• Lower Reservoirs area is 23,140 $m^2$<br>• The upper reservoir has a capacity of 380,000 $m^3$<br>• The lower reservoir has a capacity of 150,000 $m^3$<br>• Height difference between the two reservoirs is 682 m<br>• 10 MW pumping station composed of 2 x 1.5 MW pumps and 6 x 0.5 MW pumps<br>• The hydro pumping station is designed to operate with excess wind energy<br>• Estimated annual energy consumption of 29.21 GWh |
| **Hydroelectric Central** | **Penstocks** |
| • Hydroelectric Turbines 740 $m^2$<br>• 11.2 MW Installed power<br>• 4 x 2.83 kW Pelton turbines<br>• The maximum flow rate of each 2 $m^3$ per second, with a gross head height of 655 m.<br>• Estimated annual energy production of 19.34 GWh | • Piping System area is 30,000 $m^2$<br>• The pipes used to pump water from the pump station to the upper reservoir have a diameter of 0.8 m and a full length of 3,015 m.<br>• The pipes used to connect the upper reservoir and the hydro generating plant has a diameter of 1 m and a length of 2,350 m. |
| **Diesel Plant (existing)** | |
| • Diesel Plant area is 1,200 $m^2$<br>• 13.3 MW Installed power<br>• Estimated annual energy production of 41.53 GWh | |

results in (5), shown at the bottom of the page. As an example, pending emissions costs/credits regulations can be viewed by their impact on the LCOE.

From a research perspective, (5) can be shown to be sensitive to changes in oil price as it is a basis for input fuel costs to the system and relates to other costs through the CPI and IPI. Factoring the effects of oil price changes into each of these variables can be accomplished with the inclusion of variable specific percentages as shown in (6) at the bottom of the page, where $\%\mathrm{IPI}_{(\mathrm{OilPrice})}$, $\%\mathrm{CPI}_{(\mathrm{OilPrice})}$, and Diesel $\mathrm{Price/L}_{(\mathrm{OilPrice})}$ refer to the incremental change, in percentage terms, that a change in oil prices has on each of the cost variables. In order to determine what effect an oil price change would have on each of the cost variables, regression analyses were run to compare oil prices with the statistical indexes that most closely represent the prices of the cost components.

Diesel fuel price statistics in Spain made available by the European Commission were regressed against oil prices to uncover a linear relation between oil prices and diesel fuel prices since the 2002 advent of the Euro in Spain. Similarly, for fixed O\&M costs such as administration and scheduled maintenance, the Spanish CPI [46] was regressed against oil price movements to determine the incremental effect of oil price changes; for variable O\&M costs, which include a high proportion of replacement part charges, the Spanish SPI [47] for electrical equipment was regressed against oil prices.

The regression analysis performed to compare oil prices with diesel prices and IPI and CPI statistical indexes showed that, at a 95% confidence level, the coefficients of determination

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{T}(I + \mathrm{O\&M} + \mathrm{Land} + \mathrm{Fuel} + \mathrm{Emissions})_t * (1+d)^{-1} * (1+i)^t}{\sum_{t=0}^{T}(\mathrm{AEP}_{\mathrm{net}})_t} \tag{5}$$

$$\mathrm{LCOE}_{(\mathrm{Oil\ Price})} = \frac{\begin{aligned}\sum_{t=0}^{T} \Big[ &\left(\mathrm{I}_{(\mathrm{Oil\ Price\ BL})}\right)_t * \left(\%\mathrm{IPI}_{(\mathrm{Oil\ Price})}\right) + \left(\mathrm{FixedO\,\&\,M}_{(\mathrm{Oil\ Price\ BL})}\right)_t * \left(\%\mathrm{CPI}_{(\mathrm{Oil\ Price})}\right) \\ &+ \left(\mathrm{VarO\,\&\,M}_{(\mathrm{Oil\ Price\ BL})}\right)_t * \left(\%\mathrm{IPI}_{(\mathrm{Oil\ Price})}\right) + \ (\mathrm{LandLease})_t * \left(\%\mathrm{CPI}_{(\mathrm{Oil\ Price})}\right) \\ &+ (\mathrm{Fuel})_t * \left(\mathrm{DieselPrice/L}_{(\mathrm{Oil\ Price})}\right) + (\mathrm{CO_2} * \mathrm{Price} + \mathrm{NO_x} * \mathrm{Price})_t \Big] * (1+d)^{-t} * (1+i)^t\end{aligned}}{\sum_{t=0}^{T}(\mathrm{AEP}_{net})_t} \tag{6}$$

TABLE II
INSTALLATION COST FOR THE EL HIERRO HYBRID ENERGY SYSTEM

| Wind-Hydro Installed Cost Categories | | | TOTAL | % |
|---|---|---|---|---|
| 1 | General Work | | € 1,905,000.00 | 3% |
| 2 | Wind Farm | | € 15,295,583.21 | 24% |
| 3 | Civil Work | | € 14,329,076.43 | 22% |
| 4 | Mechanical & Equipment | | € 20,228,068.59 | 31% |
| 5 | Electrical Equipment | | € 7,035,675.85 | 11% |
| 6 | Engineering | | € 2,872,800.00 | 4% |
| 7 | Change Orders - Extras | | € 3,066,880.15 | 5% |
| | | **TOTAL COST** | **€ 64,733,084.23** | 100% |

TABLE III
FIXED AND VARIABLE OPERATING COSTS FOR THE EL HIERRO HYBRID ENERGY SYSTEM

| Wind-Hydro Fixed and Variable Costs | |
|---|---|
| **Wind Park** | |
| Variable O&M | €188,000 |
| Fixed O&M | €50,000 |
| Insurance | €80,500 |
| Coste de desvio | €8,000 |
| Land Cost | €12,420 |
| **Hydro Electric Park** | |
| Variable O&M | €162,000 |
| Fixed O&M | €177,000 |
| Insurance | €56,600 |
| Personnel | €1,295,000 |
| Desalinization Expenses | €5,825 |
| Electrical Consumption | €611,000 |
| Land Cost | €691,525 |

were between 0.668 and 0.968. The coefficients obtained from the regression analysis were 0.348 for IPI, 0.388 for CPI, and 0.0104 for diesel. Therefore, for the Spanish IPI, the regression analysis coefficients indicated that a 10% change in the value of oil price per barrel will yield a 3.48% change in the IPI values, a 10% change in the value of oil price per barrel will yield a 3.88% change in the CPI values, and a 10% change in oil price per barrel will yield a 0.104 €/L change in the diesel price.

## B. Case Study Data

The diesel power plant in El Hierro has an investment cost of approximately €15 million. In the case of the hybrid closed-loop wind–hydro electric system at El Hierro, the project has an investment cost of approximately €64 million. Tables II–V provide the installation and operating cost estimates for both the diesel system and the hybrid system.

This paper is based on a target of 44.6 GWh/year as the AEP of the plant. In addition, the modified LCOE model allows for a binary value for emissions to enable the inclusion of the external impact cost of the exhaust gases that the diesel plant generates during the lifecycle of the plant, taking the indexes of 20 €/t for $CO_2$ and 2980 €/t for $NO_x$ [48]. The average price for land with energy-permitted activities was assumed to be $€5/\text{m}^2$, based on local land value pricing. These emission and land variables in the modified LCOE equation can be set to zero in the nominal case and adjusted based on the local economics of the project.

## C. LCOE Evaluation

The LCOE models were developed to determine the economic equivalency or the crossover point (measured in €/barrel of oil) between the diesel system and the hybrid closed-loop energy system. The two systems' LCOE were evaluated using variable oil prices between 5 and 125 €/barrel of oil for indexing purposes in the out-years of the model and by setting oil price baselines at 30, 40, and 50 €/barrel of oil for the installation portion of the cost model. The historical data for oil prices in the past decade show that oil prices have not been below €30 per barrel since the first quarter of 2005, except for a brief period in 2009 at the depths of the European economic crisis. During the negotiation period for the El Hierro project, between 2002 and 2006, the oil prices fluctuated between 30 and 50 €/barrel. For this reason, the oil prices of 30, 40, and 50 €/barrel of oil were chosen as baseline values to compare different oil prices at which the project could be built.

The net present value method was used to discount back to present value the costs incurred during the 25 years of life operation of both systems. Sensitivity analysis was applied to each model using discount rates values of 5%, 7.5%, 10%, and 15%, and inflation rates of 0%, 3%, and 5%. Additionally, sensitivity analysis was performed with and without land costs and with and without emissions costs. Each of these variables depend on the region in which the analysis is done and may include the use of government land at no cost or the implementation of a system where emissions are not financially valued. The LCOE was also performed for two cases: one where the existing diesel system was considered a presunk cost and not factored

TABLE IV
INSTALLATION COST FOR A NEW EL HIERRO DIESEL ENERGY SYSTEM

| Diesel Plant Installed Cost Categories | TOTAL | % |
|---|---|---|
| Civil Works | € 40,000.00 | 0.3% |
| Caterpillar 3516 B HD of 1100 KVA. | € 3,441,900.00 | 22.1% |
| Caterpillar 3516 B HD of 2000 KVA. | € 9,250,000.00 | 59.4% |
| Fuel Storage System | € 40,000.00 | 0.3% |
| Electric System, Transformer and Delivery Center | € 266,000.00 | 1.7% |
| Installation Cost | € 1,064,000.00 | 6.8% |
| Engineering, permitting and procurement | € 738,476.92 | 4.7% |
| Decommissioning | € 742,018.85 | 4.8% |
| **TOTAL** | **€ 15,582,395.77** | 100% |

TABLE V
FIXED AND VARIABLE OPERATING COSTS FOR THE EL HIERRO DIESEL ENERGY SYSTEM

| Diesel Plant Fixed and Variable Cost | |
|---|---|
| **Fixed Annual Cost** | |
| Scheduled Maintenance | €796,165 |
| Insurance | €13,300 |
| Land Cost | €6,000 |
| **TOTAL** | **€815,465** |
| **Variable Annual Cost (without Fuel)** | |
| Unscheduled Maintenance | €341,070 |
| Major Overhauls | €193,816 |
| Ignition Engine | €78,264 |
| **TOTAL** | **€613,149** |
| **Fuel Used (liters per year)** | **14,162,608** |
| **Emissions** | |
| $NO_x$ | 2,980 **€/t** |
| $CO_2$ | 20 **€/t** |

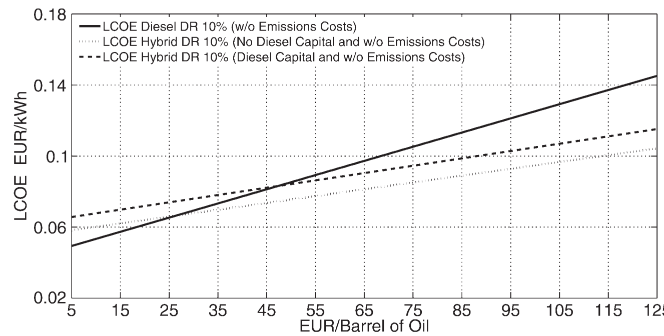


Fig. 2. LCOE crossover points between hybrid and diesel systems at 50 €/barrel as baseline oil price.

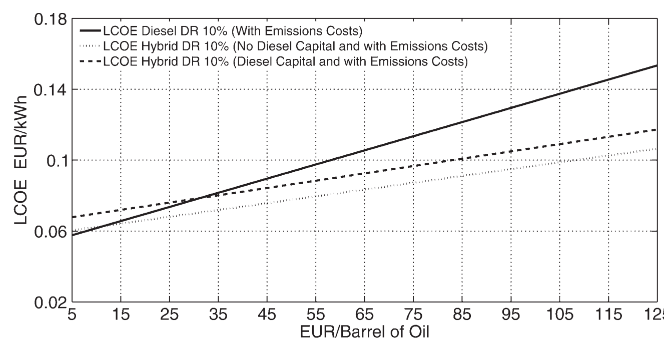


Fig. 3. LCOE crossover points between hybrid and diesel systems at 50 €/barrel as baseline oil price with emissions.

in to the LCOE and the other was the case for comparing two systems absolutely, including acquisition of a new diesel system.

Finally, using the regression analysis coefficients obtained for diesel price per liter, CPI, and IPI, values of diesel price per liter, $\Delta$CPI, and $\Delta$IP, were calculated for each oil price. The %CPI and %IPI were calculated via $\Delta$CPI and $\Delta$IPI values.

## IV. RESULTS

### A. Costs Comparison

When comparing the costs required by the diesel and the hybrid closed-loop wind–hydro electric systems to meet the power demand of El Hierro Island, it was observed that both systems are significantly different from a construction and operation perspective. The hybrid renewable energy system uses highly capital-intensive technology when compared with the diesel plant, being approximately four times more expensive to install. The high cost of the plant comes from the significant construction that must be undertaken and the equipment (wind turbines, hydro turbine,s and the rest of the mechanical equipment), which represent 77% of the total cost of the renewable energy plant. However, when it comes to O\&M, the cost trends are reversed, with the diesel plant being approximately five times more expensive to run than the hybrid system on an annual basis. The high costs for O\&M in the diesel plant is driven by the diesel fuel input costs needed to operate the diesel units.

### B. Levelized Cost of Energy Results

Using the data gathered from the El Hierro project, the LCOE versus the price per barrel of oil were calculated for several system analyses, as presented in Figs. 2–6. These charts were generated from the model using a baseline price of 50 €/barrel oil and a 10% discount rate. The high investment costs associated with the hybrid system makes their starting

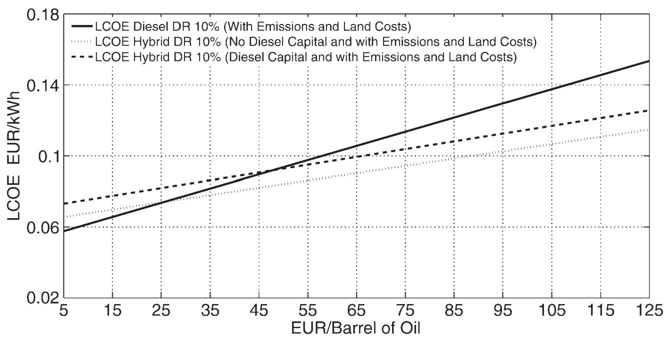


Fig. 4. LCOE crossover points between hybrid and diesel systems at 50 €/barrel as baseline oil price, with emissions and land costs.

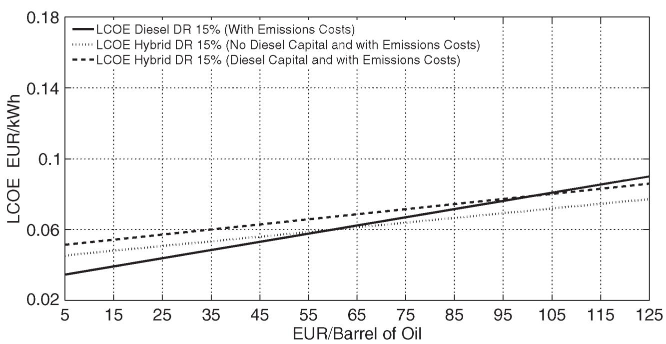


Fig. 5. LCOE crossover points between hybrid and diesel systems at 50 €/barrel as baseline oil price, without inflation rate.

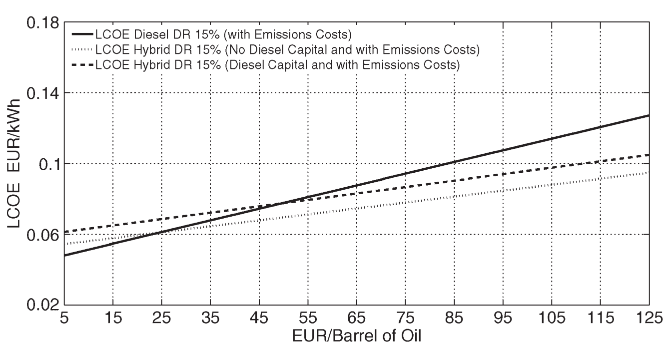


Fig. 6. LCOE crossover points between hybrid and diesel systems at 50 €/barrel as baseline oil price, with emissions and inflation rate of 3%.

points on the graph much higher than the pure diesel system. However, the out-year costs associated with purchasing and using diesel fuel show that the diesel plant is more price sensitive to the oil market (thus a steeper slope). The point at which the lines intersect, i.e., the crossover point, represents the economic equivalency between the systems. Conversely, the hybrid system is much less sensitive to oil pricing and thus has a shallower slope. Including the diesel backup system installation cost as part of the total hybrid system has the effect of increasing the initial costs of the hybrid system, thus shifting the hybrid LCOE upward, raising the effective crossover point with the pure diesel system.

The plots also show the effect of emission and land costs in the LCOE results and economic crossover points. In the first case, Fig. 2 illustrates that, when emissions are not factored in, the economic crossover point between the diesel and hybrid systems occurs when oil is priced at €26.43 per barrel (no

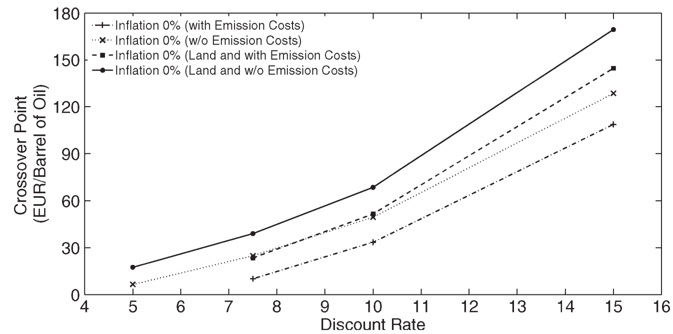


Fig. 7. LCOE sensitivity analysis for the oil price of 30 €/barrel including diesel capital.

diesel capital costs included) and €47.29 per barrel (diesel capital costs included). However, when emissions costs are factored in (€20/t for $CO_2$ and €2980/t for $NO_x$) as a cost (see Fig. 3), the LCOE values increase for the diesel system shifting the lines upward, causing the economic crossover point to move left to €11.55 per barrel (no diesel capital costs included) and €31.32 per barrel (diesel capital costs included). Fig. 4 illustrates the effect of land cost in the LCOE when emissions are included, showing that land costs have a higher effect on the hybrid system when compared with the diesel system, shifting the hybrid system LCOE line upward and causing the economic crossover point to move right to €25.64 per barrel (no diesel capital costs included) and €47.88 per barrel (diesel capital costs included). Figs. 5 and 6 show the effect of discount and inflation rates on the LCOE results. When the costs in (6) are discounted back to present value and emissions costs are factored, an increment in the discount rate from 10% to 15% decreases the LCOE, shifting the curve downward and resulting in the economic crossover point between the diesel and hybrid systems moving to the right to €59.88 per barrel (no diesel capital costs included) and €101.18 per barrel (diesel capital costs included). Finally, when emissions are factored in, an inflation rate of 3% causes the economic crossover point to decrease to €24.61 per barrel (no diesel capital costs included) and €49.63 per barrel (diesel capital costs included).

### C. Sensitivity Analysis

The sensitivity analysis results are presented in Figs. 7–9, illustrating that, as discount rate was increased, the LCOE decreased for the diesel systems, thus increasing the economic crossover point (€/barrel of oil) between the hybrid and diesel systems.

*Crossover points at 30 €/barrel of oil.* In the first analysis (see Fig. 7), the economic crossover point at specific discount rates increases with the addition of land costs and reduces with the addition of emissions costs. In both cases, the effect of discount rate has a much greater impact on the economic equivalency point between the systems than emissions or land costs, particularly at high discount rates. When inflation rates are included in the analysis, they counteract the discount rate, resulting in lower crossover points than without inflation rates.

*Crossover points at 40 and 50 €/barrel of oil.* The same general results were seen with the 40- and 50-€/barrel analyses. In all cases, the economic crossover points indicated greater

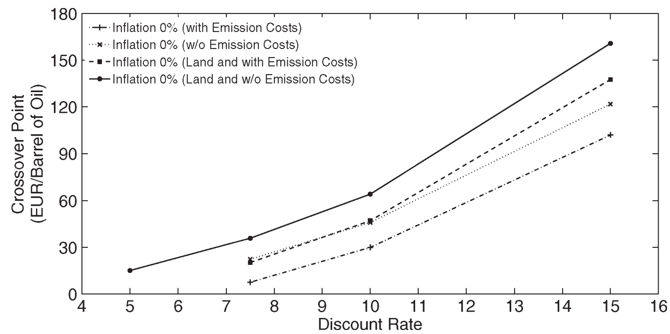


Fig. 8. LCOE sensitivity analysis for the oil price of 40 €/barrel including diesel capital.

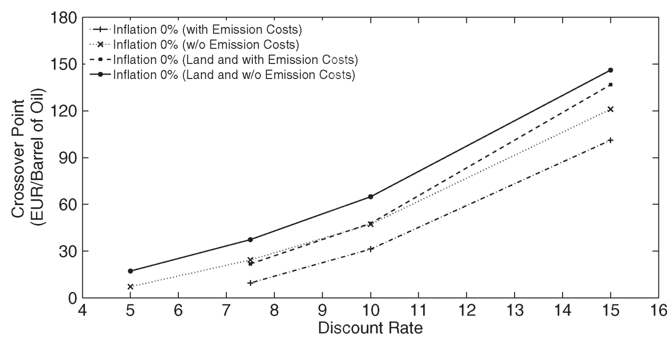


Fig. 9. LCOE sensitivity analysis for the oil price of 50 €/barrel including diesel capital.

sensitivity to discount rate. Likewise, as inflation was added in, the results were generally much lower (see Figs. 8 and 9).

The results obtained from the LCOE analyses and the case data from the El Hierro project indicate that the economic crossover point between the systems can be determined using a modified LCOE approach. In this specific case study, with a discount rate in the 5%–7% range used by the El Hierro project planners, the crossover point between the two systems accounting for land costs and no emissions occurs when the price of oil is between 30 and 40 €/barrel. This is at or above the price point when the project began. Results also illustrated that the economic crossover point is highly sensitive to discount rate, and as the discount rate increased, the LCOE decreased, and the economic crossover point (€/barrel of oil) increased. While government projects using fairly low discount rates will yield one set of crossover points, the investment community funding private projects would typically use higher costs of capital rates that drive higher crossover points and latency in switching technologies.

## V. Conclusion

As wind energy continues to play an important role in future electricity supply for islands, the economic feasibility of wind projects can be evaluated and compared with other technologies via the LCOE generation method. This paper has used a modified LCOE method and key assumptions that are applied for a case of study in the island of El Hierro in the Canary Islands. The study involved two months of fieldwork in the island where information was collected to compare the economic crossover point (€/barrel of oil) between the current hybrid closed-loop wind–hydro electric system being developed and the old diesel facility of the island. The sensitivity analysis shows the effect of oil prices and discount and inflation rates on the economic equivalency, or crossover point, between system selections.

Results illustrated that, for a fixed discount rate, the economic crossover point between the systems increased when land was included as variable costs but decreased when emission costs were factored in the model. In addition, results pointed out that the inflation rate caused the economic crossover point to decrease when compared with the model where inflation was not included. These results were expected since both discount rate and inflation influence the LCOE.

From a policy perspective, the general economic crossover point for the system implemented in El Hierro is in the range of €25–€50 per barrel that was prevalent during the decision-making stage of the project. A decision to start at an oil price lower than the economic equivalency point would indicate a sociopolitical value placed on the project and a potential option price placed on the expectation of significantly higher future oil prices. Current oil markets have passed the range of this crossover point and coincide with the operational launch of the system in El Hierro.

From an investment perspective, the extreme price sensitivity of the LCOE analysis to discount rate shows how the model may be used to either support or reject a decision to proceed on a project. Perhaps the most significant takeaway from this result is that the perspective of the entity leading the project analysis is a primary driver of sensitivity in the LCOE equation due to the discount rate that they apply, given that the discount rates used by government entities and private entities when evaluating projects are often substantially different from one another. Government-focused development and capital projects have low discount rates and will calculate a much earlier crossover point, thus favoring such hybrid systems earlier than investors that will typically have higher discount rates associated with their cost of capital and their desired return on investment. However, a constant dollar analysis supports the LCOE methodology as a robust means of comparison by removing the discount rate sensitivity.

As the first of its kind system in the world, the El Hierro project intends to demonstrate that, with the right wind conditions and topography, a hybrid renewable energy system can be successfully developed and deployed to serve a large population as a primary source of consumer power. Furthermore, the intention to decouple the wind frequency problem from the grid energy demand problem by creating a potential energy storage system via dual reservoirs, if successful, will establish a basis for further pursuit of establishing such systems elsewhere in the world.

If successful in the long term, this system design will prove out a methodology that allows for the capture and storage of excess energy during overproduction periods, and make up power during peak demand periods, and has the ability to be considered for potential system design reuse [49], [50]. Using the analysis technique provided herein as a working model, other regions of the world with similar wind and topography can perform system-level analysis of the economics of their projects and determine at what point in world energy pricing it makes sense to begin a project. The modified LCOE methods presented here also serves as a starting point for developing option pricing associated with the risk mitigation aspects of renewable energy systems that hedge against large upward price shocks in oil supply.

## Acknowledgment

The authors would like to thank the Instituto Tecnológico de Canarias (ITC) and Gonzalo Piernavieja Izquierdo, Director of Research and Development at the ITC, and G. Karau and L. Alarco for their help in developing the detailed economic data used in this paper and for their participation in site visits to conduct interviews and gather data in the Canary Islands.

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