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Abstract

This research investigates the application of hybrid closed-loop energy systems that combine multiple clean energy generation and storage technologies as an alternative to diesel fuel fired electrical generators. The El Hierro project in the Canary Islands, an Archipelago of Spain, represents the first major Megawatt-level energy project aimed at coupling continuous wind power generation with potential energy storage by pumping water to high elevation lakes. These are coupled to hydroelectric generators that can be used for load leveling, peak demand, and frequency control of the power supply to the island's grid. This first of a kind project is presented from technical, regulatory, and political perspective.

1. Introduction

The US Department of Energy's "International Energy Outlook, 2010" projects world electricity demand to nearly double from 495 to 739 quadrillion BTU between 2007 and 2035. This incredible growth in demand is projected to be met by a diverse array of energy sources including coal, natural gas, liquid fuels, nuclear, and renewable sources such as wind, solar, hydro, biomass and geothermal [1]. Based on the Department of Energy's projections, fossil fuels such as coal, natural gas and other liquid fuels will continue to supply the majority of the world's energy demands.

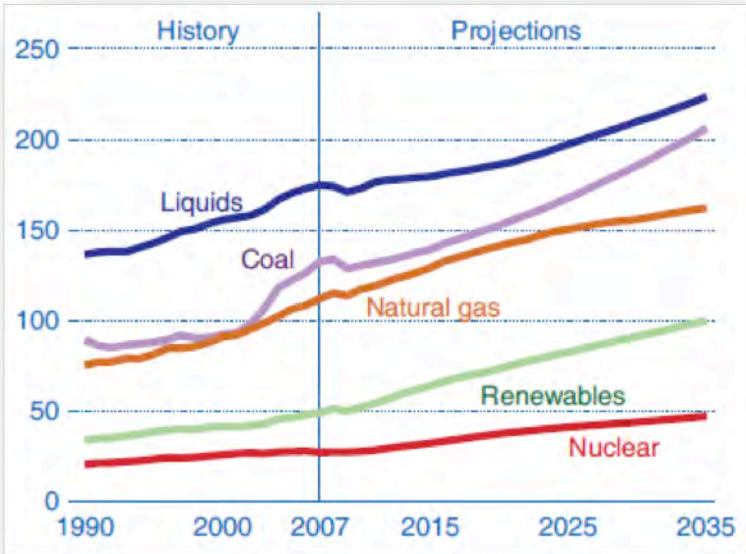


Figure1. World marketed energy use by fuel type, 1990-2035 (quadrillion Btu) [1].

While fossil fuels may continue to supply the majority of the world's energy needs, their predominant use exposes societies to an array of social, political, economic and environmental risks. Between 1980 and 2005, the price of liquid fuels including gasoline and other petroleum distillates enjoyed a 25 year period of stability, yet for the last six years the price of these fuels has been subject to much volatility, resulting in increased unpredictability in the cost of electricity generated from these sources [2]. Whether fluctuations in the prices of these energy sources is the result of market speculation, supply manipulation, or the result of the "Peak Oil" scenario where rapidly rising demand encounters production limits and declining world reserves, there exists empirical evidence to support the observation that swings in oil prices pose threats to the world's economy by raising inflation, unemployment and dampening macroeconomic growth [3].

Beyond the economic risks posed by the Oil-GDP effect, petroleum dependence exposes consumer nations to political risk, as many of the world's largest reserves of petroleum are located in politically and economically unstable regions whose interests are often diametrically opposed to Western interests [4]. The political dangers are such that the US Department of Defense states unequivocally, "the reliability of global energy supplies is at risk" and "increased competition for energy resources poses risks to international stability" in coming years [5].

In addition to economic and political risks, generating electricity by burning fossil fuels poses potential environmental risks associated with the output byproducts of combustion, including greenhouse gases along with pollutants such as Nitrogen Oxides (NO_x) and Sulfur Oxides (SO_x). Since initial investigations began in the early 1970's, a scientific consensus has emerged that increasing greenhouse gas concentrations in the atmosphere have their roots in human activity, primarily through burning fossil fuels, and that these increasing concentrations tend to warm the planet and drive the process of climate change [6]. The Intergovernmental Panel on Climate Change's 2007 report warns that if the anthropogenic rise in greenhouse gas emissions continues unabated, global warming and climate change will radically impede human access to the basic elements of life such as water, food and habitat [7]. The threats posed by climate change to the environmental systems that human societies depend upon are such that the Pentagon has identified climate change, along with terrorism, Peak Oil and the proliferation of weapons of mass destruction, as a major security challenge for the 21st Century [8].

In light of the adverse economic risks, as well as environmental and political consequences that fossil fuel dependence entails, renewable energy technologies such as wind, solar, and hydro power provide a means of electricity generation that offers relative economic independence (from fossil fuels) and political stability, while enabling ecologic sustainability due to the significant reduction (or elimination) of combustion byproduct per Watt of electricity generated. The widespread implementation of renewable technologies, however, faces several technological impediments, including energy source availability and intermittency, technical complexity associated with balancing load generation and demand, difficulties in energy storage, large upfront capital costs when compared to similarly sized conventional power plants, and the immaturity of technologies in comparison to coal or natural gas generation. All told, this suggests that renewable energy sources may still be far from reaching their optimized technological form. Looking past these technical challenges however, the benefits of increased political, economic and environmental risk avoidance offered by renewable technologies appear to outweigh the risks posed by conventional power generation.

This case study focuses on the first ever implementation of a Megawatt-class hybrid closed-loop energy system in the Canary Islands, an Archipelago of Spain off the Western coast of North Africa. More specifically, the island of El Hierro and its development of the hybrid closed-loop energy system will be the main focus of this paper. The system described in this study involves a combination of wind-driven power generation coupled to a series of retaining lakes at multiple elevations that act as energy storage mechanisms. The lakes are operated with a hydro-electric generating and pumping capability that allows wind energy to drive water up the potential grade, and then can be run down the grade to generate electricity. As will be discussed in this paper, this solves two major issues that renewable systems typically face, storage of excess generated energy, and load balancing between the production generation, including electrical frequency, and the demand load being drawn from the system.

2. Islands as Laboratories

The Canary Islands, and Islands in general, suffer from the need to import many of the necessities of life due to their geographic isolation and limited resources. This can include food, water, fuel, consumables, and electricity to name a few basic needs. This is especially relevant to food and fuel, where due to the paucity of land and productive resources, Islands experience some of the highest costs of living in the world [9]. With this perspective in mind, Islands offer a unique perspective on the world, and they can act as isolated laboratories that permit us to envision what a future with greater resource constraints and higher fuel prices looks like today. In particular, Islands are excellent sites to examine the implications and issues surrounding the creation of a low carbon, renewable energy future.

In addition to having economic incentives for examining a low carbon world, Islands are also particularly vulnerable to the effects of climate change. They host a wide range of endemic flora and fauna that are specifically adapted to their host habitat and are not particularly resistant to exogenous change - the Galapagos Island being one of the world's most well known examples. In further reaches of the Pacific, many southern atolls are already disappearing due to rising sea levels and to their low lying topography, while in the Caribbean, numerous island nations are very exposed to the increasing frequency and intensity of hurricanes that is predicted to be the result of global warming [10]. Consequentially, Islands nations today are at the forefront of experiencing the effects of global warming, and for them there are urgent biological, social and economic imperatives driving the search for energy production based on non-polluting, secure, and endogenous sources such as the sun and the wind.

2.1. The Canary Islands

From an electricity management perspective, the isolated nature of Island electrical grids means that each grid is independent, unable to draw on outside resources as in continental systems, which necessitates high levels of self-sufficiency, redundancy and resiliency in the case of external shocks. In the absence of such mechanisms, the islands are susceptible to intermittent power availability and potential brown out or black out periods that hamper daily life and the wellbeing of residents. Furthermore, for islands utilizing fossil fuel generators, the cost risk associated with importing all generating fuel poses an economic risk to the inhabitants and the government.

With respect to the Canary Islands, and El Hierro in particular, the aforementioned environmental and economic realities, along with the technical realties of this fact were officially recognized by the Canarian Autonomous Government in the 2006 political directive, *el Plan Energetico de las Canarias*, otherwise known as PECAN. PECAN is based on the premise that electricity is a fundamental necessity of modern life, and with a view to ensuring the future development of the Islands, the plan seeks to improve the quality of the energy supply for all Canarians, while complying with development agenda agreed to in the 1997 Kyoto accord in which 2020 greenhouse gas emissions will be reduced by at least 20% compared to 1990 levels [11].

The PECAN plan is based on the four following pillars:

1. To ensure the power supply to all consumers with optimum conditions in terms of regularity, quality and price. This objective is to be achieved through a diversification of energy sources that enhances the use of endogenous sources including wind, solar, wave, geothermal power, as well as the maintenance of adequate strategic oil reserves, and the provision of sufficient reserve capacity generation in the energy sector.

2. To encourage the Rational Use of Energy (RUE) through energy savings and efficiency programs which seeks to reduce the ratio of energy use per unit of GDP.

3. To integrate the environmental dimension into all energy decisions, which ultimately means stabilizing greenhouse gas emissions in order to reduce the risks associated with climate change and global warming, to which the Canary Islands are particularly susceptible.

4. To promote the maximum utilization of renewable energy sources within the Islands, especially wind and solar, as a means of reducing the external vulnerability the economy and to improve environmental protection. Goals established by the plan include reaching 30% of electricity generation using renewable energy sources by 2015 [12].

Despite the comprehensiveness of the plan and the laudable goals contained within, 2010 figures released by the Instituto Tecnologico de Canarias (ITC) show that the implementation of the plan has largely failed. The Islands have not managed to diversify their energy sources as planned. At the time of the report, installed capacity of wind power in all of the Canary Islands was 140 MW, or 13.5% of the 1025 MW planned; 1.3 MW of hydro was installed vs. 13.6 MW planned (9.5%); 110MW of photovoltaic installed vs. 160MW planned (68.75%); 145 000 m^2 of solar thermal installed vs. 460 000 m^2 planned (31.3%); and zero wave or biofuel power sources vs. 30-50 MW goals. The result is that even with one of the better wind regimes in the world and excellent solar irradiance (4000 hourly equivalence per year and 2000kWh/m^2 per year respectively), 94% of the energy consumed in the Islands still comes from petroleum-based sources [13], GHG emissions in 2010 are 41% higher than 1990 levels, and energy costs in the Islands are on average 122% higher than the price of electricity generated on the Spanish mainland [14].

With only four years remaining until the 2015 time frame established by the PECAN plan runs out, and nine years until the 2020 Kyoto deadline passes, it would seem that the Canary Islands are far from achieving their sustainable development goals. Discussions within the ITC and at Ministry of Industry round tables point out various reasons for not reaching these goal that include political challenges, land tenure issues, complications with the public tendering process, difficulties in establishing the optimal feed-in tariff that was further complicated by the economic crises that began in 2009, and the technical difficulties that a vast increase of renewable energy on the grid would entail with respect to required investments and service upgrades [15]. Complications notwithstanding, the results are that the Islands have forfeited employment in technologically advanced fields, any potential revenues that would have gone to renewable energy producers based in the Islands, and perpetuated a strategic weakness in the electricity generation sector through high exposure to the price volatility of petroleum.

El Hierro

Within the context of missed sustainable energy development goals in the Canary Islands, an exceptional stand out is the 100% renewable energy supply (RES) project on the Island of el Hierro. Located at 27.72 °N, 18.024 °W, el Hierro is the western and southernmost island in the Canary Islands archipelago, and at 268.71 km^2 it is the smallest, and the least populous with 10,892 inhabitants.

Owing to low population densities, el Hierro has a very rural landscape that is characterized by a abrupt topography defined by sea cliffs up to 1000m high, and a maximum elevation of 1501m at its highest peak, Malpaso [16]. Given its position in the trade wind latitude and its exposure to the open ocean, the Island's climate is highly variable, ranging from very dry in the south to humid and wet on the peaks. El Hierro is also known as one of the best places in the world to practice deep sea diving, and since becoming the world's first Island to be declared a UNESCO Biosphere Reserve in 2000, the Island has become a world reference point for sustainable tourism. The push to achieve biosphere status was born out of the Island's 1997 Sustainable Development Plan, in which the Island council, sensitive to the importance of the Island's unique environment to its principal export industry – tourism, embraced a development agenda that would balance the need for economic development within a framework of careful environmental stewardship. The plan rests on four pillars that include the

1. Development of the commercial sector, including agriculture and tourism, on a sustainable basis,
2. Development of the waste management system on the island to reduce resource consumption and human impacts on the environment,
3. Development of an educational system that will underpin and ensure the long term success of the sustainable development goals, and
4. Creation of and innovative energy plan that seeks to maximize to the use of the Island's abundant wind and solar resources, along with its abrupt topography, to make it one of the world's first completely 100% renewable energy supplied islands [17].

2.2. The Electric Grid on El Hierro Island

Like all of the Canary Islands, el Hierro suffers from near total dependence on fossil fuels to supply its energy needs, with 96% of the Island's demand being met by an 13.3 MW diesel power plant located at Llanos Blancos on the western side of the Island. The current electricity demand is 41.53 GWh per year, with a monthly average nearly 3,500 MWh in 2009 (Figure 2), a near 30% swing from minimum generation to peak generation per month. The Island's electrical demand is generally variable, from off peak hours between 12 and 6 a.m., to the peak hours in the early morning between 7-10 a.m., during the afternoon from 1 to 3 p.m., and finally another when people return home between 7 and 10 p.m. (Figure 3), representing a near 100% swing from minimum load to peak load during a 12 hour period.

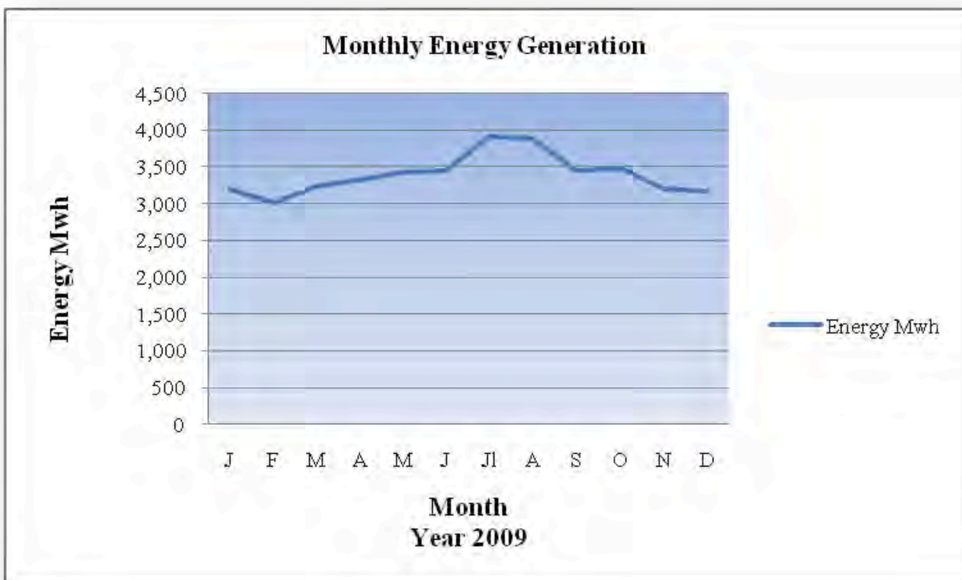


Figure 2. Monthly Energy Generation. Own elaboration [18]

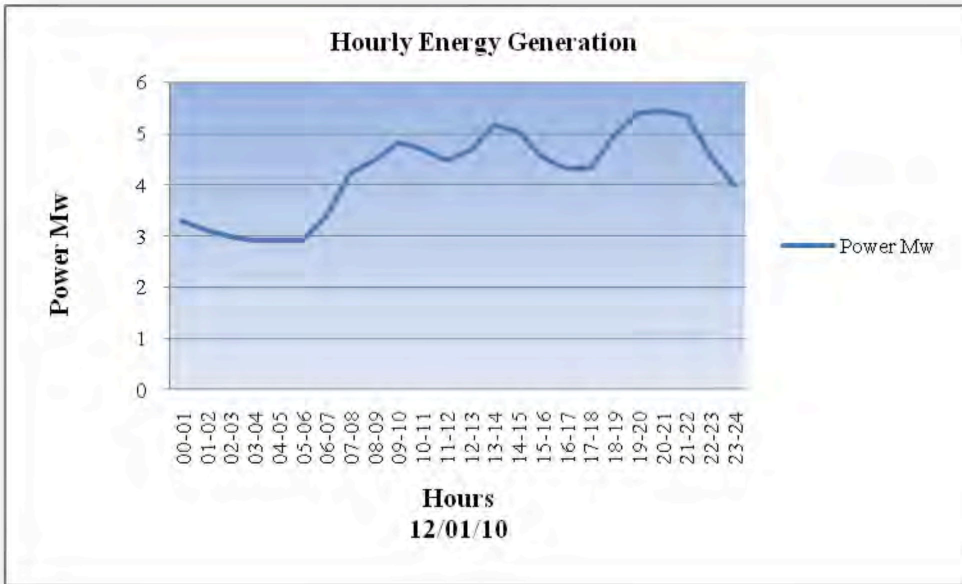


Figure 3. Hourly Energy Generation. Own elaboration [18].

Because of the island size, the electrical system and demand rates, the Island could not implement steam electric generators, so the best solution available to supply reliable electricity was diesel power generators. The weak electric system and the limited access to an oil supply market make it an extremely expensive cost of generation.

2.3. Characteristics of the Existing Diesel Electric Plant

In many distant and dispersed regions around the world that are not served by a national or regional electric grid, power is generated locally by diesel power plants ranging in size from 1MW to 100 MW. Islands, remote populations/settlements, military bases, commercial and industrial facilities, resorts and many others utilize diesel generators due to their low capital cost of electricity generation technology in the one to ten MW size range. They are also a very robust, reliable, and well understood technology maintained by a worldwide support infrastructure of companies, equipment, supplies, and labor [19]. The market of engine based power plants covers a wide spectrum in terms of engines, speeds, fuel types, power output, efficiency, and usage, however for an installation of the el Hierro size (10-100 Mw of power installed), the primary choice is diesel, as shown in Figure 4.

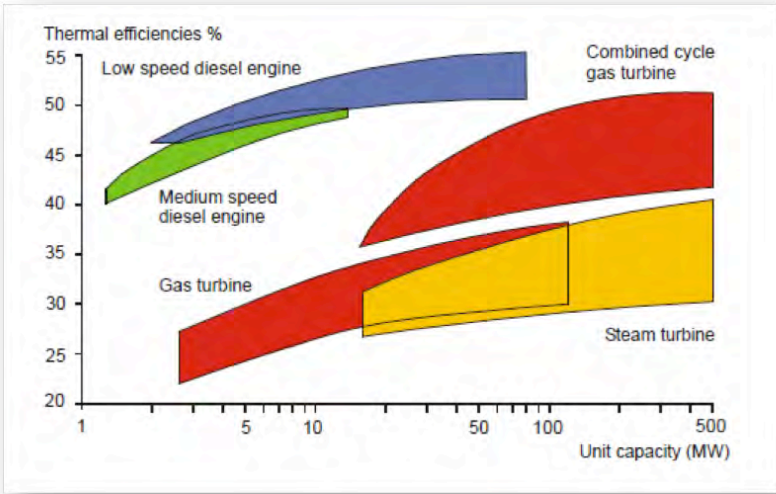


Figure 4: MAN B&W Power Plants Manufacturer

Diesel power engines have the best thermal efficiencies between 0 to 100 MW of unit capacity, and are very flexible to cover large swings of electricity demand, being capable of maintaining higher performance at lower loads compared with other technologies (Figure 5) [20]

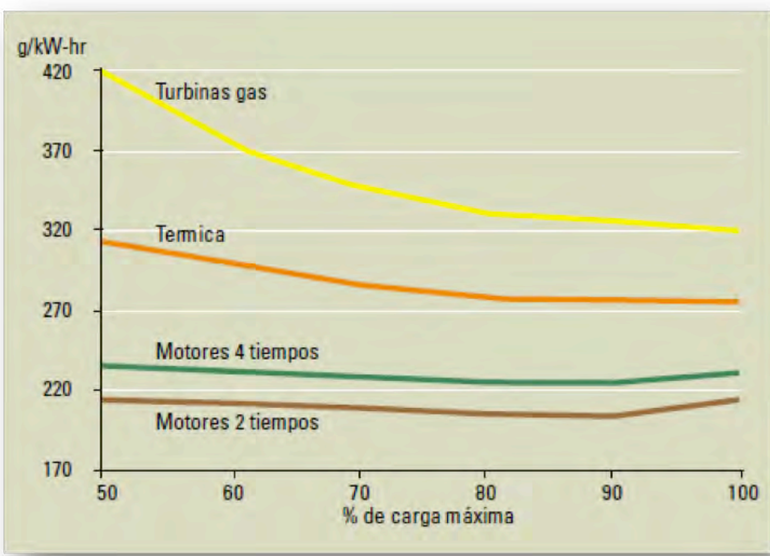


Figure 5. Fuel consumption at part load [21]

Four stroke engines with medium and high-speed engines (above 1000 rpm) have essentially captured the entire market for power generation applications, with ongoing technical developments having led to 4 stroke engines that are able to turn up to 50% of the energy in the fuel into mechanical work. With an average installed cost of approximately 300 to 900 $/Kw installed [22], diesel generator sets are also the most economical choice in prime and continuous power applications up to several thousand hours per year. Even when the cost of new emission control strategies are factored in, diesel power is predicted to still offer one of the lowest capital expenditures for power generation in this range of output [23]. Diesel engines also permit the use of different categories of liquid light distillate fuel, and even gas fuels if small changes are made to the system. From a construction perspective, diesel power solutions come in standard and normalized modules, with "plug and play" installation that allows short periods of time to construct and commission the facilities. Only small areas are required, and as such they can be located near population concentrations, lowering the cost of electricity transport and distribution. The design of the plant consist in simple rectangular blocks and the usual arrangement adopted is to place the engine and alternator on a large concrete surface, with fuel tanks located underground or outside the engine building. From an operators' reliability perspective, diesel generation also provides the most reliable quick-start and load acceptance performance. Large diesel engines can often run 40,000 hours between major overhauls [24].

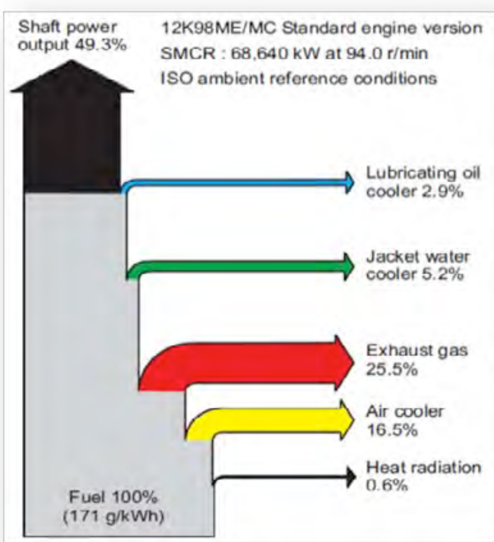


Figure 6. Heat balance diagram of the normally rated 12K98ME/MC engine of the standard engine version operating at ISO ambient reference conditions and at 100% SMCR.

Figure 7. Diesel Power Engine in SEIE system (Canary Island). Endesa Generation 2010.

The diesel-electric system in El Hierro has one small Diesel Power Plant in los Llanos Blancos composed of 9 diesel engines connected in parallel with a nominal power of 13.3 bKW and a small distribution lines (< 66kv) that supply the demand of electricity of the Hierro Island. As the main source of power, the diesel generators are designed to operate continuously at high output for extended periods of time to provide base load service. The plant has several parallel generators that are set online or offline depending on the demand of the system at a given time. Generators are electrically connected to matching voltage, frequency and phase before connecting the generator to the system. The Diesel generators of the El Hierro Island are 4 stroke, high-speed engines with a less than 2 MW power rating each, as shown in Table 1.

Table 1. Central Diesel Los Llanos Blancos (El Hierro)

Units	Brand	Model	Power	Speed (min^{-1})
6	Caterpillar	3516	1.1-1.5	1500
1	Caterpillar	D-398	0.8	1500
2	MAN	9L21/31	1.9	1000

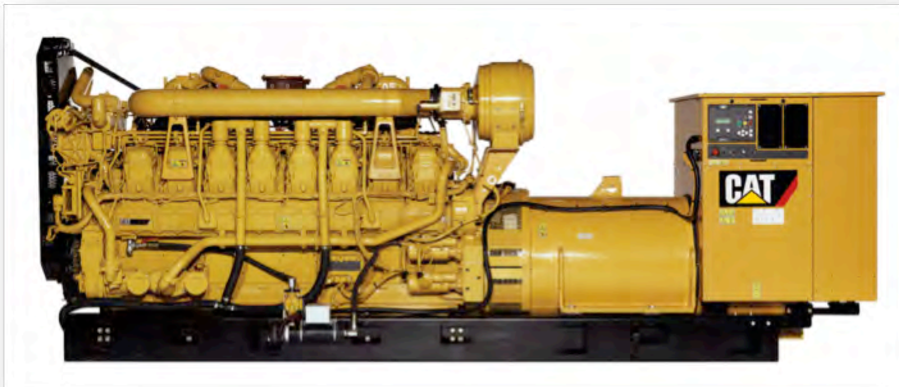


Figure 8. Caterpillar Diesel Engine 3561 series.

They are many reasons why diesel power systems are widespread all over the world, including ease of use, installation, start-up cost, and operational reliability. Diesel generators are a low capital electric generation technology up to 100 Mw size range. It is a well-understood technology with a strong worldwide support infrastructure. During the operation they are very robust and generate a reliable source of electricity during long period of times. However, diesel technology has major disadvantages such as noise, air pollution and relatively high operation and maintenance costs per kWh delivered due to the input price of fossil fuels and maintenance requirements.

Burning of diesel fuel creates exhaust gases that differ slightly from generator to generator. By knowing the type of diesel fuel characteristics, and the rate at which a generator consumes diesel per hour and heat rate, an accurate calculation of emissions can be obtained. Looking at the distillate oil plants it is important to point out that the numbers established in Figure 9 are based on averages across all manufacturers and duty cycles. Exhaust emissions from diesel powered generators can include Nitrogen Oxides (NO_x), Particular Matter (PM), Volatile Organic Compound (VOC), Methane (CH_4), Carbon Monoxide (CO), and Carbon Dioxide (CO_2).

Table 2. Internal Combustion Byproducts [25]

Power (Kw)	CO_2 gr/Mwh	NO_X gr/Mwh	PM gr/Mwh	CO gr/Mwh	CH_4 gr/Mwh	VOC gr/Mwh	CH_4 gr/Mwh
1000	35.00	31.82	18.64	1386.36	8054.55	675090.91	207.73
1200	31.82	27.73	18.18	1372.73	7977.27	670731.83	207.73
1600	27.73	22.73	17.73	1359.09	7886.36	665286.36	207.73
2000	25.45	19.55	17.27	1350.00	7831.82	662018.18	207.73

While diesel engines produce higher amounts of Nitrogen Oxide (NO_X) and particulate matter (PM) than some other prime movers and thus require control strategies, they are also notable for their low emissions of others pollutants. Due to high combustion efficiencies and low fuel vaporization, diesel engines produce low amounts of carbon monoxide (CO) and volatile organic compounds (VOC). Sulfur dioxide (SO_2) emissions depend of the sulfur content in the diesel oil used to run the diesel generator set, ultra low sulfur diesel oils are the most used, being negligible sulfur emissions. The high energy density of diesel fuel and high thermal efficiency of the combustion process combine to produce significantly less carbon dioxide (CO_2) per kilowatt-hour than generators powered by gasoline, natural gas, or LP. Although, CO_2 is not classified as a pollutant, it is considered the principal contributing greenhouse gas in global warming [23].

To protect public health and conserve natural resources, legislation from the U.S. Environmental Protection Agency (EPA) and regulatory agencies in the European Union (EU) has required that pollutants produced by diesel engines, such as NO_X and PM, be reduced. Categories of allowable emissions are set out as Tiers 1-4 in the U.S. and Stages I-IIIA in the EU. Each increasing Tier or Stage specifies lesser amounts of NO_X, HC, CO and PM based on the number of grams per kilowatt-hour of the compounds present in diesel exhaust. To meet the 2011 target - for NO_X and PM levels to have dropped 98% below unregulated levels - requires a phase on phase emissions reduction of around 40%. Reduction technologies are being applied to larger diesel engines to control oxides of nitrogen, particulate matter, carbon monoxide, and hydrocarbons. Some current and existing emission control technologies include more efficient combustion, catalytic after treatment systems, low or no sulfur fuels, and high-pressure direct injection gas technology [23].

There are active trading programs for several air pollutants. For greenhouse emissions the largest is the European Emissions Trading System (EU ETS), and there are different exchanges currently trading in pollutants allowances: European Climate Exchange, NASDAQ OMX Commodities Europe, PowerNext, Commodity Exchange Bratislava, and the European Energy Exchange. In the United States there are different scale markets focused on reducing NO_X and SO_2 levels, as well as federal and regional markets like RGCI in the North-eastern states, RECLAIM in California and exchange markets like NYMEX and Chicago Climate Exchange. Markets for other pollutants tend to be smaller and more localized. As markets fell during 2008-2009, carbon emissions pricing fell sharply as seen in Figure 9. An increase in the price of future spot prices of pollutants is expected once the economy recovers, but until then the price is expected to remain low [26], [28].

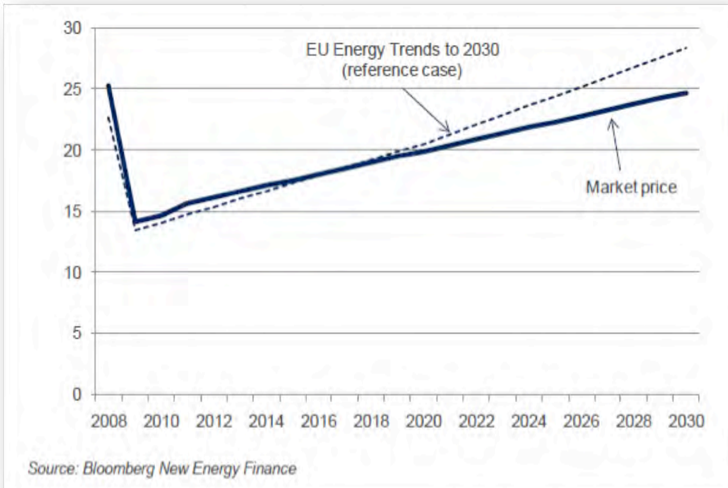


Figure 9. Projected Carbon Prices (€/ton), 2011. [27]

From a supply risk perspective, petroleum reserves are unevenly distributed in the world and are located in politically and economically insecure regions. Worldwide, oil comes largely from the Middle East and Russia, where some of the oil deposits are already above peak production rates. The Green Book of the European Union (2000) warns that if no action is taken in the near future, the oil dependency will rise from the 50% in year 2000 to 70% in 2030, at that time 90% of the oil consumed in the EU will be from imports [31]. The crude oil price outlook remains uncertain, and thus affects the input pricing of fuel for diesel generators. Among the major uncertainties that could push oil prices above or below our current forecast are risk of additional supply disruptions in producing regions, the willingness and ability of key OPEC member countries to increase and sustain higher production in response to the global increase in oil demand, the rate of global economic growth, and fiscal issues facing national and sub national governments [32].

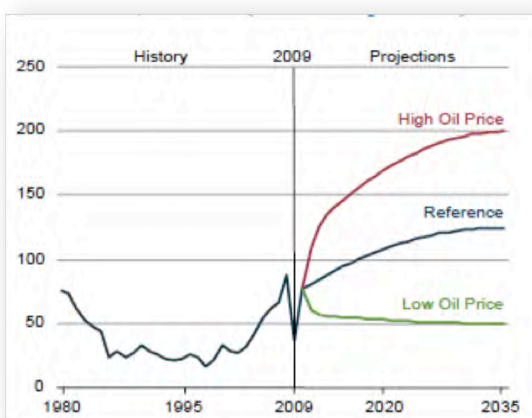


Figure 10. Average annual world oil prices in the three cases; High Oil Price, Reference Case, and Low Oil Price, for 1980-2035 year period (2009 $/barrel). Annual Energy Outlook 2011.

The uncertainty in oil price and security in energy supply remains a concern for most OECD countries and may reflected in government policies affecting generated investment in the future.

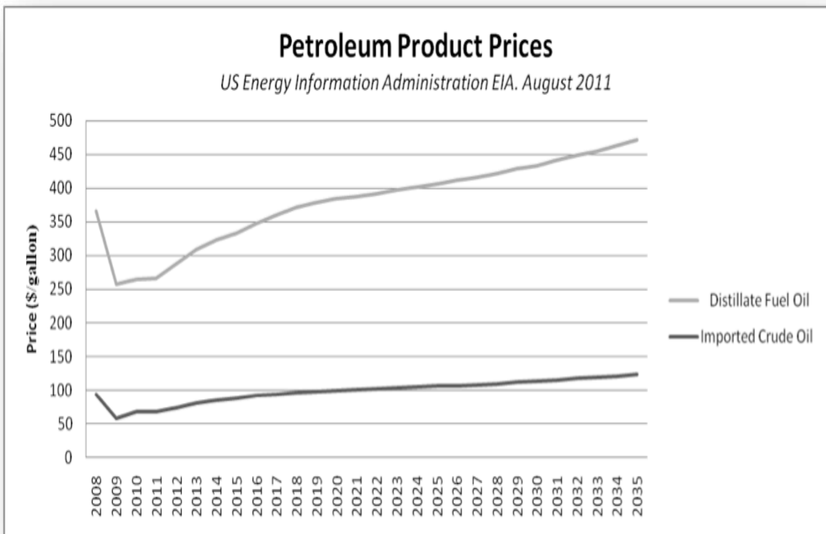


Figure 11. Annual Energy Outlook 2011 Reference Data Source. Own elaboration

The figure shows that price of the imported crude oil[1] and distillate fuel oil[2] will have an annual increase in price, from 2011 to 2035. The price of the distillate fuel oil is influenced generally from the price of crude oil, however there have different growth rates; distillate fuel oil will have a 4.1% yearly increase and imported crude oil only 3%, due to a higher cost of distillate processing and fuel transport.

The distillate fuel oil price forecast shows a dramatically increase in price in the following years. In remote and isolated places the price per gallon of diesel is much higher due to processing, transport and storage cost. The cost of fuel is the higher in the operations and maintenance activities of diesel power plants, being up to 80% [21] affecting directly to the final price per KWh

1 The price comes from weighted average price delivered to refiners.
2 The price includes electricity only and combined heat and power plants whose primary business is to sell electricity.

generated. Environmental policies will play an increasingly important role that is likely to significantly influence fossil and emissions cost in the future, so the relative competitiveness of various generation technologies will change over time based on input energy pricing, supply

Emerging new technologies for use in isolated systems

Electricity demand forecasts by the US Energy Information Administration (EIA) see increases of as much as 87% in 2035, with electricity representing an increasing share of the world's total energy demand. Electrical demand is expected to grow faster than liquid fuels, natural gas, and coal in all end-use sectors except transportation. The rapid increase in fossil fuel prices this past decade and the environmental consequences of greenhouse emissions has led to renewed interest in other types of electric generation such renewable energy. The EIA predicts that the share of renewable energies in world electricity generation will be 23% by 2023. Much of this increase in renewable electricity supply is expected to be met by hydro and wind power, which are already economically competitive with fossil fuel generation.

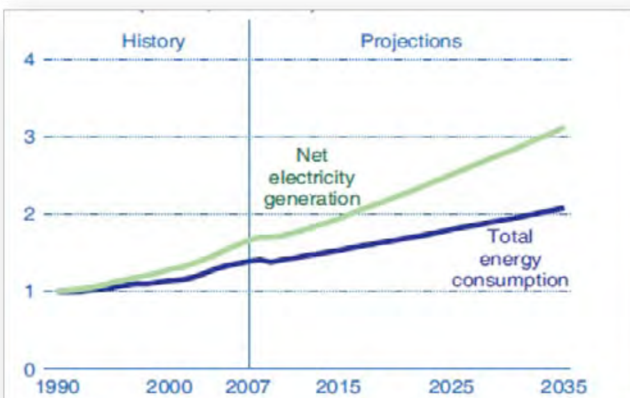


Figure 12. Growth in world electric power generation and total energy consumption, 1990-2035 (index, 1990 = 1). Source. Energy Information Administration. 2010. "The International Energy Outlook (IEO2010)".

Wind-derived electricity generation will play an important part in the future energy mix, however, energy storage systems that can guarantee more predictable power output are required to mediate the inherent intermittency in wind sources. Energy storage systems that can match daily demand requirements with generation capacity will dramatically increase the viability and the value of wind resources by making this energy available on demand. As the installed base of wind energy increases, grid integration issues in the absence of energy storage will become a limiting factor for this type of generation [33]. Thus, widespread implementation of wind will only become more attractive if it operates in tandem with energy storage technologies [34].

Although there are numerous energy storage technologies available, only Pumped Hydro Storage (PHS) is capable of storing energy on a utility scale at a reasonable cost. As seen in Figure 13, PHS systems have the capability of providing a large amount of power over a long supply time, enabling them to act as base load energy sources at the same time as being able to cover peak demand when wind power generation is less than demand. However the major difficulties associated with PHS are the topographic and geological requirements, and the potential environmental impacts of the two requisite water reservoirs, at low and high elevations.

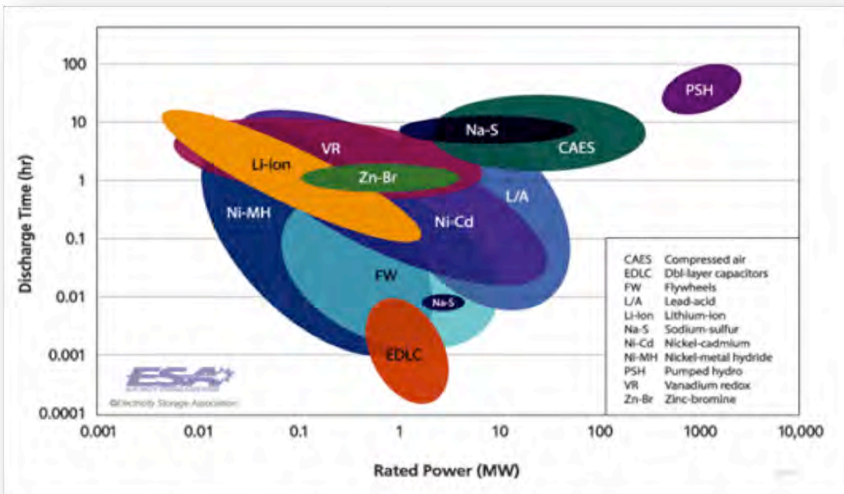


Figure 13. Systems ratings storage systems. 2008. Electricity Storage Association.

Given the maturity of the technology, PHS in combination with wind generation has the potential to be a great technical solution for remote locations with isolated electric grids. Places with low electric demand that are using small and mid-sized diesel power generators have new possibilities to integrate other generation technologies like a hybrid wind and hydro system that can help them reliably cover up to 100% of the power demand and mitigate against the risk of petroleum price rises.

The Wind-Hydro Hybrid Solution

In order to maximize the use of the available wind resources on the island of El Hierro, engineers working for Gorona del Viento, S.A. began to develop a hybrid wind-hydro electric system concept, which in its simplest form can be described as using pumped water to store the kinetic energy extracted from the wind in the form of potential energy in an elevated reservoir. Through the intermediary of this large upper reservoir, which essentially functions as a large battery, the system mitigates the risk of intermittent and variable wind power output with the highly predictable characteristics of a hydro system, thereby permitting maximum use of the wind resource by decoupling the initial wind generation and the customer load demand.

Pumped hydro storage systems are not new, having first been developed in the 1890's in Switzerland and Italy, and later being introduced in the United States in the 20th century to help balance electricity demand with generation being created by nuclear power facilities [35]. Currently, there are over 104 000 MW of installed capacity of pumped hydro storage in the world [36], with at least 12 000 MW of new capacity now under construction [37]. What makes the system at el Hierro particularity interesting is that this is the first time in the world that a pumped hydro system will be combined with wind electricity generation in order to supply the majority of a community's electrical needs. As such, the project is a milestone in the adoption of renewable energy technologies and is being closely watched by members of the power community for potential applications elsewhere in the world.

The installation of a hybrid closed-loop energy system like the one in El Hieero primarily need three general environmental conditions, namely wind availability, adequate topographic gradient, and a sustainable water supply. Like many islands in world, el Hierro has very good wind resources with yearly average of wind velocities and wind densities well in excess of 7 m/s and 300 W/m², which are the minimum conditions required to implement a profitable wind project.

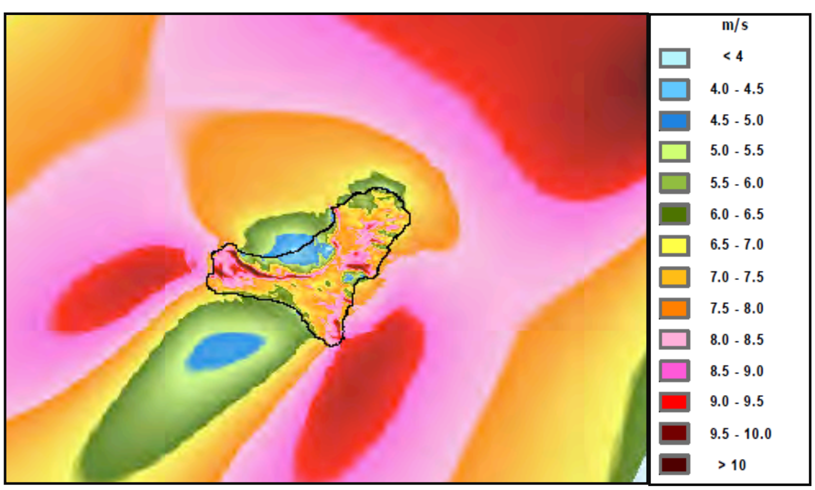


Figure 14. Wind velocity (m/s) El Hierro Island [36]

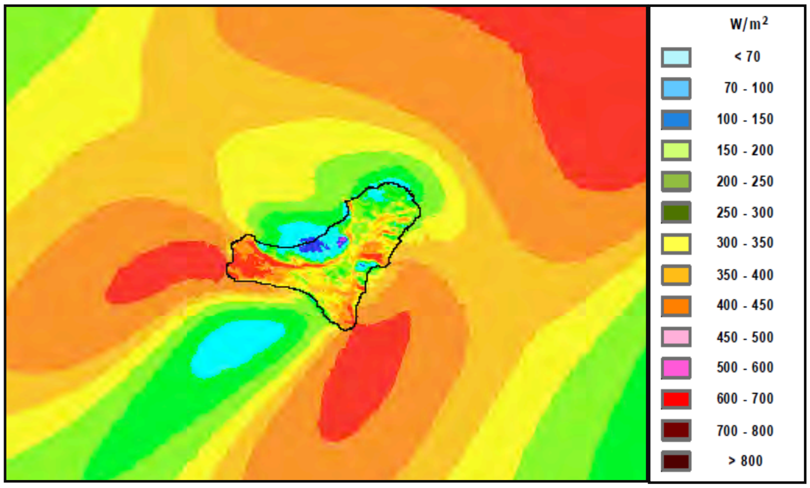


Figure 15. Wind density (W/m²) El Hierro Island [36]

As evidenced by the data in Figure 14 and Figure 15, the areas with greatest potential for onshore wind power are the western and southeast tips of the Island. The site selected for the wind farm is in the northeast coastal zone near the diesel electric plant, where the average yearly wind speeds are between 9-9.5 m/s, with top speeds in July and August of 11.0 m/s and 12.3 m/s respectively. Average wind densities in the areas are between 600-700 W/m², making the site fall well within the minimum profitable criteria for wind parks.

El Hierro has topography with good conditions in the coastal areas for implementing wind power and a pumped hydro storage project due to a lack of obstacles to the wind resource and large gradient differentials that can be exploited to store and generate hydro power. The energy available in a hydroelectric system varies directly with the height differential between the upper and lower reservoirs, therefore the greater the height difference the more energy may be stored and generated. For the el Hierro installation there will be a difference of 683m between the upper and lower reservoirs.

While surrounded by ocean, the availability of fresh water in el Hierro is a concern. As Island documents stare “the history of El Hierro has been determined by water and a fear of water shortage” [38]. The Island receives little direct precipitation, and with highly volcanic soils, rain that does fall percolates rapidly through the soils. Consequently, 50% of the electrical energy consumed on the Island goes to producing water for domestic and agricultural use. Due to the paucity of rain on the Island, the hybrid system will be connected to an existing desalinization plant, where wind power will be used to desalinate sea water that will help fill and compensate evaporation losses in the two reservoirs.

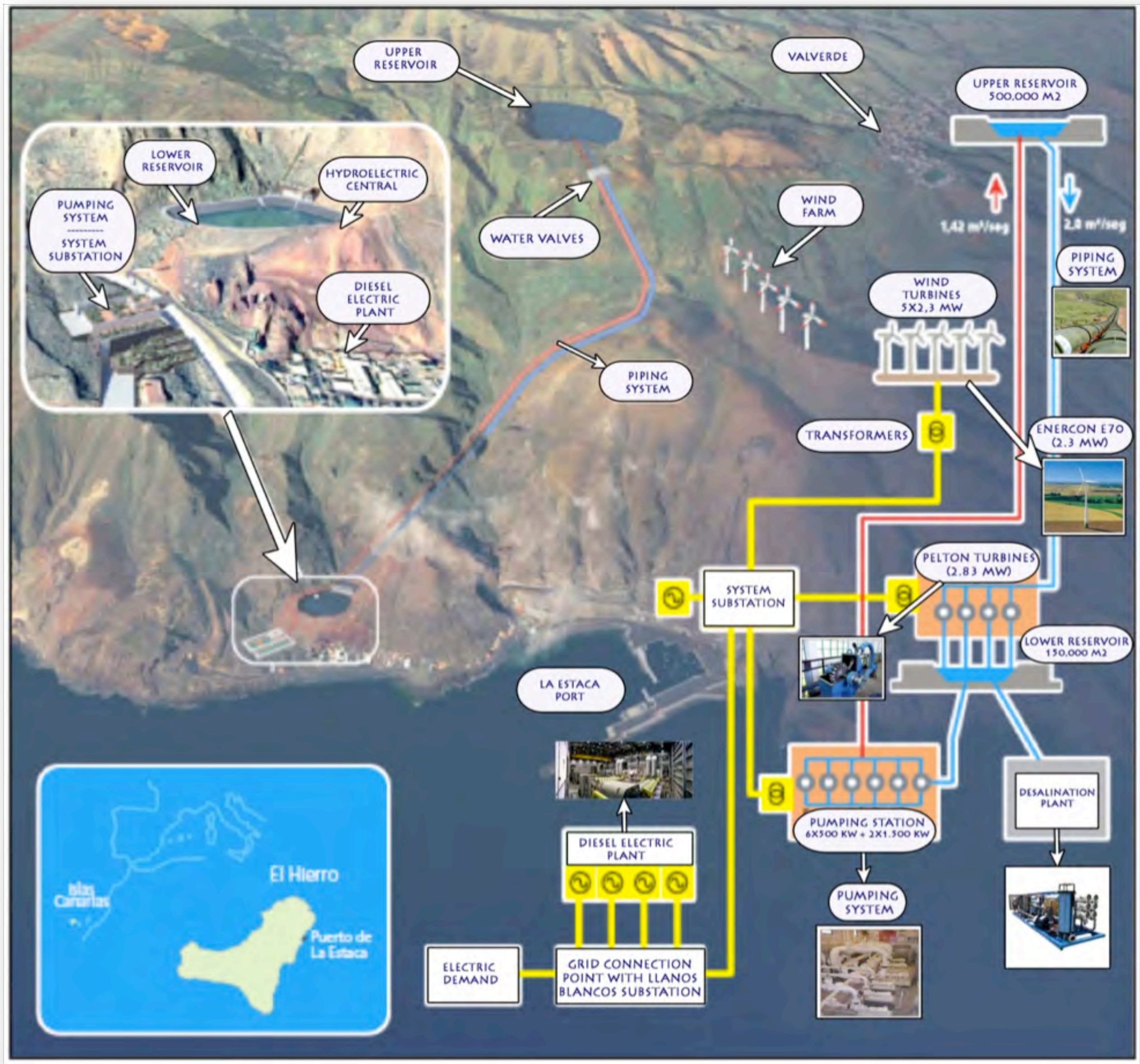


Figure 16. Diagram of Wind Hydro Hybrid System

As illustrated in Figure 16, the general design of the system includes six major subsystems, namely:

1. Wind farm
2. Hydro pumping station
3. Hydroelectric turbines
4. Penstocks
5. Existing diesel generation system
6. Existing desalination system

The wind farm is design for 11.5 MW installed power using five 2.3 MW Enercon E-70 turbine generators. The wind farm has an annual hourly equivalence of 3128 hours, which converts to a capacity factor of 35.7%. This converts to an expected annual production of 40,360 MWh, or approximately 70% of the island's annual electrical demand. The wind farm will cover up to a maximum 70% of the daily electric demand, and no more, in order to secure the energy output quality and maintain the safety of the electric network. Wind energy generated will be injected into the grid directly, with surplus energy used by the hydro pumping station and desalinization plant.

The Hydro Pumping station is designed to connect the upper and lower reservoirs. The upper reservoir is a naturally occurring caldera with a capacity of 556,333 m^3, while the lower reservoir has been designed and excavated with a capacity of 200,000 m^3. The reservoirs are separated by a hydraulic elevation differential of 682m and water is pumped via two 1.5 MW pumps and six 0.5 MW pumps, utilizing an estimated annual energy consumption of 29,208 MWh to drive water from the lower to the upper reservoir. The hydro pumping system will work with surplus energy generated by the wind farm in times of low electrical demand or high wind production. Water will be pumped to the upper reservoir until it reaches maximum capacity. Surplus energy beyond this point will be used to desalinate sea water that will be used for drinking or irrigation purposes.

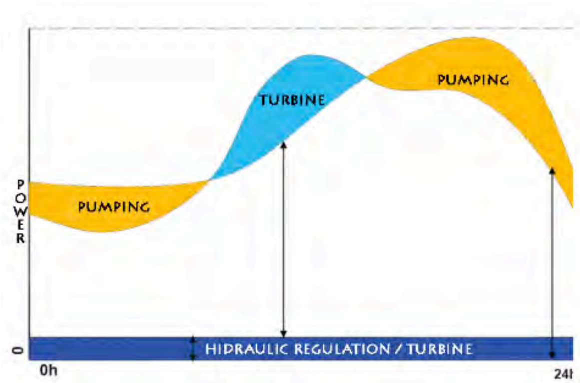
The hydroelectric generating plant is designed with four 2.83 kW Pelton turbines that operate at a maximum flow rate of 2 m^3 per second each. The system is designed to provide a minimum level of energy service for multiple scenarios, including primary supply, secondary supply, and reserve rolling inertial capacity that supplements the energy provided by the wind. The hydro stations are predicted to produce 19,342 MWh annually. The Penstocks are a set of reinforced steel tubes that permit the function of pumping and hydro generation. The tube used to pump water to the upper reservoir has a diameter of 0.8m and a full length of 3015m. The tube used to connect the upper reservoir and the hydro generating plant has a diameter of 1m and a length of 2350m.

The existing 13.3 MW diesel generating plant will be kept as a means to provide partial power supply to the island, and as a backup during maintenance, repair and overhaul times on the wind farm. The plant will operate in the event of no wind or periods in which there is no water in the upper reservoir, which is estimated to be 20% to 30% of the year, depending on wind conditions. In the first year of operation the plant is expected provide 23% of the Island's electricity. The existing desalination plant will be coupled to the system as well to use excess power for desalination purposes. The plant is being integrated with the hybrid closed loop power system to help supply water associated with evaporation losses.

There are four general conditions of operation for the hybrid closed-loop energy system, including a conventional day, a high wind day, a low wind day, and a low wind day with a low upper reservoir. The following figures outline the theoretical function of the system given these different conditions.

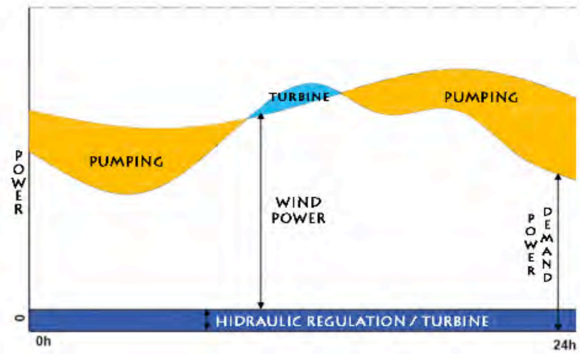
1. Conventional Day

For a nominal, or conventional day, the energy produced by the wind farm supplies the basic demands of the system off peak time. The hydroelectric turbines cover the peak periods of demand and provide base load power. Wind energy surplus is used to pump water to the upper reservoir outside of peak demand hours.



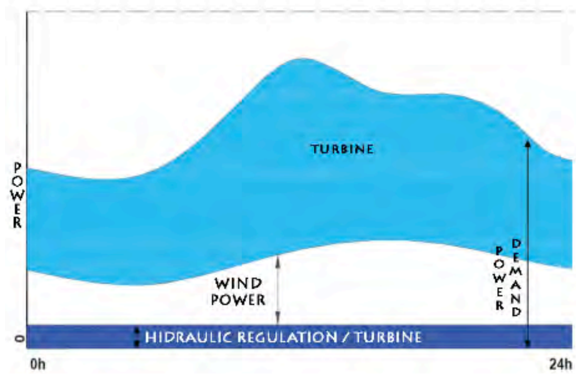
2. High Wind Day

During a high wind day, the operation is essentially the same as a conventional day, with less demand for hydro turbine production required during peak times. With excess wind energy available, surplus power not required to pump water to the upper reservoir is used for water desalination.



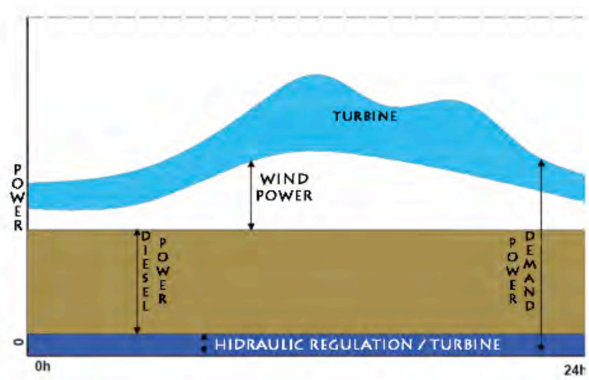
3. Low Wind Day

On a low wind day there is no energy surplus, with energy almost exclusively produced by the hydroelectric system. The level of direct wind energy production is almost negligible or inconsequential in this scenario, and sustainable only for a period required to reduce the upper reservoir to its minimal level.



4. Low Wind Period and Upper Reservoir half empty.

The fourth scenario is the worst-case scenario for the system, in which there is little or no wind load available for energy production and the reservoir is low. In this scenario, the existing diesel generating system will be used to provide supplemental power or even the majority of power, with a trickle effect from minimal wind energy and some hydroelectric power



The convergence of Policy, Technical, and Economic Considerations

From a technical standpoint, both systems are based on proven technologies. The diesel system, the wind system, and the hydroelectric system are all proven technologies that have operated independently for power generation purposes. The true “new” technical element to the hybrid closed-loop system is the use of the hydroelectric system as a storage means for power overproduction and supply for wind underproduction. This reduces the risk of load imbalance in the purely wind system. Additionally, the hybrid closed-loop system requires a convergence of wind resources and topography that supports a significant hydraulic head and land for an upper and lower water reservoir.

From an economic standpoint the diesel generating system offers the lowest upfront installation cost, however it suffers from high operating costs due to the use of fuel to run the system, and as such, is highly susceptible to input energy price risks. The hybrid closed-loop energy system is much more expensive to install than the diesel system as it requires a much larger geographic footprint, and more generating and pumping equipment. However, the hybrid solution is essentially price inelastic to input energy price changes as it requires no input fuel for normal operations in its pure “clean” form (if one ignores the diesel backup system left in place in el Hierro).

Politically, the desires of the government are several fold, including reducing oil dependency and cost risk to the operation of the government, since 100% of the diesel fuel for power generation is imported. The island has a long-term focus on sound environmental policy and growing ecologically sustainable tourism. The diesel solution is counter to both of these political pressures and leads to the desire for implementing a clean energy solution like the hybrid model. Furthermore, a period of strong economic incentives from Spain and the EU provided subsidies and grants for implementing the hybrid system. Finally, the leadership of the Canary Islands, its renewable energy institutes, and the government of el Hierro view the project as a model for other countries to follow in creating a cleaner energy economy. By being the first to implement a system on this scale, el Hierro positions itself to be a world leader in hybrid renewable energy systems and a source for hosting and advising other governments and agencies on the implementation and operation of a hybrid system. Table 4 below summarizes the technical, economic, and political considerations for this new model of energy production system installation.

Table 4 – Comparison of Technical, Economic, and Political Considerations for a Hybrid Closed Loop Energy System.

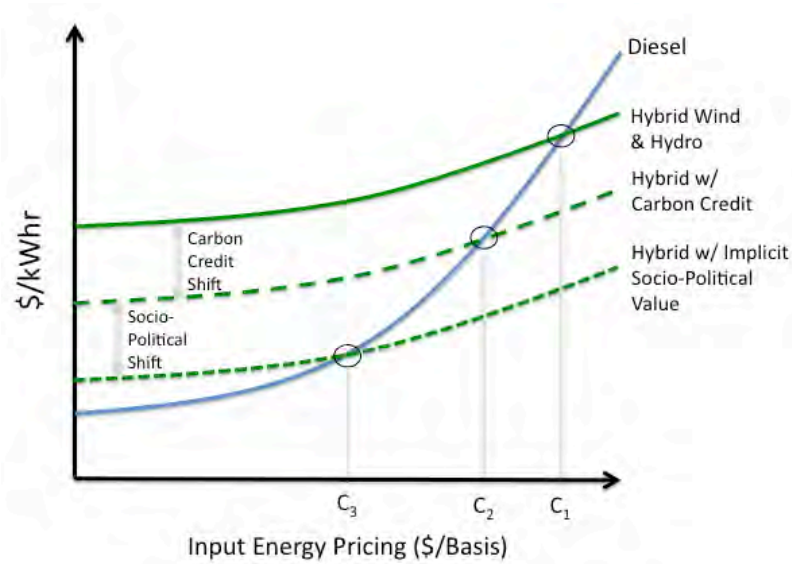
	Technical	**Economic**	**Political**
Existing System	Proven technologies Known operations Available parts Heavy maintenance and operating burden	Energy input cost risk Low install cost High operating cost	Environmental impact of emissions Oil dependency
Hybrid Closed-Loop System	Proven technologies, new design of interconnected systems Environmental requirements to sustain operations	High up front cost Long payback period Low operating costs Long life Operations input energy price inelastic	Matches with environmental mission of the island International recognition

Conclusions

The creation of the el Hierro hybrid closed-loop energy project necessarily represents the convergence of technical, economic, and political capabilities to establish the world's first large scale system. Via numerous visits to the Canary Islands to study the project it was apparent that the environmental conditions in el Hierro were well suited for the technical implementation of the hybrid closed-loop model. Furthermore, global energy pricing and the requirement to import 100% of the generating fuel were seen as significant risks to the long-term sustainability of the island. Finally, the political mindset was that a first-of-a-kind system could be built using public and private financing, along with significant Spanish and EU support. The drive ultimately was to show the rest of the world that a more environmentally sound and sustainable long-term energy solution could be established in el Hierro as a model for the rest of the world.

Research Going Forward

The study of the El Hierro project raises two key questions for further study. The first question this study raised is where is the economic crossover point (C_i) between the cost of electricity produced by a traditional diesel plant with the cost of electricity produced by the hybrid hydro-wind system being built in el Hierro. The model will use a range of input energy price projections as well as a carbon credit scenario to determine at what energy input price the electricity generated by the hybrid system will equal the cost of the electricity produced by the diesel electric system. By extension, socio-political factors identified might indicate if the project was initiated at an input energy price well below the identified crossover point.



The second questions raised by this study is how to capitalize on the development work done in this project by identifying other similar locations and conditions around the world that could implement a comparable system. Through the development of a GIS search algorithm with topographic, atmospheric, and population models, a general search approach could be applied to GIS databases to develop a probability density map of other locations. This could serve as a starting point for governments, research organizations, or developers to define target sites for future hybrid closed-loop energy system development.

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