THE UNIVERSITY OF TEXAS AT SAN ANTONIO, COLLEGE OF BUSINESS

Working Paper SERIES

Date March 21, 2012

WP # 0013ETM-537-2012

GIS Decision Model for Global Replication of Hybrid Closed-Loop Renewable Energy Systems

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12R0320 - GIS Decision Model for Global Replication of Hybrid Closed-Loop Renewable Energy Systems

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Abstract:

Larger Geographically isolated populations do not typically have access to primary grid power, and thus rely on generating plants that depend on external supplies of fossil fuels to provide consistent access to power. The application of hybrid closed-loop renewable energy systems can alleviate this dependence and significantly reduce the carbon footprint by reducing the effective combustion byproducts per unit of energy provided. Using case study data, a GIS decision model is presented for determining feasible locations for implementing such a switch, based on successive GIS data layers. Data layers include urban, electrification, geographic topography, soil/ground composition, and wind. Further consideration may exist for investigating constraints on the location choice through the application of restriction layers, including conservation areas, historic sites, etc. The probability density function can then be maximized based on the successive layers as a metric for optimizing or prioritizing initial location choice. The quality of GIS layers with respect to information content for varying international locations directly influences the optimization function in this decision model.

Introduction

The choice of energy production solution is complex as there are many variables that affect the energy output generated. The first is related to the energy resources that could vary in terms of risk, dependency and cost. The best examples are the oil and gas prices that have fluctuated wildly over the last few years from a low of $30 per barrel to a high of $150 per barrel. Other resources like Uranium for nuclear utilities have to deal with other risk factors like limited access, transportation restrictions, operation, storage, and disposal along with other political and social implications. Overall, the general deregulation of the energy sector has lead to an influx of new companies and technologies for generation and transmission, in addition to governmental operations. This is all within a market demand backdrop of world marketed energy[1] consumption projected to increase by 49 percent from 2007 to 2035. This increase is split unevenly between non-OECD countries (expected increase of 84 percent), compared with OECD countries[2] (expected increase of 14 percent)[1].

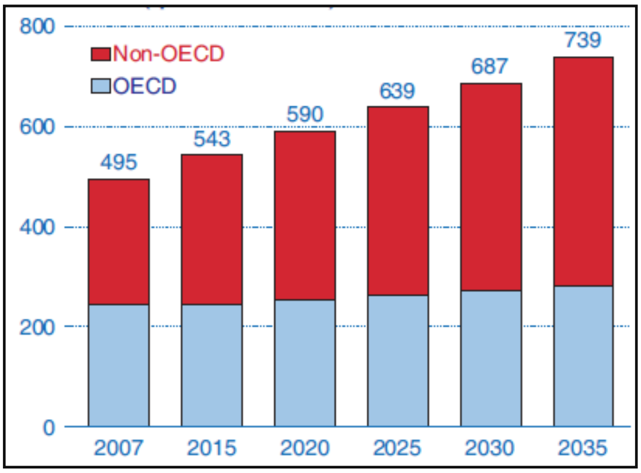

Figure 1 - World marketed energy consumption 2007-2035 (quadrillion Btu) [1].

The stability f future energy supply will be an issue as producers try to meet the increasing demand. Figure 2 shows the breakdown of this supply by type of energy source over the 2007-2035 periods [1]. Fossil fuels are expected to continue supplying most of the energy used worldwide especially in non-OECD countries where dependency will be increased disproportionately to OECD countries.

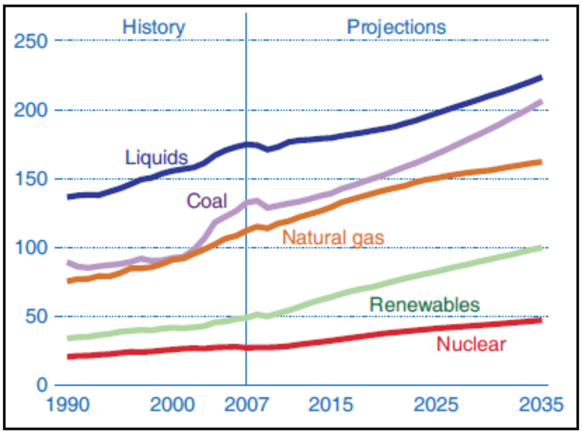

Figure 2 - World marketed energy use by fuel type, 1990-2035 (quadrillion Btu) [1].

[1] Marketed Energy is an energy source that is commercially traded. Typically, this energy is sold by a producer, through a transmission and distribution network to an end-use consumer. **Source US Energy Information Administration**.

[2] The IEO2010 Reference Case. **Source US Energy Information Administration**.

Liquids Fuels will remain the largest source of energy provision, however the variability and increase of oil price will tend to generate a decrease in liquid fuel demands where other generating technologies become more economically viable. As one of the highest cost input resources in electric power generation, liquid fuels will drop out of this use category faster with rising oil prices. Natural Gas demand will increase by 44 % during the same time period. Coal consumption during this time is expected to grow significantly with most of this growth expected to occur in Asia. In fact, the rate of electricity generation is expected to b faster than the total energy consumption rate in the world over this time frame.

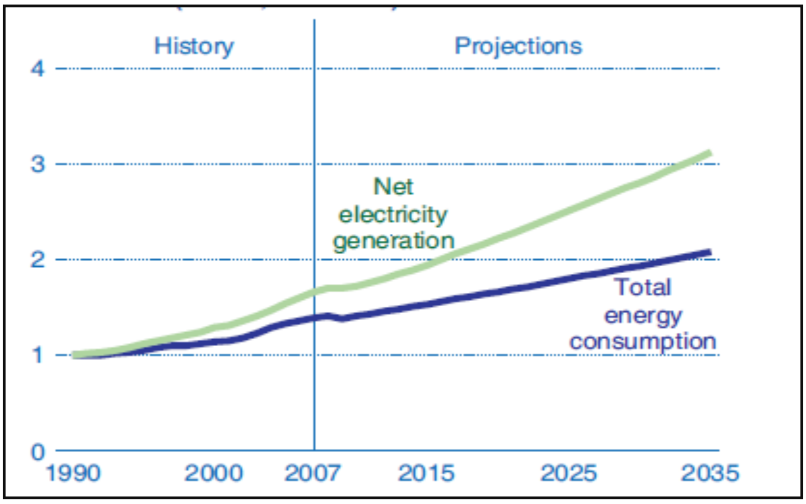

Figure 3 - Growth in world electric power generation and total energy consumption, 1990-2035 (index, 1990 = 1) [1].

By 2023 it is projected that renewable sources may make up to 23% of the world's electricity supply. Much of the world increase in renewable electricity supply is expected to be by hydroelectric and wind power, which are economically competitive with fossil fuel generation at current oil prices, without serious threats of emissions. Wind generation growth does have several issues to resolve in order to be competitive, including wind intermittency and the typical deployment of wind farms away from their intended use area, requiring long transmission paths and infrastructure [2]. To integrate wind resources as part of the baseload requirements of any electric system, it is desirable to include storage systems that could generate more predictable energy output, decoupling the timing of wind generation and system load demand. The features and benefits of an integrated system are summarized below [3, 4, 5]:

a) Shifting the peak demand using charging and discharging schemes.
b) Mitigating renewable energy intermittency output by storing renewable energy.
c) Storing energy in the night time utility power.
d) Creating operator controlled load/generation by combining load, renewable generation, and energy storage.
e) Improved reliability and power quality for consumers.
f) Lowering the power generation and capacity cost by displacing the expensive peaking power plants and reserve capacity.
g) Lowering the transmission and distribution costs by increasing the confidence in renewable distributed generation
h) Lowering emission by peaking and reserve units
i) Helping to reduce power flickers, harmonics, and improve voltage stability
j) Improving power system stability

State of art of different storage systems

Electric suppliers can use energy storage for transmission line stabilization, spinning reserve, and voltage control, which means customers, would receive improved power quality and reliability. Technologies such as ultra-capacitors, flywheels, batteries, and superconducting magnetic energy storage can be used for quality and reliability purposes. However, these applications only support a large power output over very short timescales, typically from tenths of a second to a few minutes. For load leveling and peak shaving the opposite is necessary. The power is delivered over longer timescales from minutes to hours. These systems need to store large amounts of energy but do not necessarily need to deliver power as high as for uninterruptible power supply or power quality applications. Technologies like Pumped Hydro Storage (PHS), where a generating system drives water up gradient to be stored in an upper reservoir, thus storing potential energy. When needed, the reservoir is run to a lower reservoir, with a hyrdroelectric generator located between the two [6]. Many researchers have proposed different energy storage solutions that can be associated with a primary wind source. The storage mechanism selection criteria adopted to evaluate different variables are summarized in Table 1 [4,5,6,7,10]

Table 1 – Comparison of energy storage systems.

Systems Requirements	Pumped Hydro Power	CAES	Flywheels	Batteries	SMES	Supercapacitors	Hydrogen
Primary Energy	Potential	Potential/Enthalpy	Kinetic	Electrochemical	Electromagnetic	Electrostatic	n/o
Energy Density Kj/kg	1 (100 m head)	15,000 Kj/m³	360-500	60- 1400	100-10.000	18-36	14,000.
Energy Range MWh	0.5 – 10 GWh	50 – 5000 MWh	1 Mj – 5 MWh	1.800-180.000 MJ 0.5 – 50 MWh	0.1 – 1,500 MWh	1-10 Mj	-
Power Range Mwe	100-1000	50-1.000	1-10	0.5 – 100	10-1.000	0.1-10	-
Modular systems	No	No	Yes	Yes	Yes	Yes	Yes
Efficiency %	60-80	60-70	~90	~75	~95	~90	47-66
Chage/Discharge Time	Hours	Hours	Minutes	Hours	Minutes to Hours	Seconds	Hours
Access Time	Low	Low	High	High	High	High	High
Load Management	60%	65%	40%	80%	unknown	20%	80%
Power Quality	40%	40%	80%	85%	unknown	65%	85%
Cycle life	≥ 10.000	≥ 10.000	≤ 10.000	≤ 2.000	≥ 10.000	>100.000	≥ 10.000
Lead Time	Years	Years	Weeks	Weeks	Years	Weeks	Years
Foot Print/Unit Size	Large (above the ground)	Moderate (under the ground)	Small	Small	Large	Small	Small
Sitting ease	Difficult	Difficult/Moderate	n/a	n/a	Unknown	n/a	n/a
Thermal Risk	Moderate	Moderate	Small	Moderate	Moderate/ LHe	Small	
Storage Messure	Easy	Easy	Easy	Poor	Easy	Unknown	
Maturity	Mature	Mature	Developing	Lead Acid Mature/ Rest developing	Developing	Available	Available
Application sector	Electric generation	Electric generation	Electric Transport	Electric Transport	Electric generation	Electric Transport	Electric generation /transport

Figures 4 and 5 show the general grouping of the energy storage technologies by usage and cost, with pumped hydro systems demonstrating the highest power effectiveness at one of the lowest costs, thus aligning well with wind system requirements.

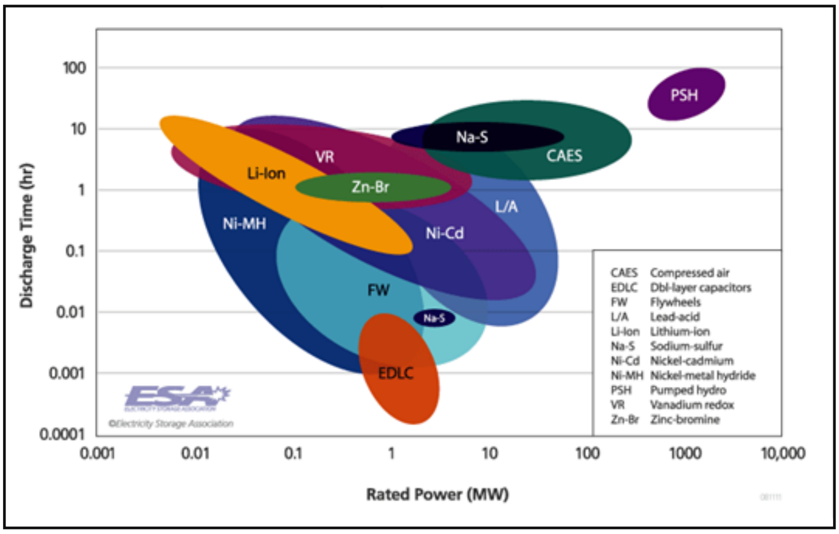

Figure 4 - Systems ratings storage systems. 2008 [11]

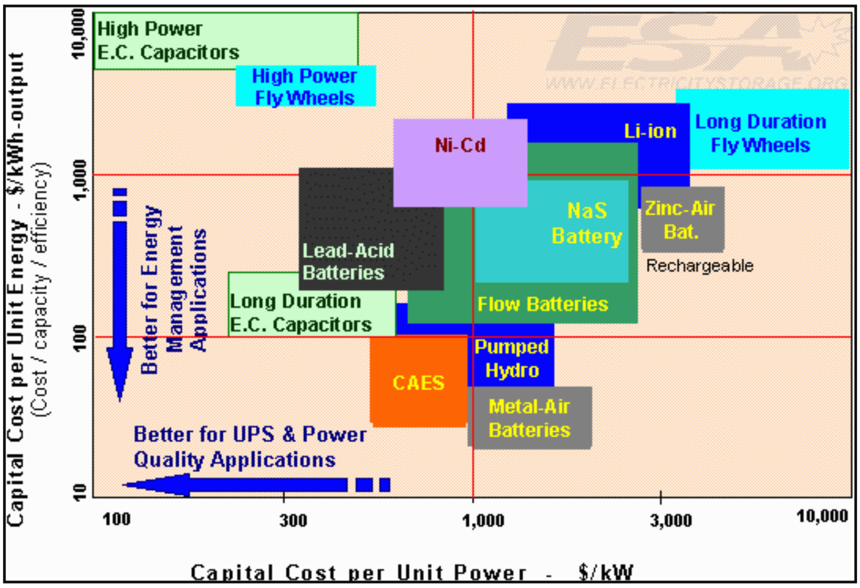

Figure 5 - Cost per unit of Power/ Cost per unit of Energy [11]

The Canary electrical system has six small and isolated electric subsystems isolated and small. Therefore, the system stability is more difficult than large interconnected systems to meet any energy fall disruption [12]. The main power generation technologies in the Canary Islands is fossil fuels, petroleum products, particularly diesel oil and fuel oil. The island of el Hierro has positioned itself with a new concept of electric generation relying on the renewable wind as the primary source coupled with PHS storage and leveling capability. With steady wind conditions and a topography that supports PHS, the island has adopted the motto of "El Hierro 100% Renewable Energy." With careful environmental planning and the declaration of the island as a Biosphere Reserve by Unesco in 2000, el Hierro has targeted becoming a global benchmark in Sustainable Tourism. The main objective of the project is to cover the 100% of the peak power demand and 70-80% of the annual energy demand of the island with the renewable system, keeping existing diesel as a backup only [17].

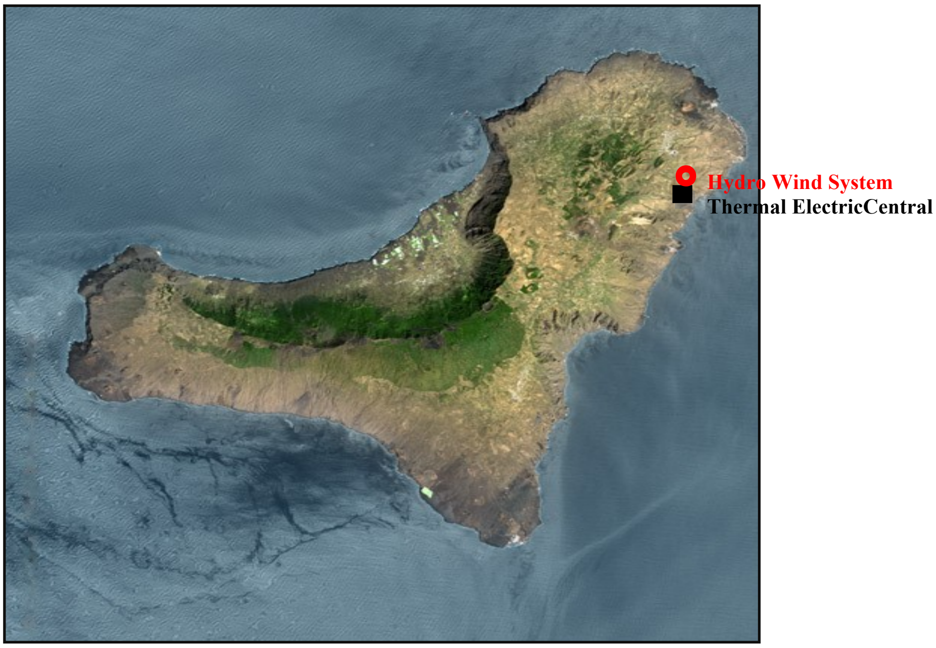

Figure 6 - Location of the Thermal Electric central and Hydro wind system.

From a site selection perspective, wind, topography, and water storage reservoir potentials are the main elements necessary to exploit a combined hybrid closed-loop power system using wind and PHS. The yearly average of wind velocity and density in the Hierro Island in many places is over 7 m /s and 300 W/m², which are considered the minimum conditions to implement wind power projects [15]. The best identified onshore places to implement the wind power utility are the westernmost and southeast zone of the Island (Figure 6) near the existing electrical system grid connection point and with an average average wind resource of 9-9.5 m/s and 600-700 W/m².

For the upper reservoir, a natural depression located in the upper area of Valverde municipality with an approximate volume 556,333 m³ will be used. For the lower reservoir, construction will rework the landscape with a volume of 200,000 m³. It will be located near a desalination plant, installed at sea level for the provision of desalinated water. A constant water supply is needed due to evaporation processes in the open reservoirs. From a technical perspective, the key elements of the system will include the elements in Table 2.

Table 2 - Major Technical Elements of el Hierro Project [18]

Wind Farm	11,5 Mw
Turbine Central	11,3 Mw
Pumping Central	10 Mw
Upper Reservoir	556,000m³
Lower Reservoir	225,000 m³
Forced Pipeline	2,35 km
Forced Jump	655
Drive Pipeline	2,8 Km
Drive Jump	675+
Hydro Wind System Substation	20/0.6 Kv

When the project is fully operational it is expected to avoid consumption of 6,000 tones / year of diesel fuel, equivalent to 40,000 barrels of oil imported by ship. During the lifetime of the system, it is expected to avoid creating the following emissions

Table 3 - Lifetime Emissions Avoidance of the System [18]

Emissions	Equivalent Metric Tons
CO2	130,118
SO2	742
NOx	2,697
VOs	47

The combination of all of these conditions and technical capabilities makes el Hierro an ideal experiment in the deployment of a hybrid closed-loop energy model. If successful, then the next question is how to find similar places around the world that could exploit the same system design.

The GIS Model

The wind hydro project is an ideal electric generator solution for isolated systems that depend primarily on costly oil sources for electricity generation. All over the world there are populations that are supplied by similar diesel systems in environments that may match that of el Hierro. Many similar islands have ideal environmental conditions to exploit the hybrid closed-loop system design and become less dependent on oil-based generating fuels. Geographic information systems (GIS) are a set of informatics tools that capture, store, analyze, manage, and present data representing geographically identifiable characteristics. GIS software tools allow users to create interactive queries, analyze spatial information, edit data, maps and present accurate results, that enable multi-dimensional decision making. This section of the paper proposes a decision methodology for structuring GIS queries in order to identify sites globally that could easily adopt the el Hierro model.

The site selection GIS algorithm for a hybrid closed-loop wind and hydro system will focus on the primary elements of wind energy resource availability, environmental/topographical conditions, and technical characteristics. The use of such a GIS algorithm in the site decision making process is one of the key advantages of this methodology due to its low cost, efficient search characteristics. Details of the algorithm are required to contain defined attributes, thresholds, and the decision process for selection. In more advanced versions, probability density maps can be generated showing the comparative magnitude of meeting requirements overlayed on a map. The first order model does not consider local regulations or other site-specific singularities that could void the search. The first algorithm could serve as a search function, to which a second could be applied including the following additional layers searching the smaller data set, namely:

- **Land/ Urban Planning Data Layers**: In each location the land use and restrictions associated with any kind of land/urban planning that must be considered in terms of the activities and uses allowed, and removing any locations that would not permit the hybrid closed-loop system.

- **Urban Data Layers**: Information about location and characteristics of urban nodes is relevant for electric generator facilities in terms of energy supply and demand. Normally, some restrictions might be established in terms of allowable distance to locate an electric generator near urban nodes, also impacting the cost associated with transmission and interconnectivity to the grid.
- **Airport Data Layers:** Air traffic areas will typically have restricted buffer areas to ensure flight operations and airport safety.
- **Road Data Layers:** Existing road infrastructure will be important for access to the identifiable build areas, and also be a potential barrier for identified installation sites where roads might have to be moved.
- **Environmental and Archaeological Data Layers:** Many islands have some form of international, national and local environmental and/or cultural restrictions which would reduce the potential places to install a hybrid closed-loop wind and hydro system, including but not limited to natural conservation areas, archaeological sites, and historic monuments.
- **Land Use:** Some states and governments enforce "energy use" land restrictions, further reducing the number of available sites for the system to be installed. However, these restrictions may only apply to certain energy production types, such as coal or nuclear generating facilities.

- **Technical regulation:** Normally, national and local regulations affect the technical development of the project in terms of energy supply and connection, in addition to emissions and pollution requirements.

Wind Models

Several key wind characteristics are required to determine the GIS site selection criteria, including the two primary ones of average wind speed and wind energy density. Contributing factors are wind speed data, wind shear, surface roughness, and availability of this information for use in a GIS model. Wind data sets exist for specific sites in the world, however, there is not a comprehensive set of wind data for all global locations. Historic local and regional wind data and GIS modeling must be matched to create detailed global wind data information. Meteorological and cartographic parameters could be considered for estimating the wind resource in each location via some form of interpolation between sites, involving a limiting ratio of distance between measurements and the rate of change of the topography.

Wind is caused by rotation of the earth and heating of the atmosphere by the sun. Due to the heating of the air at the equatorial regions, the air becomes lighter and starts to rise, and at the poles the cold air starts sinking. The rising air at the equator moves northward and southward. Differential heating of sea causes more minor changes in the flow of air. The nature of the terrain, ranging from mountains and valleys to more local obstacles such as buildings and trees, also has an important effect on the wind [26]. The power in the wind is proportional to the cube of the wind speed or velocity. It is therefore essential to have detailed knowledge of the wind and its characteristics, if the performance of wind turbines is to be estimated accurately. These characteristics will also be used to assess the performance and economics of the wind plant.

The magnitude of the wind shear is specific for each size of wind turbine of interest, and dependent on wind direction, wind speed, and atmospheric stability. By determining the wind shear, one can extrapolate existing wind speed or wind power density data to other heights. The surface over which the wind blows affects its speed as well. Rough surfaces, such as areas with trees and buildings, will produce more friction and turbulence than smooth surfaces such as lakes or open cropland within the vicinity of the wind turbines. Greater friction will reduce wind speed near the ground. The extent to which wind can be exploited as a source of energy depends on the probability density of occurrence of different wind speeds. To optimize the design of a wind energy device, data on speed range over which the device must operate to maximize energy extractions are required, which requires the knowledge of frequency distribution of the wind speed [26].

The wind speed variation during the year can be modeled as a Weibull distribution. The mean wind speed (MWS) or the scale parameter, is used to indicate how windy the site is, on average. The shape parameter (k), tells how peaked the distribution is as shown in Figure 7.

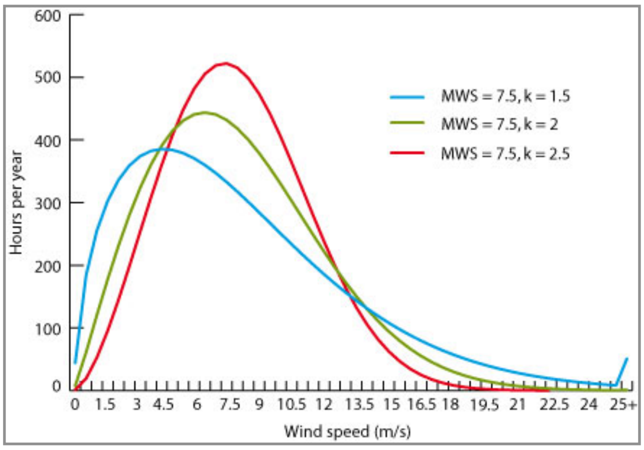

Figure 7 - Example of Distribution of Wind Power Density

If we multiply the power of each wind speed with the probability of each wind speed from the graph, we have calculated the distribution of wind energy at different wind speeds. However, the values on the wind resource maps must based on the estimated wind power density, not wind speed. Wind power density (WPD) is a better indicator of the available resource than the average wind speed. Wind power density, expressed in watts per square meter (W/m2), incorporates the combined effects of the wind speed frequency distribution, the dependence of the wind power on air density, and the cube of the wind speed [27] as follows

$WPD = \frac{1}{2} * d * v^3$

where

d= (rho) = the density of dry air

v = the velocity of the wind measured in m/s (meters per second).

For the GIS model build up, two wind specifications are required, one based on wind velocity and the second based on the wind power density. In general, locations with an annual average wind resource greater than 7.0 m/s (speed) and 300 W/m2 (WPD) at the turbine hub height are suitable for utility grid-connected wind energy systems.

Table 4 - Wind Requirements for the GIS Model

Variable Wind Resource	Measure	Database	Resource Potential	Threshold
Average Wind Speed	Meters/second	• **Georeference Data.** • **One square kilometer Km^2 data source** • **Height of data >30 meters to 80 meters** • **>5 years of data**	Good	7.0 to 7.7
			Excellent	7.7 to 10.5
Average Power Density	Watts/square meter	• **Georeference Data.** • **One square kilometer Km^2 data source** • **Height of data >30 meters to 80 meters** • **>5 years of data**	Good	300 to 400
			Excellent	400 to 1000

This first set of wind data provides a measure of the natural resource used to generate the initial energy. The second part of the GIS model will look at the geographic/topographic conditions.

Normally terrain above a 20% slope is not economically feasible to implement Wind turbines. The difficult access to places with more than 20% slope will increase the cost and difficulty to transport materials and the civil work to prepare the terrain to anchor the tower will be expensive[25][28]. Additionally, the water reservoirs need relatively low gradient areas in that can support large enough volumes. The location characteristic in the GIS model for the reservoirs will be up to a maximum 10% of slope in order to reduce the cost of civil works. Finally, the water jump, or pressure head, must be at least 200 meters between the upper reservoir and the hydroelectric turbomachinery [21].

Table 5 - Geographic and Topographic Requirements

Geography/Topography	Measure	Database	Resource Potential	Threshold
Wind Technical Potential	Slope	**Georeference Data**	Good	≤20%
Water Potential Reservoirs	Slope	**Georeference Data**	Good	≤10%
Water Jump Potential	Contour	**Georeference Data**	Good	≥ 200 m

The position of the wind turbines in the park must be calculated to avoid the wake effect. As a preliminary sizing requirement, the distance between wind turbines must be set to 3 and 6 times the rotor diameter (D). Thus, the value will be obtained by assuming that each turbine occupies an area of 3D x 6D = 18 D^2 [29] [30]. The maximum turbine density of the Enercon E70 wind turbine used in el Hierro with a diameter of 70m and a rated capacity of 2 MW, is 11 turbines per Km^2.

The area needed for the water reservoir will depend of the on the availability of a large enough water jump, and on the necessary volume of the reservoirs. However from a cost perspective, the larger the jump, the greater the installed cost for the piping. At each reservoir location, either high or low, a relatively flat area is needed to create the water reservoirs with a target depth of 20 meters. For the el Hierro project, approximately 80,000 square meters are necessary for the upper reservoir and 40,000 square meters for the lower reservoir.

Table 6 - Requirements for Land Area

Surface Area Variable	Measure	Database	Resource Potential	Threshold
Wind Technical Potential	Minimum required for a wind turbine	**Georeference Data**	Good	≥18 D^2 per Wind turbine installed
Water Reservoir Technical Potential	Minimum required for a water reservoir	**Georeference Data**	Good	Upper reservoir ≥80.000 m^2 Lower reservoir ≥40,000 m^2

The Distance between water reservoirs will directly affect the cost of the piping system. The maximum linear distance of piping between the water reservoirs for el Hierro is 2,500 meters. The road data is relevant information for a Wind Hydro system. Information about the location of the nearest access roads to the project, and the ability to transport heavy materials are a determinant for the feasibility of the project. The maximum distance of major operating points from an access road in el Hierro is 500 meters. The electric grid and connectivity data is necessary information for the Wind Hydro system. The information needed from the electric system must be detailed including location and characteristics of substations, distribution and transmission lines. Information must include line characteristics, grid accessibility, substation capacity and planned systems upload. The maximum distance from a grid connection point is 2,000 meters in the el Hierro project. The cost to install major transmission lines would have a serious impact on the levelized cost of energy (LCOE) projected for the system, as such, being contiguous to an existing grid and/or node point is critical to the GIS decision model.

Table 7 - Distance Variables to Consider in the GIS Model

Distance Variable	Measure	Database	Resource Potential	Threshold
Water reservoir technical potential	Distance between reservoirs.	**Georeference Data**	Good	≤ 2,500 meters
Road connection technical potential	Maximum distance to a access road	**Georeference Data**	Good	≤ 500 meters
Electric connection technical potential	Maximum distance to grid connection point (Substation)	**Georeference Data**	Good	≤ 2,000 meters

The analysis of the el Hierro project results in a series of requirements and thresholds that can be codified into a general GIS search algorithm, as shown in Figure 8. The step-by-step process shows provides for a termination for the search at each level of the process if the threshold cannot be met. This quickly limits database search process to fewer locations and variables at each stage, thus improving overall search efficiency.

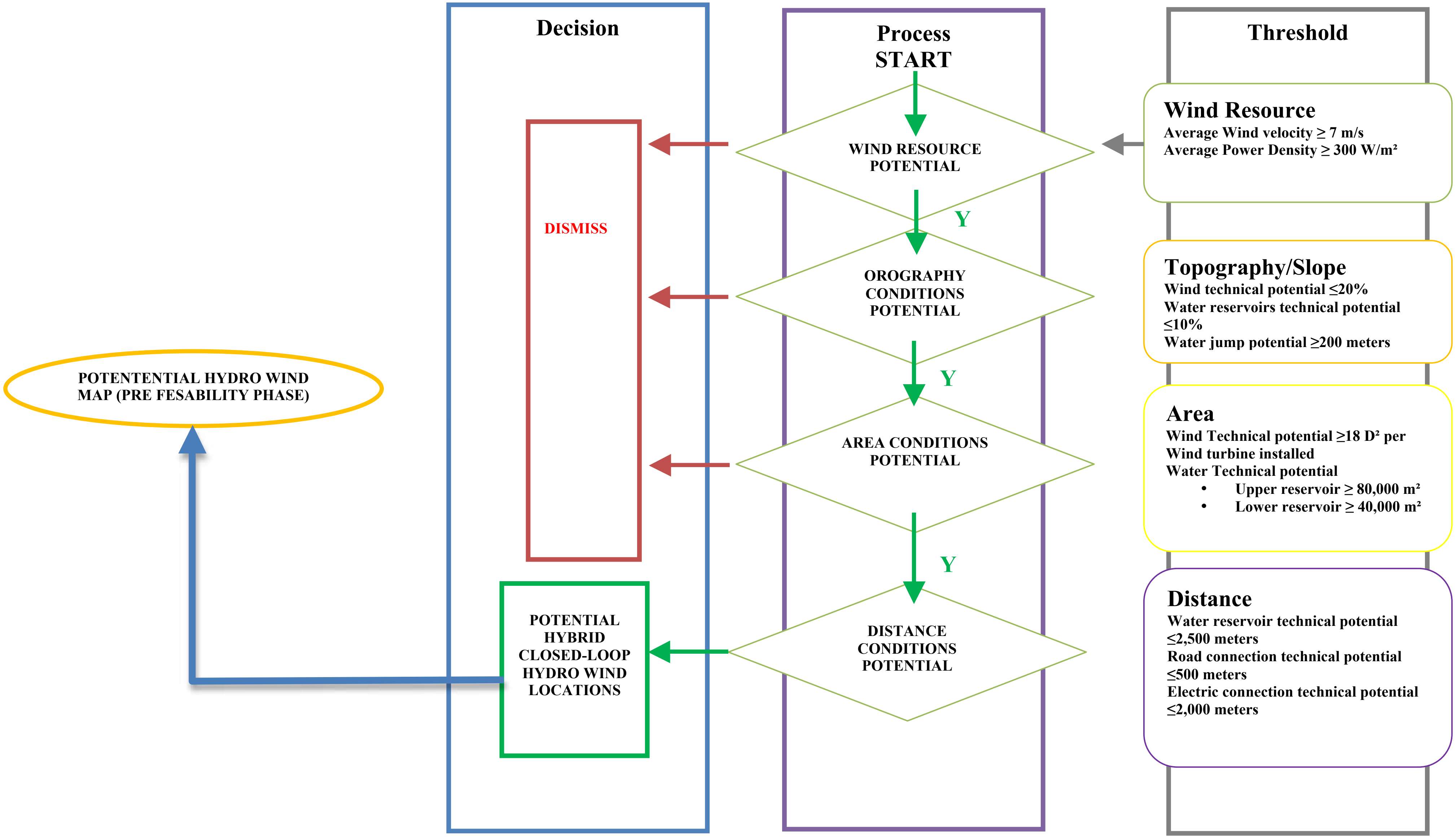

Figure 8 - GIS Decision Algorithm for Global Location of Hybrid Closed-Loop Energy System

Conclusion

El Hierro is currently the only large scale example of a hybrid closed-loop wind and hydro energy system built in the world. The set-up cost is significantly higher than a diesel electric facility, but the long term LCOE and avoidance of environmental impact has made the choice of this type of power generating system a key socio-political decision for the Canary Islands. The system demonstrates that a reliable electric supply can be developed with wind and hydro providing baseload and peak power. Most of the problems associated with renewable energy supply reliability have being solved by temporally decoupling the production and demand requirements. Also, the pumping hydro storage system appears to be the best option for isolated systems with high power demand during long time frames, when the topography is conducive to supporting such an installation.

Most of the islands of the world have good average of wind resources that in many cases are not utilized to cover electric needs. With the GIS search algorithm developed in this paper, a quick feasibility study can be run to identify the most promising locations in the world for exploiting the el Hierro hybrid closed-loop model. Using this proposed methodology, GIS can manage and filter potential places all over the world to implement this type of technology. However, an accurate and updated database is needed to establish potential locations. Additionally, local regulation could be a determining factor in the development possibilities of this technology, and this information does readily exist in most GIS databases.

The penetration of wind energy use in isolated geographic regions could be a reality if stakeholders, including political, social, technological, and economical align. This would reduce the dependence on oil and oil derivates. The European Community has supported the hybrid closed-loop wind and hydro project in el HIerro and is now working on expansion to the Azores which has very similar conditions and thresholds identified in this proposed GIS algorithm.

Future Work

Current research is focused on investigation the availability of the necessary GIS layers identified in this search algorithm. This initial assessment will help identify which areas if the world can be analyzed with the proposed methodology. Partial data sets may be available for some of the data layers, while others may not be available at all. As such, the first pass model will have probabilities assigned to each requirement sand threshold, resulting in an initial "best likelihood" assessment of the databases.

Next, the density function can be built using the thresholds as minimums, with greater weighting applied to results that exceed the minimum requirements, thus providing a second pass of the data to rank the "best likelihood" sites by the overall "best expected performance". This will result in a targeted set of locations to begin investigating the use of a hybrid closed-loop energy system.

The Azores, the intended next site for a hybrid, closed loop system provides a potential case study to look at applying the algorithm and comparing the results against the decisions being made on location by the design/development teams working on the project. A comparison of investment effort to identify the site could indicate a potential cost and time savings achievable using the GIS methodology.

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