Optimization of Pumped Storage Capacity in an Isolated Power System With Large Renewable Penetration

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***Abstract*—This work describes an economic analysis of the inclusion of pumped storage in a small island system that has abundant renewable energy available but that at times cannot accept all of this power because of limits imposed by security criteria. The question of whether or how much pumped storage to include is addressed by formulating a linear programming optimization problem. The stochastic nature of load and renewable production is addressed using scenarios developed through fuzzy clustering. Both the unit capacity in MW and the reservoir storage capacity in MWh are optimized, and optimal operating strategies for the scenarios are produced.**

Results showed that including pumped storage can be an effective means of allowing larger penetration of intermittent renewable energy sources, improving both the dynamic security and the economic operation of a test system. Including the dynamic security criteria in the economic question of dimensioning the pumped storage unit proved to make a significant difference in the optimal pumped storage capacity.

***Index Terms*—Energy storage, optimization, power systems economics, stochastic processes, wind energy.**

I. Introduction

Rising fossil fuel costs and concerns about the environmental impact of burning fossil fuels have generated tremendous interest in the use of renewable energy sources to supply more and more of the electrical energy needs of society. The strong growth in renewable generation is expected to continue, and as its role increases, it will bring new challenges. These are principally related to the intermittency of renewable resources. The primary energy sources for technologies like wind and solar power are not controllable and can be, at best, forecast. Energy storage used in conjunction with renewable energy has been suggested as a means to increase the use of renewable energy while maintaining a high quality of service reliability [1]–[3]. The use of storage devices can help offset the effects of the inclusion of renewable energy sources and allow them to gain a larger penetration in the electrical energy supply. Storage may also be used to transfer energy from low-use periods to peak-use periods, allowing the system to operate at a more constant level and reducing energy supply costs.

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Isolated island systems have felt these pressures even more strongly since they often face exaggerated fuel costs due to extra costs of shipment and small overall system size. They also frequently have substantial renewable energy resources available. However, the use of these renewable resources, such as wind and hydro generation, is often limited by dynamic security concerns. The power system must be operated within tight margins of frequency and voltage, and wind parks and other renewable sources are generally unable to assist in maintaining the system at the necessary operating point–and in fact may have a negative effect due to their intermittency.

In choosing to install a power storage station, in this specific case a pumped storage station, there are two important economic questions to consider: 1) Is it worthwhile to install any storage units? 2) If so, how much should we install? “How much?” means both the amount of energy that will be able to be stored as well as the limit of power that will be able to be put into or taken out of storage at any given time. In the context of a pumped storage station, storage capacity will be related to the size of the reservoirs used to store the water. The amount of power available corresponds to the dimensioning of the electrical machines, mechanical housings, waterways, etc. In this paper, these two ratings are considered to be independent of one another.

Optimization problems considering the influence of renewable resources have been solved before. Some of these works focus on the operation of systems that include wind power and pumped storage [4]–[6]. The approaches taken generally seek to maximize profits of a combined wind-hydro system given market prices for electricity and interconnection limits. Provisions are made to penalize deviation from a schedule for overall net power output. Uncertainty in the wind production is treated by introducing error in the predictions for future production.

This paper describes a new approach that seeks to optimize the capacity of pumped storage to be installed in an isolated power system with large amounts of renewable energy available, including the stochastic nature of the production from renewable resources and the dynamic security constraints related to frequency regulation.

II. Approach

In the case of a large power system, a storage unit of small or medium size will not change the price of energy. The optimal size of the storage station will depend upon the expected prices of energy, the costs of the storage unit, and the round-trip efficiency of the storage technology. Prices may be considered fixed or treated stochastically but in any case are not affected by the presence or dimension of the storage unit being considered.

When optimizing a power storage station for a small power system, the approach must be different. The storage station will likely have a significant impact on the operation of the power system. In a small power system, the number of thermal generators used to meet load is relatively small. For the example system used in this research, twenty-three diesel units are available, and during off-peak hours, the number of online units may be quite low. Under these conditions, even a relatively small storage station may significantly change the unit commitment and accordingly the marginal costs of generation during off-peak and peak hours. Since it is expected that the marginal costs will be modified by the inclusion of a storage station, the optimization problem should consider the entire energy supply system and not merely accept fixed energy prices for peak and off-peak hours.

Additionally, the test case under study includes large components of wind and hydropower production. This is particularly significant because, during low loading periods in which a large amount of wind and hydro power is available, the technical limits and security concerns related to frequency regulation may require a minimum amount of thermal generation to be left online. The use of pumped storage can increase the system load during these off-peak periods and allow larger penetration of renewable energy sources. Pumped storage can also be used as low-priority load that can be shed early in the load-shedding scheme to guard against widespread generation loss and general system load shedding [7]. The formulation presented here includes these uses of the pumped storage unit in the dynamic security criteria.

Optimization must take into account the amount of wind and hydro power available throughout the year. Hydropower production in particular demonstrates very strong seasonality. Wind park production also shows some seasonality, and system load exhibits weekly and seasonal variations. Scenarios are generated to approximate the distribution of wind and hydro power and load throughout the year.

The simplest way of creating scenarios is to divide the year into seasons according to known weather patterns and take averages of renewable production during each season to produce scenarios. This approach suffers in that the selection of seasons remains at the mercy of the choice of the researcher, which may not be optimal, and also may not account for some low-probability but high-impact conditions that may exist only a few days per year but which in terms of cost or profit opportunity are quite significant.

Since several years of data were available for the test system, fuzzy clustering techniques were adopted to produce scenarios for the optimization problem. These scenarios characterize the *net load* of the system, that is, the load less the possible production from renewable resources. This is the amount of net power that must be produced by the conventional thermal units in conjunction with the pumped hydro storage station. By using fuzzy clustering, a set of prototype twenty-four-hour series are produced that are representative of the shape and magnitude of the recorded daily curves of load and renewable power production.

The operation costs of the wind and hydropower units have not been included in the problem since, in the case being considered, the system operator is obliged to give priority to renewable power sources, in order to fulfil the EU directive on renewable energy sources [8], accepting all the renewable energy at pre-defined price settled in a feed-in tariff. Wind and hydropower production is therefore not affected by the use of the pumped storage unit except when production must be curtailed for technical reasons to meet dynamic security criteria. This type of formulation would not be appropriate to problems where the economic cost and benefit of renewable generation must be considered in the operation of the system.

The approach used considers the benefits of a pumped storage unit in terms of energy storage on a daily cycle, storing energy during off-peak hours to be used during peak hours, as well as in terms of providing additional load during off-peak hours that can allow greater penetration of renewable energy sources without compromising system security. These are not the only benefits of pumped storage. Using the pumped storage unit to supply peak loads and allow greater utilization of renewable sources may play an important part in the expansion of the energy supply system in addition to or instead of investment in thermal generators [9]. The operation of a power storage station will also help level the loading on the diesel groups, allowing them to operate more constantly and avoid some start-up and shut-down costs [10]. It is important to keep in mind that these effects are not included in the present study and will serve to increase the value of the pumped storage station.

III. Problem Formulation

A hydro pumping storage station was considered to be installed in the system to help its operation. The identification of its storage capacity is a key problem and was addressed as an optimization problem, as described next.

This problem is formulated as a single-objective constrained linear programming optimization problem. The primary problem variables are the energy capacity ($E_{\max}$) and the power capacity ($P_{\max}$) of the pumped hydro station. The identification of the optimum storage capacity required the definition of an objective function that represents the minimization of the sum of operating costs and appropriately annualized installation costs. Operating costs are the expected operating costs over all scenarios of wind and hydropower production and load. In each scenario the operating costs are independently minimized in a sub-problem that considers as problem variables the pumping/generating use of the pumped storage station, constrained by $E_{\max}$ and $P_{\max}$.

By formulating the problem in the way, this solution provides not only an answer to the question of how much pumped storage to install, but also provides insight into operating strategies for various wind/hydro/load scenarios. The uncertainty of future wind or hydropower production throughout the day is not considered in the subproblem optimization; instead, each day is optimized with all of the production values known. In this respect it will be optimistic compared to what can be achieved in real-time operation. Optimizing the operation of a pumped storage unit in conjunction with uncertain wind production has been treated in other works [5].

In this formulation the energy capacity and power capacity ($E_{\max}$ and $P_{\max}$) are treated as continuous variables. Likewise, in the subproblems, the generation and pumping of the storage station (P_g and P_p) are treated as continuous variables. The cost of thermal generation is represented by a single piecewise linear function.

1) Objective Function: The objective function to be minimized is the expected daily cost of operation and amortization

$$\text{Minimize } t \cdot \sum_{i,j,k} p_i \cdot C_{T,k} \cdot P_{i,j,k} + a \cdot C_{E_{\max}} \cdot E_{\max} + a \cdot C_{P_{\max}} \cdot Pg_{\max}. \quad (1)$$

In the objective function (1), the second line corresponds to the annualized install costs of energy and power capacity. The sum in the first line is the expected operation cost over all scenarios. The subscript i indexes scenarios, j indexes periods during the day, and k indexes parcels of power for thermal generation.

2) Constraints: The equality and inequality constraints of the problem are in (2)–(11) at the bottom of the page.

3) Problem Variables: The problem includes the following variables. The subscript i is used to index over scenarios and the subscript j is used to subscript over time periods within the scenario.

$E_{\max}$ (MWh) is the maximum amount of energy that the system can store. It corresponds to the capacity of the reservoirs of the pumped hydro station.

$Pg_{\max}$ (MW) is the active power rating of the power storage station while in generating mode. It can also be thought of as the maximum rate at which energy may be taken out of storage and injected into the power system. It corresponds to the rating of the electric generating machine that is to be used.

$Pp_{\max}$ (MW) is the active power rating of the storage station while in pumping mode. As in the case of $Pg_{\max}$, it can also be thought of as the maximum rate at which energy may be taken out of the power system and injected into storage. It corresponds to the rating of the electric pump that is to be used. In the case that a single reversible machine is used, $Pg_{\max}$ and $Pp_{\max}$ are equal. This condition is enforced by a constraint in this problem formulation.

$Pg_{i,j}$ (MW) is the amount of power generated by the pumped storage station in generating mode.

$Pp_{i,j}$ (MW) is the amount of power consumed by the pumped storage station in pumping mode.

$P_{i,j,k}$ (MW) is the amount of power produced by block k of thermal generation. The sum $\sum_k P_{i,j,k}$ gives the total of thermal generation during time period j of scenario i.

$P\text{curtailed}_{i,j}$ (MW) is the amount of renewable power that could be produced but has been curtailed. It could be wind power or hydro power or some combination of the two.

$E_{i,j}$ (MWh) is the energy balance of storage. This represents the reservoir's level at the beginning of time period j of scenario i.

$E\text{dump}_{i,j}$ (MWh) is energy in the storage device that is dumped. This represents water that is allowed to flow from the upper reservoir to the lower one without turning the generator.

4) Parameters: The following parameters are associated with the problem:

$C_{E_{\max}}$ (EUR/MWh) is the constant incremental cost of installing reservoir capacity.

$C_{P_{\max}}$ (EUR/MW) is the constant incremental cost of installing pumping station power capacity.

a is a dimensionless annualization parameter used to express the cost of the pumped storage station on a daily basis.

p_i is the relative frequency of the ith scenario.

$$0 \le E_{i,j} \le E_{\max}, \ \forall\, i,j \quad (2)$$

$$0 \le Pg_{i,j} \le Pg_{\max}, \ \forall\, i,j \quad (3)$$

$$0 \le Pp_{i,j} \le Pp_{\max}, \ \forall\, i,j \quad (4)$$

$$E_{i,j+1} = E_{i,j} + t \cdot \eta_p \cdot Pp_{i,j} - t \cdot \frac{Pg_{i,j}}{\eta_g} - E\text{dump}_{i,j}, \ \forall\, i,j \quad (5)$$

$$E_{i,0} = E_{i,n} \quad (6)$$

$$\sum_k P_{i,j,k} + Pg_{i,k} - Pp_{i,j} = P\text{load}_{i,j} - P\text{hydro}_{i,j} - P\text{wind}_{i,j} + P\text{curtailed}_{i,j}, \ \forall\, i,j \quad (7)$$

$$\sum_k P_{i,j,k} \ge \frac{1.5 \cdot \text{UnitSize} \cdot \text{TechMin}}{1 - \text{TechMin}}, \ \forall\, i,j \quad (8)$$

$$\sum_k P_{i,j,k} \ge \text{TechMin} \cdot \text{RegFactor}(\text{TechMin} \cdot \text{UnitSize} - Pp_{i,j} + Pg_{i,j}) + \text{UnitSize}, \ \forall\, i,j \quad (9)$$

$$0 \le P_{i,j,k} \le P\text{ParcelMax}_k, \ \forall\, i,j,k \quad (10)$$

$$Pg_{\max} = Pp_{\max} \quad (11)$$

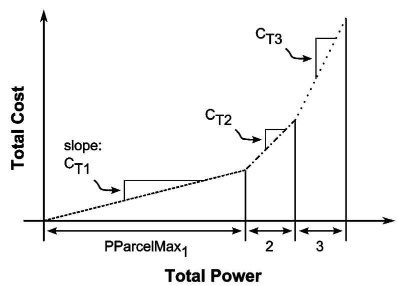

Fig. 1. Thermal cost function.

$P\mathrm{load}_{i,j} - P\mathrm{hydro}_{i,j} - P\mathrm{wind}_{i,j}$ (MW) defines the net load that must be met by the thermal generators and the pumped storage station together. Each scenario is defined by this series of values.

η_p is the efficiency of the pumping cycle of the pumped storage station. The value is dimensionless and should be the ratio of energy put into storage to energy taken from the power system.

η_g is the efficiency of the generating cycle of the pumped storage station. The value is dimensionless and should be the ratio of energy injected into the power system to the energy drawn from storage.

$\mathrm{UnitSize}$ (MW) is the active power capacity of the first diesel machines to be committed. It is assumed that three of similar size are committed first and that no less than three may be committed.

$\mathrm{TechMin}$ is the per-unit technical minimum of the diesel generating sets, below which the generators are not to be operated.

$\mathrm{RegFactor}$ is the regulating factor for frequency regulation. This value is equal to the product $f_{\mathrm{base}}/\Delta f_{\max} \cdot a \cdot r$ as used in the frequency regulation security criterion developed in [7]. A short description of the security criterion adopted here can be found in Section V.

$C_{T,k}$ (EUR/MWh) are the marginal costs of the blocks of the cost curve for thermal generation. Fig. 1 illustrates how C_T and $P\mathrm{ParcelMax}$ define the cost curve.

$P\mathrm{ParcelMax}_k$ (MW) are the sizes of the blocks of the cost curve for the thermal generation.

n is the number of time periods in each scenario that will be considered.

t (h) is the length of each time period in the scenarios.

5) Description of Constraints: The problem constraints presented in (2)–(11) are explained as the following.

The constraint in (2) limits the reservoir level in every time period of every scenario to the maximum of $E_{\max}$. Likewise, (3) and (4) limit the generation or pumping power of the pumped storage station to a maximum of $Pg_{\max}$ and $Pp_{\max}$, respectively, for all time periods of all scenarios.

Constraint (5) couples the reservoir level between subsequent time periods and takes into account the efficiencies of pumping and generating (η_p and η_g). The possibility of dumping water without using it to turn the generator is allowed by the inclusion of $E\mathrm{dump}$. This could arise if pumping is done in order to raise system load in order to meet spinning reserve requirements or frequency regulation unit commitment requirements as expressed in (8) and (9).

In (6) the boundary conditions of the reservoir level are set. Since the pumping/generating cycle is supposed to be repeatable on a daily basis, the beginning and ending balance of each scenario have been fixed as equal. This allows the storage cycle to start and end at any balance as long as the beginning and ending balances are equal. In real operation, the station will not have this freedom; each day in fact begins with the ending balance of the previous day. Results showed that all scenarios resulted in very similar boundary values, so the supposition of repeatability seems quite reasonable in practice.

In (7) the power balance between generation and load is enforced for every time period of every scenario. To allow for cases in which of the power from renewable sources cannot be accepted, the term $P\mathrm{curtailed}$ has been included. No upper limit is needed for $P\mathrm{curtailed}$ as long as the limits imposed by (8) and (9) are always below system load.

The constraint in (8) requires that the spinning reserve requirement be able to be met. It assumes that at the limit, the committed generators will be operating at their technical minimums $\mathrm{TechMin}$ leaving $1 - \mathrm{TechMin}$ as spinning reserve. The spinning reserve criterion adopted here is 1.5 times the load carried by the largest unit.

In (9), the thermal dispatch is constrained by a minimum unit commitment as determined by the frequency regulation security criterion [7]. The Pg term does not properly belong in this constraint, however, it has been included to keep the solution from giving Pp and Pg both positive in the same time period. The inclusion of Pg has no effect as long as the load is sufficiently high during periods in which the pumping station is in generating mode (i.e., $Pg > 0$) that this contraint is not active.

The constraint (10) sets the power limits for the blocks of power at each marginal cost level in the piecewise linear thermal cost function.

Finally, in (11), the power limits for generation and pumping are fixed equal. This corresponds to the use of a reversible machine. In the case that separate machines are used for pumping and generating, this constraint could be removed and two separate cost elements used in the cost function.

IV. Production and Load Scenarios

In order to account for the variety of conditions that can be encountered for renewable energy production and for load, a set of scenarios has been produced. Each scenario consists of a set of 24 hourly values for $\mathrm{NetLoad}$, which is the total system load less the contribution from wind and hydro generation. This allows consideration of the time-series evolution of both load and renewable production over a pumping cycle of one day. It does not take into account the evolution of load or renewable production over a longer time span such as weeks or months, but it does account for seasonal variations since these are reflected the relative frequencies of the various "typical days" represented by the scenarios.

For the test system used in this study, five years of hourly or semi-hourly power production data were available for thermal, hydro and wind power sources. With this amount of detailed data available, the most reasonable approach is to use data analysis to determine scenarios. Fuzzy clustering algorithms were chosen as a good means to determining adequate scenario prototypes.

Fuzzy clustering seeks to discover natural groupings that exist in the data set through an optimization process based on the dissimilarity (distance) between the data points. Fuzzy clustering algorithms assign each data point to each cluster with a degree of membership that ranges between 0 and 1, in a way that the total membership of a point to all the clusters is 1. Each cluster is represented by a prototype or centroid, typically a weighted sum of the points under consideration where the weights are the degrees of membership. The prototypes can then constitute a reduced representation of the entire set.

The most basic fuzzy clustering algorithm is fuzzy c-means (FCM) as developed by Dunn [11], [12]. The objective function of FCM is the following:

$$J(X;U,V) = \sum_{i=1}^{c}\sum_{k=1}^{N} (\mu_{ik})^m \left\| x_k - v_i \right\|_A^2 \tag{12}$$

where $X = [x_k]$ is a vector of N data points, $U = [u_{ik}]$ and $V = [v_i]$ are, respectively, the resulting degrees of membership and prototypes for c clusters, and A is the norm-inducing matrix used in the distance calculation.

In the formulation given in Section III, the scenario for load, wind, and hydro production appears merely as a net load to be met by some combination of thermal generation and pumped storage, as appear on the left- and right-hand sides of (7). What is therefore most important to identify in creating scenarios is the shape of this net demand and its overall level.

Since the present problem deals with the economic benefits possible from shifting energy from offpeak to peak periods, the values in these two time periods is of special interest. From typical daily load curves, three daily time periods present themselves:

- off-peak, the period in which load reaches a minimum, between 3 and 5 AM;
- peak, the period at which load generally reaches a maximum, between 8 and 10 PM;
- intermediate, the mid-day period in which load rises to an intermediate peak, between 12 noon and 4 PM.

During each of these periods, the mean net load has been calculated and is used as the attribute set for clustering analysis. The probability of each scenario was calculated by summing the fuzzy membership values of the data points in each cluster and dividing by the number of data points considered. These probabilities could also be calculated by first hardening the fuzzy sets to crisp sets and then counting the data points assigned to each cluster. Both methods gave similar probabilities and did not impact the outcome of the optimization problem.

In order to produce the prototype scenarios consisting of a series of twenty-four hourly values, the data points that most strongly belonged to each cluster were averaged. That is, for each hour, the mean of the net load in that hour over all of the data points that had a membership value of at least 0.7 in each cluster was used as the net load value for that hour of that cluster prototype. Thus the net load level for off-peak, peak, and intermediate periods is used produce clusters of days with similar shape of net load, and the days that most closely follow these typical shapes are used to produce the scenario prototype series.

V. Dynamic Security Criteria

A dynamic security criterion (9) was developed to ensure that the power system is able to regulate frequency sufficiently well to avoid emergency underfrequency load shedding. The criterion takes into account the advantage provided by being able to shed pumped storage pumping load before customer loads are affected. This criterion was developed by using the steady-state step response of the diesel unit speed governors to approximate the maximum frequency deviation caused by changes in the active power balance. The criterion seeks to keep the maximum frequency deviation, Δf, below a specified threshold.

The expression used to estimate the maximum frequency deviation is the following:

$$\frac{\Delta f}{f_{\text{base}}} = a \cdot r \cdot \frac{\Delta P}{P_{\text{base}}}. \tag{13}$$

In this equation, r and P_{base} are the droop and per-unit power base of the single-machine equivalent generator. If r is the same for all machines participating in frequency regulation, then P_{base} may be chosen to be simply the sum of the per-unit power bases of all the participating generators. The factor a (< 1.0) serves to account for the effect of load damping and for the integral gain loop in the generator governors' response. This value can be obtained experimentally, by observing the typical frequency behavior for system under study with and without integral control loop in the governors.

With this definition, the equation may be rearranged to give a security criterion as follows:

$$P_{\text{base}} > \frac{f_{\text{base}}}{\Delta f_{\max}} \cdot a \cdot r \cdot (\Delta P_{\max} - P_{\text{shed}}) + P_{\text{genlost}} \tag{14}$$

where $\Delta P_{\max}$ is the maximum active power imbalance that is expected, generally the loss of the largest generating unit or the loss of part of the wind generation, P_{shed} is the load that can be shed quickly, for this problem, this is the pumped storage pumping load, and P_{genlost} is the amount of generating capacity that is lost in causing the power imbalance.

Since the diesel generating units have technical minimums below which they are not operated, the above criterion also results in a lower limit on the thermal generation production as constrained by this security criterion. This is the constraint that appears in (9) and defines a dynamic security restriction for the problem.

VI. Case Study

A test system was created based upon a real island system. The test system has a peak system load of about 180 MW and off-peak load of about 80 MW. Energy is supplied by a combined wind-hydro-thermal system that includes several wind parks totalling 60 MW of capacity, significant hydropower generation, totaling 50 MW of capacity, and two thermal generating stations with a total generating capacity of 220 MW. Although it

TABLE I
THERMAL GENERATING UNITS

Number of Units	Capacity (MW)	Approx. Fuel Consumption (kg/kWh)
2	6.0	0.215
1	5.0	0.215
3	6.9	0.215
4	9.4	0.215
1	13.0	0.215
1	4.0	0.215
8	10.1	0.273
3	16.5	0.273

may appear that the reserve capacity of the system is quite high, the capacity factor of the wind and hydropower units is not large, and it would be economically advantageous to no longer use the old, inefficient thermal generators, decommissioning them or using them only in emergencies. Table I lists the thermal generation units available in the test system and their approximate fuel consumption rates.

Of the generators connected in the test system, only the diesel-fueled generating sets and and one hydro station are capable of frequency regulation. Almost all of the hydropower stations are run-of-the-river and do not have the ability to adjust their output in response to system needs. A significant amount of wind power is also installed. This means that a sizeable block of power does not provide frequency regulation.

During off-peak hours the power provided by wind parks and hydro stations may at times be a large portion of the total power demand of the system. This leaves only a small amount to be carried by the diesel generating units. From an economic point of view this is good since it means that fuel is not being used to provide energy, but from the perspective of frequency regulation it becomes difficult since it means that a relatively small number units are responsible for regulating frequency for the entire island. A small number of units means low rotating inertia, little spinning reserve, and weak response to frequency deviations. Additional details about the test system used may be found in [7].

A. Determining Values for Parameters

The formulation of the optimization problem as described above includes several parameters that must be defined.

Approximate costs for installing pumped storage can be found in [13] and [9]. These reference costs have been converted to Euros to give the $C_{E_{\max}} = 13776\ \mathrm{EUR/MWh}$ and $C_{P_{\max}} = 377200\ \mathrm{EUR/MW}$.

The constant a is an annualization factor. This takes into account the time value of money and converts the one-time installation cost to a stream of daily costs. The value can be found by choosing a time period over which the installation cost will be spread out and the interest rate to be used and then applying the appropriate engineering economics formula to equate a present value P to a series of future cash flows A. A 30-year life with an annual discount rate of 5% is used, consistent with [13]. This results in $a = 0.000174$.

The constants η_p and η_g are the efficiencies of pumping and generating, respectively. These are each given values of 0.9. This gives a round-trip efficiency of 0.8, which is in the usual range for pumped storage facilities [9], [10], [13].

TABLE II
COST OF THERMAL GENERATION

n	Power (MW)	Marginal Cost (EUR/MWh)
1	60	87.0
2	30	88.0
3	10	111.0
4	10	111.2
5	10	111.4
6	5	111.6
7	5	111.8
8	5	112.0
9	5	112.2
10	5	112.4
11	5	112.6
12	5	112.8
13	80	113.0

The value for $\mathrm{UnitSize}$ is the capacity of the first diesel units to be committed. For the test system, this is 16.5 MW. $\mathrm{TechMin}$ is the per-unit technical minimum of these machines and is chosen to be 0.7. The test system operator does not operate below this point because efficiency of the diesel generating set decreases quickly at lower operating points.

The constant $\mathrm{RegFactor}$ must be evaluated based on the frequency regulation characteristics of the test system and the security requirements being used. From dynamic analysis presented in [7] $\mathrm{RegFactor}$ should be 5.1.

The sections of the thermal power cost function are shown in Table II. The diesel units of the test system are divided into two groups: new units and old units. The approximate fuel consumption of the newer generating sets is 0.215 kg/kWh while the approximate consumption of the older units is approximately 0.273 kg/kWh. The fuel price is estimated at 70 USD/barrel or 0.41 EUR/kg. This is consistent with current prices, including cost of shipment.

The constant n is the number of number of time periods over which to optimize each scenario. A daily cycle composed of 24 one-hour periods is chosen, so $n = 24$ and $t = 1$.

VII. RESULTS

A. Scenario Generation

The number of scenarios to use was determined by doing fuzzy clustering analysis using various numbers of clusters ranging from two to twenty and calculating the validation indices for each of the resulting sets of clusters. No number of clusters was clearly superior to the others, but there was some weak support for the use of thirteen or eighteen clusters, so thirteen was chosen as the number of scenarios to use.

Curves of the 13 hourly net load series are shown in Fig. 2 with their respective probabilities shown in Table III. These are the scenarios that were used in the various sub-problems to determine system operation costs for a range of loading and renewable production conditions. In order to illustrate how the daily net load curves in the data set were assigned to the clusters, the prototype for Scenario 1 is shown in Fig. 3 with the daily net load curves that were more strongly associated with that cluster than with any other. Results showed that the prototypes produced by applying fuzzy clustering techniques were

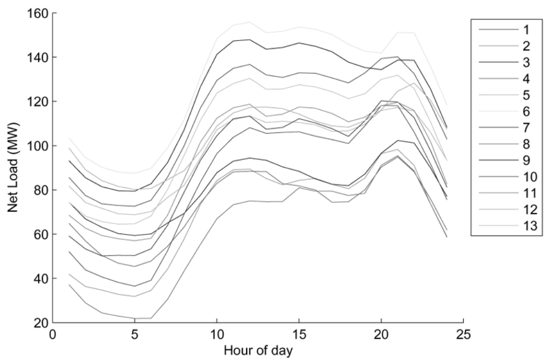

Fig. 2. Clustering results: net load scenarios.

TABLE III
SCENARIO PROBABILITIES

n	Probability
1	0.107
2	0.049
3	0.070
4	0.060
5	0.083
6	0.083
7	0.080
8	0.031
9	0.110
10	0.058
11	0.092
12	0.076
13	0.102

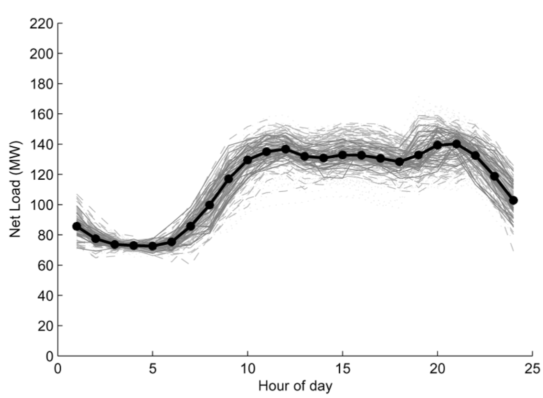

Fig. 3. Clustering results: Cluster 1.

able to represent well the shape and level of the daily curves that were assigned to them.

B. Optimization Results

The FlopC++ libraries [14], [15] were used with the CLP solver from the COIN project to build a C++ program using modeling language syntax that solves this linear-programming problem. The problem results in 5944 variables and 10 934 constraints with 32 165 nonzero elements. On a computer with a CPU operating at 2.0 GHz, the optimal solution was arrived at in 1.2 s.

The primary solution results obtained from the solution of the optimization problem are the values for the capacity of the pumped storage station and the amount of energy that can be

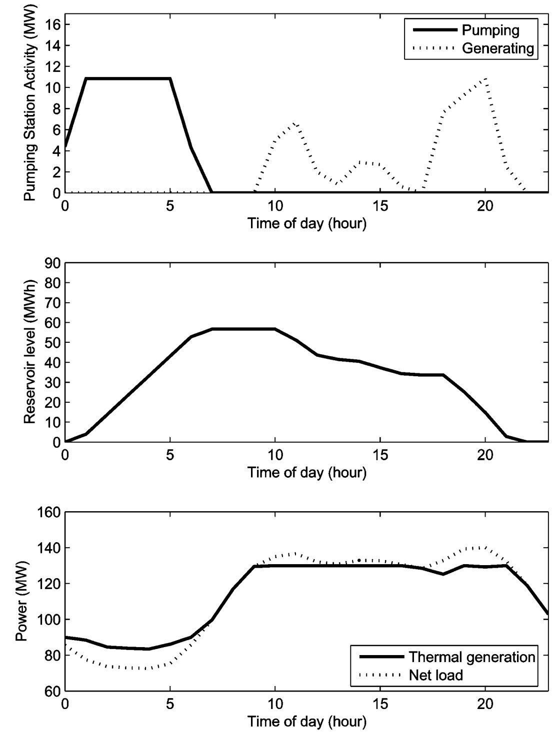

Fig. 4. Optimization results: Scenario 1.

stored. The optimal value for $P_{\max}$ was found to be 10.9 MW and the optimal value for $E_{\max}$ was found to be 80.2 MWh.

This gives a total project cost of 5.07 million EUR, which is divided as 3.96 million for the power capacity and 1.11 million for the reservoir storage capacity. Amortized over a 30-year equipment lifespan, this gives 881 EUR per day. The expected fuel cost savings from using the pumped storage plant is 1363 EUR per day, or 0.6% of the total fuel cost. The expected average daily curtailment of renewable generation is reduced from 25.8 MWh to 10.2 MWh.

As an illustrative example, consider Scenario 1, results shown in Fig. 4. During off-peak hours, the net load is below the cost breakpoint at 90 MW and the storage station operates at full pumping power. As the net load rises through the morning, the pumped storage station is switched off. When the load reaches the peak that is sustained throughout the day, the storage station enters into service in generating mode and shaves the peaks off of the net load giving thermal generation production that is nearly constant for a period of twelve hours. The daily peak is reduced by about 10 MW, the generating capacity of the pumped storage station.

C. Sensitivity Analysis

In order to see the effect that each problem parameter has on the results, a sensitivity analysis was performed. In this analysis, each parameter is changed by a small amount and the new optimum solution is compared to the original solution. The results of this analysis are shown in Table IV.

The optimization problem as also been solved with the spinning reserve security constraints removed, allowing all renewable generation available to be used. In this case, no pumped

TABLE IV
SENSITIVITY ANALYSIS RESULTS

Parameter	Value	Value Change (%)	P'_{max} (MW)	E'_{max} (MWh)	P_{max} Change (%)	E_{max} Change (%)
Reference	—	-	**10.9**	**80.2**	-	-
$C_{E_{max}}$ (EUR/MWh)	12398	-10.	10.9	80.2	0.0	0.0
$C_{E_{max}}$ (EUR/MWh)	15154	+10.	10.4	77.0	-4.6	-4.0
$C_{P_{max}}$ (EUR/MW)	339480	-10.	12.4	91.0	+13.8	+13.5
$C_{P_{max}}$ (EUR/MW)	414920	+10.	9.8	72.7	-10.1	-9.4
$\eta_p \cdot \eta_g$	0.72	-10.	7.5	44.5	-35.2	-45.5
$\eta_p \cdot \eta_g$	0.88	+10.	12.4	88.2	+13.8	+10.0
$UnitSize$ (MW)	14.9	-10.	6.8	48.6	-37.6	-39.4
$UnitSize$ (MW)	18.1	+10.	13.1	91.8	+20.2	+14.5
$TechMin$ (pu)	0.63	-10.	0.5	3.4	-95.4	-95.7
$TechMin$ (pu)	0.77	+10.	21.1	136.3	+93.6	+70.0
$RegFactor$	4.6	-10.	10.9	80.2	0.0	0.0
$RegFactor$	5.6	+10.	10.0	71.3	-8.3	-11.1
Fuel Price (USD/barrel)	63	-10.	8.1	60.4	-25.6	-24.7
Fuel Price (USD/barrel)	77	+10.	12.4	91.0	+13.8	+13.5

storage is indicated to be installed at all. It is clear that it is the security constraints that make the installation of the pumped storage unit economically viable. The strong dependence of the security constraints on the size of the largest thermal unit and the technical minimums of the diesel generators is reflected in the large changes that occur in the optimal sizing of the pumped storage when changes are made to these parameters.

VIII. CONCLUSIONS

In this work, dynamic security criteria have been included in an optimization problem that is able to determine both the power capacity and the best reservoir capacity for a potential pumped storage station in an island system. Fuzzy clustering techniques have been used to deal with the stochastic nature of load and renewable production and produce scenarios for the optimization problem.

Results showed that including pumped storage can be an effective means of allowing larger penetration of intermittent renewable energy sources, improving both the dynamic security and the economic operation of a test system. Including the dynamic security criteria in the economic question of dimensioning the pumped storage unit proved to make a significant difference in the optimal pumped storage capacity.

The sensitivity analysis of the results of the optimization showed that the security criteria are what primarily provide the economic incentive for the installation of pumped storage in the test system. Since the dynamic security issues are of primary importance, it may be worthwhile to consider the use of another storage technology to better meet the reserve needs. The shedding of pumped storage load is able to limit large frequency excursions, however, it is not a substitute for spinning reserve, and the use of renewable generation continues to be limited by the dynamic security constraints. A technology that is able to provide full spinning reserve and frequency regulation services could be a very good option. Some storage technologies that have already been used in this type of application include lead-acid or nickel-cadmium batteries [16], [17] and flow batteries [18].

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