Feasibility Study of Operating An Autonomous Power System in Presence of Wind Turbines

A Practical Experience in Manjil, Iran

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***Abstract*—Commonly facing some irregular situations such as natural disasters and experiencing power interruptions as a consequence, the power grid in Manjil located in the north of Iran needs to be capable of power delivery to its local load points in an isolated manner. This paper aims to study the feasibility of this situation once local wind turbines are used as the power generation facilities. The imbalances of power supply and demand due to the high variation of wind power is overcome in this paper via employing and comparing two hydro-wind and diesel-wind power systems which are comprised of energy storage systems. This paper also investigates the balance feasibility of power supply and demand once the system is isolated from the whole power grid and offers an approach to identify the size and type of energy storages in this respect. The proposed method is proved to be an economic approach and results in an acceptable level of system reliability.**

Keywords-component; Isolated Microgrids; wind power; energy storage; power balance.

I. Introduction

Isolating a part of power system is reported as one of the most challenging problems in power system planning and operation once dealing with a catastrophic natural disaster [1]. This issue would be more challenging when wind power has to lend the power system operator a hand in providing the requested demands with sufficient power. The reason lies in the intermittency and variability of wind power once considered as a means of power generation [2]. Hence, major efforts have been so far concentrated on the isolated micro grids and their planning and operation in presence of renewable sources of energy.

Isolating a part of power system can have significant influences in the reliability of the customers, as reported in [3]. Wind power penetration in power systems has seen an enormous research in the recent two decades to bring itself as a promising source of local power generation in small and medium-size isolated micro grids. Such power systems often use the diesel generators as a complementary to the employed wind farms [4]. As a result, these systems are usually called diesel-wind power systems.

If the hydro-wind power generators are employed in addition to the conventional diesel generators, the result would be named a hybrid hydro-wind power generator.

An autonomous power system with a high level of wind power is always facing an important question whether it can satisfy the balance of power generation and demand or not. The isolated hybrid power systems could guarantee the long-term power balance of supply and demand via the complementary units of wind power. In response to the fluctuations in the produced power of wind turbines, reference [4] proposes a scheme for the utilization of energy storage systems.

This paper is founded based on the energy storage systems to implement a practical isolated micro grid in Manjil, Iran.

This paper aims to offer a feasibility study to put into practice an autonomous power system in Manjil once facing some critical conditions. It also strives in finding the optimal sizes of hybrid wind-diesel and hydro-wind energy storage systems. The paper finally provides a thorough economical and technical comparison of these two types of energy storage systems and investigates their applicability and effectiveness in the system operation. In this respect, the obtained results and guidelines not only would be of great assistance when planning the Manjil power system as an isolated micro grid, but also gives conductive policy guides to the all power system decision makers around the world .

The rest of the paper is organized as follows. Section II deals with the system introduction and tries in order to model its components. The type identification and sizing design of system components are conducted in Section III, wherein the proposed methodology in this paper is offered. The Manjil isolated power system is introduced in Section IV, the procedures are remarked, and finally the conclusion is outlined in Section V.

II. System Introduction and the Modeling Procedure

Numerical analysis is one of the most important tasks in the design, evaluation, and implementation process of isolated power systems. However, no numerical model can effectively and comprehensively cover all the operational

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features. The following characteristics need to be evaluated and taken into consideration in the modeling procedure.

- ***Simulation Purposes***

In this project, the goal was to supply the required demand of the Manjil power system once experiencing a blackout. Due to the fact that the occurred blackout in some critical situations can longer up to several months, the simulation period is therefore considered to be several months. Also worth mentioning is that the simulation time steps are supposed to be in one hour.

- ***Modeling Strategy (Deterministic/Probabilistic)***

The stochastic behavior of the wind power and the produced output power of wind turbines in one hand, and the existent uncertainties on the other hand leads to the fact that both the deterministic (on the basis of the wind speed and load demand time series) and probabilistic (on the basis of Monte Carlo Simulations) models can be applied to evaluate the Manjil Power system after isolating from the whole grid.

- ***Technical and Economic Scenarios***

Each scenario in the modeling process includes a set of power generation sources (hydro, diesel, and so on) with a certain size and one type of energy storage system (battery, flywheel, hydrogen storage system, and so on) with a certain size. Each scenario is economically attributed a certain amount of cost and is technically assigned a reliability index after being implemented, such as expected energy not supplied (*EENS*) per year.

Modeling the output power of each wind turbine is conducted in two steps. The first step deals with the wind speed modeling and the second one incorporates the output power estimation of the wind turbine via the associated power-speed characteristic curve. Some other methods are also available for the wind speed modeling. In [5]-[7], time series are employed in this respect. Its main superiority has been proved to be its capability in considering the correlation of wind speed in successive hours. However, a main shortcoming is assigned to this method, i.e., its accuracy is dependent to the system- under scrutiny and the local wind trend. This means that this method can find the accurate wind trend solely in some points. Both deterministic and probabilistic methods can be applied in the cases of load modeling. In this paper, the hourly load is created through the Monte Carlo Simulation approach and the required data is borrowed from that of Manjil load. In [8], [9], the main effective factors on the electrical energy consumption which have to be investigated in the load modeling procedure are presented in detail.

Diesel generators are employed here in order to compensate for the wind turbines' output power fluctuations. Diesel generators are located where the coal and water are exceedingly rare, or where the power production needs to be low such as for the cases of emergencies, or somewhere the stand-by components are necessary. Among the main superiorities of this type of generators are their simple designs, easy installations, faster starting, the requirement to a smaller fuel storage compared to that of other generators, and the lower need to the inspection and maintenance considerations. Moreover, these diesel generators are capable of responding to any load shifting with no further problem [9]. Amongst the main disadvantages assigned to diesel generators are high maintenance and operation costs, high noise makings, and that due to some technical and economic limitations, they cannot be manufactured in larger sizes. Also note that the efficiency assigned to these generator types are usually assumed to be within the range of 30 to 43 percent [10].

With the decrease in the output power of the diesel generator, its fuel consumption would be linearly decreased. However, the consumption cannot be equal to zero even in the zero load level. Fig. 1 presents the relationship between the fuel consumption as a percentage of the maximum fuel consumption rate and the special fuel consumption in liter/kWh. This relationship is regarded as a function of the produced power in the percentage of the maximum load.

Eq. (1) introduces the fuel consumption rate in terms of the produced power in accordance with Fig. 3.

$$Fuel(i) = P_d.fcr.(0.3 + 0.7 \times \frac{P_d(i)}{P_d}) \qquad (1)$$

where, $Fuel(i)$ is the consumed fuel in the i^{th} time interval in m^3, fcr is the fuel consumption rate at the maximum power in m^3/kWh, and $P_d(i)$ is the consumed power of the diesel generator in the i^{th} time interval.

The other technology introduced here to compensate the imminent output power fluctuations of wind farms is the hydro power generators. According to [9], the hydro power generators are assigned some major superiority in comparison with that of the others. Amongst are their high reliability, well response to the fast variations of the loads and higher efficiency. As a result, these sources of electrical energy can be quite appropriate for the cases of isolated micro grids. The costs associated with the hydro power generators are deeply dependent to the site conditions. According to [11], about 75% of the investment costs are within the range of 1200 to 6000 $ per kW of installed capacity. The variable cost of hydro power generators are negligible compared with that of fixed [11].

Another important issue in the installment process of a new hydro power generator is the volumetric flow rate of input water at different times. In so doing, a long-term investigation would be needed to identify the flow rate of the river water in terms of m^3 per second. Once these flow rates on the basis of different time intervals are available, the hydrograph curves would be obtained. The cumulative integral of the flow in time, which is called the mass curve, is also an important issue once designing a hydro power generator. The other expression which seems to be important is the *run-off* or *stream flow*. This is obtained through the subtraction of the evaporation rate from that of raining [9].

The produced power of a hydro power generator with a water flow rate can be obtained through (2).

$$P = w.Q.H.\eta_t.\eta_g \qquad (2)$$

in which, P denotes the output power (W), W is the special weight of water (N/m^2), Q denotes the water flow rate (m^3/s), H is the flow height (head)(m), η_t is the turbine efficiency, and η_g is the generator's efficiency.

In this paper, the simulations are performed to investigate the demand and supply balance in the isolated power grid of

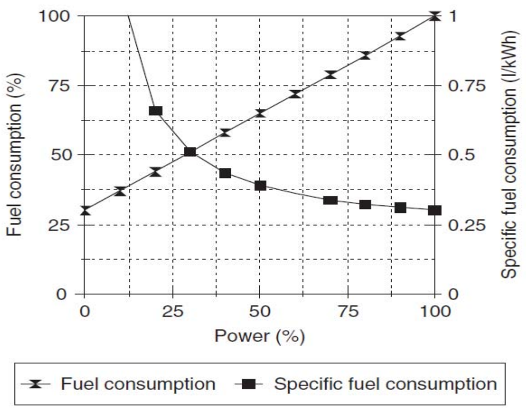

Figure 1. The fuel consumption of conventional diesel generators in terms of output power [4].

Manjil. The output power of the associated hydro power generators is also modeled on the same basis. If the demand at time *t* is $P_d(t)$ and the output power of the hydro units at time *t* is $P_h(t)$, the hydro generators output can be obtained through (3).

$$P_h(t)=\begin{cases} P_{h,\max} & P_{h,\max}<P_d(t) \quad R_{\min}<R(t) \\ P_d(t) & P_d(t)<P_{h,\max} \quad R_{\min}<R(t) \\ P_{h,\min} & P_d(t)<P_{h,\min} \quad R_{\min}<R(t) \\ 0 & R(t)<R_{\min} \end{cases} \tag{3}$$

where $P_{h,\max}$ and $P_{h,min}$ are respectively the maximum and minimum possible output power of hydro power generators, $R(t)$ is the reserved water available at the dams at time *t*, and R_{min} is the minimum required reserve water to produce the electrical power.

As can be seen in (3), the hydro power generator can always produce the required power except when there is not enough water at the dams to provide the required power. The reason lies in the fact that it prevents the increase in wind penetration level in the micro grid by then. This, on the other hand, leads to some system stability and power quality problems.

In addition to the hydro unit modeling procedure, the reservoir and the water at the dams should also be modeled. In order to model the reservoir, it requires the amount of water at that time to be definite. The entrance rate to the reservoir is equal to the *run-off* and the departure rate of the water can be obtained through (2) and accounted as a function of produced electrical power of the hydro electric unit. In [12], some constraints associated with the planning and operation of hydro power units are introduced of which are the electrical power balance, water flow, de-charging of the units and the reservoir constraints. Reference [13] has introduced four important constraints which are as follows: the dynamic balance equation of water, the reservoir storage volume equation, the production constraints of a hydro power generator, and the de-charging constraints of this hydro unit.

Having obtained the output power of a hydro power generator in each hour, the departure rate of water from the reservoir, $f_0(t)$, can be calculated via (2) as in the following.

$$f_0(t)=P_h(t)/(w.Q.H.\eta_t.\eta_g) \tag{4}$$

The dynamic balance equation of water can be addressed as in (5).

$$R(t+1)=R(t)+f_1(t)-f_0(t) \tag{5}$$

In which $f_i(t)$ is the net entrance rate of water into the reservoir or the run-of which is a resultant of both the raining rate and evaporation rate.

The energy storage system is the last part which has to be introduced here and also needs to be modeled. In [14], three applications are addressed for the energy storage systems to be adopted together with the distributed generations. The first two applications are associated with the power systems isolated from the main grid and aim to: 1) maintain the system stability in such a way that system stability would be still guaranteed even with load growth and variations; 2) providing the required energy once the distributed generations cannot be available or implementable. For instance, when the maintenance of the distributed generations are done or when at nights once using the photovoltaic systems or when there is no wind once the wind energy is penetrated and in practice; 3) allowing the distributed generating units which are non-dispatchable to operate as the dispatchable sources of power generation.

Among the main features of a battery or any energy storage system, power density, energy density, electricity efficiency, useful lifetime, costs, re-charging rate, control system, physical volume and so on are introduced in [14] which are all among the most important parameters of the energy storage system design and control. In this paper, a general scheme is proposed for the energy storage systems which are able to use and extend different energy storage technologies. As a result, for an energy storage system, a typical power rate and a sample charging and de-charging time is considered. The size of energy storage system can be found by a simple multiplication of the aforementioned parameters. The nominal power of the energy storage systems when charging or de-charging can be accounted different or as the same. Also worth noting is that the charging and de-charging efficiency, as the other variables considered for the energy storage system modeling, can be also accounted different or as the same. The bilateral efficiency (η) can be calculated through the multiplication of the charging efficiency (η_c) and the de-charging efficiency (η_d). In this study, and in order to simplify the modeling process, both the nominal power and the efficiency of the storage system are accounted the same.

III. Designing the Size of Various System Elements

Sizing design of the generation equipments and energy storages in the micro grid electric system of Manjil is a decision making problem whose goal is to find the optimal solution. These studies necessitate some technical and economic evaluations of the possible solutions. One of the most suitable techniques in dealing with the comparisons among the available alternatives in finding the size of system equipments is the simulation approach [14]. According to [14], the superiority of the simulation approaches in such studies is the amount of details which if put in use in the other techniques, can make them very difficult to handle or impossible to solve. Especially once facing the multi-objective decision making problems in designing the storage systems, simulating each alternative and finding the optimal solution by means of searching the possible alternatives is the best approach. If the number of alternatives or all the possible solutions is finite, it is rather possible to simulate all of them and will lead to finding the optimal solution. However, if the number of decision variables gets larger, the solution range would be so extended that analyzing all of them would be too time consuming. In such circumstances, employing the heuristic search methods to search all the solution territory can be of great assistance. One of the commonest ones is the genetic algorithm which is able to search the solution territory in a multi-objective manner.

Different goals can be pursued once designing the isolated micro grids; however, the planners commonly concentrate on two of the most important ones, i.e., the economic costs and system reliability. Moreover, the decision variables can also be various. In this project, the variables are the number of wind turbines, sizes of water pools or fuel reservoir, sizes of diesel generators or hydro power generators. The steps going to be followed in order to conduct an initial size determination of the system elements can be as follows.

a) Selecting an initial generation for the decision variables (initial values for each size of the system elements)

b) Simulating the performance and operation of the designed electric micro grid in each generation and with the defined decision variables and also calculating the suitability criteria of the solutions incorporating the economic costs and interruption costs (if a given sized design alternative lead to a power interruption in the simulation period, the above design would be inappropriate)

c) Investigating the termination criteria if the required criteria and thresholds have been satisfied. Then the optimal point has to be identified in which no loss of load would occur and the economic costs are the minimum rates.

d) Smart selection of the next solution generation in accordance with the genetic algorithm and then returning step b.

In order to behave as a constraint in the solution territory, it is rather necessary to define an upper and lower limit for the size of each element. The algorithm termination criteria include a combination of the maximum number of generations, time constraints, and variation rate of the solutions associated with the two successive generation.

Due to the main aim of this study, the operation and performance investigation of the Manjil isolated micro grid and also feasibility study of the balance between the electric energy supply and demand in presence of long term unavoidable and unpredictable happenings, the simulation periods are assumed to be several months and with the time steps of one hour.

Manjil power system would be operated separately and in an isolated manner only if the natural disasters or unpredictable events with undefined or unknown time of occurrence or their probability distribution functions take place. Because such events may occur after several years, their operation costs are assumed to be negligible. So, in order to economically evaluate the alternative design of system elements, investment costs are used instead of the life cycle costs. The system reliability criterion can be the expected energy not supplied (*EENS*) or system hours (the energy not supplied in terms of system peak hours in a year). After simulating each design alternative, if the load interruptions occur, the lower limit of suitability in reliability point of view should be assigned to the associated alternative. If no power interruptions have been reported in the simulation process of the size identification in each design alternative, the associated solution would be the most appropriate from the system reliability viewpoint. The second suitability criterion is assumed to be the investment costs whose minimization is the aim of this algorithm.

Due to the various wind flowing patterns in various seasons of a year, 12 scenarios are assumed with respect to the wind flowing patterns and the multi-month time period starts from each month and as a result, 12 simulations are conducted for each possible design alternative. The reliability index would be eventually obtained with the mean value of all the reliability indices in these studies.

IV. The Isolated Power System in Manjil

In this Section, the proposed method is applied in dealing with the size identification of the elements of an isolated micro grid in Manjil. Employing a designed and implemented small hydro power generator on the SEFID ROOD river is regarded as the first alternative and using a diesel generator is considered as the second alternative in addition to the available wind turbines and energy storage systems at Manjil to operate an isolated micro grid there.

In the time being, some small hydro power generators are located on the SEFIDROOD river. Also a positive idea can also be traced among the system planners to its expansions in such a way that for instance in Gilan Province, 12 projects with the total capacity of 26 MW are conducted in the study phase. Amongst, it can be exampled as the DARK dam in vicinity of Roodbar City. The data associated with this project is presented in Table I which is borrowed in the case of the reservoirs or the pools of the employed hybrid power units.

The problem variables which are obtained through the optimization problem are the generator size (P_h) and the variables associated with the energy storage systems including P_{ess} and E_{ess}.

The number and size of wind turbines are assumed constant equal to two 770 KW Vestas generator turbines. The daily load is considered in accordance with the consumed power of Manjil City at 2009. It is also assumed that if any isolation of Manjil occurs in response to a natural disaster or unpredictable phenomenon, it is only required to provide the 35 percentage of the whole city loads which are deemed to be the critical ones.

The simulation time period which is also accounted as the isolation period is assumed to be 100 days.

The investment costs of the energy storage systems are comprised of two parts: the first is a function of system power rate and the other is a function of system energy rate. In contrary, the investment cost of hydro power generators is only the function of its installed capacity in MW. The investment cost of the diesel units are also a function of their installed capacities, and the investment cost of the fuel reservoirs are functions of fuel volume in m^3. As a result, it

TABLE I. THE ASSUMED DATA OF DARK DAM

Reservoir Volume	5 million m^3
Flowing Altitude	8.5 meter
Flow Rate of each Unit	19 m^3/s
Installed Capacity	2.8 MW
Turbine Type	kaplan
Number of Units	2
Generator Capacity	1.8 MVA
Generator Output Voltage	6.3 kV

is stated that the required investment cost associated with an energy storage system, hydro generator, and diesel generator can be obtained through (6)-(8).

$$C_{ess} = P_{ess} \times PRC + E_{ess} \times ERC \quad (6)$$

$$C_h = P_h \times HC \quad (7)$$

$$C_d = P_d \times DC + V_d \times RC \quad (8)$$

In which, *PRC* is the costs associated with the power of energy storage system in \$/kW, *ERC* is the costs associated with the energy of the energy storage system in \$/kWh, *HC* is the costs associated with the hydro power generator in \$/kW, *DC* is the costs associated with the diesel power generator in \$/kW, *RC* is the fuel reservoir costs in \$/m^3, and V_d is the reservoir volume in m^3. The assumed values for the aforementioned parameters are as presented in Table II.

TABLE II. PARAMETER VALUES USED IN THE STUDIES

HC	1000 $
PRC	225 $/kW
ERC	150 $/kWh
DC	800 $/kW
RC	500 $/m^3

The last assumption done in this paper is the minimum power limits for the hydro power generators and diesel generators. The maximum power of the hydro power generator is then obtained as a decision variable in the system design through the optimization process. However, the minimum power of such units can be regarded and designed as a semi-independent quantity. But in reality, it is a common trend that a fraction of the maximum power is attributed to this value and in many cases it is assumed within the range of a half to one third of the maximum power. In this paper, it is assumed that the minimum power of a hydro power generator is one third of its maximum power. In the cases of the diesel power generators, the generators with the minimum power of zero can be used.

Running the optimization problem via the genetic algorithm, the selected points are as below:

For hydroelectric unit:

- Power rating of storage system= 141 kW
- Power rating of hydroelectric= 1751 kW
- Investment cost= 1866800 $

For diesel unit:

- Power rating of storage system= 164 kW
- Power rating of diesel= 1749 kW
- Investment cost= 1858900 $
- Tank volume= 649 cubic meters

As it can be seen, with the assumed input data, the cost of using the diesel unit is a little lower than that of the hydro unit. Also, with a decrease in the possible duration time of isolation from the whole grid, which is assumed to be 100 days in this study, the costs associated with the wind-diesel system would decrease in response to the decrease in the required fuel reservoir volume. In contrast, with the increase of the isolation time, the costs of the wind-hydro system will increase. Table III presents a sensitivity analysis on the investment costs with respect to the variations of the possible isolation duration times. It should be noted that this negligent difference in the investment costs of these two technologies can be disregarded. The reason lies in the fact that there are major uncertainties in the input parameters and meanwhile, the optimization result gained from the genetic algorithm are assigned some stochastic degrees.

TABLE III. ELEMENTS' SIZE SENSITIVITY WITH RESPECT TO THE VARIATIONS IN THE ISOLATION TIME FROM THE WHOLE GRID

The investment costs of wind/hydro units (1000 $)	The investment costs of wind/diesel units(1000 $)	The possible isolation time from the whole grid (days)
1877	1618	25
1876	1708	50
1875	1756	75
1869	1859	100
1878	1937	125
1889	1982	150
1903	2068	175
1982	2146	200

The wind-diesel system is assigned superiority when compared to the wind-hydro systems. It is not only technologically more efficient, but also has lower amount of uncertainties associated with its parameters. Once there are some uncertainties either in some parameters of the optimization problem or some assumptions in studies, the sensitivity of the optimal point with respect to the variations of these uncertain parameters have to be evaluated. The uncertainties are mainly incorporated in the parameters of hydro power generators on the river. The initial investigations demonstrate that the optimal solution is not sensitive to the initial volume of the hydro reservoir. The reason is because the reservoir size of the hydro power generators on the rivers are usually not too big (compared to those of larger dams) and all of the reservoir volume can be filled with the input water in a short time.

The other factor which is assigned a great amount of uncertainty in the isolation studies of Manjil power system is the input water flow rate to the reservoirs which is assumed a constant value in this study equal to 25 m^3/s. In Table IV, the sensitivity analysis is conducted on genetic solutions with respect to the input water flow rate to the reservoirs. According to this table, the optimal point is too sensitive to this parameter and as a result, its accurate determination is of great importance in system design. The reason is that in the power generators with small volume reservoirs, the hydro power production, which is dependent to the water existence, calls for an adequate and reliable amount of input water. The water flow rate is different in different times of a year and that is why considering it as a constant value is a kind of modeling simplification. However, the accurate design and evaluation studies can be conducted using the time series resulted from the hydrograph curves for the input water flowing into the reservoir.

Table IV demonstrates that if the input water rate of flow to the reservoir is lower than 20-21 m^3/s, it would not be feasible to implement a hybrid wind-hydro system. The differences of the optimization results for the flow rate of more than 21 m^3/s is negligible and are mainly due to the stochastic nature of heuristic genetic algorithm.

TABLE IV. ELEMENTS' SIZE SENSITIVITY WITH RESPECT TO THE VARIATIONS IN THE INPUT WATER RATE OF FLOW TO THE RESERVOIR

Hydro Power Rating (kW)	Battery Power Rating (kW)	Investment Costs (1000 $)	System Hours Index of Reliability	Flow Rate of the Input Water (m^3/s)
1751	141	1867	0	**21>**
1649	1979	3282	5.3	**20**
1255	1986	2893	318	**15**
838	1816	2337	1043	**10**
445	1938	2044	1899	**5**

In short, it can be concluded that once deciding about the distributed generation technology among the hydro and diesel power generators, two important criteria, i.e., input water rate of flow to the hydro reservoir and the isolation time from the whole grid (duration of being operated in an isolated manner) need to be put under vast focuses; because the design sensitivity to the uncertainties associated with these two parameters are more influential than the other effective parameters.

The more the isolation duration, and the more the accessibility to the river water, the more technically and economically suitable means of distributed power generation would be the hydro power generators to be in company with the wind turbines. In contrast, once the accessibility to the river water with an appropriate flow rate is limited or the isolation time is also short, the diesel power generators are the best alternatives.

V. CONCLUSION

In order to provide the required load of Manjil once facing some unpredictable phenomenon or natural disasters, it seems necessary to conduct a feasibility study with respect to the isolation and autonomous operation of the micro gird power system. Using the 660 kW wind turbines located at Manjil, this paper took some steps in designing a hydro power generator or diesel power generator as the generating systems and also designing an energy storage system as the system backups. The size identification of their constituent elements is the first step in the system design. This paper introduced an approach in the size optimization of the generating units and energy storage systems with the final goals of the interruption minimization and economic cost minimization on the basis of the simulation of the possible alternatives via genetic algorithm. Having employed the suggested approach on Manjil cases study, it was claimed that the optimization results are more sensitive to two parameters, i.e., the isolation time from the whole grid, and the water flow rate to the reservoir of hydro power generators. As a result, these two parameters are the most effective on the selection of diesel or hydro technology alternatives in addition to the existent wind turbines.

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