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Retrofit of a Resilient Hybrid Power System for a Remote Island

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A mathematical model is presented for the synthesis and retrofit of a resilient electricity network for a remote island. The current electricity network uses diesel fuel power plant as the main power source and will be supplemented with wind turbines in this study, where part or all of the electricity generated from the wind turbines is used to pump water into the upper reservoir for providing the smooth hydraulic electricity. The role of this pumped hydro storage (PHS) is to support the hybrid power system (HPS) and to smooth the unstable and uncontrollable renewable power sources. Based on the proposed superstructures for the hybrid power system, the hybrid power system retrofit problem is formulated as a mixed-integer linear program (MILP) with power losses during the allocation of power generated from power supplies to power loads or PHS. With the given collection of data for the island, the minimum electricity supply of the traditional power plant, the minimum numbers of renewable energy equipment, the minimum capacity required and the minimum power generation of PHS can be determined through a four-step optimisation approach. A practical case study is solved using historical data to illustrate the proposed approach.

1. Introduction

There are 98 thousands citizen living in the studied K Island, which is one of a small remote islands located near Taiwan. Since always, the electricity consumption has been provided by a diesel fuel power plant. However, traditional electric power production generated by fossil fuel is causing not only environmental pollution and global warming, but also the depletion of fossil fuel reserves, which is an issue that has been of concern in recent years. Rapid industrial development and population growth result in an enormous increase in global energy demand. Therefore, clean and sustainable energy technologies have been created for reducing dependence on fossil fuel resources.

As the fuel price has increased by almost four times during the past decade and the environmental pollution from burning fuel, the hybrid power system (HPS) is selected to assist in reducing the diesel consumption in K Island. The HPS is a combination of power sources for electricity generation and energy storage, which is applied to remote villages or islands, where power supply extension is not feasible or is uneconomical and the cost of fuel transportation is expensive (Nema, 2009). Recently, the power pinch analysis (PoPA) technique is proposed by Wan Alwi et al. (2012) to target and optimal power allocation for HPS during start up and normal operation. Mohammad Rozali et al. (2013) further modified the PoPA and developed the storage cascade table by taking possible power losses during electricity conversion and transformation into consideration. Most recently, Chen et al. (2013) and later Lee et al. (2014) presented a superstructure-based mathematical model for targeting and design of an HPS with power loss consideration. Ma et al. (2014, 2015) developed a mathematical model of the hybrid system and introduced operating principles to support the standalone micro-grid hybrid solar-wind system on a remote island. This study aims to design and retrofit the HPS of K Island base on a set of proposed superstructures and can be formulated as a mixed-integer linear program (MILP). Furthermore, the effect of power losses during the allocation of power among power sources, power loads and pumped hydro storage (PHS) is considered and all possible power allocation options in a typical HPS are proposed. The

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MILP model is then applied to retrofit the current power supply system in K Island to demonstrate the efficacy of the proposed model.

2. Problem statement

The problem studied in this paper focuses on the possibility to expand the installed renewable energy equipment and construct the PHS on K Island. Three power sources consist of wind power, solar power and diesel-fired power, but the supply of solar photovoltaic is so small that it can be ignored even though it is one of the power sources. Then, it is assumed that electricity is transmitted from two sources to demand, and the regulation of electricity is supported by an electricity storage system. Furthermore, PHS is considered as an electricity storage system for future use.

Given a set of power sources ($i \in \mathcal{I}$) consist of wind power ($i = w$) and diesel-fired power ($i = d$). The overall power demand is supplemented by the public grid, which can be regarded as the sum of wind power and diesel-fired power. A set of days ($n \in \mathcal{N}$) and a set of time intervals ($t \in \mathcal{T}$) are used to address available/operating times and differentiate between the peak demands and off-peak demands. The PHS is used to attenuate impact of intermittent behaviour and facilitate power allocation. It is assumed that the whole HPS operates with alternating current. Furthermore, the generated power from diesel power plant is consumed completely by demand loads. The excess wind supply is sent to be stored for later use, and the deficit electricity is complemented by hydraulic power of PHS. The objective is to determine the minimum diesel-fired power supply, minimum installation of wind turbine, minimum capacity required of reservoir and minimum power generation for PHS.

3. Superstructure and MILP Formulation

Figure 1 shows the proposed superstructure with key elements of a typical HPS. All feasible options for power allocation are considered, which consist of incorporate available time-dependent power sources such as wind turbine and diesel engine, power demand and pumped hydro storage unit. The mathematical model is formulated as follows.

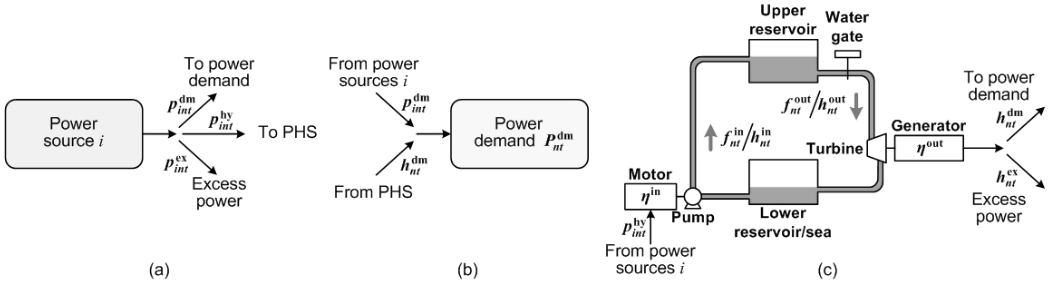


Figure 1: Schematics of key HPS elements: (a) power source, (b) power demand and (c) pumped hydro storage system.

For maximum use of renewable energy, the objective function is to minimize the total diesel-fired power consumption. Here, $\boldsymbol{x}_1$ is a vector of variables, and $\boldsymbol{\Omega}_1$ a feasible solution space defined by the constraints. Due to the use of binary variables, the formulated optimization problem is a mixed-integer linear program (MILP).

P1: $$\min_{\boldsymbol{x}_1 \in \boldsymbol{\Omega}_1} \phi_1 = \sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}_n} p_{int} \Big|_{i=d}$$

$$\boldsymbol{x}_1 \equiv \left\{ \begin{array}{l} p_{int}, p_{int}^{\mathrm{dm}}, p_{int}^{\mathrm{ex}}, p_{int}^{\mathrm{hy}}; h_{nt}^{\mathrm{dm}}, h_{nt}^{\mathrm{ex}}, h_{nt}^{\mathrm{in}}, h_{nt}^{\mathrm{out}}; q_{nt}; \\ f_{nt}^{\mathrm{aux}}, f_{nt}^{\mathrm{in}}, f_{n}^{\mathrm{out}}, f_{nt}^{\mathrm{out}}; Y_{nt}^{\mathrm{out}}, z_{nt}^{\mathrm{out}}, z_{nt}^{+}, z_{nt}^{-}; m_i \Big|_{i=w}; \\ \forall i \in \mathcal{I} = \{w, d\}, \forall t \in \mathcal{T}_n, n \in \mathcal{N} \end{array} \right\}$$

$$\mathbf{\Omega}_1 = \left\{ \boldsymbol{x}_1 \;\middle|\; \begin{array}{lll}
p_{int} = m_i \overline{P}_i \left(\dfrac{P_{int}^{\text{gen}}}{P_i^{\text{inst}}} \right) & i \in w, \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (1) \\
p_{int} \le \overline{P}_i & i = d, \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (2) \\
p_{int} = p_{int}^{\text{dm}} + p_{int}^{\text{hy}} + p_{int}^{\text{ex}} & \forall i \in \mathcal{I}, t \in \mathcal{T}_n, n \in \mathcal{N} & (3) \\
p_{int}^{\text{hy}} = p_{int}^{\text{ex}} = 0 & i = d, \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (4) \\
P_{nt}^{\text{dm}} = \sum_{i \in \mathcal{I}} p_{int}^{\text{dm}} + h_{nt}^{\text{dm}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (5) \\
h_{nt}^{\text{in}} = \eta^{\text{in}} p_{int}^{\text{hy}} \Big|_{i=w} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (6) \\
\eta^{\text{out}} h_{nt}^{\text{out}} = h_{nt}^{\text{dm}} + h_{nt}^{\text{ex}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (7) \\
z_{nt}^{\text{out}} \underline{H}^{\text{out}} \le h_{nt}^{\text{out}} \le z_{nt}^{\text{out}} \overline{H}^{\text{out}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (8) \\
f_{nt}^{\Psi} = 3.6 \times 10^6 \dfrac{h_{nt}^{\Psi}}{\rho \text{gH}} & \Psi \in \{\text{in}, \text{out}\}, \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (9) \\
q_{nt} = \left[q_{n-1,T_n-1} \Big|_{n>1,t=1} + q_{n,t-1} \Big|_{t>1} \right] (1 - \sigma \Delta_t) + \left(f_{nt}^{\text{in}} - f_{nt}^{\text{out}} \right) \Delta_t & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (10) \\
q_{nt} \le Q^{\text{cap}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (11) \\
f_{nt}^{\text{out}} \Delta_t \le q_{n-1,T_n-1} \Big|_{n>1,t=1} + q_{n,t-1} \Big|_{t>1} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (12) \\
f_{nt}^{\text{out}} \le f_n^{\text{out}} \le f_{nt}^{\text{out}} + f_{nt}^{\text{aux}} & \forall t \in \mathcal{T}_n^{\text{p}}, n \in \mathcal{N} & (13) \\
f_{nt}^{\text{aux}} \le \overline{F} \left(1 - z_{nt}^{\text{out}} \right) & \forall t \in \mathcal{T}_n^{\text{p}}, n \in \mathcal{N} & (14) \\
f_{nt}^{\text{out}} \le \overline{F} z_{nt}^{\text{out}} & \forall t \in \mathcal{T}_n^{\text{p}}, n \in \mathcal{N} & (15) \\
z_{nt}^{\text{out}} = 0 & \forall t \in \mathcal{T}_n^{\text{p}}, n \in \mathcal{N} & (16) \\
Y_{nt}^{\text{out}} = z_{nt}^{\text{out}} - z_{n,t-1}^{\text{out}} \Big|_{t>1} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (17) \\
\sum_{t \in \mathcal{T}_n} Y_{nt}^{\text{out}} = 0 & \forall n \in \mathcal{N} & (18) \\
z_{nt}^{+} - z_{nt}^{-} = Y_{nt}^{\text{out}} & \forall t \in \mathcal{T}_n^{\text{p}}, n \in \mathcal{N} & (19) \\
z_{nt}^{+} - z_{nt}^{-} \le 1 & \forall t \in \mathcal{T}_n^{\text{p}}, n \in \mathcal{N} & (20) \\
\sum_{t \in \mathcal{T}_n^{\text{p}}} z_{nt}^{+} \le 1 & \forall n \in \mathcal{N} & (21) \\
p_{int}^{\text{dm}} \Big|_{i=w} \le \alpha_1 P^{\text{off}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (22) \\
\sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}_n} p_{int} \Big|_{i=d} \ge (1 - \alpha_2) \sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}_n} P_{nt}^{\text{dm}} & & (23)
\end{array} \right\}$$

Eq(1) and (2) describe the constraints of rated power generation from wind turbine and diesel power plant within time interval t at specific day n, respectively. The rated power generation of wind turbine is a ratio of rated power generation from basic size. The maximum available rated power generation for diesel-fired power is limited by current capacities of the power plant. Eqs(3) and (5) are energy balances for power source i and a given lumped demand within time interval t at specific day n. Eq(4) is used to restrict the consumption of diesel-fired power. Eqs(6) and (7) are energy balances to portray the equivalent electricity accumulation and consumption for PHS within time interval t at specific day n, respectively, allowing for the pumping and generating efficiencies. Eq(8) represents the upper and lower limits for hydraulic power produced within time interval t at specific day n. Eq(9) is used to transform the effective power into the equivalent water flow rate. The overall energy balance for accumulated water in the upper reservoir is given by Eq(10). Depending on the capacity of reservoir, Eq(11) is imposed in the formulation. Eq(12) is a constraint to portray the maximum amount of water outlet for PHS during within time interval t at specific day n. Eq(13) expresses the quantitative outlet flow rate during peak time at specific day n. Eqs(14) and (16) are additional logical constraints for obtaining a value of outlet flow rate at specific day n. Eqs(17)-(21) are logical constraints to confirm that water gate could be turned on and off once a day at most. Eqs(22) and (23) express that two subjectively given α_1 and α_2 are used to restrict maximal allowable real-time supply and over-all supply from renewable energy.

Solution of problem **P1** gives the minimisation of electricity supplied by the diesel-fired power plant. Note that the number of wind turbines, m_i, has multiple solutions. Eq(24) is presented to an additional constraint for minimise the number of wind turbines. The subsequent MILP formulation, **P2**, is used to find the minimized number of wind turbines of HPS.

P2: $$\min_{\boldsymbol{x}_2\in\boldsymbol{\Omega}_2} \phi_2 = m_i\big|_{i=w}$$

$$\boldsymbol{x}_2 \equiv \boldsymbol{x}_1$$

$$\boldsymbol{\Omega}_2 = \left\{ \boldsymbol{x}_2 \left| \begin{array}{ll} \text{Equations}(1)-(23); & \\ \displaystyle\sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}_n} p_{int}\big|_{i=d} = \phi_1^* & (24) \end{array} \right. \right\}$$

As there would be degenerate solutions with the same minimum number of wind turbines, the third objective has to be imposed to obtain the preferred designs among the alternatives. Eq(25) is presented to supplement the constraint, Eq(11). In addition, the earlier determined solution of **P2** is regarded as another constraint, Eq(26).

The third MILP formulation, **P3**, is to minimise the upper reservoir capacity, in which case the upper reservoir capacity is treated as a variable to be optimized.

P3: $$\min_{\boldsymbol{x}_3\in\boldsymbol{\Omega}_3} \phi_3 = q^{\text{cap}}$$

$$\boldsymbol{x}_3 \equiv \boldsymbol{x}_2 \cup \left\{ q^{\text{cap}} \right\}$$

$$\boldsymbol{\Omega}_3 = \left\{ \boldsymbol{x}_3 \left| \begin{array}{lll} \text{Equations}(1)-(24); & & \\ q_{nt} \le q^{\text{cap}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (25) \\ m_i\big|_{i=w} = \phi_2^* & & (26) \end{array} \right. \right\}$$

Solution of **P3** gives the minimisation of upper reservoir capacity. In order to determine the minimum requirement of generator equipment, Eqs(27) and (28) are presented to supplement the model. Eq(27) is used to restrict the hydraulic power generation and then obtain the value of h^{out}. Eq(28) is a solution of **P3** imposed to a constraint.

With the additional restrictions, one can formulate the following **P4** to determine the minimum power production from generator of PHS.

P4: $$\min_{\boldsymbol{x}_4\in\boldsymbol{\Omega}_4} \phi_4 = h^{\text{out}}$$

$$\boldsymbol{x}_4 \equiv \boldsymbol{x}_3 \cup \left\{ h^{\text{out}} \right\}$$

$$\boldsymbol{\Omega}_4 = \left\{ \boldsymbol{x}_3 \left| \begin{array}{lll} \text{Equations}(1)-(26); & & \\ h_{nt}^{\text{out}} \le h^{\text{out}} & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (27) \\ q^{\text{cap}} = \phi_3^* & \forall t \in \mathcal{T}_n, n \in \mathcal{N} & (28) \end{array} \right. \right\}$$

4. Illustrative Example

A remote K Island is studied to demonstrate the application of the proposed MILP model. The model is implemented in the GAMS (Rosenthal, 2008) environment on a Core i7-4770K, 3.50 GHz processor with 4.00 GB RAM using solver CPLEX.

The HPS has two power sources, including wind power and diesel-fired power; it also has one power demand, which is historical data from 2010. Total annual electricity production of wind energy and conventional energy are 8.577 GWh and 245.737 GWh. Then, the annual electricity demand is assumed to 254.314 GWh. Figure 2 shows the corresponding chart for collection of data in 2010. The existing energy capacities for wind turbine and diesel power plant are 4 MW and 64 MW; the basic available size of wind turbine is 2 MW. In order to comply with the variation of electricity generation and consumption, 8760 time intervals (24 time intervals each day) are used for the HPS. The surplus power can pump the water to the upper reservoir for accumulating energy every time and the generator of PHS can produce hydraulic power during peak time period. In addition, the generator stops working during off-peak time period. The peak time period is from 7 A.M. to 10 P.M. In this case study, efficiencies of pump and generator are assumed to be 84 % without evaporation and leakage loss for PHS. Additionally, the total head of upper reservoir is 140 m, water density is 1,000 kg/m^3, and gravitational acceleration is 9.81 m/s^2.

In order to maintain the stability of the grid, direct wind-power share is lower than a particular value ($\alpha_1 P^{off}$). Moreover, a given ratio (α_2) is used to limit total wind-power share of overall demand. Four scenarios will be studied with different circumstances including $\alpha_1 = 0$ and $\alpha_2 = 0.2$ (scenario 1), $\alpha_1 = 0$ and $\alpha_2 = 0.4$ (scenario 2), $\alpha_1 = 0.2$ and $\alpha_2 = 0.2$ (scenario 3), $\alpha_1 = 0.2$ and $\alpha_2 = 0.4$ (scenario 4). With the increase of α_2, consumption of conventional energy is decreasing and demand of renewable energy is increasing, so that the HPS needs more wind turbines. More power can be transferred directly from renewable energy sources to demand for increasing α_1, which is causing the numbers of wind turbine to decrease. Solving the MILP model gives the optimal power supply as shown in Figure 3, which conforms to the situation previously described. Notice that the accumulation of water in the upper reservoir is larger during the last three months of the year. The high wind season makes more power production of wind turbines and a glut of wind power is stored in PHS when needed, which can be seen from comparison between Figures 4(a) and 4(b). The optimization results for all scenarios are summarized in Table 1. Different circumstances are examined in sequence.

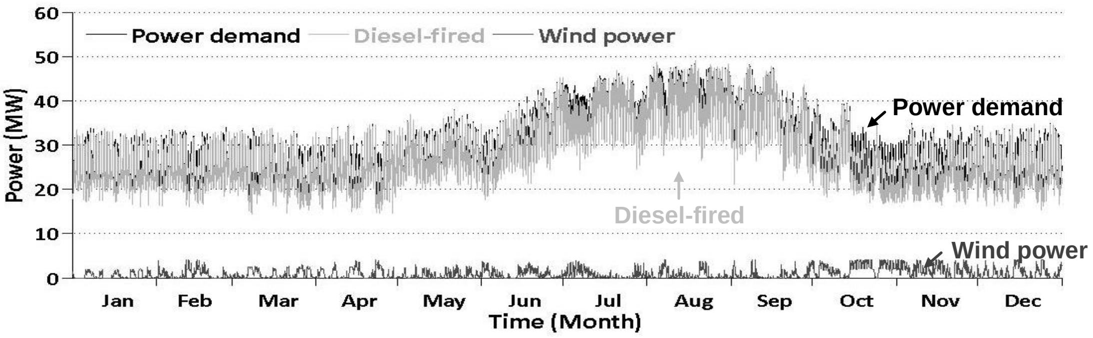


Figure 2: Sources and power demand for existing energy facilities in 2010

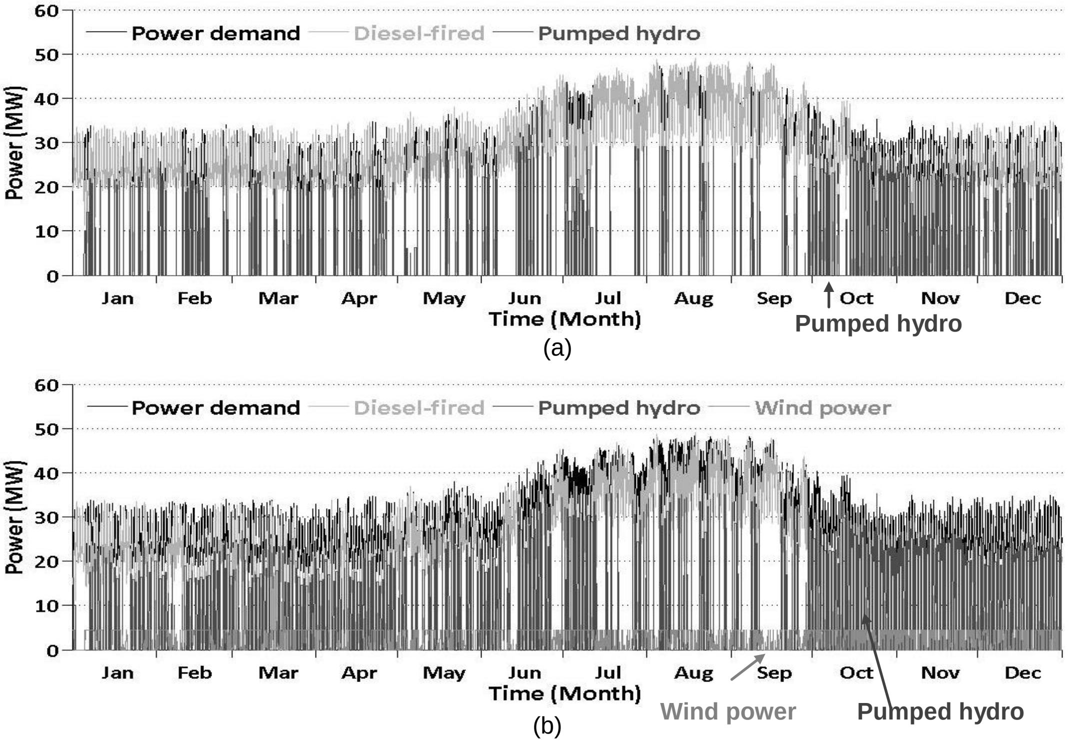
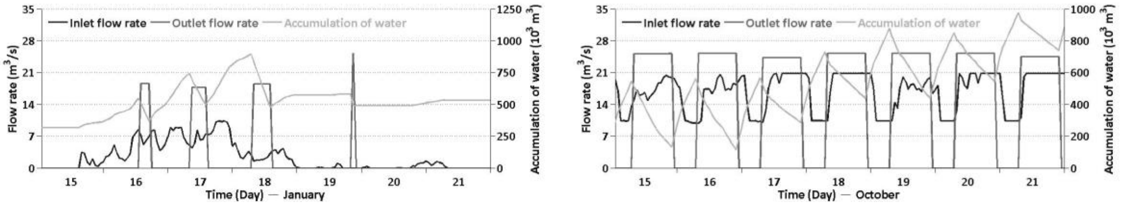


Figure 3: Optimal sources and power demand (a) for scenario 1; (b) for scenario 4 in 2010.



(a) (b)

Figure 4: Water inlet/outlet flow rate and accumulation for scenario 1 (a) Jun 15-21; (b) Oct 15-21 in 2010.

Table 1: Optimal results for the studied island

Scenario	S1	S2	S3	S4
No. of wind turbine	17	38	15	34
Elect. gen. of diesel oil (GWh)	203.45	152.59	203.45	152.59
Elect. gen. of wind turbine (GWh)	72.90	162.96	64.33	145.81
Elect. gen. of PHS (GWh)	51.39	111.64	28.74	83.57
Excess elec. of wind power (GWh)	0.08	8.95	1.53	8.80
Excess elec. of hydraulic power (GWh)	0.53	6.94	0.04	1.71
Water reservoir				
Capacity (GWh)	0.44	5.38	0.10	3.00
Volume (10^6 m^3)	1.16	14.11	0.27	7.85
Min. power gen. (MW)	5.95	11.90	5.95	11.90
Max. power gen. (MW)	34.69	43.61	28.12	41.99
Min. outlet flow rate (10^3 m^3/h)	15.60	31.21	15.60	31.21
Max. outlet flow rate (10^3 m^3/h)	90.92	114.30	73.72	110.06
times of power gen. (h)	2,336	3,911	1,970	3,475

5. Conclusions

A mathematical model for optimization and the retrofit of HPS in a remote area has been developed for enhancing the renewable energy usage. A MILP model is proposed, including all feasible connections between basic units in a typical HPS. This model considers the power losses during the transfer and storage of power occurring in an HPS and deals with the targeting of minimum total diesel electricity, minimum install capacities of wind turbine, minimum storage capacity required and minimum power generation of PHS. The proposed formulation is applied to K Island. Results of the example show that the electricity demand for conventional power can be significantly reduced by increase of renewable energy and installation of PHS in a HPS. In future work, this model will be extended to incorporate PHS with batteries and confer on techno-economic optimization.

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