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A Water-Based Approach for Addressing RES Integration Challenges in Insular Energy Systems

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Abstract High shares of RES-based power capacity in island electricity grids often imply significant energy curtailments of non-dispatchable power generation, which in turn limits islands' capacity to leverage RES environmental and economic benefits. The presence of energy storage systems and/or grid interconnections can improve this situation, but at the same time add considerable costs in terms of capital expenditure. We argue that exploitation of already existing assets, at the demand side, offers the opportunity for low-cost demand-based schemes, providing power systems with increased flexibility which, in turn, can support increased RES penetration. This study demonstrates the application of a demand side management strategy for exploiting the high deferability of load demand of a set of water pumping stations, in an isolated grid on a Greek island. The strategy, given a sufficient implementation scale, seeks to reduce limitations, with regards to wind energy contribution in RES-saturated grids, under an energy consumption minimization function, fulfilling at the same time constraints related to water management.

Keywords: Isolated Grids, Demand Side Management, Water-Energy Nexus, RES Integration, Sector Coupling

1. Introduction

Greek islands have an excellent Renewable Energy Sources (RES) potential arising from the wind and solar energy potential abundance (Oikonomou et al., 2009). At the same time, there exist within the country 29 isolated electricity grids associated with Non-Interconnected Islands (NII) typical of the Greek archipelago. These small-scale NII grids rely mostly on fossil fuels, since their size and the absence of interconnections to the mainland's electricity network makes it difficult for them to deal with intermittent power, such as RES. The Hellenic Electricity Distribution Network Operator reports that NII RES annual supply is below 25%.

Wind power in such autonomous networks is subject to certain limitations; on the one hand, the thermal power stations have to serve loads above a certain threshold, i.e. indicated by the technical minima of the operating gensets. On the other hand, the stochastic nature of wind introduces a degree of uncertainty in power production from wind farms, which in turn dictates the so-called dynamic penetration limit. In this context, local grid operators have to maintain a spinning power reserve, while gensets have to be able to offset any instantaneous rate of power change, to avoid voltage deeps and frequency excursions. Considering the above, and also the overall production costs, grid operators produce a commitment schedule for the thermal units, while also applying operating set-points for each of the connected wind parks, often limiting their energy production.

In this study we introduce a Demand Side Management (DSM) strategy able to exploit the high deferability of load demand by water assets, providing additional flexibility that, in turn, assists in reducing RES curtailments. The strategy is encapsulated in an optimisation model, which produces a 24-hour, day-ahead operation schedule for the water pumping stations of a small-scale island community. The decision-making process is driven by water demand, pursuing two objectives: prioritize load allocation over time-periods that feature RES curtailments and minimize overall electricity consumption. We demonstrate the application of the strategy in the case of Tilos, a small island in the south east Aegean Sea.

2. Methods

We created a model of the operation of a small-scale water supply system, which is integrated with the load deferral strategy. The operation of the supply system is driven by the water demand over the time set, *T*, of discrete time-periods, *t*, each having a duration Δt, based on the approach of Hong et al., 2019. Given a set of network nodes, *N*, the sum of water discharge, *q*, towards each node *n*, coming from each node *i*, of the upstream nodes set of *n*, N^u, equals with the sum of water discharge towards each node *j*, of the downstream nodes of *n*, N^d, plus an extra amount of water, *s (eq. 1)*. The latter represents water demand at that node, given negative values, or, the water supply, given positive values.

If a node is registered to the set of water tanks, *WT*, then, any difference between upstream and downstream water discharge is converted into a difference in the stored water volume, and the eq. 2 is used instead of eq. 1, with the maximum stored water volume capped by the tank's capacity, *V* (eq. 3).

$$\sum_{i\in N_n^u} q_{n,i}^t = \sum_{j\in N_n^d} q_{j,n}^t + s_n^t,\ \ for\, n \in N - WT, \forall t \in T \quad (1)$$

$$\left(-\sum_{i\in N_n^u} q_{n,i}^t + \sum_{j\in N_n^d} q_{j,n}^t + s_n^t\right)\Delta t = A_n\left(h_n^{t+1} - h_n^t\right), \quad (2)$$

$$A_n\left(h_n^t - Z_n\right) \le V_n,\quad for\, n \in WT, \forall t \in T \quad (3)$$

where, *A*, the water tank surface, *Z*, the elevation of the water tank and *h*, the total water head, i.e. the sum of pressure, kinetic and potential energy divided by the weight of water.

The water discharge from one node to another through a pipe causes friction, which results to energy losses. The friction losses are estimated using the Hazen-Williams equation (SI units), which associates the energy loss with water discharge, *q*, of a pipe, *p*, which has a length, *L*, a roughness coefficient *C* and starts and ends with nodes *n* and *j*, respectively. Additionally, other design particularities of the network, which disrupt the water flow, introduce local energy losses. For that purpose, the abovementioned friction losses are increased using a minor to major losses ratio *r*, according to eq. 4, which is applied to the network's set of pipes *P*, for each *t* of *T*, excluding the set of pipes with valves, V, and the set of pipes with pumps, K.

$$h_n^t - h_j^t = \left(r_{n,j} + 1\right)\frac{10.67 L_{n,j}}{C_{n,j}^{1.852} d_{n,j}^{4.8704}}\left(q_{n,j}^t\right)^{1.852} \quad (4)$$

A valved-pipe is incorporated using an arbitrary node, linked with zero-length pipes, hence accounting only for minor losses. The valve openness, *v*, adjusts the differential head at the particular valved-pipe according to eq. 5.

$$h_n^t - h_j^t = v_{n,j}^t\left(q_{n,j}^t\right)^2,\ \ for\, p \in V, \forall t \in T \quad (5)$$

In order to transfer water, the differential head between an upstream and downstream node of a pipe has to be bridged. The energy deficit is supplied by the network water pumps, *K*, in the form of pressure. At this point, it is worth noting that pressure shall remain positive in all nodes, i.e. accomplished by imposing a lower bound in total head, according to eq 6:

$$h_n^t \ge Z_n + \frac{\left(q_{j,n}^t\right)^2}{2gA_p^2},\ \ for\, n \in N, \forall t \in T \quad (6)$$

where, *A*, is the cross-sectional area of a pipe *p*, which links the node *n* with its upstream node *j*, and *g*, is the gravitational acceleration.

Pipes accommodating a pump, *k*, deliver energy to the system via eq. 7. The head a centrifugal pump may supplement (eq. 8) is associated with the water discharge, q_k, and the operating angular speed, *ω*. In case of fixed-speed pumps the grid frequency determines *ω*. In case of variable-speed pumps, it ranges within permittable limits, according to the installed equipment.

$$h_n^t - h_j^t = -h_k^t,\ \ for\, k \in K, \forall t \in T \quad (7)$$

$$h_k^t = a(\omega_k^t)^2 + b\omega_k^t q_k^t + c(q_k^t)^2,\ for\, k \in K, \forall t \in T \quad (8)$$

with, a, b and c being constants of each pump, computed using the nominal rotational speed, and the manufacturer's head-discharge characteristic curve.

In order to encode the operating state of each pump, *k*, into a binary variable, x_k, while forcing the operation over the characteristic h-q curve, the eq. 8 is transformed using the Big-M method into the following equations set:

$$\begin{aligned} & h_k^t \le A(\omega_k^t)^2 + B\omega_k^t q_k^t + C(q_k^t)^2 + M_k(1 - x_k^t), \\ & h_k^t \ge A(\omega_k^t)^2 + B\omega_k^t q_k^t + C(q_k^t)^2 - M_k(1 - x_k^t), \\ & q_k^t \le M_k x_k^t,\ \ x_k^t \in \{0,1\},\ for\, k \in K, \forall t \in T \end{aligned} \quad (9)$$

where, M_k, an arbitrary scalar with a value that exceeds the shut-off head of the pump *k*.

The present study aims at defining the day-ahead operation schedule of a pumping stations set, in which i) the system's energy consumption is minimized, while ii) the system's operation exploits expected wind power rejections (load deferral strategy). In this context, the electricity demand of a pumping station is:

$$E_k^t = \frac{\rho g h_k^t q_k^t}{\eta_k^t}\Delta t \quad (10)$$

where, *η*, is the energy efficiency of the respective motor-pump set. Efficiency depends on both, the water discharge and the rotational speed. The q-η curve is approximated using a polynomial function, according to the manufacturer's data for the nominal angular speed. In case of a variable speed pump and given a reduction in ω, efficiency curve shifts towards smaller water discharge values (Georgescu et al., 2014), based on eq. 11:

$$\eta_k^t = 1 - \left(1 - \eta *_k^t\right)\left(\frac{\omega *_k^t}{\omega_k^t}\right)^{0.1},\ \ for\, k \in K, \forall t \in T \quad (11)$$

The objective function of the problem then becomes:

$$min\left\{\sum_t^T \sum_k^K \left(E_k^t\right)\right\} \quad (12)$$

With regards to the load deferral strategy, a binary variable, x_e, is employed for encoding the comparison between day-ahead wind energy curtailments, $E_{curtailed}$, and the total electricity demand of the pumping stations:

$$\sum_t^T \left(E_{curtailed}^t\right) \ge \sum_t^T \sum_k^K \left(E_k^t\right) - M_e\left(1 - x_e\right) \quad (13)$$

$$\sum_t^T \left(E_{curtailed}^t\right) \le \sum_t^T \sum_k^K \left(E_k^t\right) + M_e x_e \quad (14)$$

with, M_e, an arbitrary scalar, the value of which exceeds the day-ahead curtailments and the electricity demand.

In case that the total $E_{curtailed}$ is greater than the total demand over T, x_e becomes 1, which in turn bounds the pumping stations demand below the wind energy curtailments, for every time-period *t* (eq. 15). Inversely, if x_e equals zero, the constraint of eq. 16 forces the pumps to exploit the total amount of $E_{curtailed}$, while tracking any additional demand under the variable $E_{auxiliary}$.

$$x_e\left(\sum_k^K\left(E_k^t\right)-E_{curtailed}^t\right)\leq 0,\quad \forall t\in T \tag{15}$$

$$(1-x_e)\left(\sum_k^K\left(E_k^t\right)-E_{curtailed}^t-E_{auxiliary}^t\right)=0,\forall t\in T \tag{16}$$

Due to the non-linear associations of water discharge with head losses and the pump's efficiency, and due to the binary variables, which encode the 'if-statements' and the 'on-off' states of the pumps, the model becomes a Mixed-Integer Nonlinear Program. To solve the problem, the Gurobi optimizer was utilized, while adopting Piece-Wise Linear approximations for relaxing the constraint of eq. 4 and the pumps q-η curve. Eq. 5 was also relaxed into eq. 17, with n, j the preceding and following nodes, respectively, of the valved-pipe, p.

$$h_n^t\geq h_j^t,\ for\ p\in V,\forall t\in T \tag{17}$$

3. Case study

Typically, in small-scale island communities, water supply systems consist of a number of pumping stations that deliver water from underground resources and spring tanks to a main reservoir tank, which, in turn, provides water to a gravitational supply network. The DSM strategy is applied on such a system (Fig. 1), which is located at Livadia, at Tilos, a small island in the south east Aegean Sea. The system consists of 3 fixed-speed pumping stations; Potamos (Power: 7.5kW; Shut-off head: 131.86m) exploits spring water, while Athymies and Fraktis are drilled wells, with the same pump-motor set installed (Power: 11kW; Maximum head: 227.66m; Minimum discharge: 6m^3/h). The stations operate at low water discharge levels, with the drill studies suggesting an upper exploitation bound of 10m^3/h for a total of 10h/d, an upper bound that is also applied at Potamos.

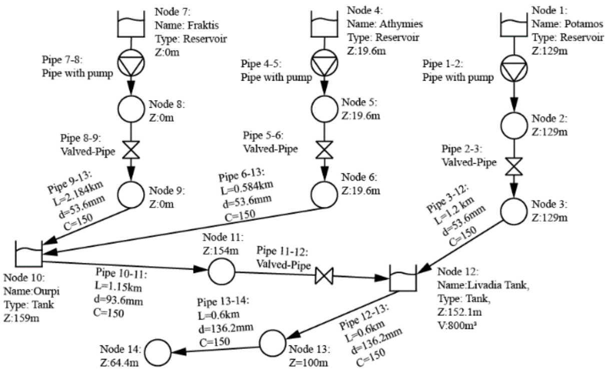

Figure 1. The Livadia water supply network scheme

The model, using an hourly time step, seeks for the most energy efficient operation schedule of the 3 water pumps, based on a day-ahead water demand profile. At the same time, the algorithm ensures that energy demand is allocated according to the day-ahead wind energy curtailments timeseries.

The hourly water demand profile was computed using the average daily water consumption of Livadia community and a set of hourly multipliers (Kanakoudis et al., 2015). During 2020, the invoiced water demand of Livadia community was 22,128m^3 or an average of 60.6m^3/d, with 87% registered as residential and hotel water consumption.

On the other hand, two indicative hourly profiles of the daily wind energy curtailments were utilized for testing the strategy. The profiles have a much larger scale than the size of the flexible loads, thus, time-related bounds receive the focus of the decision-making. Tilos is interconnected to the Kos-Kalymnos electricity system, which features 9 islands that together consume 360GWh per annum. The system hosts 16MW of wind power, with the estimated wind energy curtailments (Zafirakis et al., 2017) approaching 30%, or 14.5GWh, of the respective potential production. Their duration curve, in terms of size and hourly events is displayed in Fig 2. The 1st profile features 5MWh of energy curtailments, distributed over 3h. That amount of energy is curtailed for at least 230d/y, while exactly 3 hourly events/d occur for 23d/y. The 2nd profile features 28.6MWh of energy curtailments, distributed over 10h. That amount of energy is curtailed for at least 35% of the year.

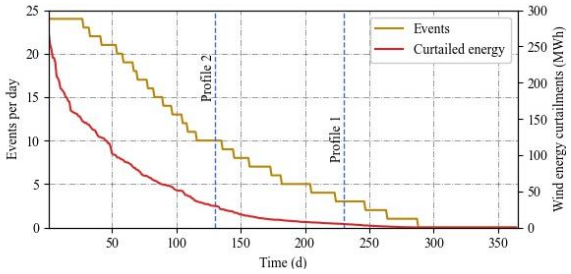

Figure 2. Duration curve of the daily wind energy curtailments and of the daily hourly rejection events.

4. Results

The optimizer is a branch and bound based algorithm, that can provide the best feasible solution quite fast. In particular, using 1 CPU thread, a time-limit of 200s, 24 segments for the PWL approximation of the efficiency curve and 16 for the major head losses, the minimum value of daily electricity consumption for the 1st profile is 55.97kWh, having an optimality gap of 0.21%, i.e., the difference with the estimated lower bound of optimal objective value. Similarly, the total energy consumption using the profile 2 is 38.40kWh, with a gap of 0.30%.

With regards to the hourly operation scheme that derives from the 1st profile (Fig. 3), the concentrated curtailments propel the operation of 3 water pumps.

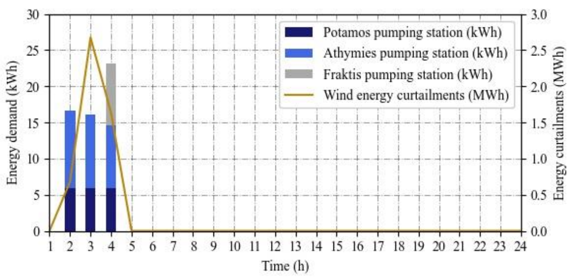

Figure 3. The electricity demand of the water pumping stations, using the 1st wind energy curtailments profile.

Potamos, the most energy efficient station, operates at the upper bound of the allowed water discharge, i.e. 10m^3/h for each of the 3h that feature wind energy curtailments. The rest of the water demand is covered by Athymies and Fraktis, which have the same pump-motor set that operates between 6m^3/h and 10m^3/h of water discharge, delivering a head that ranges between 225.1m and 208.3m. Since the pumps cannot reduce their rotational speed to match the lower head of system's curve, the system's valves are used to increase the head losses, matching the h-q curve. Thus, both stations demand an equal amount of energy for the same water discharge.

Although energy curtailments are sufficiently large to cover the daily electricity demand of the pumps, curtailments do not occur at the first hour, establishing the need of a water buffer to cover the water demand (i.e. 1.1m^3 for the 1st h). The buffer, with a size of 10m^3, gets restored by the end of the operation schedule (Fig. 4).

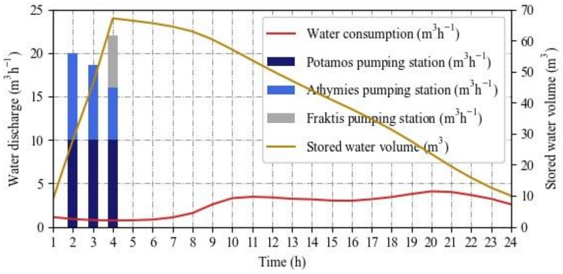

Figure 4. The pumps water discharge in comparison with the water demand and the operation of the water tank, using the concentrated wind energy curtailments profile.

On the contrary, given a longer time-duration of wind energy rejections throughout a day, the less energy intensive water resources get the opportunity to operate for more time, replacing the operation of more inefficient pumping stations. That case is demonstrated in Fig. 5, featuring 10h of wind energy curtailments (Profile 2). The water demand is covered using 31.4% less energy. Accordingly, the sparse operation of pumps led to the reduction of the peak water volume to be stored by half (Fig. 6), stressing the link between the water storage capacity and the water assets load demand flexibility.

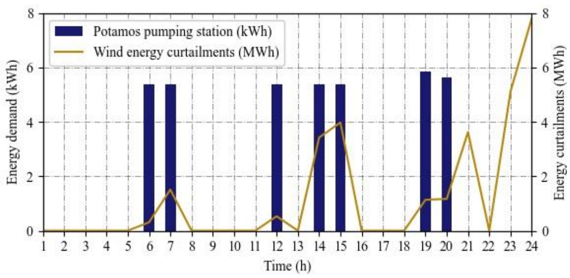

Figure 5. The electricity demand of the water pumping stations, using the 2nd wind energy curtailments profile.

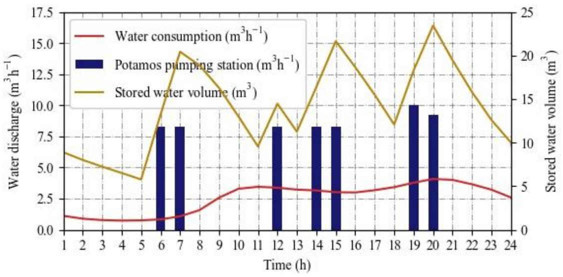

Figure 6. The pumps water discharge in comparison with the water demand and the operation of the water tank, using the sparse, in time, energy curtailments profile.

5. Discussion and Future Work

A sustainable future for isolated communities, such as small islands, is linked to their capacity to leverage environmental and economic benefits of RES while securing water supply. To assist in that direction, a load deferral algorithm is devised, taking day-ahead decisions with regards to the 'on-off' states of a set of water pumps and their discharge level. The information signals that guide load shifting are two: day-ahead forecasts of hourly wind energy curtailments and forecasts of hourly water demand. The work demonstrates that profile shapes have a significant impact on pump operations schedule, with more concentrated, in time, wind energy curtailments resulting in a higher energy toll towards carbon-free operation.

Future work will investigate the feasibility of such applications in Greek NII, experimenting with the scale of the deferable load demand, the water storage capacity, and with constraints related to water resources management, while exploring the impacts of accuracy in day-ahead forecasts of water demand and wind energy curtailments to the resulting optimized performance.

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