On the Mitigation of Renewable Energy Curtailment by Using Pumped Hydro Storage Systems

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***Abstract*—To increase the penetration of renewable energy sources into electrical systems, it is essential to lessen renewable energy curtailment. Pumped Hydro Storage (PHS) systems are a promising alternative to achieve lower curtailment rates. This work analyses the effect of a PHS system in an electrical network regarding renewable energy curtailment behaviour. The analysis is addressed through an optimal power flow formulation to minimize power loss while satisfying operating and renewable energy curtailment constraints. Preliminary results for a modified IEEE 14-bus test feeder suggested that implementing the PHS decreased transmission losses by 2.2% and mitigated 16.8% of curtailed renewable energy for whole-year simulations.**

Keywords—Optimal power flow, Pumped hydro storage, Renewable energy curtailment

I. INTRODUCTION

As Europe faces strategic challenges in the energy transition, there is growing adoption of renewable energy sources in the power system. However, this transition poses challenges for power distribution system planning, control and operation. The intermittent characteristic of renewable energy source-based generators may result in reduced sustainability and increased energy cost [1].

In addition to the challenges posed by the adoption of renewable sources in the electric grid, there is also the issue of renewable energy curtailment (REC). When there is excess energy being generated from renewable sources, it may not always be possible to balance it, leading to the deliberate reduction of energy output in renewable power plants. This is becoming an increasingly important issue in the planning and operation of power distribution systems worldwide [2].

There are several approaches in use to control and mitigate REC. The employment of policies, regulations and incentives is a common option [3], but from a technical approach point of view, demand response programs and energy storage systems have been proposed and are widely used [4, 5, 6].

The demand response approach often gives incentive to energy consumers to detach non-essential loads from the grid, while the energy storage approach strives to reduce the difference between energy demand and supply [7].

In electrical power systems, energy storage systems contribute to frequency regulation, renewable energy integration, black start services, energy shifting and transmission congestion relief. Pumped hydro storage (PHS) systems are the most common energy storage technology employed in power systems, representing more than 90% of installed storage capacity [8].

The basic functionality of PHS systems is based on two reservoirs, one higher than the other, which allows pumping water upwards when there is surplus energy in the grid and using that stored potential energy to generate electricity when demand is higher.

REC can be categorized as a problem that requires grid flexibility measures. Loss of load is also a consequence of the need for increased grid flexibility. An efficient solution to address the loss of load in standalone systems has been the integration of a PV-PHS hybrid system, as proposed in [9].

The work performed in [10] exploits a method for evaluating several technologies for renewable energy sources' accommodation. The PHS system was considered the most effective to prevent energy curtailment, from technical and financial terms.

PHS technology is mature, cost-effective, with a long lifespan and has high-power capabilities. In this way, it became a commonly used technology, even though it has some limitations, such as a high implementation cost and geographical characteristics restrictions. Nevertheless, in China, PHS systems have been a successful solution to different problems in power systems [11].

In Europe, systems operators must comply with a Regulation stating that re-dispatching of renewable energy sources should be avoided and is limited to 5% of total annual generation to avoid reimbursement costs. In addition, REC should be non-discriminatory between generators, unless not feasible [12]. In [13], the authors exploited the integration of those regulatory restrictions in an optimal power flow (OPF) as boundary conditions of possible curtailment and non-discriminatory behaviour. The OPF exploited a hybrid Genetic Algorithm (GA) formulation to minimize active transmission losses.

The present work strives to lessen the effects of REC in electrical networks by using a storage system. The work proposes and exploits a PHS operation model into a transmission loss minimization using OPF based on hybrid GA. A modified IEEE 14-bus system, including renewable sources-based power plants, is proposed to better analyse the effects of the integration of the PHS in the system.

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The remainder of this paper is structured as follows. The following section discusses the optimal power flow formulation, the additional constraints to manage curtailment limits and the non-discriminatory characteristic. The hybrid genetic algorithm proposed for the optimization procedure is then briefly introduced. In Section III, the case study is presented, with details about the IEEE 14-bus test feeder and the generation and load profiles that were simulated. Section IV presents the most important results for an exemplary day in order to better illustrate the behaviour of the grid, which has been then exploited for a whole-year scenario. The final section presents the main conclusions of the work and future improvements to the proposed system.

II. Optimal Power Flow

Optimal power flow is widely employed in power systems as an optimization problem with constraints, where the variables of the system can determine the state of the electrical network. OPF can be used to solve single or multiple objectives, being the most common for problems such as generation costs, transmission losses and voltage instability. This work focuses on transmission loss minimization while respecting curtailment requirements, formulated through constraints, as presented hereinafter. The implementation of the OPF is dynamic in the period T over time steps t, in accordance with the generation and load profiles data.

A. Optimal Power Flow Standard Constraints

The conventional constraint formulations for power systems comprise three main categories, the node voltage limits, maximum currents in the branches and operating limits of the generators. The reactive power of generators is constrained based on the rated apparent and active power of the generation profiles using measured or forecasted values [14].

For the power system with δ nodes and τ branches, each branch $(i,j) \in \tau,\ \forall\, i,j\ \in\ \delta$ is represented by the complex impedance, $z_{ij} = r_{ij} + \mathbf{j}x_{ij}$, where $\mathbf{j} = \sqrt{-\mathbf{1}}$ and r_{ij} and x_{ij} denote the resistance and reactance of the branch, respectively.

Defining the problem variables as x, the optimization formulation is represented as:

$$\min f(x) = \sum_{(i,j)\in\tau} r_{ij} L_{ij} \tag{1}$$

Subject to the constraints:

$$V_{min} \leq V_i \leq V_{max} \tag{2}$$

$$L_{ij} \leq \left(I_{ij}^N\right)^2 \tag{3}$$

$$-\sqrt{(s_i^N)^2 - (p_i)^2} \leq q_i \leq \sqrt{(s_i^N)^2 - (p_i)^2} \tag{4}$$

where L_{ij} is the square of the magnitude of the current flowing in the branch (i,j); $V_{\min(max)}$ is the minimum (maximum) allowable value of the voltage at the node, and V_i denotes the magnitude of the voltage at node i; I_{ij}^N represent the rated current magnitude for the branch (i,j), p_i and q_i denote the active and reactive powers generated at node i, and finally, s_i^N is the rated apparent power capacity for the generator at node i. The equality power flow constraints were not included in the presented formulation, for the sake of simplicity.

B. Optimal Power Flow Curtailment Constraints

In order to enforce limitations on curtailed power and promote the non-discriminatory use of renewable energy sources, constraints are added to the formulation. Therefore, the active curtailed power is defined as:

$$C_{DG,i} = p_{DG,i}^{max} - p_{DG,i} \tag{5}$$

being $p_{DG,i}^{max}$ and $p_{DG,i}$, respectively, the maximum active power generation and the operating point of each individual renewable energy source power plant at node i. To limit the maximum curtailed energy to 5% of total generation,

$$C_{DG,i} \leq 0.05 p_{DG,i}^{max} \tag{6}$$

To comply with the non-discriminatory behaviour of the generators, a cumulative standard deviation is applied, such that:

$$\sqrt{\frac{1}{n}\sum_i \left(\sum_t \left(C_{DG,i}(t) - \mu(t)\right)\right)^2} \leq d \tag{7}$$

where n is the number of nodes that contain the renewable source-based generator and $\mu(t)$ the mean of the active power curtailed of all generators till the time step $t \in T$. This approach has been exploited in [13].

C. Genetic Algorithm Approach

The genetic algorithm (GA) is an evolutionary method based on the human population. It is a powerful optimization method for addressing unconstrained and constrained optimization problems. This method uses a population of individuals, where each individual represents a possible solution.

In each GA iteration, the population improves during the method execution promoting new generations: individuals are randomly selected from the previous generation for the crossover and mutation procedures. The crossover procedure involves exchanging information between two individuals, while the mutation procedure introduces new information in one individual.

As OPF problems can be described as neither convex nonlinear programming problems, GA has been used to guarantee convergence for otherwise unfeasible solutions

The classical GA method is combined with a derivative-free local method named Nelder-Mead to obtain a better precision solution. The obtained hybrid method is promising in terms of execution time archiving feasible solutions with higher accuracy. In [13] a similar approach has been used to carry out a sensitivity analysis of the value for the standard deviation.

III. Case Study

To better understand the effects of the use of PHS systems to mitigate renewable energy curtailment, a modified version of the IEEE 14-bus test feeder, presented in Fig. 1, was set up by using MATPOWER [15]. To model the behaviour of the grid over the period T of one year, i.e., considering the variation of the load and generation by using different scenarios, OPF has been implemented dynamically in MATLAB, with the inclusion of the hybrid GA approach as proposed in [13] and including the curtailment and non-discriminatory constraints, previously described.

A. *Input Data*

To represent the operation of the network for the whole year, four generation and two load scenarios were defined. The load profiles were obtained using the real dataset of residential and industrial loads [16] as proposed in [13] and were combined and scaled to fit the magnitude of the original test feeder data. Buses 3, 4 and 5 have a fully residential profile, while buses 2, 6 and 10 have a fully industrial profile. The remaining load buses, 9, 11, 12, 13 and 14, are obtained by combining industrial and residential profiles. The two proposed load scenarios model winter and summer profiles, with the winter having an overall higher energy consumption.

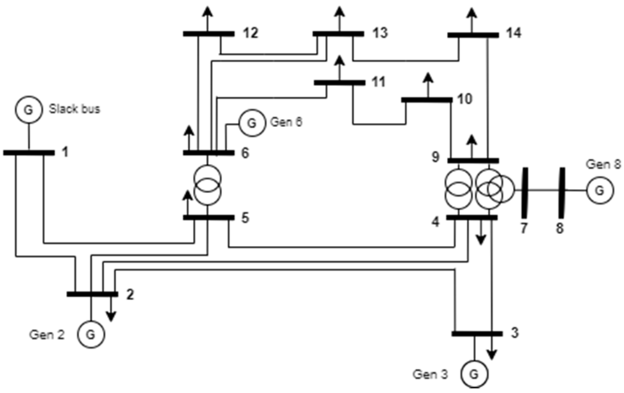

Fig. 1. IEEE 14-bus test feeder [13]

In terms of generation profiles, bus 3 generator models a wind park and the generators in buses 6 and 8 model photovoltaic power plants. Since these generation profiles depend mostly on the weather, to create the corresponding profiles, data from 20 years from the city of Bragança, Portugal [17] were used, in a procedure similar to the one described in [13].

To better embody the variability of wind power, the wind farms were scaled according to their energy generation in "windy" versus "non-windy" conditions. The latter translates to a 50% reduction in generation relative to the former. This approach resulted in the identification of four distinct scenarios: windy summer (S1), summer (S2), windy winter (W1) and winter (W2).

Regarding the standard constraints of the OPF, thermal line limits are set to 100 MVA to every branch, the limits of voltage magnitude are minimum 0.95 p.u. and maximum 1.05 p.u., voltage phase angles are limited to -90º and +90º, and the remaining data of the 14-bus test feeder model are according to original data [18]. In terms of the specific curtailment constraints, curtailed energy is limited to 5% of the generation, and the standard deviation between generators is also limited to 5%.

To understand the behaviour of the electrical network, the W1 scenario, presented in Fig. 2, was inserted in the model as an exemplary day, which will be explored in Section IV.

B. *Proposed Pumped Hydro Storage Model*

The proposed PHS system is modelled by two reversible 40 MW pump turbine machines, as to guarantee more flexibility to the system. The rated power value of the machines was defined based on the IEEE 14-bus original data [18]. For the sake of simplicity, it is assumed that those machines, when active, always operate at rated power. The machines have a round-trip efficiency of 85%, as indicated in several works [19]. The energy capacity of the system is 960 MWh, in the hypothesis of both of the machines (80 MW) working for 12h, and said capacity is not affected by seasonality. The maximum and minimum capacities of the PHS are determined by the usable energy stored in the PHS, as proposed in [9].

The system may operate in three states, *static*, i.e., when the machines are off, *charging*, when pumping water to the upper reservoir and *discharging* when the water from the upper reservoir is used to generate electricity. Fig. 3 models the proposed operation logic of the overall system. It consists of deciding, for each hour, whether one, two or none of the machines will be on, and also in which of the states the PHS system must operate: *charging*, *discharging*, or *static*.

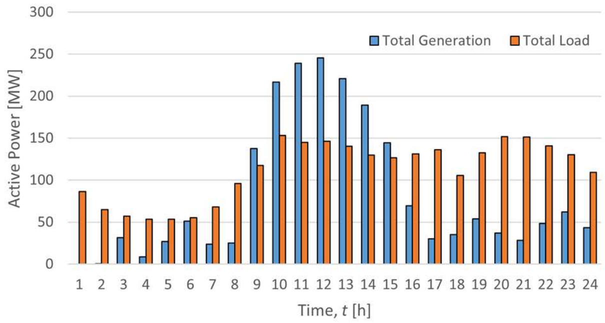

Fig. 2. Load and generation profiles for windy winter (W1) scenario

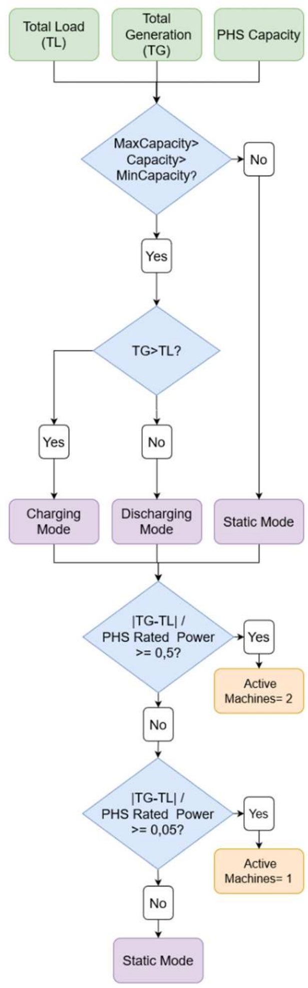

Fig. 3. Proposed operation of the PHS system

The inputs to the algorithm are the total load (TL) and total renewable generation (TG) of the network and the PHS capacity at a moment *t*. First, it should be checked if the capacity of the PHS (Capacity) is between the minimum (MinCapacity) and maximum (MaxCapacity) stored energy capacity. Then, the algorithm checks if the Total Load is higher than the Total Generation, to decide if the PHS should inject power to the grid (*discharging*), or if the grid should inject power to the PHS (*charging*) when there is excess energy being generated. Afterwards, it is decided if one, two or none of the machines will be turned on. As both of the machines have 40 MW of rated power, the PHS has a total of 80 MW to dispatch. The number of machines is determined by the module of the difference between load and generation, divided by the rated power of the PHS, in this case, 80 MW. If the result is less than 5%, no machine is turned on, resulting in the static operation. If the result is between 5% and 50%, a single machine is turned on, and if the result is higher than 50%, both machines are turned on. It should be noted that this approach is simplified, as the PHS may respond with more or less power than required by the network. For instance, suppose that at a given time *t*, the load is 140 MW, and the renewable generation is 70 MW. In this case, the PHS system will discharge, activating both machines, leading to a response of 80 MW, which exceeds the amount required to achieve a balance between load and generation. In the W1 scenario, a comparable PHS response would occur at the 18th hour.

IV. Curtailment Mitigation Analysis

The windy winter (W1) scenario was further investigated, exploiting it as an exemplary day for its load and generation profiles. To better understand the impacts of the usage of the PHS system, two benchmarks were defined and studied, along with the PHS system, regarding REC, transmission losses, slack bus behaviour and the PHS capacity.

A. Benchmark and PHS cases

Two benchmark cases were considered as references, Ref1 and Ref2. Both of them run the OPF described before, for an exemplary day of the scenario W1.

Ref1 stands for the standard IEEE 14-bus test feeder with a conventional 40 MW generator attached to bus 2. This reference aims to enlighten the advantages of the PHS in comparison with a conventional generator. Ref2 considers the network without the conventional generator in bus 2, which is important to investigate the energy exchange of the modelled system with the utility grid, used as a buffer, through the slack bus. The PHS case integrates the proposed PHS system in bus 2, to study the effects of the PHS system in an electrical network under curtailment scenario.

Fig. 4 shows the sum of curtailed energy of each generator for the exemplary day under analysis, from which it is possible to infer the variation of total curtailed energy for the references and PHS cases. For each bus, the PHS case presented less curtailed energy. Fig. 5 presents the evolution of the total curtailed power curve during the exemplary day for the cases under study. The curtailment occurs mostly between hours 9 and 15 for all cases, which is when the generation is higher than the load for W1 scenario.

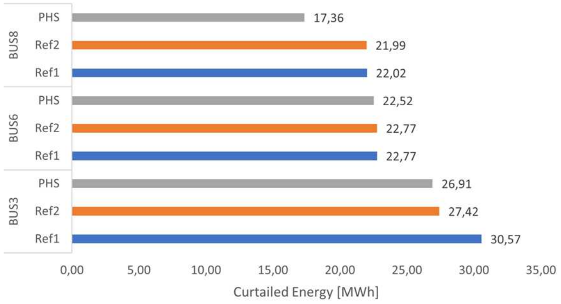

Fig. 4. Curtailed energy in the exemplary day from the windy winter (W1) scenario per generation bus

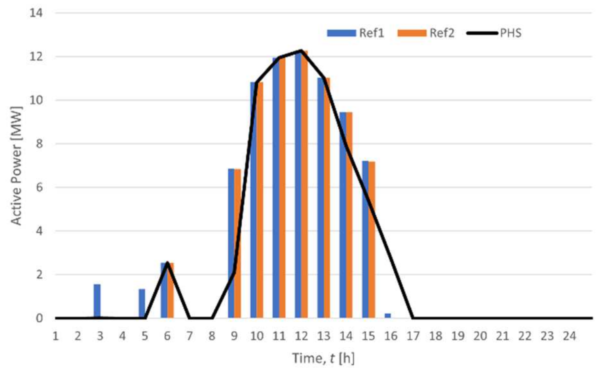

Fig. 5. Curtailed power in the exemplary day from the windy winter (W1) scenario

Table 1 presents the total losses for the studied cases for the exemplary day of W1 scenario, as well as the percentage of increased losses for Ref1 and Ref2 in comparison to the PHS case. The PHS case presents the lowest losses between all cases. These results may be attributed to the flexibility of the PHS system, which enables the system to effectively balance the load and generation profiles, mitigating transmission losses.

Ref2 has higher losses when compared to Ref1. This difference may be attributed to the fact that most of the power generated from the conventional generator in Ref1 now must come from the slack bus in the Ref2 case.

B. Pumped Hydro Storage Capacity and Slack Bus Behaviors

Different generation and load profiles present different operations of the PHS. Fig. 6 presents the capacity curve for the specific exemplary day of the W1 scenario. The rated power of the PHS machines limits the pumping and generation rates, limiting how much power is exchanged with the grid (delivered or consumed).

TABLE I. Transmission Losses Comparison for Windy Winter (W1) Scenario

Cases	Transmission losses [MWh]	Increase in relation to PHS [%]
Ref1	30.83	10.82
Ref2	33.23	19.45
PHS	27.82	-

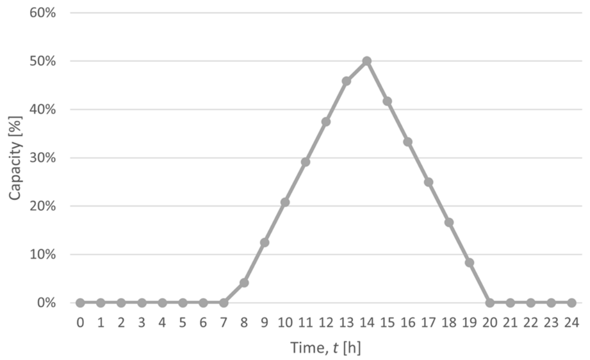

Fig. 6. PHS system capacity for the exemplary day from windy winter (W1) scenario

It is important to analyse the energy exchange through the slack bus to guarantee that the operation of the PHS system does not impose a much higher dependence on the utility grid.

Fig. 7 shows the slack bus active power curve for the Ref1, Ref2 and PHS cases in the W1 scenario exemplary day. Ref1 and Ref2 show very similar curves, as the conventional generator in the Ref1 case basically offset the curve. On the other hand, the PHS case shows a distinct behaviour between the 8th and 20th hours, when the PHS system is operating. Fig 8 shows the sum of active energy in the slack bus. When compared to Ref1, the PHS case presents a higher dependence on the utility grid. Comparing the PHS case with Ref2, there is a slight decrease in the total active energy for the PHS case. The dependence of the utility grid is mitigated by the conventional generator in the Ref1 case when compared to the Ref2 case. From the above, it can be considered that the differences between Ref1 and PHS cases may be disregarded from further analyses.

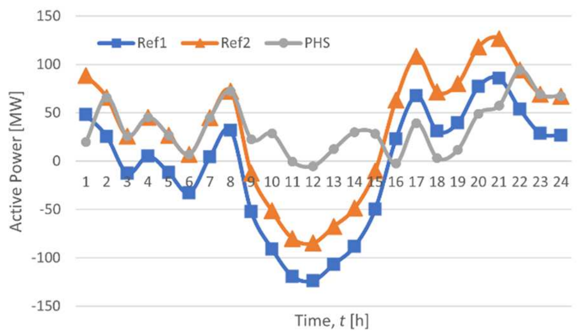

Fig. 7. Slack bus active power curve for the exemplary day from windy winter (W1) scenario

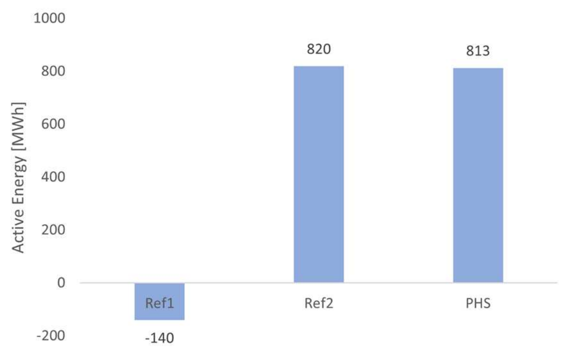

Fig. 8. Slack bus active energy for the exemplary day from windy winter (W1) scenario

V. Yearly Analysis

The annual simulations were only run for cases Ref1 and PHS, as the objective of this analysis is to compare the behavior of the system regarding transmission losses and curtailed energy when operating with a conventional generator and with the proposed PHS system. Scenarios W1, W2, S1 and S2 were used to represent the whole year. The year is considered as 92 straight days of each scenario.

The final capacity of the PHS may vary depending on the initial capacity, as demonstrated in Fig. 9, where the system was simulated in arbitrary initial states for exemplary days of all the proposed scenarios. Nevertheless, a single transition day for each scenario with a different initial and final capacity would eliminate this difference. It should be noted that preliminary whole-year simulations consider the final and initial capacity of each day the same. The simulations were considered as such for the sake of simulation computing needs. Future works may run the whole year in a single simulation.

Table 2 shows the results of the yearly analyses. The results show that there was a decrease both in energy curtailment and transmission loss in the PHS scenario, when compared to Ref1. The presented annual results show a total decrease of 16.8% (4535 MWh) of curtailed energy and 2.2% (207 MWh) of transmission losses for the PHS case when compared with the Ref1 configuration.

As mentioned before, curtailment and non-discriminatory behaviour are exploited via constraints in the objective function. Table 3 summarizes the curtailed energy at each renewable generator bus. From these results, the curtailed energy is limited below 5% for all buses in both scenarios, thus complying with the required restriction. Notably, in the PHS case, the curtailed energy is consistently lower then in the Ref1 case for all buses. The discriminatory analysis, performed by the limitation of the standard deviation as a percentage of the annual generation, produced a deviation of 0.87% for the Ref1 case, and 1.22% for the PHS case.

Even though the discrimination between renewable energy generators is higher in the PHS case, a more rigid approach to the non-discriminatory constraint would decrease curtailed energy and increase total losses.

The results of the yearly operation of the system provide some information regarding the comparison of both cases. As mentioned, both cases complied with the limitation of curtailed energy, as well as with satisfactory non-discriminatory behaviour. The PHS system proved to be a suitable solution to mitigate curtailed energy, as the operation of the system managed to reduce curtailed energy and transmission losses. The use of PHS proved to improve the reliability and sustainability of the system, as it replaced a conventional generator.

VI. Conclusion

This work exploited the use of a PHS system to mitigate the curtailment of active power in electrical networks with high penetration of renewable energy sources. A case study was conducted, using a modified version of the IEEE 14-bus test feeder, which included intermittent renewable generators using real data from Portugal, and load data from the literature.

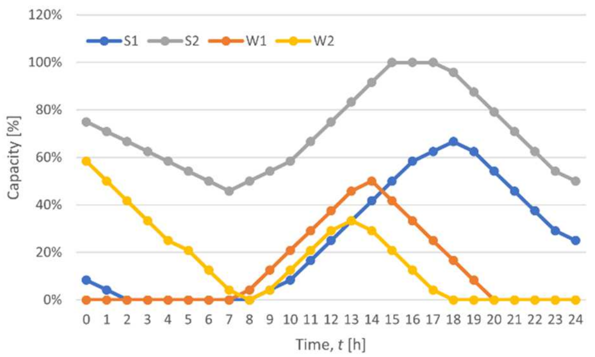

Fig. 9. PHS system capacity for exemplary days from all scenarios

TABLE II. YEARLY ANALYSIS OF CURTAILED ENERGY AND TRANSMISSION LOSSES

Scenario	Total load energy [MWh]	Active energy curtailed [MWh]	Total transmission losses
Ref1	833119	26972 (3.237%)	9394 (1.128%)
PHS	833119	22436 (2.693%)	9187 (1.103%)

TABLE III. YEARLY ANALYSIS OF CURTAILED ENERGY PER RENEWABLE ENERGY GENERATOR BUS

Bus	Total renewable energy [MWh]	Active energy curtailed (Ref1) [MWh]	Active energy curtailed (PHS) [MWh]
BUS 3	249234	8254 (3.312%)	5833 (2.341%)
BUS 6	188515	9219 (4.891%)	8994 (4.771%)
BUS 8	200951	9497 (4.727%)	7607 (3.786%)

The analysis of the network was implemented as an OPF problem which has been solved via a hybrid genetic algorithm. The results of the analysis concluded that the proposed PHS model could mitigate renewable energy curtailment and transmission losses, as well as comply with the constraints imposed by European regulations. Annual simulations suggested a decrease in energy curtailment by 16.8% and in transmission losses by 2.2%. The proposed PHS proved to be an efficient system to mitigate curtailed energy and improve the sustainability of the grid.

It is possible to improve this work by refining the PHS model and operation, testing the PHS under different load and generation scenarios, and optimizing the PHS siting. The authors aim to address these areas of improvement in future works.

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