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Hybrid Variable Renewable Power Plants: A Case Study of ROR Hydro Arbitrage

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Abstract: Wind and solar energy sources, while sustainable, are inherently variable in their power generation, posing challenges to grid stability due to their non-dispatchable nature. To address this issue, this study explores the synergistic optimization of wind and solar photovoltaic resources to mitigate power output variability, reducing the strain on local grids and lessening the reliance on balancing power in high-penetration renewable energy systems. This critical role of providing stability can be effectively fulfilled by run-of-river hydropower plants, which can complement fluctuations without compromising their standard operational capabilities. In this research, we employ a straightforward energy balance model to analyze the feasibility of a 100 MW virtual hybrid power plant, focusing on the northern region of Portugal as a case study. Leveraging actual consumption and conceptual production data, our investigation identifies a specific run-of-river plant that aligns with the proposed strategy, demonstrating the practical applicability of this approach.

Keywords: wind power; solar photovoltaic power; variable renewable energy systems (vRES); renewable generation complementarity; renewable deployment scenarios; renewable large-scale integration; hybrid central; virtual central power; ROR storage

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1. Introduction

In the age of imperative and policy-driven energy transition, characterized by the shift from fossil fuel-based primary resources and power plants toward the widespread adoption of renewable energy sources, such as wind turbines and solar photovoltaic technologies, the need to reduce dependence on gas and address the inherent challenges of wind and solar energy systems has become paramount. The primary hurdles to their large-scale integration into power systems and competitive trading in electric energy markets are their reduced or non-dispatchable nature and the unavailability of on-demand storage for their primary resources.

Energy policies aimed at decarbonization align with the European Green Deal's ambitious target [1] of reducing greenhouse gas emissions by 55% by 2030 and achieving climate neutrality by 2050. These policies underscore the importance of advancing renewable fuels and clean energy technologies across various sectors. While significant investments have been made in research and development of renewable technologies, the integration of both conventional and emerging technologies at the process or system level is a critical [2] yet essential step that requires further exploration to facilitate the energy transition.

The integration of variable renewable sources (vRES), such as wind and solar photovoltaics (PV), into the electrical system is complex due to their limited controllability and, in some cases, non-dispatchability. To enable the higher penetration of technologies harnessing clean energy sources and address the temporal and spatial disparities between generation and demand, energy storage and/or energy carrier transportation offer potential solutions. Energy storage systems provide flexibility to energy system strategies and facilitate smart interoperability solutions. Notably, thermal and electrical energy storage systems are considered essential [2] components in achieving ecological transition goals.

The concept of "Power-to-X" encompasses energy carriers in the context of renewable fuels and energy storage, including the chemical production of hydrogen or ammonia. It presents a viable option for the large-scale integration of renewable generation and long-term energy storage, as well as for balancing variable renewable energy and system integration [3,4]. Excess energy generated by vRES units can be used to power technologies like batteries or hydrolyzers, creating energy carriers that can be employed not only for electric power system balancing but also as feedstock for the chemical industry or transportation fuels.

In this study, we focus on the utilization of energy storage units to time-shift vRES generation within a virtual power plant setting. Specifically, the excess power generated by the combined solar photovoltaic and wind power units is regulated by a run-off-river (ROR) power plant, which modulates and reduces its generation, conserving potential upstream water energy. In cases of vRES generation deficits, the ROR plant can provide supplementary power. By leveraging the controllability and storage capacity of ROR plants, local balancing strategies can be implemented, enabling higher vRES penetration.

This research delves into the storage capacity of ROR plants and their potential synergies with the variability of "wind + solar PV" generation within a specific region. We characterize their potential operation using an aggregated and synergistic operating strategy for short time scales, employing a deterministic energy balance model. Wind resources exhibit variability on both short and long time scales, often following a well-defined daily profile influenced by geography. Solar resources exhibit pronounced daily fluctuations, seasonal variations, and sensitivity to cloud cover. The depletion of solar resources during late daylight hours, coinciding with peak electric demand, necessitates increased balancing energy production, such as hydroelectric power or operational reservoirs. Maximizing the efficiency of the production-storage-utilization process for integrating vRES remains a key research challenge in the current energy transition era.

Approximately 30% of Portugal's hydroelectric capacity is derived from run-off-river (ROR) technology [5], making it a compelling candidate for exploring its potential role in bridging the gap between demand and vRES profiles. ROR plants exhibit seasonal variability, primarily due to variations in water flow, which is less noticeable on a daily scale.

A virtual power plant (VPP) serves as a representation of spatially dispersed renewable power plants, allowing for the creation of an operating profile that combines each renewable technology with its specific constraints. Equipped with a dispatchable plant or an energy storage unit, a VPP can emulate the behavior and properties of conventional dispatchable power plants [6]. The concept relies on aggregating and managing distributed primary energy resources and associated conversion technologies. A similar concept, often referred to as a hybrid power plant, is characterized by connecting all generating groups to a common point of connection [7–9]. While not always economically competitive with traditional fossil fuel-based energy production [10], environmental considerations make virtual and hybrid power plants a compelling alternative for meeting energy demand.

Several methods can be employed to optimize the sizing of different vRES units [9–11], representing a current challenge in portfolio definition.

This study explores a dispatchable hybrid power plant, combining an optimized proportion of wind and solar photovoltaic power, which can be marginally complemented by a ROR hydro plant. While the complementarity of wind and PV resources has been demonstrated for certain regions of Portugal [12], where wind generation tends to peak during nighttime, the hourly consumption profile still necessitates an auxiliary component [12]. A detailed review of literature on optimization methods, objectives, and applications of hybrid wind and PV power systems is provided elsewhere [9,13] and falls outside the scope of this work.

Energy storage in batteries has gained widespread adoption in conjunction with variable renewables and their combinations [9]. A decision-aid stochastic algorithm was developed to optimize the bidding strategy for aggregating wind and solar PV in a virtual power plant equipped with batteries [7,12,14]. Earlier combined power plants, such as the *Kombikraftwerk* project in Germany [15], showcased the potential to entirely match demand with solar PV and wind production, backed by biogas and storage, although without considering hydropower. These projects demonstrated grid stability in a renewable virtual power plant. The transition to cost-efficient integration of distributed energy resources into power systems through VPPs has been addressed by researchers [6,16], emphasizing their environmental benefits.

While aggregation of vRES with hydropower plants is frequently reported [11,17–19], including those with reservoirs and pumped hydro storage (PHS) [17], the utilization of run-off-river (ROR) hydropower plants has not been extensively studied. Table 1 summarizes the balancing techniques as described in the literature. ROR plants, lacking dams, are less flexible than PHS facilities, making them an underexplored option for vRES integration, although enhancements to their operation have been proposed, such as incorporating battery energy storage as in a Swedish case study [20]. The complementary use of vRES and a run-off-river station was economy-modeled along with an upstream PHS [21]. Risk to benefit was taken into consideration in a strategy for the use of cascade hydropower in a nested operation with an optimized mix of wind and PV [11]. The complementary use of ROR generation to balance wind power production has been studied and suggested for the case of Germany [22]. Polish ROR plants were analyzed in conjunction with PV in a small local hybrid energy system, and the accumulation of water in Polish ROR plants for compensating variable energy output from wind and PV power was also suggested [23], although finding a prohibitive needed size of the reservoir and a solution with a pumping installation to a pondage is envisaged. However, no study was found regarding the application of a hybrid run-off-river arbitrage to balance the spatially distributed mix of wind and solar photovoltaic plants. A recent study on hybrid wind plus PV plus water along the Yalong River in China [11] concluded that run-off-river plants without power control capacity could not effectively complement vRES variability. Some European ROR plants, however, do possess some regulation capacity, aligning with the aim of this current work.

This document presents the rationale for the energy balance of integrated wind and photovoltaic resources aided by a run-off-river hydropower plant within a conceptual region of Portugal. It is followed by a review of similar studies, descriptions of the model and data used, discussions of the obtained results, and, finally, conclusions.

Table 1. Description of literature techniques for balancing VRES.

vRES Balancing Technique	Description	Reference
vRES + biogas	Proves entirely match demand with solar PV and wind production, backed by biogas and storage in Kombikraftwerk project. Does not consider hydropower.	Barnham, 2013 [15]
vRES + batteries	Stochastically optimized to solve optimal bidding strategy on the aggregation of wind and solar PV in a virtual power plant equipped with batteries. Does not consider hydropower.	Estanqueiro, 2022 [14]
vRES + ROR	A storage 1 MW ROR plant to balance wind power or photovoltaic generation is economically discussed. Reduces overall production by varying the water level by 30 cm peak-to-peak in German plants. Does not consider wind—solar aggregation.	Hase, 2021 [22]
	A mathematical model for a Polish hydroelectric power station ROR with pumping installation shows that it is possible to reduce the overall installed capacity. The pumping is indispensable and mainly usable on a small scale, or the pondage sizes turns prohibitive. Does not consider a non-pumping ROR.	Jurasz, 2018 [23]
	Optimization for a cascade hydropower station complementing wind and PV along the Yalong River in China, well above GW concluded that run-off-river plants without regulatory capacity could not effectively complement the forecast error of vRES output. Does not consider one single hydropower station.	Wen, 2022 [11]

2. Materials and Methods

2.1. Modeling for Variability Compensation

To address the potential compensation of resource variability, an empirical approach was employed for the selected conceptual case study. The objective was to optimize the complementarity between wind and solar photovoltaic (PV) generation, referred to as variable renewable energy sources (vRES), and evaluate their aggregate variability in conjunction with the limited dispatchability offered by a run-off-river (ROR) hydroelectric plant.

2.2. Load Profile

A load profile was constructed based on 2015 yearly national consumption data [24,25]. Hourly average sampling data were used, normalized to 80% of the assumed installed power capacity of 100 MW for the conceptual case study. The resulting load profile is depicted by the red line in Figure 1.

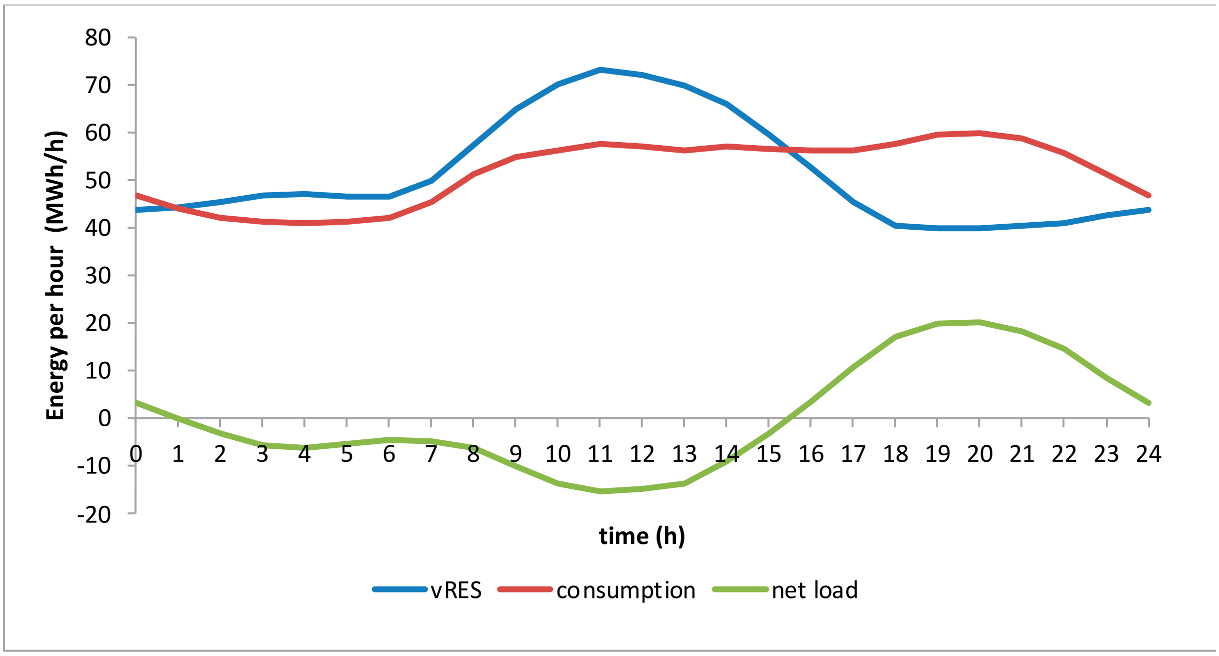


Figure 1. Daily profile of vRES generation, consumption, and net load.

2.3. Variable Renewable Energy Sources (vRES)

An energy management model was developed to handle the combined production of wind and solar PV, assuming that their production is not dispatchable, unlike the ROR hydroelectric plant. The installed capacity was distributed between these vRES sources.

2.4. Wind Power

Hourly wind production data were calculated from real data for the reference year of 2015, referencing a wind farm in the interior of the north region of Portugal [24,25].

2.5. Solar PV

Hourly solar PV generation data were obtained using PVGIS [26] and later normalized to a location near the considered wind power plant. Assumptions were made regarding the optimal slope and azimuth for a crystalline silicon panel with a 10% system loss, as well as the capacity factor and nominal power.

The analysis revealed a strong negative cross-correlation (−0.62 Pearson coefficient) between daily PV and wind data. This complementarity was further confirmed with annual hourly data of irradiance from the PVGIS database and hourly average wind speed; the correlation of the solar and wind hourly data (for the reference year of 2015) yielded a Pearson correlation factor of −0.62.

To create a 100 MW installed vRES power plant, a suitable proportion of wind and solar PV technologies was determined. Optimization aimed to minimize vRES power fluctuations using hourly sampled data. The optimal mix was found to be 10% PV and 90% wind, while minimizing electric power step changes resulted in a mix of 18% PV and 82% wind. For conservative purposes, a proportion of 20% PV and 80% wind was assumed for this study. This combination reduced the standard deviation to 11 MW, one-sixth of the pure solar production standard deviation, thereby enhancing stability. Figure 1 illustrates the vRES aggregate production for the case under study, along with the net load, representing the difference between consumption and vRES generation.

Daily-scale fluctuations were managed through an energy balance approach, utilizing the vRES production hourly data and the load profile. The fluctuations were addressed with an ROR hydropower plant with marginal storage and additional production capabilities for short time scales.

2.6. Geographical Context

The hypothetical location for the renewable plants in this study was the northern region of Portugal, consistent with the technical data used for the ROR plant analysis. Consumption data were assumed to follow the typical national load profile for the 2015 NPEC reference year. Historical time series data were normalized and applied to the consumption analysis [25].

2.7. Run-Off-River (ROR) Hydro Plant

The daily cycles exhibited by variable renewable energy sources (vRES) and the limited capacity to control the production of run-off-river hydropower plants presented significant constraints. ROR plants, often constructed without reservoirs, rely on a regularization weir of varying size to retain a limited amount of upstream water, facilitating optimal technical management.

For this study, data were sourced from the Carrapatelo run-off-river plant [27], situated along the Douro River in the northern region of Portugal. This plant boasts an installed capacity of 201 MW, equipped with three Kaplan-type turbines [28]. Key characteristics of its water pond are summarized in Table 1. Hourly historical data for water affluence flux are publicly available [27].

2.8. Calculation of Hydroelectric Power Production

Typical efficiencies for Kaplan turbines [29] were considered along with the time series of turbined water flow [27] to estimate the energy produced by the ROR hydroelectric plant, assuming a constant hydraulic head. The hydraulic potential energy is proportional to both the stored volume of water and the height difference between the reservoir level and the turbine, with the latter being assumed as constant, since it only varies about 3% maximum (Table 2). The stored volume is limited to the minimum and maximum volume of the regulation pond. The hydropower production (PH) can be computed using the following equation:

$$P_H(t) = \rho g h \times Q(t) \times \eta(Q) \quad (1)$$

where the following apply:

P stands for power (W);
ρ is the water density, taken as 10^3 kg m^{-3};
g is the gravity constant (9.81 m s^{-2});
h is the useful height;
$Q(t)$ is the time dependent turbinated water volumetric flow;
η is the efficiency of the turbine, which is dependent on flow.

Table 2. Carrapatelo ROR pond main characteristics; data from [27].

Total Volume (10^6 m^3)		Full Storage Level (m)	Minimum Exploitation Level (m)	Hydraulic Head (m)
Minimum	Maximum			
134.6	148.4	46.5	45.0	31

The regulation pond can store up to a maximum of 1.2 GWh in potential energy, with operational limits set to avoid efficiencies below 10% (8% of maximum flow or 1.8 MW) and above 750 m^3 s^{-1} (210 MW). A maximum limiting (flooding) flow of 22,000 m^3 s^{-1} was also assumed. To emulate an energy storage device acting complementarily to vRES generation, a 15% reduction in turbine operation for $Q_{hybrid} < 0$ was assumed.

2.9. Analytical Solutions for Power vs. Flow

Equation (1) is not suitable for analytical solutions of $Q(P)$ due to the efficiency dependency on volumetric flow. Data from the historic series of turbined flow were linearized to obtain $P(Q)$ functions for practical use. For an average hydro year (from 1972 to 2020) [30], the $P(Q)$ relation is expressed as

$$P(Q)_{average} = 0.3552 \times Q(t) - 15.82 \quad (2)$$

For a dry year (2004/2005), the $P(Q)$ relation is expressed as

$$P(Q)_{dry} = 0.2810 \times Q(t) - 14.33 \quad (3)$$

2.10. Hybrid Operation

This study implements two scenarios to achieve instantaneous equilibrium between energy production and consumption. If the net load is positive, indicating that consumption exceeds vRES production, extra generation is called upon to bridge the gap. Conversely, if the net load is negative, meaning vRES production exceeds consumption, the generation of hydro turbines is regulated to balance the excess, storing water in the reservoir.

Energy produced by the ROR plant is computed by integrating historic power time series data [27]. Several restrictions apply, including maximum and minimum admissible water levels in the dams (as specified in Table 1) and limits on turbine power ($1.8 < P < 210$ MW). Beyond these intervals, the energy balance cannot be maintained, and the control of the hybrid wind–hydro plant fails.

The reservoir water volume (V_{dam}) is computed as a balance of the flows using the following equation:

$$V_{\text{dam}}(t) = V_{\text{dam}}(t - \Delta t) + \left[Q_{\text{affluent}}(t) - Q_{\text{planturbo}}(t) - Q_{\text{hybrid}}(t)\right] \times \Delta t \quad (4)$$

where the following apply:

$V_{\text{dam}}(t)$ is the reservoir water volume at time t;
$Q_{\text{affluent}}(t)$ is the river flow at time t;
$Q_{\text{plan turbo}}(t)$ is the planned turbined flow at time t;
$Q_{\text{hybrid}}(t)$ is the hybrid flow at time t;
Δt represents the time interval.

It is important to note that this study primarily serves as a proof of concept, and the focus is on utilizing a simple energy balance model. Monitoring and control aspects are not within the scope of this investigation.

3. Results

This study used the characteristics and tributary flows of the existing Carrapatelo hydroelectric plant, located on the Douro River in the district of Viseu (Portugal), as the basis for the run-off-river hydropower plant model [30]. This simplified approach aimed to investigate the contribution of run-off-river power stations to the operation of a (near) 100% renewable electrical system with a substantial component of variable renewable energy sources (vRES). In this conceptual framework, it was assumed that it was possible to control the power output of the hydro groups as a function of vRES generation and local consumption needs.

The study's operational approach involved calling upon the run-off-river (ROR) plant in response to the net load, which represents the difference between consumption and variable renewable energy sources (vRES) generation. Depending on whether the net load was positive or negative, different actions were taken.

3.1. Positive Net Load (Consumption Exceeds vRES)

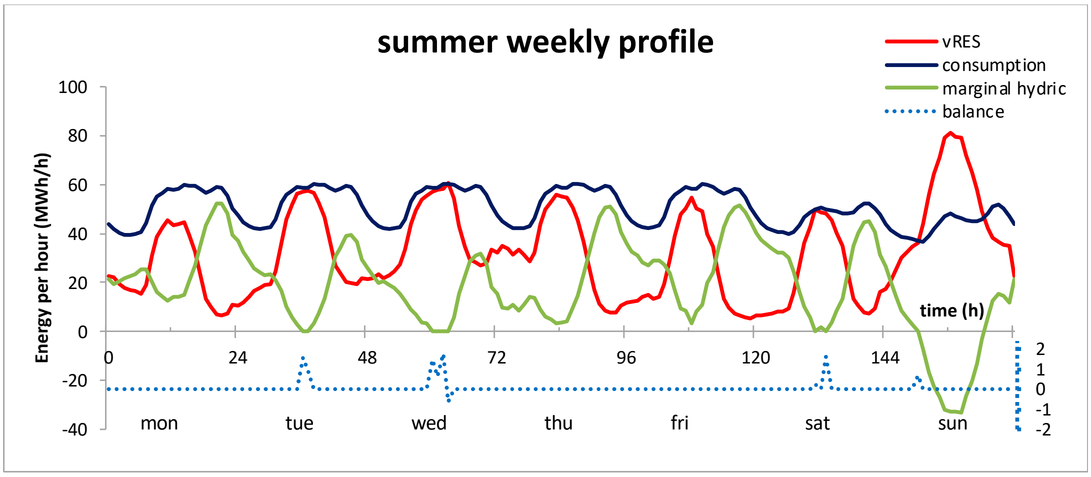
In this scenario, when consumption exceeded vRES generation, the ROR plant was called upon to generate the necessary electricity to meet the shortfall.

3.2. Negative Net Load (vRES Exceeds Consumption)

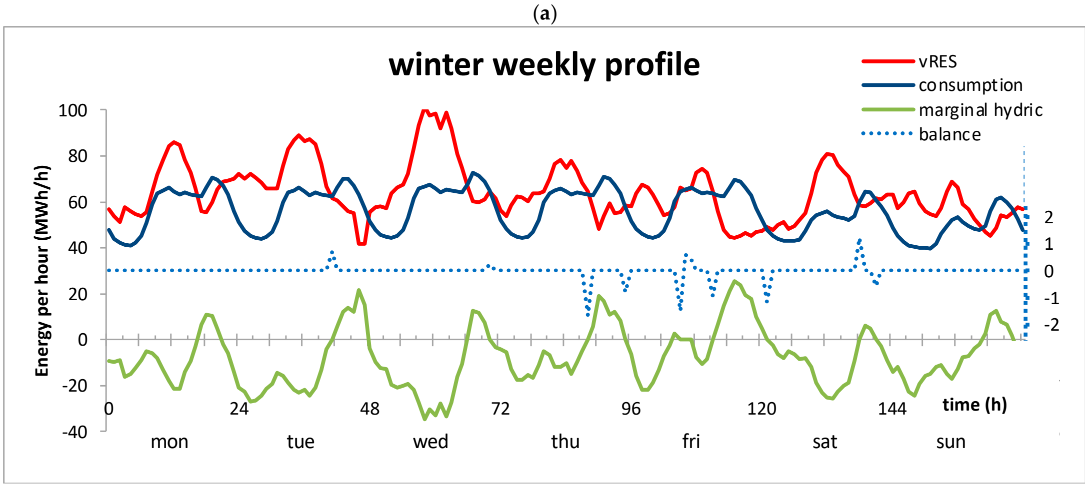
When vRES generation exceeded consumption, the ROR hydro plant retained (stored) the excess energy by controlling its production downward.

Physical limits were considered for both excess hydropower generation and water levels. Water level calculations were based on subtracting the planned and differential flows from the affluent flow.

The study's findings led to the conclusion that the autonomous system concept could maintain a null average value of the net load in the region under study on a daily scale. This means that it ensured a perfect balance between production and consumption on an hourly average basis, displaying a zero in the balance lines of Figure 2. A positive balance value represents the number of excess hours, and a negative value represents insufficient hours.



(**a**)



(**b**)

Figure 2. Average energy per hour in a weekly profile for the extreme seasons: (**a**) summer and (**b**) winter in an average year.

Figure 2 presents the weekly consumption and generation profiles of the vRES and ROR plants for two extreme seasons, winter and summer, during a typical hydrologic year (calibrated using 2015 data).

Analyzing the results for both summer and winter weeks, several key observations were made.

3.3. Summer Scenario

Except for certain periods, such as Sundays and occasional short intervals, vRES production alone was insufficient to meet local consumption demands during the summer season. This necessitated support from the ROR plant to achieve the goal of autonomous and balanced system operation. However, achieving this objective was not always possible due to limitations in river flow, particularly during periods of reduced water inflow.

3.4. Winter Scenario

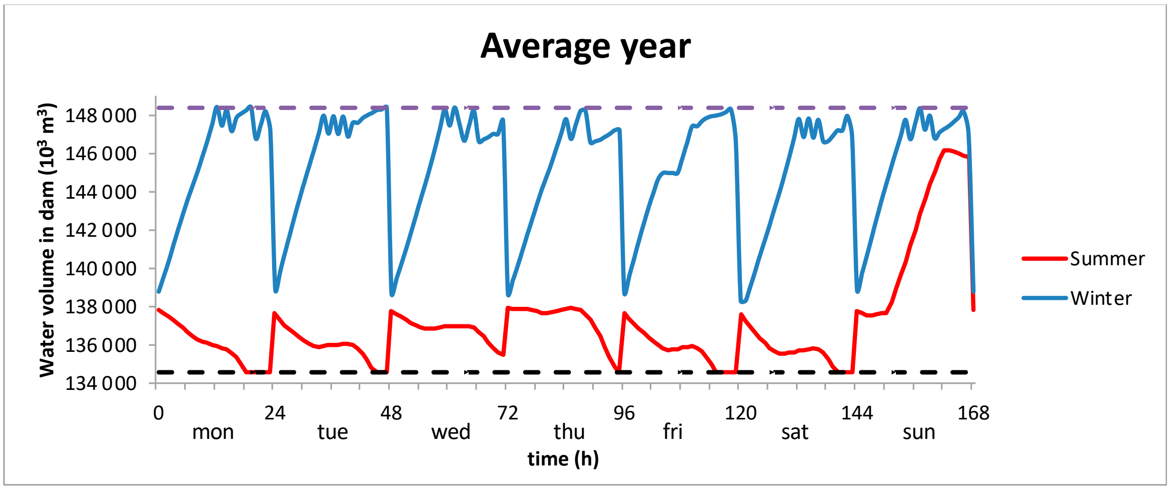
In contrast to the summer situation, during winter, the balance between vRES production and consumption was generally maintained with little significance. Only in occasional situations was this balance not guaranteed by the ROR hydro plant, and these instances involved relatively small amounts of energy.

For a dry year, where water flow influence on hydropower was adjusted according to Equation (3), the results were consistent with the previous findings. Even in a dry year, the ROR plant remained suitable for the intended purpose. The moments of imbalance, represented by dotted lines in the graphs, did not exceed 2 MWh/h and were primarily due to imposed restrictions on operation limits, specifically a minimum net charge to surpass the low turbine efficiency. Relaxing this minimum charge requirement would eliminate such limitations.

Overall, this study demonstrated the potential of using a combination of vRES and ROR hydro generation to achieve a balanced and autonomous electrical system, even in challenging scenarios such as periods of low water flow.

3.5. Key Findings

The study's most significant findings, applied to years with varying hydrological conditions, highlight the capability of the regulation weir of the run-off-river (ROR) plant to ensure water storage and perform arbitrage on a daily scale in response to the combined variability of "wind + solar PV". This capacity is essential for achieving a balanced energy system without exceeding the technical water limits of ROR plant operation, as detailed in Table 1 and represented in Figure 3 for both an average year and a dry year.



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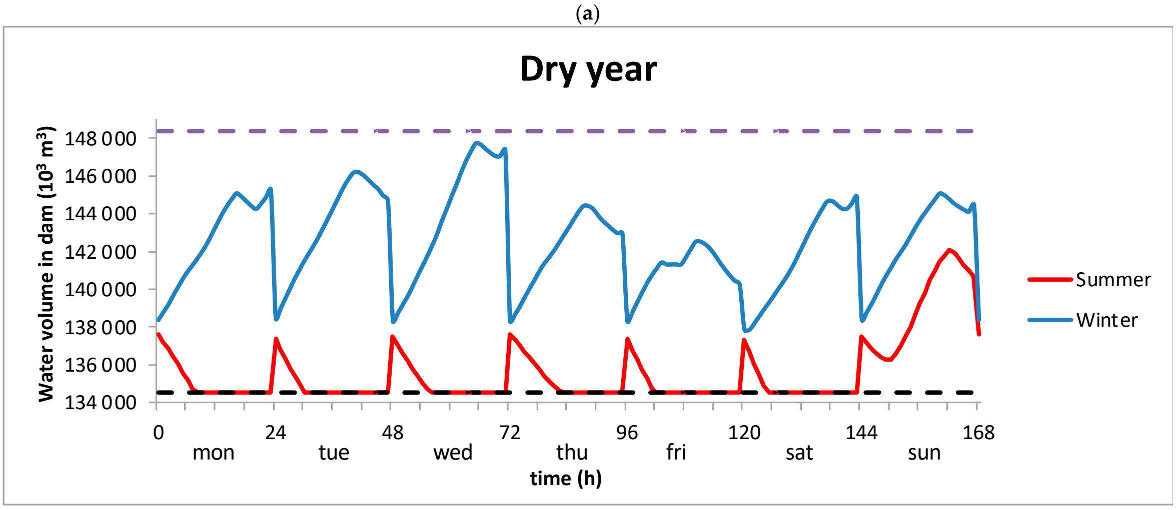

(**b**)

Figure 3. Profiles of water volume in the run-off-river reservoir for a winter (blue line) and a summer (red line) week of (**a**) an average and of (**b**) a dry year, bounded by the minimum and maximum operating levels assumed (dashed lines).

For an average year, the optimal operation of the Virtual Power Plant (VPP) results in frequent water discharges during wintertime, primarily to prevent the volume of the reservoir from exceeding its limits. However, there is enough capacity to complement vRES generation during this period, with only a few hours of potential insufficiency during summer days.

In a dry year, which poses challenges due to water scarcity, the water volume is sufficient for the intended purpose during winter (as indicated by the blue curve in Figure 3). However, during summer days (as shown by the red curve), the reservoir may not have adequate water supply to support vRES generation. Only on dry summer Sundays does vRES generation comply with the ROR's regulation due to insufficient water in the dam.

It is worth noting that this study's approach is deterministic and simplified in several aspects. Nonetheless, the results are highly interesting and warrant further exploration, especially in the context of the accelerated transition toward nearly 100% renewable energy systems (RES). Portugal, with its significant installed water capacity and the considerable size of some of its regulation dams, is currently experiencing this transition. These findings suggest that ROR plants can play a valuable role in optimizing the integration of vRES into the energy system, even in challenging scenarios like dry years. Further research and refinement of these strategies could enhance the resilience and sustainability of renewable energy systems.

4. Conclusions

In this study, a conceptual hybrid variable renewable power plant was developed by combining the two dominant forms of variable renewable energy (vRES) generation: solar photovoltaic and wind power, along with a semi-dispatchable (within technical limits) run-off-river (ROR) hydropower plant for arbitrage. The vRES plant had an installed capacity of 100 MW and was located in the northern region of Portugal. This study used historical consumption data from 2015 to design a local energy community where the vRES generation system was complemented by a 201 MW ROR power plant for balancing purposes within the same region and network.

The simulation, based on a typical meteorological year, yielded the following conclusions:

- Daily Net Zero Balance

On a daily basis, the local energy network was capable of maintaining a net zero balance between production and consumption. However, due to strong weekly consumption patterns, there were deviations in seasonal profiles, mainly attributed to the operational limits imposed on the hydro turbines.

- Seasonal Variations

Seasonal simulations revealed that wind and hydro resources were less available during the summer season, resulting in a higher demand for the operation of the hydro plant. ROR hydro storage between seasons was not feasible due to the small size of the reservoirs, which primarily served flow regulation purposes. To overcome summer deficits, potential solutions included the installation of dedicated batteries, increasing PV capacity, or implementing demand-side management (DSM) strategies.

- Dry Year Resilience

Even in the scenario of a dry year, where water availability was limited, vRES generation continued to achieve a net zero balance for all winter days.

- Promising Concept

This study demonstrated that using an ROR plant for daily arbitrage in a hybrid variable renewable power plant showed promise for the case studied. This approach allowed for the integrated and synergistic operation of wind, solar PV, and hydropower within a (near) 100% renewable power system while minimizing the need for additional energy storage units.

In conclusion, an ROR hydropower station having no pumping facility does not have a high storage potential. Nevertheless, the concept of combining wind, solar PV, and ROR hydro for daily energy arbitrage holds the potential for creating sustainable and balanced renewable energy systems at low capital expenditure. The capacity of the ROR pond being critical, adding other storage technologies, such as pumping water, storing electric energy in batteries, storing heat, or using excess energy to electrolyze water into green hydrogen, are interesting solutions, although more costly and beyond the scope of this work. The first approach choice of 100 MW of installed vRES capacity could also be optimized in the next iteration. Further research and exploration of this approach, including optimizations and real-world implementations, could contribute to the transition toward a more sustainable energy future.

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