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Integration of Floating Photovoltaics and Pumped Hydro Energy Storage with Water Electrolysis for Combined Power and Hydrogen Generation

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Abstract. This study proposes a floating photovoltaic - pumped hydro energy storage system integrated with a water electrolyzer for combined power and hydrogen generation. Compared to solutions without electrolyzers, this integrated system is able to further mitigate the non-programmable photovoltaic generation and simultaneously decarbonize hard-to-abate sectors. The performance of the integrated system is herein studied on daily, monthly, and yearly bases using a mathematical model with a 1-hour time resolution for a real case represented by a pumped hydroelectric energy storage system in Sardinia. The study considers integrating the existing system with a 11 MW floating photovoltaic system and a 4 MW PEM electrolyzer, appropriately sized to achieve a hydrogen production target of 100 tonnes per year and a photovoltaic self-consumption not below 95%. The power used for pumping water and producing hydrogen is 100% renewable, as it is supplied solely by the floating photovoltaic plant, and the electricity is fed in the grid at night, aiming to increase the share of renewables in the nighttime energy mix of the Sardinia region. Results show that the integration provides significant benefits to the grid, with 8.5 GWh/year of nighttime inertial feed-ins. Moreover, since the integrated plant is characterized by annual self-consumption values of photovoltaic generation around 97% and monthly values never below 93%, the negative impact caused by its non-programmable feed-ins on the grid is minimal. Hydrogen production, capable of replacing approximately 0.1% of the current yearly fossil fuel-based thermal demand of the regional industrial sector, exhibits strong seasonality, with daily production averaging 65 kg/day during winter months and over 7 times more (465 kg/day) during summer months, suggesting the opportunity for a seasonal storage.

1. Introduction

Due to increasing concern over climate change and the need to decarbonize various sectors, global efforts towards the transition to Renewable Energy Sources (RES) are increasing. According to the International Energy Agency (IEA), global energy-related CO_2 emissions have reached a new record of 37.4 Gt in 2023, mainly driven by the combustion of fossil fuels for energy production, industrial processes, and transportation [1]. Therefore, to reach full decarbonisation and meet the Net Zero emissions requirements [2], greater efforts are required to reduce greenhouse gas emissions also in the so called hard-to-abate sectors.

The shift from fossil fuels to RES will be mainly driven by wind turbines and solar photovoltaic (PV) systems [3]. However, the intermittent nature of these variable RES (VRES) sources poses significant challenges to grid stability [4] and management [5]. Consequently, the growth of VRES requires the concurrent development of strategies [6] to effectively mitigate their negative effects on grid flexibility [7,8] to the point that grid-oriented performance indicators for the power plants are being increasingly proposed [7]. These strategies are mainly based on hybrid configuration [9–13] and on the integration of RES power generation plants with Energy Storage Systems (ESS) [14]. In particular, an interesting option to store the overgeneration of PV systems is their integration with Pumped Hydroelectric Energy Storage (PHES) plants, which currently represent 96% of global energy storage capacity [15] and in 2023 reached about 1.4 TW of installed power [16]. What is more, these PV-PHES integrated systems could benefit from the use of floating PV (FPV) panels instead of ground-mounted (GPV) panels. FPV systems are directly mounted on floating water structures, this way allowing reduced soil occupation, reducing panels' maintenance and damage, and benefiting from an efficiency increase due to the water cooling effect [17].

Such PV-PHES systems already operate in some areas of the world and are expected to increase widespread in the future. However, the integration of PV and PHES systems in electrical grids characterized by high penetration of VRES can be challenging. In fact, when PV generation is outside the operational range of PHES pumping groups or when reservoirs reach maximum capacity, these systems may face partial or complete PV curtailment, resulting in clear economic and environmental drawbacks. To reduce the share of this unwanted PV curtailment, an interesting option is given by the production of hydrogen by means of water electrolysis processes powered by the PV surplus power [18]. Green hydrogen can be a very useful option to decarbonize hard-to-abate sectors by substituting fossil fuels [19]. Moreover, according to Kanellopoulos et al. [20], blends up to 10% of hydrogen in volume can be distributed in existing gas networks without modifications and only minimal changes are required for blends up to 15-20%.

For this reason, the novelty of this work lies in including an additional section to the FPV-PHES conventional system configuration, aimed at reducing generation curtailment and supporting decarbonization of hard-to-abate sectors. This is achieved through the introduction of a PEM electrolyzer for green hydrogen production, powered by the FPV surplus power. This integrated FPV-PHES-PEM system exhibits significant flexibility characteristics. In fact, the electrolyzer can be sized according to local hydrogen requirements, while the FPV system can be tailored to achieve given levels of Self-Consumption (SC). Moreover, if the electrical grid to which the FPV-PHES-PEM system is connected already faces management challenges due to high levels of VRES penetration, the FPV can be sized for SC values around 100%.

Specifically, this study refers to a case study based on the Tirso 1 PHES plant in Sardinia, which is currently under development. The performance of the FPV-PHES-PEM system is evaluated under the assumption of producing at least 100 tonnes of green hydrogen per year (equivalent to about 0.1% of current fossil fuel-based thermal consumption in the industrial sector of Sardinia, Italy) while simultaneously achieving a SC of at least 95%.

2. Methods

The present study analyses the performance of the integrated FPV-PHES-PEM system with reference to a case study represented by the hydroelectric power plant (HPP) "Tirso 1" operated by ENAS (the Sardinian water management public company) in Sardinia, Italy [21]. The HPP is based on a Francis turbine and uses the water of the Tirso river collected in the Omodeo lake by the Eleonora D'Arborea dam. Downstream the Tirso 1 plant, the Santa Vittoria dam collects the water at the outlet of the hydro turbine as well as the water of the Flumineddu river. The Santa Vittoria reservoir is equipped with a pumping group (Pranu Antoni pumping station), which was designed to pump water of the Flumineddu river from the lower reservoir to the upper reservoir during periods of severe drought, but for cost reasons, the pumping station is rarely used. However, a project to convert the Pranu Antoni pumping station and the hydro turbine into a PHES system is currently in progress and this configuration is considered as the base for the present study.

Therefore, the considered PHES plant consists of an upper reservoir, a lower reservoir, a Francis turbine, and a pumping system. The turbine has a nominal power of about 20 MW, while the pumping station includes 6 electric pumps that can operate individually or in parallel with a power range from 600 kW to 6 MW. Table 1 reports the main characteristics of the PHES plant.

Table 1. Tirso 1 PHES plant design parameters.

Component	Parameter		Value	Unit
Upper reservoir	Authorized capacity	V_{UP}	420	10^6 m^3
	Elevation	h_{UP}	105	m a.s.l.
Lower reservoir	Authorized capacity	V_{DOWN}	9.5	10^6 m^3
	Elevation	h_{DOWN}	45	m
Francis hydraulic turbine	Rated power	$\dot{E}_T$	21.2	MW
	Rated flow	$\dot{V}_T$	108,000	m^3/h
	Useful head	h_T	78.2	m
	Nominal efficiency	η_T	0.94	-
Electropump type 1	Number of installed pumps	-	2	-
	Rated power	$\dot{E}_{P1}$	627.55	kW
	Rated flow	$\dot{V}_{P1}$	2,250	m^3/h
	Rated head	h_{P1}	80.5	m
	Nominal efficiency	η_{P1}	0.78	-
Electropump type 2	Number of installed pumps	-	4	-
	Rated power	$\dot{E}_{P2}$	1,204.8	kW
	Rated flow	$\dot{V}_{P2}$	4,320	m^3/h
	Rated head	h_{P2}	80.5	m
	Nominal efficiency	η_{P2}	0.78	-

In this study, the described PHES plant is considered to be integrated with a FPV power generation plant, and the schematic configuration of the overall FPV-PHES-PEM system is reported in Figure 1, where the main energy flows are also shown. Apart from the hydrogen generation, the introduction of the hydrogen production section also allows to reduce the imbalances on the power grid caused by the FPV-PHES system. In particular, with reference to the energy flows shown in Figure 1, the FPV system primarily charges the PHES system ($E_{FPV\ TO\ PHES}$), secondarily the PEM electrolyzer ($E_{FPV\ TO\ PEM}$) and lastly (only in a residual manner) feeds power into the grid ($E_{FPV\ TO\ GRID}$). In this way, the integrated system can decouple FPV electricity production from feed-ins, as well as produce hydrogen for external uses. As shown by Figure 1, hydrogen is generated through a PEM electrolyzer, while the electrical energy supplied to the grid ($E_{PHES\ TO\ GRID}$) is generated by using the water stored in the upper reservoir to drive the Francis turbine. Moreover, $E_{PHES\ TO\ GRID}$ is fed to the grid only during dark hours (starting immediately after the sunset), with a constraint on the minimum time of continuous operation of the Francis turbine set to 8 hours. This discharge strategy, chosen for increasing the share of renewables in the nighttime energy mix of the Sardinia region, ensures a consistent and continuous feed-in of inertial and predictable power into the electrical grid for a duration sufficient to cover a significant portion of average nightly hours throughout the year. However, it is important to note that the reactivity and flexibility of PHES systems allow for adapting the discharge strategy according to the needs of the grid, in order to also provide a variety of ancillary services, including peak shaving, spinning reserve, grid stabilization and regulation [22].

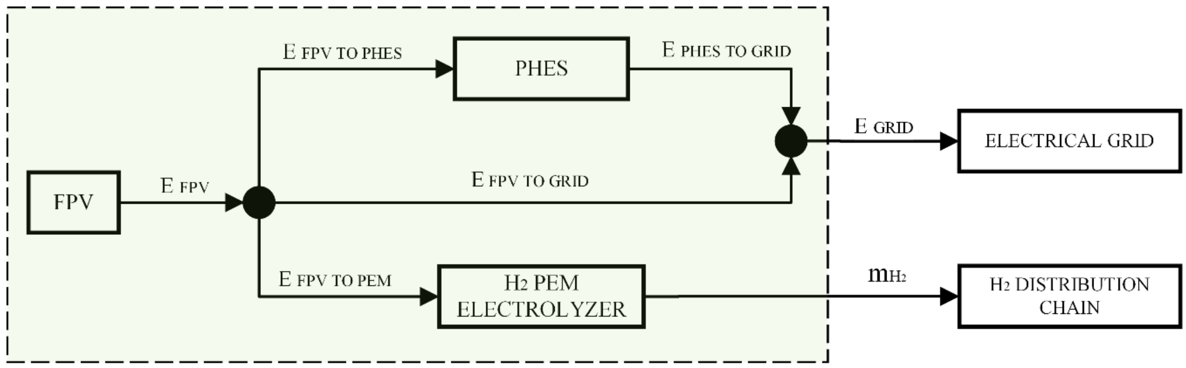

Figure 1. Energy and mass flows of the integrated FPV-PHES-PEM system.

The mathematical model for the integrated FPV-PHES-PEM system was developed using the software MATLAB version R2024a [23] and simulations were carried out throughout one year and with a time step of 1 h.

As abovementioned, the system input energy is provided by a FPV system, based on commercial 500 W monocrystalline silicon cell modules [24], characterized by a nominal conversion efficiency of 21.1 %. The power generation of the FPV plant was calculated according to Liu et al. [25] considering the increased efficiency of FPV systems over GPV reported by Ranjbaran et al. [26]. The electricity production was estimated considering the input parameters and correction factors reported in Table 2 and the weather data for the "Tirso 1" location, obtained using the software Meteonorm version 7.2 [27]. As shown in Figure 1, the FPV system powers both the pumping and the PEM electrolyzer systems.

As mentioned, the pumping system of "Tirso 1" already exists, and it was herein assumed not to be modified. Since it is not equipped with inverters, flow modulations occur based on the number and type of pumps activated. Therefore, to exploit the utilization of FPV power most effectively, the combination of type and number of pumps operating at each time interval was herein optimized. Furthermore, since the head required by the pumping system is practically unaffected by the water level of the reservoirs (there is only a 7-meter elevation difference between full and empty lower reservoir levels), it was assumed that each pump operates always under average conditions between its maximum and minimum required head.

Regarding the PEM electrolyzer, its performance was calculated by means of a steady-state model, whose detailed description can be found in [28] and under the assumptions reported in Table 2. In particular, starting from the calculation of the cell voltage and the overpotentials, the hydrogen production is estimated using the Faraday Law based on the operating current. Furthermore, it was assumed to use an electrolyzer array with various power levels to maximize the utilization of the PV power without penalization due to deep partial loads.

Table 2. FPV and PEM design parameters.

Component	Parameter	Value	Unit
FPV system	Nominal power of a PV module [24]	500	Wp
	Tilt angle*	10	°
	Azimuth angle	0	°
	Conversion efficiency [24]	0.211	-
	Nominal inverter efficiency	0.98	-
PEM electrolyzer	Nominal power of the PEM module [29]	2	MW
	Specific energy consumption	59	kWh/kg
	Operating temperature [29]	40	°C
	Operating pressure [30]	30	bar
	Pump and heater energy consumption on total	0.3	%

* Reported by Farrar et al. [31] as the best option for FPV systems.

The discharge phase of the PHES section of the integrated FPV-PHES-PEM system was considered to be carried out employing the existing "Tirso 1" turbine. To always operate at peak efficiency, the turbine power output was calculated considering a fixed volume flow rate equal to 80% (24 m^3/s) of the nominal flow rate, while the hydraulic head varies based on the volume of water stored in the upper reservoir.

3. Results and Discussion

The performance of the FPV-PHES-PEM system was evaluated for a typical year under the assumptions summarized in Table 3. As one of the novelties of the proposed configuration is the possibility of decarbonizing hard-to-abate sectors, a production of at least 100 tonnes of green hydrogen per year was assumed. The latter production would allow to replace about 0.1% of the current fossil fuel-based thermal consumption in the industrial sector in the region of Sardinia, Italy [32]. At the same time, considering that the FPV-PHES-PEM system is designed to minimize the negative impact of VRES on the electrical grid, the following yearly Self-Consumption (SC) index of the energy generated by the FPV system has been evaluated:

$$SC = \frac{E_{FPV\ TO\ PHES} + E_{FPV\ TO\ PEM}}{E_{FPV}} \quad (1)$$

The SC index is assumed here to be no less than 95% and the reservoirs' capacity as of January 1st and December 31st were considered coincident. Under these assumptions, it was calculated a size of 11 MW for the FPV system and 4 MW for the PEM electrolyzer.

Table 3 Parameters of the FPV-PHES-PEM system.

Parameter	Value	Unit
FPV nominal power	11	MW
PEM electrolyzer nominal power	4	MW
PHES turbine run time (duration of each discharge cycle)	8	hours
Upper/Lower reservoir capacity as of January 1st.	420 / 3	10^6 m^3
Upper/Lower reservoir capacity as of December 31st.	420 / 3	10^6 m^3
Yearly green hydrogen production	>100	tons
SC of FPV yearly energy production	>95%	-

Apart from the SC rate, the performance of the system is herein evaluated in terms of energy and mass of hydrogen generated. The energy associated with hydrogen has been calculated considering a Lower Heating Value (LHV) of 120 MJ/kg. Given that, the performance of the FPV-PHES-PEM system is first discussed for a typical day during summer and winter, then aggregated on a monthly basis and finally on an annual basis.

3.1 Daily performance (winter and summer days)

Figure 2 shows the difference in energy flows and system performance between a typical winter day (Figure 2a and Figure 2c) and a typical summer day (Figure 2b and Figure 2d). According to the energy management strategy, priority is given to the PHES system (in blue), subsequently to the PEM electrolyzer (in orange), while the remainder (in yellow) is fed to the grid. After the sunset, the power is fed to the grid by means of the PHES turbine (in purple).
Although the FPV power available during the winter period (Figure 2a) is significantly lower compared to the summer period (Figure 2b), it is still sufficient to power the PHES pumping system ($E_{FPV\ TO\ PHES}$) in both days, albeit with differences in power levels and duration. Clearly, the residual FPV energy available for powering the PEM ($E_{FPV\ TO\ PEM}$) is much lower during the winter day, leading to the seasonal trend in hydrogen production (Figure 2c and Figure 2d) discussed in Section 3.2. The full capacity of the PEM electrolyzer is reached during the central hours of the summer day, with a hydrogen production of around 70 kg/h (Figure 2d), while in winter it reaches approximately 40 kg/h (Figure 2c). Direct feed-ins ($E_{FPV\ TO\ GRID}$) do not occur during the winter day (SC=1 for the entire day), while they reach values of up to 2 MWh/h during the summer day, with a corresponding SC minimum value of about 0.8 (Figure 2b). Finally, with reference to nighttime energy production ($E_{PHES\ TO\ GRID}$), it is evident that the discharge phase in winter begins earlier (at 7 PM) compared to summer (at 9 PM), due to the different sunset times.

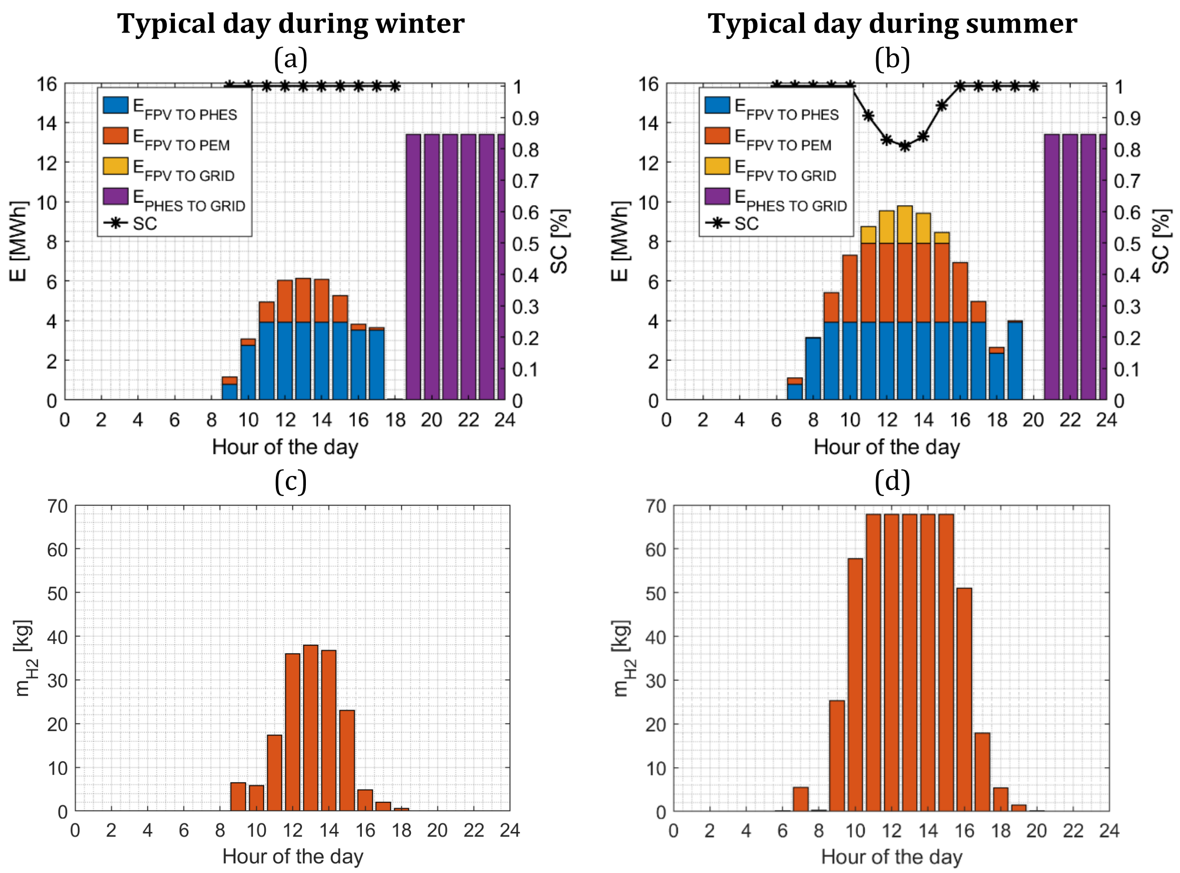

Figure 2. Performance of the FPV-PHES-PEM system for a typical day during winter (a,c) and summer (b,d).

3.2 Monthly performance

Figure 3 reports the performance of the FPV-PHES-PEM system over the 12 months. The system energy input E_{FPV} (Figure 3a) follows the typical trend of FPV productions, peaking in the summer months. Focusing on its components, $E_{FPV\ TO\ PHES}$ increases from 0.65 GWh/month in the winter months to roughly 1.3 GWh/month in the summer months. $E_{FPV\ TO\ PEM}$, on the other hand, increases from 0.12 GWh/month during the winter months to approximately seven times as much during the summer months (0.83 GWh/month).
The SC index (Figure 3b), which is designed for an annual average value above 95%, falls below this threshold only in May, June, and July (even with values above 93%), while in the other months it is consistently above 95%. What is more, from October to February, the FPV energy is entirely used by the PHES pumping system and by the electrolyzer (SC = 1). Given the assumption of an annual average SC of at least 95%, the solar generation during summer months exceeds the system's capacity. Therefore, as increasing amounts of energy are fed to the grid, the energy self-consumption of the plant decreases below 95%.

With regard to the FPV-PHES-PEM outputs (Figure 3c), the PHES system is capable of providing a minimum electricity production of approximately 0.43 GWh/month, which increases to about 1 GWh/month during the summer months. The monthly trend of hydrogen production, ranging from 2 tons (65 kg/day) to 14 tons (465 kg/day) (Figure 3d) and mainly concentrated during the summer months, suggests the possibility of a seasonal hydrogen storage.

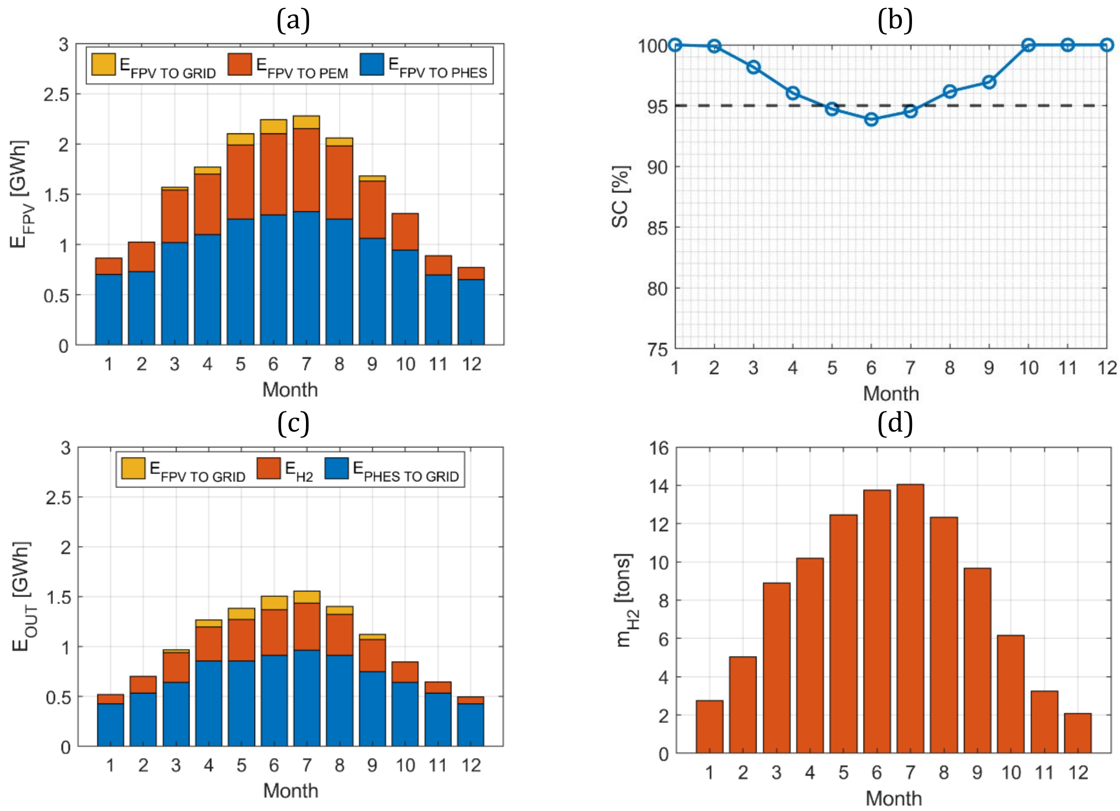

Figure 3. Monthly performance of the FPV-PHES-PEM system.

3.3 Yearly performance

Figure 4 shows the yearly energy flows throughout all the sections of the FPV-PHES-PEM system. As it can be observed, 65% (12.0 GWh) of the energy produced by the FPV (18.5 GWh) is used to power the PHES pumping system, 32% (5.9 GWh) is used to produce hydrogen via the PEM electrolyzer, and only 3% (0.6 GWh) is directly fed to the grid, with a corresponding yearly SC index equal to 0.97. Regarding the latter SC value, it is important to consider that, especially with reference to economic analysis of such investments, if grid conditions do not allow dispatching, these direct feed-ins of energy could be partially or entirely curtailed. Out of the 12 GWh of energy required to charge the PHES system, 8.5 GWh are returned to the grid during the hours of darkness, resulting in a PHES system efficiency of 70%. This efficiency is typical of PHES systems [33].

Out of the 5.9 GWh of energy input to the PEM electrolyzer, approximately 3.4 GWh of hydrogen are produced (100 tons), resulting in a PEM system efficiency of approximately 58%.

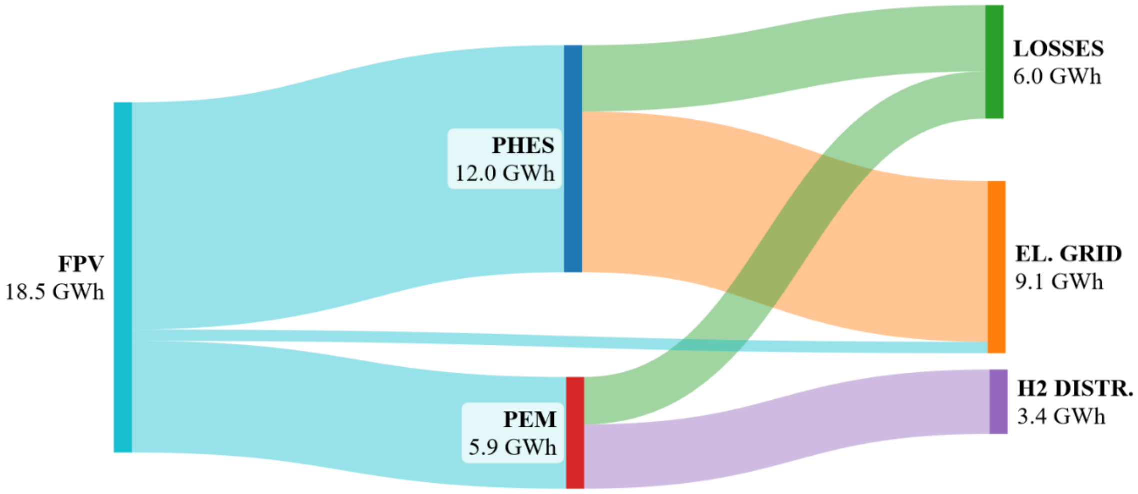

Figure 4. Yearly energy flows of the FPV-PHES-PEM system.

4. Conclusions

This study assesses the performance of a renewable-powered integrated system for combined power and hydrogen generation. The FPV-PHES-PEM system comprises a floating photovoltaic system, a pumped hydroelectric power plant, and a water electrolyser. Starting from an existing hydroelectric plant located in Sardinia (Italy), the proposed plant is designed to produce power and green hydrogen using exclusively renewable energy provided by a FPV plant.

In order to generate 100 tons of hydrogen per year and achieve a self-consumption of at least 95%, a 11 MW FPV system and a 4 MW PEM electrolyzer are required. Given that, a detailed analysis was carried out to determine the daily, monthly and yearly performance of the integrated system, based on the assessment of the energy and hydrogen generation and self-consumption rate.

The results show that the FPV-PHES-PEM can effectively utilize the FPV generation to drive the PHES storage system and generate hydrogen, without negatively affecting the power grid. Specifically, hydrogen production during summer months increases by 7 times compared to winter, reaching 14 tons/month in July. Conversely, the SC is maximum during winter months. These trends highlight the possibility of a seasonal hydrogen storage. On a yearly base, about 65% of the FPV generation is used to drive the PHES system, 32% is used for hydrogen generation, while only 3% is directly fed in the grid. Consequently, for the considered case, the overall SC reaches 97%, allowing to generate about 8.5 GWh of energy from the PHES system during the nighttime hours.

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